Investigation of a system for micro-alignment and assembly manufacturing with respect to laser fine weldability

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Investigation of a System for Micro-Alignment and Assembly Manufacturing with Respect to Laser Fine Weldability

by

Andreas Buenting

Doctoral Thesis

Submitted in partial fulfilment of the requirements for the award of

Ph.D. Mechanical & Manufacturing Engineering of Loughborough University

21\textsuperscript{st} March 2008

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Abstract

Laser beam welding processes, with their inherent potential of controlling the energy input, give rise to new applications with respect to the manufacturing of optical active and compact laser diode beam assemblies. In electronics and fine mechanics, components require increasingly high strength joining technologies to replace the conventional gluing or soldering process. Alternative joining methods for commercial laser diode beam assemblies often reach their limits in terms of product quality and reliability.

The objectives of this thesis, examined by the author, are as follows: The first objective is the development and validation of a semi-automatic laser fine welding station (pulsed Nd:YAG-lasers) with an automatic micro-alignment solution for optomechanical components.

The second objective in the course of this work is the construction and manufacturing of new laser diode beam assembly (LDBA), taking into account the laser weldability of the components. This includes the development of a reliable laser fine welding procedure supported by a FE-analysis of the clamped components during welding.

The LDBA as an optomechanical example consists of a laser diode pigtail with gradient index lens (GRIN) for beam collimation. Beam deviation was reduced by modification of the laser diode (TO-5 case) casing using a special alignment technique (hexapod manipulation) and surface modification.

For the first time, a pulsed fine laser welding process was successfully carried out on thermal and electrostatic sensitive devices. The welding procedure, the adapted clamping technique and the optimised laser and process parameters allowed the thermally induced distortional positioning changes of the separate components to be minimised.

The adjustment of the LDBA-components is carried out and optimised by an intensity sensitive beam profiler that is located in the output beam path of the LDBA. Moreover, 2D-FineScan software controls a 3-axis motion controller with a precision micro-handlings system and data acquisition via photo detector that can be integrated in the laser fine welding station for adjusting the output coupler. All components have to be adjusted precisely in ranges of 3 – 6 micrometers to build the LDBA.

Laser spot welding has an important advantage for welding of small fine-mechanical and electronic components. One of the benefits is the ability to apply a very precise amount of energy in a very short time (0.4 – 20 ms) to small area locations on the work piece. In addition, the process has the advantages of low heat input, small heat affected zone, minimum distortion and absence of filler material.

A wide range of laser and process parameters could be identified. These include pulse duration, average peak power density, pulse energy, wavelength, focus position and spot diameter. Material dependant properties such as absorptivity and thermo-physical properties play a vital role in laser material processing. Understanding the technology is a key issue for improving and optimisation of the laser welding processes.

For laser welding for most assembly components a process window (P=1400 W at v=5 mm/s) could be experimental identified, evaluated and successfully applied. An SMA-fibre collimator can be connected to the LDBA, allowing the beam to be easily coupled into a multimode fibre.

Within the bounds of this thesis the effects of laser beam welding concerning LBDA-component-functioning and the divergences from the adjusted optical beam profile are examined and evaluated.

Key words

Nd:YAG-Laser, pulsed laser spot welding, laser diode beam assembly, GRIN-optics, laser weldability, conduction welding, fibre optics, fine welding station
Foreword

This dissertation originated during my activity as research associate at the University of Applied Sciences (FHO/O/W) and the University of Loughborough.
My special thanks are due to Professor R M Parkin, the Head of the Wolfson School of Mechanical and Manufacturing Engineering for the friendly encouragement and generous support, which decisively aided the success of my work.
I thank Prof. Dr. H. Kreitlow for the constructive discussion and the exchanging of experiences and knowledge.
I further thank my parents for their consideration and the support and encouragement over many years.

Aurich, March 2008

Andreas Bünting
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Nomenclature

The following is a list of the main symbols used in this thesis, together with a brief description of significance:

A : Absorption index [1]
AP : Absorbed power [W]
A : Area [m²]
α : Angle [rad]
αG : Max. angle [rad]
β : Angle [rad]
φ : Angle [rad]
β : Imaging relation [1]
αG : Limiting angle of incidence [rad]
C_D : Duty cycle [1]
dc : Core diameter [m]
do : Beam waist diameter [m]
e : Elementary charge (1.602x10⁻¹⁹) [C]
e : Euler number (2.7182818)
ev : Dielectric constant (vacuum) 8.85x10⁻¹² [Fm⁻¹]
E_s : Energy unit length [J]
E_th : Threshold energy [J]
E_ph : Photon energy [J]
f : Frequency [s⁻¹]
f : Focal length [m]
f_lBPO : Focal length of laser beam processing optics [m]
f_RR : Pulse repetition rate [s⁻¹]
g : Gradient constant [m⁻¹]
h : Planck’s constant 6.625x10⁻³⁴Js [Js]
hg : Height of gap [m]
h_r : Edge offset [m]
h_M : Melt enthalpy [kJkg⁻¹]
I, I₀ : Intensity [Wm⁻²]
I_F : Forward current [A]
I(z) : Intensity as a function of z [Wm⁻²]
I(r,z) : Intensity as a function of r,z [Wm⁻²]
Φ_e : Intensity [Wm⁻²]
L₀ : Length of overlap [m]
L_h : Threshold current [A]
K : Beam Quality [1]
k : Imaginary part of refraction index [1]
K : Thermal conductivity [Wm⁻¹K⁻¹]
l_O : Length of gap [m]
M² : Quantity of Diffraction [1]
M : Magnification [1]
m_e : Mass electron [kg]
n : Refraction index [1]
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>Numerical aperture</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
</tr>
<tr>
<td>P_{av}</td>
<td>Average peak power</td>
</tr>
<tr>
<td>P_p</td>
<td>Average peak power</td>
</tr>
<tr>
<td>E_p</td>
<td>Pulse energy (J/pulse duration)</td>
</tr>
<tr>
<td>E_S</td>
<td>Energy per unit length</td>
</tr>
<tr>
<td>P_D</td>
<td>Average peak power density</td>
</tr>
<tr>
<td>P_M</td>
<td>Mean laser power</td>
</tr>
<tr>
<td>(\theta_{\text{MAX}})</td>
<td>Emission angle</td>
</tr>
<tr>
<td>(\theta)</td>
<td>Divergence angle</td>
</tr>
<tr>
<td>(\varphi)</td>
<td>Propagation angle</td>
</tr>
<tr>
<td>(\theta_f)</td>
<td>Divergence angle focusing</td>
</tr>
<tr>
<td>(q, q^*)</td>
<td>Beam parameter product</td>
</tr>
<tr>
<td>R</td>
<td>Reflection index</td>
</tr>
<tr>
<td>R_S</td>
<td>Reflection (vertically polarised)</td>
</tr>
<tr>
<td>R_P</td>
<td>Reflection (parallel polarised)</td>
</tr>
<tr>
<td>r</td>
<td>Radius</td>
</tr>
<tr>
<td>(\eta)</td>
<td>Quantum efficiency</td>
</tr>
<tr>
<td>s</td>
<td>Depth of focusing</td>
</tr>
<tr>
<td>(\Delta s)</td>
<td>Shift in x-direction</td>
</tr>
<tr>
<td>(\Phi)</td>
<td>Polarisation</td>
</tr>
<tr>
<td>T</td>
<td>Transmission index</td>
</tr>
<tr>
<td>T</td>
<td>Period time</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>T_M</td>
<td>Melting point</td>
</tr>
<tr>
<td>T_0</td>
<td>Room temperature</td>
</tr>
<tr>
<td>t_p</td>
<td>Pulse duration</td>
</tr>
<tr>
<td>t_z</td>
<td>Cycle time</td>
</tr>
<tr>
<td>t</td>
<td>Thickness</td>
</tr>
<tr>
<td>t_k</td>
<td>Circular orbit deviation</td>
</tr>
<tr>
<td>(\tau_H)</td>
<td>Pulse duration</td>
</tr>
<tr>
<td>(\tau)</td>
<td>Time</td>
</tr>
<tr>
<td>u,v</td>
<td>Cartesian coordinates</td>
</tr>
<tr>
<td>v_S</td>
<td>Track velocity, processing feed</td>
</tr>
<tr>
<td>v_C</td>
<td>Shock frequency</td>
</tr>
<tr>
<td>V_M</td>
<td>Critical welding speed of the work piece</td>
</tr>
<tr>
<td>(\omega_p)</td>
<td>Plasma frequency</td>
</tr>
<tr>
<td>w</td>
<td>Beam radius</td>
</tr>
<tr>
<td>w_0</td>
<td>Beam waist radius</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Wavelength</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>Heat conductivity</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>Thermal diffusivity of material</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>x</td>
<td>Cartesian coordinate</td>
</tr>
<tr>
<td>(\Delta x)</td>
<td>Target position</td>
</tr>
<tr>
<td>y</td>
<td>Cartesian coordinate</td>
</tr>
<tr>
<td>z</td>
<td>Cartesian coordinate</td>
</tr>
<tr>
<td>(\Delta z)</td>
<td>Focus situation</td>
</tr>
<tr>
<td>z_R</td>
<td>Rayleigh-length</td>
</tr>
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</table>
### List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>Laser</td>
<td>Light Amplification by Stimulated Emission of Radiation</td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>Neodymium Yttrium Aluminium Garnet</td>
</tr>
<tr>
<td>LWG</td>
<td>Light Waveguide</td>
</tr>
<tr>
<td>EN</td>
<td>European Norm</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>ISO</td>
<td>International Standardisation Organisation</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon-Dioxide</td>
</tr>
<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
</tr>
<tr>
<td>LDBA</td>
<td>Laser Diode Beam Assembly</td>
</tr>
<tr>
<td>DPSS</td>
<td>Diode Pumped Solid State Lasers</td>
</tr>
<tr>
<td>LPSS</td>
<td>Lamp-Pumped Solid State Lasers</td>
</tr>
<tr>
<td>SSL</td>
<td>Solid State Lasers</td>
</tr>
<tr>
<td>SHADOW®</td>
<td>Stepless High Accurate and Discrete One Pulse Welding</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GRIN-Lens</td>
<td>Gradient Index Lens</td>
</tr>
<tr>
<td>LD</td>
<td>Laser Diode</td>
</tr>
<tr>
<td>PD</td>
<td>Photo Diode</td>
</tr>
<tr>
<td>MD</td>
<td>Monitor Diode</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time between Failures</td>
</tr>
<tr>
<td>BPP</td>
<td>Beam Parameter Product</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>HAZ</td>
<td>Heat Affected Zone</td>
</tr>
<tr>
<td>LBPO</td>
<td>Laser Beam Processing Optics</td>
</tr>
<tr>
<td>CCD</td>
<td>Charge Coupled Device</td>
</tr>
</tbody>
</table>
1 Introduction

Modern industrial nations can develop only if they obtain and realize new physical-natural-scientific knowledge and technologies. Suitable material and production processes are necessary to realize technical ideas, and progress therefore depends on constructing a scientific technological basis in material sciences and in production engineering. It is imperative to master innovative technologies, not only in research laboratories but also within an efficient production regarding economic efficiency and reliability [16].

This applies in particular to production processes due to a high interest in the creation of value. It is also important to develop these processes continuously in order to make complete use of the process-potential [1][2][3].

Here, laser technology has great potential, regarded as an interdisciplinary key- and growth technology for innovative applications in different areas of research and industry [1][5].

Demands increase continually for compact, optically efficient OEM Laser Diode Beam Assemblies (LDBA) in consumer electronics, medical and optical measurement areas. This is as a result of the steady reduction in laser diode costs and compact optics based on GRIN (Gradient Index) technology. GRIN optics are characterised by the possession of very good optical qualities and small physical dimensions.

The OEM systems at present available on the market are very restricted in optical quality and physical size. Further, these units display a short lifetime when used in aggressive atmospheres, due to the aging of adhesive joints within the device.

The scope of this work is to construct and manufacture a novel LDBA based on a modified laser diode. The construction is carried out taking account of the laser weldability of all components. For welding, a lamp pumped Nd:YAG laser is used. A specialised half-automatic laser welding station was built for the production of the LDBA. This welding station may serve as prototype for commercial, fully-automated unit.

There are numerous advantages of using laser supported technologies in industrial production, such as high flexibility, production velocity and quality, good automation capability and high availability [6].
Looking at laser supported technologies, two growth rates have been recorded. Between 1986 and 1990 the annual rate of growth was about 14% and from 1994 to 1998 around 25%. Even from 2001 to 2003, the market for laser macro-processing (total decrease of 19%) has developed better than the machine tool market (total decrease of 23 %). With 37%, Europe was international market leader in laser systems for material processing in 2003. This was better than North America with 23 % [7].

The long-term prospect of growth for laser markets is still very good. Figure 1.1 shows the market growth for laser machining systems in different regions of the world. The steepest growth is expected for East Asia [9][10].

![Bar chart showing market growth for laser material processing systems](Fig. 1.1 Market growth for laser material processing systems [9])

Figure 1.2 shows the market-capitalization for material processing laser sources according to laser types (2003). At present CO₂ lasers are predominate but in future, solid state lasers are expected to take the lead. However, the steepest growth is expected for diode-pumped solid state lasers, which will probably reach the highest quota in 2010. Fighting for future market shares, various diode-pumped solid state laser technologies are competing:
Disc lasers, fibre lasers and slab lasers - each laser having its specific advantages. We see a fast growing acceptance of fibre laser technology in marketing and material processing. Applications in fine- and micro-processing are predominating. Prognosis for the future supports the present demand of sub-200 W laser systems. Leading laser system manufacturers say the ratio of kW to sub-200 W laser systems is 1:10 [11].

Due to their high flexibility, lasers can be used for every major manufacturing method [1]. Laser processing systems and applications are easily automated. Lasers are suitable for manufacturing large production capacities and can be operated continuously in three shifts [12].

The most important reason for laser applications is that the production quality can be improved in most cases [13]. A laser beam, as a focal-acting, non-contact tool, works without mechanically loading the work piece. Compared to other thermal methods, laser has the advantage of a very small heat contribution and consequently a small heat affected zone. Reworking a device or component can often be minimized or even spared completely [14] [15].
Finally, using laser enables certain applications or constructions which will save material and weight but at the same time offer improved strength.

One economically important branch of laser technique is laser machining. This comprises the fields of physics, material sciences and production engineering. Laser material machining can be divided into beam sources such as solid state lasers, diode lasers, Excimer lasers and gas lasers. They can also be divided into laser types according to their production process such as ablation, cutting, drilling, welding, surface treatment, etc. These types may again be sub-divided into macro processing and laser micro processing. Great importance is attached to laser beam welding of precision components, in different joint geometries and in precision engineering [16].

In this work, laser beam welding using pulsed solid state lasers (YAG-lasers) within laser beam precision machining is examined. As an example, application to an assembly consisting of passive and active opto-mechanics.

The development and use of new materials and material combinations cause conventional joining techniques to reach their limits, which can only be exceeded by the application of applying of new technologies. The restrictions on conventional joining techniques are caused by using materials and material combinations with low welding suitability and by demanding flexible, automated production of small lots. In addition to conventional joining techniques, alternative laser supported joining techniques are highly acceptable as they offer the following advantages:

- Higher flexibility regarding design and joint geometry
- High power densities enable high process velocities
- Joining of material combinations by fine adjusted laser radiation
- Non-abrasive, precise working tool (laser beam)
- High flexibility and ease of automation, as well as economic production for small lots
- Small thermal influence on the joint surfaces
- Non-contact weld processes
1.1 **Level of Technology in Laser Beam Welding**

The use of industrialized and/or automated welding methods is the epitome of modern welding production. The choice of a weld method depends on the quality of the product and the economic efficiency of the method. This applies in particular to the trend of using high-strength materials, or using light metals producing thin-walled and light weld constructions which have to meet high technological requirements. Laser beam welding is a new method which will oppose the pressure of rising production cost if planned correctly. In addition, laser beam welding is known as a suitable tool because of the locally limited and concentrated energy contributions it achieves, rework of the seam usually not being required [17-25].

The state of the art of this innovative technique changes constantly and fast. In this respect trying to provide a full description of what is possible now and can in practice be used for production purposes is a demanding undertaking.

Laser beam welding takes increasingly part of the conventional joint technique and has already been completely established in many fields (Tailored blanks, ship-building, aerospace, railway stock).

Recently, high power fibre lasers (multimode up to 30 kW and single mode up to 6 kW) with excellent beam quality are being used for industrial welding of various steel- and aluminium-alloys [26].

In addition to this, lasers play an important role in producing precision components for different industrial fields [27].

New laser joining systems have been developed which are now used for example in electronic components [29], medical components [30], LIGA components [31], and components in watch-and-clock industries [32].

With a growing novel of pump sources, beam delivery and shaping systems, a growing spectrum of focus diameters available for material processing (10 μm up to 1 mm) and improved beam quality, laser beams can be perfectly adjusted and be precisely positioned at the given joint geometry [28]. Diode pumped solid state lasers are predominate in the field of micro material processing today, particularly micro-welding of heat sensitive components.

The scope of applications in which laser beam welding is used extends from very thin metal foils (<20 μm) to sheet-widths of several millimetres.
High power densities enable very high process velocities (e.g. ultra-speed-keyhole welding up to 1500 mm/s – [33].

Due to a good absorption at a wavelength of 1064 nm, high grade steels, noble metals and light metals such as titanium are highly suitable for beam welding. Figure 1.3 shows four examples of laser fine welding and micro-welding are applied.

By adjusting the laser pulse form, different materials such as nickel and titanium alloys can be bonded by welding. Laser beam welding supports both welding using filler material according to the width of gap.

Potential applications of laser beam welding are to be distinguished by macro, fine and micro processing.
At present commercial solid state lasers (YAG-lasers, disc lasers, diode lasers), gas lasers (CO\textsubscript{2}) and fibre lasers of all power ranges are successfully applied for welding use in industrial and scientific spheres.

Fibre laser systems are a new generation of solid state lasers which have become firmly established for many applications as a replacement for conventional laser systems [37]. Fibre lasers are available as single mode or multi mode. They provide better performance parameters such as excellent beam quality and, at the same time, high efficiency, high density, lower operating costs, with reduced maintenance. This also improves production effects while increasing reliability [38].

Modern handling systems consisting of linear translation axis, rotation axis, robots and scanner systems offer high positioning accuracy and high process velocities [39]. Hybrid handling systems such as a combination of robot- and scanner systems reveal new perspectives and new fields of application in remote welding to the user. The trend regarding power ranges of 10–500 W is covered by modulated CW-lasers. These lasers can be operated in CW, pulsed or q-switched mode according to the processing requirement [40]. In order to produce homogeneous welding seams a stable laser power output is required.

By using modulation techniques, a high density chain of spot welds is achieved which resembles a homogeneous welding seam. In this case the process can be optimized by changing the pulse energy and pulse repetition rate [41].

At present there are many applications, particularly in microelectronics, medicine-techniques and micro systems techniques, where materials of different material properties are required to be welded [42].

At this time, this is only possible with newly developed pulsed solid-state lasers, as these offer a variable, user-defined and reproducible modulation technique and pulses within the range of milli- to microseconds.

Modulation technique and pulse shaping represent therefore a powerful instrument to influence the temperature-time curve during the welding process and consequently influencing laser weldability [43].

In addition, continuous welding seams can be produced with pulsed lasers both in overlap mode of single spot welds and in Stepless High Accurate and Discrete One Pulse Welding mode (SHADOW) [44].
However, high process velocities are required as the continuous welding seam, (without discrete lap-joint and consequently cooling between two pulses) is produced during one pulse duration. The new welding strategy SHADOW produces a weld contour with one single pulse of e.g. 10-50 ms. The intervention in the fusion-phase is so dramatic that a stationary mixing in the weld pool cannot occur. As a characteristic of this method, thermal side effects are reduced and the weld efficiency improved.

The successful SHADOW-method is suitable particularly for continuous seams up to a weld seam length of up to 20 mm enabling a drastic reduction of the processing time of at least one order while, at the same time, the contributed energy is reduced, compared to conventional pulse welding. Figure 1.4 shows two applications in micro welding.

![Laser welding of micro bearings](image1.png) ![Micro welding of miniaturised tubes](image2.png)

Fig. 1.4 Applications for micro-welding (SHADOW-method)

At the present time, laser opens new fields of applications in medical-technology using new bio-compatible materials such as nitinol.
1.2 Level of Technology concerning Laser Diode Beam Assembling Systems

In the course of the fast development of semiconductor-technology it has been possible to produce smaller and more efficient laser diodes emitting in different wavelength and power ranges (1mW -10W). This development has not yet ended. Today, laser diodes are mainly used in consumer-electronic products (DVD, CD-player, DVD-recorder), spectroscopy, laser-measuring technology and as excitation source for lasers. The AIGaInP-laser diode has a multi-quantum-well-structure and is available in a 5.6 mm standard case TO-5 with monitor-diode. Improving the wave-guide and MQW-structure new laser diodes have a lower operating current of typical 75mA with 50mW output power. Additional data are a low threshold power of typical 30mA and a low operating voltage of approximately 2.3 V. The fields of applications extend from medical and biomedical applications to industrial applications in the printing industry [47].

Being a result of the inner structure (sandwich-structure) of this barrier-layer and the resulting radiation characteristics, the laser beams generated have to be corrected and collimated by special optics. By doing this, special applications are adjusted and optimized.

Nowadays commercial systems of different qualities for laser diode beam shaping are offered. In laboratories, mechanical cage assembly systems and collimation tubes have been applied successfully for beam collimating and correction. With only few movements and mechanical components (cage plates and rods) extensive systems for beam shaping can be produced. In addition OEM-laser pigtails are available. These are specially adjusted to the desired application according to customer requirements [147].

Attaching laser diodes to the input face of the beam waveguide has been particularly successful thus reducing the component dimensions considerably.

Since then, so-called single emitting laser diodes have been used as a pump source for fibre lasers. Here several single emitting laser diodes are spliced to the cladding of the pump fibre using a special bonding technology [37].
1 Introduction

1.3 Unusual Features of Material Processing with Laser Beams

The important difference between laser beams and thermal light (lamp) sources is found by comparing both beam types. One quality-aspect which is most important for material processing is the possibility of focusing laser beams down to the smallest given diameter within the wavelength. The focus diameter which can be achieved with a thermal light source usually lies far beyond these values. The low resultant divergence of laser beams therefore allows them to be transported over a long distance with a minimal beam expansion only [48].

Various consequences for material processing result from this. On account of a low focus diameter, in practice values from 10 µm to some 100 µm are obtained. According to the laser system, lasers can process microscopic structures specifically and precisely. When working macroscopic structures, minimal processing zones can be obtained. In association with highest achievable continuous or pulse powers, an intensity at the work piece of $10^5 - 10^{10}$ W/cm² can be reached for these focus diameters. With these intensities every known material melts or vaporizes. High intensities have the advantage that the heat which is produced during processing only minimally penetrates in to the work piece which results in less shrinkage and small heat affected zones [49].

Another advantage of lasers is their simple spatial and temporal controllability as well as good laser beam guidance and shaping. In particular, laser systems are available to a high degree and offer the user, together with processing optics a high automation-potential. Not least the safety and reliability of commercially available laser units is a very important aspect for the operator [50].

The power output of modern solid state lasers leads to a considerably increasing energy density in the focusing laser beam which can be used immediately for reducing the energy per unit length when using the key-hole welding method. By reaching the predetermined depth of weld the output power can be reduced or the process velocity can be increased. Distinctly thinner width weld seams are always produced resulting in a smaller component shrink rate and a reduction of the heat effected zone.
1.4 Objective

The increasing share of microelectronic and micromechanical components in products of the consumer- and the capital goods industry require the availability of suitable production systems and joining methods for metallic and dynamically balanced components. In mechatronics, optoelectronics and medical precision engineering (instruments, implants and system components) the use of laser fine welding increases continually and is more and more accepted as a joining technique using pulsed solid state lasers.

Following EU-standards, laser precision welding without filler material places high demands on the weldability of the components as well as automated handling and clamping technique of individual components. Through an exact and reproducible focus positioning and at the same time stability of laser and process parameters high quality precision welds can be produced.

This thesis has two objectives with regard to material processing by laser beams. The first objective is developing a semiautomatic laser fine welding station with Nd:YAG Lasers on the basis of industrial module components. This includes the development of a reliable laser fine welding procedure supported by a FE-analysis of the clamped components (laser diode and GRIN-lens holder) during welding.

A clean-room cabin of laser safety class 2 with special ESD-safety fitting creates the required safe working conditions required for producing sensitive, optical and ESD-sensitive components. The constructive and manufacturing requirements of the LDBA are many and comprehensive.

The greatest difficulty consists in the creation of a stable, low distortion laser weld process on assemblies of optical and mechanical parts, which have been precision adjusted relative to each other. The thermal effects of the laser welding process may not negatively affect this precision.

The qualitative demands on the laser seams are high. The required seam depths (200 – 300 μm) are also to be gas-tight (Helium). Especially the thermally and electrically sensitive laser diode and the GRIN-lens may not be functionally degraded by the laser weld process. Excessive thermal influences can permanently change the gradient index and thus affect the imaging qualities. This requires precision setting of laser powers with selected laser and process parameters at the site.
As no handling systems are available for the specialised manufacture of an LDBA, a half-automatic fine laser welding station with fine positioning technology is built and commissioned as part of this work.

Further, special clamping tools for the LDBA components will have to be developed.

The secondary objective is the construction and production of a new laser diode beam assembly (LDBA) suitable for welding in special consideration of laser weldability with pulsed Nd:YAG lasers systems. This includes the development of a new assembling and manufacturing procedure as well as a low distortion laser welding process.

Here the LDBA consists of optically active and passive components of different metals. A commercial laser diode with a TO-5 case is used and has been modified just for this application. It is a rather sensitive system component.

Within the bounds of this thesis, the effects of laser beam welding with respect to LDBA-component functioning and the divergences of beam width from the optimised result of adjustments are examined. Since beam welding is applied as an innovative joining technique (the advantages of laser beam welding shall be used in particular) it is necessary for all applied LDBA-system components to be suitable for welding and easy to handle. When constructing the system the selection of suitable materials regarding laser weldability is a central point. Furthermore all components have to be adjusted precisely in ranges of some micrometers.

For precise clamping of LDBA components special tools and devices have to be developed and modified regarding the desired joint configuration.

The adjustment of the LDBA-components is carried out and optimised by an intensity sensitive beam profiler that is located in the beam path of the LDBA. Moreover a 2D-FineScan software controls a 3-axis-motion controller and data acquisition via photo detector that can be integrated in the laser fine welding station.
1.5 List of Contributions

The main contributions of the research are as follows:

The first contribution is the development and validation of a semi-automated laser fine welding station with pulsed Nd:YAG-lasers. This system consists of two decoupled handling systems. One Cartesian handling system for manipulation of the laser beam processing optics and one special Cartesian micro-handling system for precision on-axis alignment of small, active components, e.g. laser diodes and Gradient Index lenses.

The second contribution is the development and implementation of a low distortion and reliable welding procedure by means of a pulsed solid state laser. This welding procedure is capable of welding thermal sensitive components, e.g. laser diodes without negative effect on them.

The third contribution is the construction and manufacturing of a unique laser diode beam assembly (LDBA) with regard to laser weldability. A laser diode with corrected direction deviation is therefore applied. The laser diode beam collimation is performed by a GRIN-lens and is optimised by means of Ray-Trace simulation.

The fourth contribution is the development and modification of clamping tools for the LDBA production. The influences of clamping during welding on the laser diode and GRIN-lens holder are examined by FE-analysis.

The fifth contribution is the development and validation of a reliable process parameter window for LDBA manufacturing.

The sixth contribution is the examination of pulsed laser welding influences on precision assembly alignment and component function.
The work presented in this thesis has resulted in the following peer reviewed publications:

Conference paper:

1. T. Vahrenkamp, J. Miesner, A. Bünning, H. Kreitlow


5. A. Bünning, F. Asche, R. M. Parkin, M. R. Jackson, H. Kreitlow

6. A. Bünning, J. Thieme; Industrial Application for Fibre Lasers;
1.6 Thesis Structure

Initially, every laser-technical basis relevant regarding Nd:YAG Lasers has to be calculated. In addition, the functioning of the beam guidance component LWG and its influence on homogenizing the laser beam is investigated, followed by different handling concepts for laser beam material processing regarding the aspect of track precision, which will be analysed and examined.

Furthermore, each seam and joint geometry used for laser beam welding will be described and discussed. A feasibility study regarding the relative positioning precision of the joint geometry with regard to the focus diameter is carried out in consideration of the production of the LDBA. Finally the most important parameters for characterising a laser beam regarding its propagation, beam quality and focusing ability are examined and discussed.

In chapter 3, joining and laser welding methods are described in detail. In particular the effects of welding with a thermal source are demonstrated.

In addition, a fundamental understanding of the interaction between laser beam and material is imparted. Furthermore, the principles of laser beam welding regarding thermal conducted welding and keyhole welding are described.

Finally the differences and disassociations in comparison to conventional joint processes are represented.

Chapter 4 works out the fundamental basis of semiconductor lasers and their radiation. By means of Ray-Tracing the collimation characteristics of different GRIN-lenses (Gradient Index) are examined. Here a GRIN-lens collimates the divergent ray beam of a laser diode assumed as point light source. For the precise handling of the precision components during adjustment and welding the clamping components together with clamping techniques are presented and explained.

Additionally laser welding constructing, with regard to constructing an LDBA, is described. Furthermore the influence on the seam weld quality by prepared weld seams and edges is explained.

The technical profile of the fine welding station concerning the production of precision components is the subject of chapter 5. These are the basis for developing the handling concepts for focus positioning and LDBA alignment.
The construction of a fine welding station with Nd:YAG lasers and measuring system for data acquisition and focusing optics are also presented.

In chapter 6 the mechanical deviation of linear handling systems for focus positioning and the deviation from the ideal rotation of the rotational axis are determined and discussed.

In particular the quantities of beam radiation (Rayleigh-length and minimum spot weld diameter) typical for material processing are determined and compared to the theoretical quantities.

In chapter 7 different opportunities of focus positioning by laser beam processing optics (LBPO) are explained. The laser triangulation sensor is a useful extension for a quick and reproducible focus positioning by LBPO.

Chapter 8 and 9 work out the characteristic processing basics of laser beam welding with pulsed laser beam welding and special regard to LDBA.

In chapter 10 the construction and production of an LDBA, with regard to a suitable laser weld formation are carried out and examined.

In chapter 11 an economic examination and comparison of capital equipment for different laser systems regarding LDBA production is carried out.

At the end of this thesis chapter 12 there are a summary, conclusion and outlook.

Figure 1.5 depicts the thesis block diagram.
Chapter 1

Introduction of the thesis

Chapter 2

State of Technology concerning solid state lasers in laser machining

Examining the track accuracy of different kinematic concepts
- Feasibility check of the 2D-track processing

Laser beam qualities and its application

Calculation of 2D-intensity profile (Gaussian beam)

Description and control variables

Chapter 3

Operating principle of welding and interaction of laser beams with matter

Laser beam absorption and optical constants n and k

Influences of Fresnel absorption
Chapter 4

Laser diode beam assembly

Temperature dependence and MQW laser diodes

Gradient index optics

Characterisation of beam propagation by means of Ray-Tracing

Modification of LD concerning beam direction deviation

Concepts and definitions of clamping tools for the LDBA

Chapter 5

Concept and development of laser fine welding station (test rig)

Control and handling system for focus positioning
GUI FineWeld

Micro handling systems for precision alignment of LDBA components
GUI FineScan
Chapter 6 (contribution by the author)

Determination and evaluation of spot weld diameter and Rayleigh-length

Determination of handling systems deviation

Chapter 7

Focusing and de-focusing procedure of a laser beam

Focus positioning supported by laser distance sensor

Chapter 8 (important background)

Process characterisation of pulsed laser welding

Conduction welding versus keyhole welding

Chapter 9

Characterisation of pulsed laser welding parameters

Overlap processing theory for pulsed laser welding

Modelling and calculation in conduction welding with respect to Fresnel absorption
Chapter 10

Manufacturing of laser diode beam assembly with respect to laser weldability

LDBA design and alignment procedure

Modification of joint configuration of LD-pigtail

Pigtail Alignment procedure and laser seam welding

2D-alignment of output coupler by means of FineScan

Laser welding of gas-inlet and interface connector

Results and discussion

Contribution by the author

Background work

Fig. 1.5 The thesis structure
2 Basics and Definitions concerning Laser Beam Welding Systems

In this chapter a laser arrangement with a solid state laser as laser device and beam delivery with and without light wave guide are described. The characteristics of laser beams by important beam parameters and the resulting fields of application are described in the following. Furthermore the components required for laser beam welding are presented and important terms are defined.

Chapter 2 contains a comprehensive introduction to laser material processing with special reference to state of the art solid state laser and the system components required for the manipulation of the process optics and work piece.

Special attention is paid here to laser beam finest processing and the positioning of filigree components. Relevant, process related deviations such as the thermal focal shift of a process optic are presented and discussed.

Analysis of different handling systems with reference to positioning and rotational accuracy led to a feasibility study of two-dimensional laser beam processing. Exact knowledge of the deviation from the ideal mechanical movement of the different types of manipulating system had important effects on the clamping concept covered in chapter 4, where the work pieces to be welded were positioned and fixed. Further, it allowed a reproducible laser weld seam quality to be attained.

Further, all important laser beam parameters and their influences on the beam dispersion and intensity distribution are discussed. The knowledge of the inter correlation of these parameters is decisive for the later laser welding equipment concept (chapter 5) and the process optimisation and qualification for laser beam welding of smaller, sensitive components (chapter 6, 9 and 10), using the example of a new Laser Diode Beam Assembly (LDBA). The structure of this chapter is summarized in Figure 2.i.
Subchapter 2.1
Solid state lasers (Nd:YAG) in laser fine machining

Subchapter 2.2
Solid state lasers (Nd:YAG) – Physical Basics

- Construction and mode of action
- Beam sources and light waveguide LWG
- Handling systems for material processing
- Examining track accuracy concepts
- Analysis of joint configuration

Subchapter 2.3
Feasibility check of 2D-track processing

- Examining Feasibility criterion
- Permitted deviation of weld shape
- Conclusion of Analysing for fine welding

Subchapter 2.4
Laser beam qualities

- Description and control variables
- Beam quality, propagation and focusing
- Laser beam expansion

Subchapter 2.1/2.2/2.3/2.5 are used in chapter

- Chapter 5 – Fine welding station
- Chapter 6 – Characterisation of handling systems deviation

Fig. 2.1 The subchapter block diagram
A complete system for the processing of components by laser is referred to as a laser system according to European norm EN ISO 11145 (1994). According to Figure 2.1 - a laser device consisting of laser and supply facilities is illustrated.

![Schematic diagram of a laser system (EN ISO 11145) [51]](image)

The laser device with beam delivery and beam shaping is referred to as a laser arrangement and together with handling-, measure and control systems as a laser system. There can, however, be differences to the EN ISO 11145 standard concerning the construction of special-purpose machines.
2.1 Solid State Laser in Laser Fine Machining

2.1.1 Physical Basics of Modern Laser Systems

The acronym "laser" stands for light amplification by stimulated emission of radiation. A light amplifier which increases the intensity of light, emitted from a medium, by stimulation. In Figure 2.2 the most important functional units are described schematically:

1. The active medium (gas, liquid, solid or semiconductor) must have specific atom-physical qualities (4-level standard scheme) so that a laser process can occur.

2. The optical feedback amplifier (Resonator - Mirror 1 and 2) providing a stimulated emission

3. A suitable energetic stimulation by pump-sources (lamps, flash lights, high-voltage or laser radiation)

The wall plug efficiency being very low, 1-4 % is typical for Nd:YAG-lasers, a cooling system for removing the loss-energy is necessary [52, 136].
All lasers are classified into the kind of active medium which the laser radiation is produced in and which sets the wavelength.

- Solid state lasers: e.g. Ruby, Nd:YAG, fibre lasers, diode lasers or semiconductor
- Gas lasers: e.g. CO₂, HeNe, Excimer
- Liquid lasers: e.g. Rhodamin 6G

For welding, cutting, drilling, and for surface treatment, mainly CO₂-Lasers, diode lasers and Nd:YAG lasers are used. Only these provide enough radiation efficiency under a technical und economically justifiable expenditure delivering a good beam quality.

2.2 Solid State Lasers

The following chapter describes the physical basis of laser technology. It includes the mode of action and construction of lasers, the description of the laser beam with its parameters and its ability to narrowly focus a laser beam.

For transmitting laser light from the laser device to the processing station, mirrors or flexible light wave cables may be used. By means of a laser light cable it is possible to bridge the distance between laser and processing point with almost no loss. Integrating lasers into an existing production plant or connecting lasers to a handling machine (portals, robots, etc.) becomes as easy as an electrical connection. In order to increase the economical efficiency of a rather expensive laser device several processing stations can be connected to one laser. In this way a simultaneous or staggered processing will be possible.
2.2.1 Nd:YAG Lasers Construction and Mode of Action

The active medium of an Nd:YAG laser is neodymium (Nd) which is doped in a YAG-crystal lattice (yttrium-aluminium-garnet). This crystal is often shaped such as a rod. In order to understand the action of light amplification inside a neodymium-ion it is required to look at its energy standard scheme. Figure 2.3 shows this 4-state-scheme with both energy states and the laser-transition.

By means of the pump lamp electron energy of the neodymium-ions are driven into higher energy levels. From there they reach the upper laser state rapidly (1 ns) without radiation. During this action the energy-difference is passed on to the host material as heat. Within the fluorescence lifetime (230 μs) the stimulated ion relaxes spontaneously, emitting the energy-difference as radiation with a wavelength of 1.064 μm, first to the lower laser state and very fast (30 ns) from there without radiation to the ground state. The laser transition takes places between the upper and the lower laser state.

If a stimulated Nd-ion is hit by the radiation wavelength of 1.064 μm it will emit energy as radiation energy from the laser transition towards the same direction and in the same phase (coherent radiation). This transition is called stimulated emission.

Laser can be regarded as light transformer absorbing the pump light of the stimulating source inside the rod thus transforming the stimulated emission into laser light radiation.
In Figure 2.4 the construction of a Nd:YAG lasers with its most important components is described schematically.

![Schematic representation of a lamp-pump solid-state laser (LPSS-Laser)](image)

Gas discharge lamps serve as stimulating mechanism. If required, one or even two lamps can be used according to the construction form. Stimulation by laser diodes (diode pumped solid state lasers) is becoming more and more interesting on efficiency grounds. Two resonator mirrors, one of which being semi-reflecting output mirror, form the optical regenerator (resonator). The light emitted by the rod is reflected several times and is intensified by stimulation of the remaining upper-state electrons. At a given intensity the semi-reflecting output mirror lets part of the radiation field inside the resonator pass, which can be used as laser beam for material processing. The characteristic of this output mirror plays a vital part in the output power and pulse duration, dependent on the level of reflective qualities of semi-reflecting surface.

In order to couple the pump light of the stimulating source into the rod as efficiently as possible to ensure homogeneous illumination, both are surrounded by a reflector.

As the spectrum of the pump source extends from ultraviolet to infrared, whereas only a small region of the spectrum around 0.8 \( \mu \text{m} \) is required to activate the medium, there is
only an efficiency factor of some percent. The remaining light energy of the pump lamp spectrum warms the rod. The resulting thermal stress may exceed the mechanical strength of the rod and cause its destruction. Therefore, it is required that the rod be cooled efficiently.

The assembly of laser rod, stimulating lamp and reflector is called pump chamber or cavity. For sourcing the pump chamber a supply unit is required. The following functions are carried out by the supply unit:

- Supplying the stimulating energy for the discharge lamp
- Controlling, monitoring and adjusting the laser operation
- Ensuring the cooling of the pump chamber and other devices of the laser (e.g. mirrors, screens, blinds)
- making suitable interfaces available so that the laser unit can be integrated in the production plant

The Nd:YAG lasers can generate radiation in either continuous wave (CW) or in a pulsed operating method according to the construction of the supply unit. The required voltages are transformed from the public network and rectified. During pulsed operation, capacitors serve to store energy, thus avoiding the necessity of taking high power pulses from the supply network. For a laser pulse with a power output of 7 kW and an efficiency factor of 1 – 4 %, 160 kW have to be added to the flash lamps. The high voltages are supplied to the lamps by a fast operating switch. This switch can be used to modulate the energy within the pulse duration in some Nd:YAG lasers of some manufacturers. This is referred to as pulse shaping. Before the stimulating energy is passed to the lamps, they require to have their internal gas content to be ionised by an internal electrical discharge. This sets the lamp in an electrical low-impedance state for stimulation.

The central component of the supply unit is the control unit. Here every important function of the laser device is controlled and monitored. Every internal operating processes and adjustment of the laser parameters by the operator are processed by this control unit. Instructions and messages about the operating state of the laser system are exchangeable via interfaces.
Short pulses may also be generated by use of a so called quality-switch (Q-switch). This is a fast optical switch (mechanical, acoustic-optical, electro-optical) placed in the resonator and interrupting the laser process when closed. As power is still being pumped into the resonator by stimulating lamps, the opening of the Q-switch at a later time-point as without this feature causes a far higher output energy pulse as more energy is available in the rod at this later time-point. This technology can be used for pulsed as well as continuously emitting lasers. For currently available Nd:YAG lasers with YAG-rods the highest efficiency achievable regarding rod-length is restricted. The reason for this is the stress resulting from laser-active medium due to the poor cooling of the material and heating effects from the stimulating lamps. The highest achievable length of rods ensuring a sufficient quality is also restricted. Due to this the highest achievable laser beam efficiency is limited to approx. 500 - 700 W. To produce higher output powers several pump chambers are connected in series or the laser beams of several systems are joined in parallel to the component by processing optics.
2.2.2 Thermally Induced Lens Effect of the Laser Rod

On account of the low efficiency of the Nd:YAG laser the rod becomes highly heated when being pumped by the stimulation lamps. De-Ionized (DI) water is used to cool the pump chambers by transporting the dissipated heat. As the dissipated heat can only be transmitted via the outer surface of the rod, a radial temperature gradient is produced within, resulting in a thermal lens characteristic in the resonator. This thermal energy depends on the pump power and can affect the generated beam and its geometry as well as performance characteristics during the start (usually for some seconds). Subsequently, the depth of weld or weld width can as example be affected during welding. These side effects increase the focusing quality. For lasers showing distinctive thermal start behaviour, an online beam diagnostic for a reproducible adjustment of the laser parameters is an important precondition to maintain the desired processing quality. Further measures are:

- Warming up the laser first by means of pre-pulsing it in a beam shutter
- The laser is provided with a light wave guide constantly keeping the output beam within its beam dimensions
- The rod is replaced by a slab-shaped geometry (slab-laser). Opposing thermal lens effects tend to neutralized each other
- The use of laser diodes for optical pumping, only emitting within a small spectral range, by which the heating of the rod is reduced considerably
2.2.3 Development concerning Nd:YAG Lasers

In order to be able to develop further application fields for Nd:YAG lasers, great efforts are made to improve the beam qualities further.

The most important objectives of development are:

- Increasing the beam power; currently CW-devices with an efficiency $\eta$ of 4% are available
- Minimizing the forming of thermal lens and/or reducing its effects on the ejected beam
- Improving the total wall-plug efficiency of the laser by using new stimulation techniques such as laser diodes
- Improving the beam parameter product and thus further improving the focusing ability

Each itemized objective cannot be viewed individually. The objectives described require each other and can only be processed together. One of the currently most important works in this field is the stimulation of a laser active medium by laser diode arrays. Laser diodes are semiconductors emitting at a specific wavelength. If this is well coordinated with the stimulation wavelength of the Nd-atoms, an Nd:YAG lasers can be pumped with considerably smaller stimulating losses. The rod does not require to be cooled as much, there is only a small thermal lens effect and the total efficiency increases. As a result of moderately falling costs for laser diodes, these are increasingly used as stimulation sources for commercial lasers. Since the use of laser diodes for stimulating Nd:YAG lasers will provide economical benefits, on account of its long life and higher pump efficiency, further developments and an optimization of the stimulation method are to be expected in case of further falling prices.
2.2.4 Laser Beam Sources for Laser Material Processing

The only beam sources currently used for laser beam welding in industrial field are CO₂-lasers and solid state laser systems Nd:YAG lasers, disc lasers, diode lasers and fibre lasers. Industrial users have been able to use high power fibre lasers with excellent beam quality of up to 30 kW [26][37]. If the high efficiency of fibre lasers is considered, the long life of the stimulation sources (single-emitter-diodes - MTBF 100,000 h) and its distinctively compact size, they may even today be described as potentially alternative systems for lamp- and diode-pumped Nd:YAG lasers and CO₂ lasers [37].

Table 2.1 gives a view of the laser systems currently used by the industry:

<table>
<thead>
<tr>
<th></th>
<th>Fibre Laser</th>
<th>Nd:YAG</th>
<th>CO₂</th>
<th>Disc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Plug Efficiency</td>
<td>30%</td>
<td>2-4%</td>
<td>10%</td>
<td>15%</td>
</tr>
<tr>
<td>Output Powers</td>
<td>up to 50 kW</td>
<td>to 6 kW</td>
<td>to 20 kW</td>
<td>to 6 kW</td>
</tr>
<tr>
<td>BPP 1) [mm x mrad]</td>
<td>&lt; 2.5</td>
<td>25</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>BPP 1) (4/5kW)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diode Lifetimes in hours</td>
<td>100000</td>
<td>10000</td>
<td>N.A.</td>
<td>10000</td>
</tr>
<tr>
<td>Cooling</td>
<td>Air/Water</td>
<td>De-ionized</td>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td>Floor Space (4/5kW)</td>
<td>&lt; 1 m²</td>
<td>6 m²</td>
<td>3 m²</td>
<td>&lt; 4 m²</td>
</tr>
<tr>
<td>Operating Cost/hour</td>
<td>$21.31</td>
<td>$38.33</td>
<td>$24.27</td>
<td>$35.43</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Not Required/Less</td>
<td>Often</td>
<td>Required</td>
<td>Often</td>
</tr>
</tbody>
</table>

1) Beam parameter product

At present CO₂-lasers have the widest field of application. High available efficiencies, very good beam quality, high availability and moderate investment costs make these lasers very impressive. Due to flexible beam guidance via waveguides, adapted pulse shaping and good focusing ability, Nd:YAG lasers are of great importance to micro-and fine material processing.

Solid state laser systems with an output power of up to 4 kW have been available for some time [136].
Greater attention, however, is paid to the increasing development regarding fibre-coupled CW-solid state lasers. Lamp- and also diode rod lasers, which do not measure up to the standard of CO₂-Lasers regarding output power, beam quality and efficiency at all, are also excelled by the new generation of disc and fibre lasers.

Using ytterbium-doped laser-active substrates and pumping with laser diodes results in an enormous increase in efficiency. New laser concepts, which optimize the substrate cooling by making the most of the large volume-related surface of a thin disc or fibre and thus avoiding thermal effects, lead to an improvement of the beam quality and can be scaled to very high output efficiencies [54].

The laser active medium of fibre lasers typically consists of (up to) a 50 m double-core glass fibre whose inner core is doped with ytterbium. The diode laser beam, which is used for pumping, is coupled into the cladding and led to the outer fibre by total reflection. The light passes the laser active medium inside the core many times and emits part of its efficiency, Figure 2.5a. By means of a fibre module an output power of up to 800 W in a fundamental mode with near diffraction limited beam quality can be produced [116 – 117].

Higher efficiencies can be achieved by coupling a number of TEM₀₀-fibres using special splice-technique in which a multi-mode beam with a reduced beam quality is produced. The efficiency of multi-mode fibre lasers is therefore more than 25 % [37].

![Fig. 2.5 a) Schematic representation of a novel fibre laser module [38], b) Fibre laser YLR-400SM (single mode)]
2.2.5 Light Waveguide for Material Processing

As glass is translucent at a Nd:YAG laser wavelength of \( \lambda = 1.064 \, \mu m \) not only glass optics can be used for beam shaping but also glass fibres can be used for the wave guiding of laser beams for processing optics. Using these glass fibres has been very popular in information technology for some time and is a well-known technology. The special demands of laser material processing on glass fibres are much higher beam powers which have to be transmitted.

The optical effect referred to as total internal reflection forms the basis of the possibility to transmit light almost without any losses over long distances. When the light energy transmitted in one medium graduates into another, a part of the light may be reflected at the common interface. The rest graduates into another medium. Under special conditions light can be reflected almost without loss at this common interface. If it is arranged that the two surfaces are held parallel and the medium between them held as translucent as possible to the wavelength of the light, it will reflect from surface to surface (interface of \( n_1 \) and \( n_2 \)) (Figure 2.7) and thus be transmitted inside this almost loss free medium \( (n_2) \) over a long distance without any significant reduction in energy.

By arranging the optically thinner medium around a medium with a higher refraction index it can be achieved that the light beams be zig zag transmitted. In Figure 2.7 such an arrangement is illustrated schematically.

![Diagram of total reflection within a light waveguide](image)

**Fig. 2.7** Schematic representation of total reflection within a light wave guide
The arrangement described above consists of a material with a higher refraction index $n_2$ inside the core and a cladding with a smaller refraction index $n_1$. Most of the laser transmitters used for material processing are of quartz glass. There is only a small difference between the refraction indices of core and cladding. The fibre is provided with one or more coatings over the cladding to increase mechanical strength.

The refraction index given for quartz glass as inner ring and fluorine doped quartz glass as outer ring results in a limiting angle of approximately $\alpha_e \approx 80.5^\circ$,

$$\theta_{\text{max}} = \arcsin\left(\frac{n_2 \cdot \sin(90^\circ - \alpha_e)}{n_{\text{air}}}\right)$$  \hspace{1cm} (2.1)

$n_{\text{air}}$: refraction angle air

This biggest emission angle $\theta_{\text{max}}$ also called acceptance angle of the fibre, is a matter constant and is indicated as numerical aperture (NA) by the manufacturer:

$$\text{NA} = \sin \theta_{\text{max}} = \sqrt{n_2^2 - n_1^2}.$$  \hspace{1cm} (2.2)

The value in the example above is: $\text{NA} = 0.24$

The numerical aperture determines the biggest focusing angle by which the laser beam is allowed to be lens coupled into the glass fibre. Beams which are coupled at a greater angle enter into the cladding by refraction and can destroy the fibre if there is sufficient power.

If a laser beam is intended to be transmitted by a light wave-guide (Figure 2.7),

1. $\theta_0/2 < \theta_{\text{max}}$ The focusing angle of the laser beam behind the focus lens has to be smaller than the acceptance angle of the fibre.

2. $d_0 < d_c$ The diameter of the laser beam $d_0$ on the input fibre interface has always to be smaller than the core diameter $d_c$ of the glass fibre.
3. $E < E_{\text{threshold}}$ The power density of the focusing laser beam on the fibre interface has to be smaller than the destruction threshold of the fibre which is at some GW/cm$^2$.

In the description above the profile of the refraction index radial to the fibre was assumed to be stepped. According to this step-index profile, such fibre is called step-index-fibre (SI). Gradient-index fibres (GI) are also used for laser material processing. The fundamental difference is shown in Figure 2.8.

The SI-fibre shows a constant development of the refraction index above the core diameter while the refraction index of the GI-fibre decreases from the centre of the fibre.

![Fig. 2.8 Schematic representation of a gradient index - GI-fibre (above) and a Step index - SI-fibre (below) [8]](image)

Thus the beam at the SI-fibre is only reflected on the interfaces passing through the light wave guide in a zigzag manner. At the GI-fibre the beam is already refracted inside the fibre core transmitting the wave.
If a laser beam is transmitted through a glass fibre, it will be influenced by power losses and changes of the power density distribution and the beam parameter product. Power losses mainly occur by reflection on fibre end faces at both gas-air crossovers. Currently these losses are within 3 - 5 % per end face so that the power losses of one glass fibre are approx. within 6 - 10 %. The length of the glass fibre has only little share in the power losses because it only shows little attenuation and can be neglected in real applications (typical light waveguide lengths are 5 - 20 m).

Due to multiple reflections inside the fibre the power density distribution in the beam cross section is homogenized. In this way peaks are degraded or elliptical beams are rounded. This form of distribution is determined by the kind of fibre. Whereas it shows a similar Gaussian beam profile from the GI-fibre, it assumes a column-shaped distribution from the SI-fibre. The post-connected processing optics reflects this distribution in the depth of sharpness. Figure 2.9 gives model description of the power-density forms in input and output transmission of a step index fibre.

<table>
<thead>
<tr>
<th>Height line representation</th>
<th>Gray value representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Output Laser Resonator</td>
<td><img src="image1" alt="Output Laser Resonator" /> <img src="image2" alt="Gray value representation" /></td>
</tr>
<tr>
<td>b) After fibre transmission Output face of fibre</td>
<td><img src="image3" alt="After fibre transmission Output face of fibre" /> <img src="image4" alt="Gray value representation" /></td>
</tr>
</tbody>
</table>

Fig. 2.9 Laser power density distribution in front of SI-fibre a) (output laser) and behind b) [6]
The equalizing of the distribution is clearly discernible at the fibre exit. The deviation from the circular area is only a result of smallest aberrations inside the fibre, its end face quality and the following optics (lens aberrations). The described height line profile at the fibre output is called top-hat or flat-top hat profile. This distribution provides significant advantages for laser fine welding application.

### 2.2.6 Handling Systems for Laser Material Processing

For 3D- and 2D-applications of laser beam welding it is required to use multiple-axis, linear and rotary handling devices. The most frequently applied systems and the precision in track guidance, which each one can achieve, is described in the following chapter. High demands are placed on handling devices in laser material processing. They must have both fast processing velocities and at the same time have positioning accuracy possible. Apart from producing a relative motion between work-piece and processing optics, the laser beam has to be guided simultaneously in a suitable way to the focusing optics.

The handling concepts possible according to Table 2.2 are classified by the arrangement of their axes and the components moved [15]. There is a distinction drawn between the Cartesian systems combined of linear axes and systems and devices with rotary axes in robot kinematics. The relative motion required between laser and component is produced either by motion of the beam source, work piece, processing optics or by hybrid kinematics solutions [55][56]. Moved optics requires components for beam guidance. Here, a distinction is made between internal and external beam guidance [57].

On account of the large mass of the laser beam source there are very rare applications for moved beam sources. This approach will only obtain relevance to the industry with the distribution of diode lasers and fibre lasers of a much more compact construction. Solutions with moved work pieces are mainly applied for two-dimensional joint geometries such as rotary friction welding. Table 2.2 gives an overview of the most common variations of beam- and work piece guidance, which can be realized by Cartesian handling and robot systems.
Table 2.2 Cartesian and robot handling systems [8]

<table>
<thead>
<tr>
<th>Cartesian handling systems</th>
<th>Robot handling systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>moved beam source</td>
<td>moved beam source</td>
</tr>
<tr>
<td>moved work piece</td>
<td>moved work piece</td>
</tr>
<tr>
<td>moved optics with internal beam control</td>
<td>moved optics with internal beam control</td>
</tr>
<tr>
<td>moved optics with external beam control</td>
<td>moved optics with external beam control</td>
</tr>
</tbody>
</table>

Hybrid handling systems such as a combination of moved and rotated work pieces can be used depending on the kind of application. For this a rotational axis is firmly adapted to the x,y-translation unit. However, if complex 3-dimensional contours are to be processed, processing optics moved by a robot or moved beam sources are the correct systems. On account of the wide and flexible range of applications and high positioning velocity, more and more scanner-systems combined with linear units and robots are used. Focusing is realized by means of a post-connected F-Theta optics.
With remote welding or scanner-welding, the laser beam is not brought to the work piece by processing optics but by scanner optics at a distance. In the scanner-optics 1 or 2 movable mirrors position the laser beam extremely fast (dependent on the mirror size up to $10 \text{ ms}^{-1}$) to each welding position [68]. The weld order can be optimized for a number of applications so that heat input and distortion are very small. Scanner-welding is used for welding overlap and butt joints.

Selecting a suitable handling concept, with regard to track and positioning accuracy, has to be carried out according each application and required marginal conditions.

### 2.2.7 Examining the Track Accuracy of Different Kinematic Concepts

Nowadays 3-axis CNC-handling systems are the most popular handling devices for laser material processing.

Considering handling techniques, precision and handling are decisive with regard to focus positioning during laser beam welding. Different characteristic quantities have to be taken into account. These are comparatively analysed for laser CNC-handling systems, standard robot systems and scanner systems.

The compatibility of the current position of the robot effector and the position calculated by the control unit is interpreted as position- and absolute precision. The track accuracy describes the observed quality of a predetermined track of base points connected to linear or circular interpolated motions. The repetitive precision is of particular importance for programming the handling devices by CAD-data. Deviation can achieve an order of magnitude of some millimetre. However, evaluating a welding track by a direct teach-in mode at the system, only track- and repetitive accuracies are important.

In order to determine the track accuracy of Cartesian- and robot kinematics, the contour element circle was examined where $t_k$ circular orbit deviations were discovered. Investigations of a laser portal robot manufactured by the company Trumpf showed circularity deviation under $120 \mu \text{m}$ over a velocity range of 2 - 5 m/min [58]. Compared to this, typical circular orbital deviations are between 0.4 and 1.2 mm within the same velocity-range. In Table 2.3 the values achieved in track accuracy circular orbit deviation and repetitive accuracy are given.
2 Basics and Definitions concerning Laser Beam Welding Systems

Table 2.3 Cartesian and robot handling systems [8]

<table>
<thead>
<tr>
<th></th>
<th>Portal</th>
<th>Robot</th>
<th>Scanner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track accuracy:</td>
<td>&lt;0.10 mm</td>
<td>0.4 – 1.2 mm</td>
<td>0.02 – 0.05 mm</td>
</tr>
<tr>
<td>Repeatability:</td>
<td>&lt;0.03 mm</td>
<td>0.02 – 0.1 mm</td>
<td>0.01 – 0.05 mm</td>
</tr>
</tbody>
</table>

Reducing the circular orbital deviation for robot down to 0.15 mm by additional controlling techniques inside the robot gearings has been successful [59]. Currently available systems are only provided with conventional controls and achieve therefore less accuracy. The reasons for the reduced track accuracy of robots are to be found in kinematics, mechanics and dynamics [59].

High quality scanner-systems achieve high process velocities while providing good track accuracy. Through very high positioning velocities between processing sequences the ancillary phases are reduced considerably.

The combination of galvanometer scanner and image processing is a highly precise and flexible kinematic concept.

Rotational axes are a lower-cost and, at the same time, precise kinematic system for 1-D processing. The circular orbit deviations range from 20 – 100 µm.

Due to the very good path accuracy and reproducibility of Cartesian plane and rotary handling systems compared to robots, a hybrid solution using both was found for the LDBA producing laser fine welding station. Scanner systems offered the highest positioning accuracy, but as process optic for focal positioning very cost intensive.
2.2.8 Analysis of Joint Configurations and Work Piece Misplacement

The demands on laser beam welding strongly depend on the geometry of the joint that has to be welded. Therefore, joint geometries relevant for laser beam welding are presented. Different possibilities are known in welding technique for joining components together to a welding assembly. These joints and seams are classified by type. The type of joint describes the constructive arrangement towards each other, while the type of seam describes the shape of the finished welding seam. The joints and seams most important for laser beam welding are summarized in Table 2.4.

Table 2.4 Joint configurations

<table>
<thead>
<tr>
<th>Joint Type</th>
<th>I-weld</th>
<th>Fillet weld</th>
</tr>
</thead>
<tbody>
<tr>
<td>Butt joint</td>
<td><img src="image" alt="Butt joint" /></td>
<td><img src="image" alt="Fillet butt joint" /></td>
</tr>
<tr>
<td>Overlap</td>
<td><img src="image" alt="Overlap" /></td>
<td><img src="image" alt="Fillet overlap" /></td>
</tr>
<tr>
<td>Parallel-joint</td>
<td><img src="image" alt="Parallel-joint" /></td>
<td><img src="image" alt="Fillet parallel joint" /></td>
</tr>
<tr>
<td>T-joint</td>
<td><img src="image" alt="T-joint" /></td>
<td><img src="image" alt="Fillet T-joint" /></td>
</tr>
<tr>
<td>Corner-joint</td>
<td><img src="image" alt="Corner-joint" /></td>
<td><img src="image" alt="Fillet corner joint" /></td>
</tr>
<tr>
<td>Multiple joint</td>
<td><img src="image" alt="Multiple joint" /></td>
<td><img src="image" alt="Fillet multiple joint" /></td>
</tr>
</tbody>
</table>
From the focus positioning of a laser welding process, only the geometry directly near the joint positions is important. For this reason different joints and seams are summarized here and the general terms overlap-, butt-, and T-joints are used.

The component deviation - Δ joint position - at the join patch can have many reasons (Figure 2.10). There is a difference between dynamic and static deviation [60]. Geometric alterations of the track during processing, such as thermal expansion during welding, are interpreted as dynamic deviations. Static deviations are subdivided into global and local deviations. Global deviations are produced by position deviation of the work piece. Clamping deviations due to incorrect positioning of the component at the device, or impurity of the component causes these. Local deviations are subdivided into form and dimensional tolerances.

Position- and dimensional deviation cause errors in the positioning of the components regarding position and orientation. When being joined with a joint-partner, defects of form at the lining, such as mismatch or joint-gaps may occur [61].

An example of form tolerances in laser material processing is position deviation resulting from preparing and clamping processes, ranging within some 100 μm.

Measured tolerances are extremely important to precision components, which are being clamped or cut to size prior to the joining procedure. The tolerances are summed up
within a system assembly leading to an impairment of the desired assembly function during production such as the adjustment and laser welding of a multi component assembly. 

Materials and components with strong heat expansions cause dynamic deviation. For example, the thermal induced component distortion on precision components destructs or reduces the functionality or even the whole assembly.

In remote or scanner welding, the laser beam is not conducted by process optics close to the work piece but by scanner optics at a large distance from the work piece. In scanner optics there are 1 or 2 flexible mirrors, which rapidly steer the laser beam to the new welding position. The welding seam order can be optimized by teach-in methods, so that heat input and distortion are minimal. Scanner welding method precisely by using vision systems for laser beam positioning welds overlap seams and butt joints.

Selecting a suitable handling system, with regard to track- and position accuracy, must be done according to the current application.

2.3 Feasibility Check of the 2-Dimensional Track Processing

2.3.1 Feasibility Criterion

In order to check the feasibility of an operation of laser beam welding by means of linearly and rotationally moved axis, the deviation occurring in the track guidance of the processing optics and position of the joint have to be compared to the tolerances allowed by the process. It is postulated that the maximum displacement allowed by the joint – geometry between laser beam and joint position minus the maximum deviation of the actual tracks of the used linear- and rotational-axis of the nominal track has to be higher or equal to the maximum deviation of the actual positions of the joints and its nominal positions at the work piece [62].

The relation is as follows:

\[
\Delta \text{Process} - \Delta \text{Handling system} \geq \Delta \text{Joint position}
\] (2.3)
Following permissible deviation of the joint $\Delta$ process, the track behaviour of the $\Delta$ handling system, as well as the components that have to be joined by the laser regarding precision and position of the joint components $\Delta$ joint position have to be examined.

Displacements of the joint position can influence the focus situation $\Delta z$ in beam direction as well as vertically influence the target position $\Delta x$. The resulting deviations of the laser focus position are described as $\Delta$ process.

The meaning of the term focus situation is the position of laser focus towards beam direction relative to the component. Another important size is the on-meeting place of the laser beam on the component. The focus positions as well as the target position of the laser beam have a great influence on the welding seam quality. Both terms describe the distribution of the laser beam efficiency on the component (Figure 2.11).

![Laser beam, target position, focus situation, weld joint]

Fig. 2.11 Definition of focus situation and target position

The track velocity $v_s$ describes the motion of the laser focus along the joint edge. It indicates the velocity of the laser focus towards advance direction. The quotient of the laser power $P$ and welding velocity $v_s$ is indicated as energy unit length of weld $E_s$. 
2.3.2 Permitted Deviation of Weld Shape

The processing optics cannot always be kept at the defined operating point due to component tolerances and errors in handling techniques. As a result, deviations in the position of the laser focus $\Delta$ process occur. The description of these deviations is summarized and important weld shapes are given as an example in Figure 2.12. Mistakes in joint configuration can be both a welding gap $h_s$ and a component mismatch at the butt joints $h_v$.

![Diagram of weld shapes and symbols](image)

**Fig. 2.12 Definition of the deviation of the seam situation and form [8]**

The different weld shapes show different process windows with regard to the deviation from the ideal situation and ideal shape. Orders of magnitude of the permitted deviation in laser beam welding of steel materials are indicated in Table 2.5. These can only serve as indication due to a large number of applied beam sources and materials. For Lightweight materials such as aluminium and magnesium, lower quantities are valid. For assessing the precision achieved by a track guided handling technique this description is sufficient.

The permitted field of focus position is independent of the used weld shape and extends from $\Delta z$ 0.25 to 0.6 mm [63]. The focal distance of the applied optics and depth of focus
is responsible for the actual value depending on the beam quality. The I-seam places the lowest demands at the overlap-joint regarding the on-meeting place. The position is determined by the size of the overlapping field \( l_o \) or the possible collision with component and clamping technique. Here the position is determined by the size of the overlapping area \( l_o \) or possible collisions with component and clamping technique.

When welding the fillet weld at the overlap joint and welding the I-weld at the butt joint the beam has to be positioned in a way that the focusing laser beam touches both components at all times. This only guarantees that the melted area covers both components thus guaranteeing a bond between the components. This results in permitted deviation of \( \Delta x \) in an order of the beam radius [64].

<table>
<thead>
<tr>
<th>Deviation</th>
<th>I-weld butt joint</th>
<th>I-weld overlap joint</th>
<th>Fillet weld overlap joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus situation ( \Delta z )</td>
<td>0.25 - 0.6 mm</td>
<td>0.25 - 0.6 mm</td>
<td>0.25 - 0.6 mm</td>
</tr>
<tr>
<td>Target position ( \Delta x )</td>
<td>( 0.5 D_o,u )</td>
<td>( \sim l_o )</td>
<td>0.5 ( D_o,u )</td>
</tr>
<tr>
<td>Joining gap ( h_a )</td>
<td>0.1 - 0.25 ( t ) or ( &lt; 0.2 \text{ mm} )</td>
<td>0.05 - 0.1 ( t ) or ( &lt; 0.15 \text{ mm} )</td>
<td>0.4 ( t )</td>
</tr>
<tr>
<td>Edge offset ( h_e )</td>
<td>0.1 - 0.3 ( t )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( l_o \): Length of overlap \( D_o,u \): Focus diameter \( t \): Thickness

A joint gap between the components leads to missing material in the weld if, as assumed here, it is welded without filler material. This results in an increasing seam relapse with a growing width of gap, a decrease in the supporting connection area and a fatigue notch occurs. The seam relapse and the permitted gap size of all weld shapes are in proportion to the plate thickness \( t \) [65 - 66]. Depending on the thickness of the plates there is an absolute maximum for the size of joint gap, which must not be exceeded.

If this maximum size is exceeded the bonding of the components cannot be guaranteed. In case of butt joints the laser beam passes through the joint gap without fusing the components.
A misalignment of edges between the joint partners is also another possible defect on butt joints. A misalignment of edges again is responsible for a decrease of the supporting connection area and the strength of the welding assembly. Another one is the deterioration of the force flux by the weld [67].

In addition to the demands mentioned on the relative positioning of the laser focus towards the component, the positions of the component and processing optics, regarding environment have to be considered. The restrictions are placed by the workroom of the positioning system or the beam guiding system and the collision other parts of the component or the clamp and measuring devices. There are no generally valid quantities as these are highly determined by the current application.

2.3.3 Conclusion of Analysing the Feasibility Criterion for Laser Fine Welding with Respect to LDBA Production

Assuming a focus diameter of 0.5 mm typical for a standard laser system for laser beam welding there is a maximum permitted positioning deviation for fillet welds and butt joints in flat formation of 0.25 mm. The maximum track deviation of an operation carried out by robots is approx. 0.2 mm if programmed accordingly. Applying equation 2.5, a minimum component deviation of 0.05 mm is permitted. As described above, this is not always the case. Summarizing, it can be said that faultless processing cannot be guaranteed.

The permissible variation for precision components in precision mechanics is below 50 \( \mu \text{m} \). Furthermore, a technical zero gap between the components is strived at. Assuming a Cartesian processing with a maximum track deviation of 0.05 mm and a work piece with a focus diameter of 0.3 mm, a minimum component deviation of 0.1 mm is permitted. This interval has to be regarded rather as safety reserve for lateral and focus positioning.
2.4 Laser Beam Qualities

Some parameters result from the construction and operating modes of the lasers dependent on output power.

Apart from the laser itself further optical components are required for laser material processing in order to adjust the laser according to its task. The radiation efficiency must be guided to its processing place. This can be done by mirrors or by using light waveguides. The easiest way is to focus the laser beam towards the work piece using lens systems (processing optics) or reflecting mirror which are specially shaped.

2.4.1 The Laser Beam, Description and Control Variables

Characterizing a laser beam there are predetermined, system-determined and controllable parameters. The type and the assembly of the laser determine system sizes. Apart from these parameters different operating methods can be adjusted by the operator. The controllable parameters must be adjusted to the various tasks of laser material processing. The terms and descriptions of the different sizes are defined by European standard EN ISO 11145 (1994) and EN ISO 11146 [147].

System-determined parameters (laser parameters):

- **wavelength $\lambda$:**
  
  The wavelength of the laser radiation is predetermined by the active medium neodymium and is $\lambda = 1.064 \ \mu m$.

- **Beam waist diameter $d_0$:**
  
  The beam waist diameter is predetermined by the diameter of the laser rod and the optical resonator.
• **Divergence angle (far-field divergence) \( \theta \):**

The divergence angle describes the angle by which the diameter of the free propagating beam is increased in diffusion direction.

• **Distribution of the power density across the beam cross-section \( I(r) \) (W/mm\(^2\)):**

The resonator determines the distribution of the power density by the illumination of the laser rod across the beam cross-section. A distribution rotating symmetrically around the beam axis is required to achieve operating results, which are independent of the direction.

• **Polarisation \( \Phi \):**

The polarisation describes the distribution of the electrical field vector (vibration direction) vertical to the direction of propagation. There is a distinction made between arbitrarily polarized, linear polarization and circular and elliptic polarization radiation.

**Controllable parameters (process-parameters)**

• **Pulse peak power \( P_p \):**

Pulse peak power is the maximum value of the current radiation efficiency during one pulse duration. This depends on the power-supplying device.

• **Pulse duration \( t_p \):**

Pulse duration is the period within the laser emits its radiation. This is a period of the full width of half maximum for a predetermined pulse.

• **Pulse energy \( E_p \):**

Pulse energy is the caloric equivalent heat quantity of one single pulse. It is determined by the integration of the current output power over the pulse duration. By medium power \( P_{av} \) and pulse repetition rate \( f_{RR} \) the pulse energy can be
calculated. For square pulses it is calculated out of peak power $P_{\text{max}}$ and pulse duration $\tau_H$.

$$E_p = P_{\text{AV}} / f_{RR}$$

(2.4)

- **Average peak power $P_{\text{AV}}$:**
  Pulse power is the average value of the current power within the pulse duration. For square pulses it is calculated out of pulse energy $E$ and pulse duration.

- **Pulse repetition rate $f_{RR}$:**
  The number of pulses per second is the pulse repetition rate.

- **Average power $P_{\text{av}}$:**
  The average power can be determined by use of a calorimetric measuring instrument.

$$P_{\text{av}} = E \cdot f_p$$

(2.5)

- **Duty cycle $D_C = T_P / T_F$ ; $D_C = (T_P \times P_M) / E_P$**

Fig. 2.13 Rectangular power pulses with varied pulse duty cycle $D_C$
- **Pulse shaping P(t):**

Beam efficiency can be changed within one pulse. Pulse shaping is also possible at short pulse durations (<0.5 ms).

![Fig. 2.14 Single pulse shape P(t)](image)

The special pulse shape of a rectangular pulse offers a sufficiently appropriate alternative to general pulse shaping for many laser-welding applications where materials of the same type or different materials are used for welding.

![Fig. 2.15 Special pulse shape (rectangular pulse)- pulse modulation](image)
Nd:YAG-laser sources with flash lights as pump light sources enable pulsed operation with frequencies between 20 and 500 Hz per cavity. Compared to CW-sources a peak power can be achieved which is 10 to 100 times higher but at the same time it achieves only a small thermal load.

2.4.2 Beam Quality, Propagation and Focusing

Each rotationally symmetrical laser beam can be characterised according to three parameters:

- Position of the beam waist $z_0$
- Diameter of beam waist $d_0$
- Divergence of beam waist $\theta_0$

Describing the beam quality different characteristic numbers are used: $K$ (Beam propagation factor), $M^2$ (beam quality factor) and $q^*$ (beam parameter product) (Figure 2.16).

Quantities $K$ and $M^2$ are standardized for laser beam parameter products and refer to the physical limit of a laser beam regarding focusing ability.
The dimensional distribution of laser beams towards beam directions, also called propagation, is determined by size and place of the smallest beam diameter and divergence angle. In order to characterise a laser beam it is defined as beam propagation factor $K$. The dimensionless value is calculated according to equation (2.6).

$$K = \frac{\lambda}{\pi d_0 \cdot \theta_0}$$  \hspace{1cm} (2.6)

$\lambda$ = wavelength in [m]
$\theta_0$ = divergence angle in [rad]
$d_0$ = diameter of the beam waist in [m]

The quantities of beam propagation factor $K$ range between 0 and 1. Typical quantities of the beam propagation factor for lasers above 10 kW are 0.1 to 0.3.

An important fundamental optical constant can be produced out of beam parameters. The product resulting from beam diameter $d_0$ and divergence angle $\theta$ is called beam parameter product $q^*$.

$$q^* = \frac{1}{4} d_0 \cdot \theta = \text{const.} \hspace{1cm} (\text{mm} \cdot \text{mrad})$$  \hspace{1cm} (2.7)

This size, also known as beam quality, cannot be changed by optics inside the beam path and is a measure for the focusing ability\(^1\). The smaller the value of the beam parameter product, the better the focusing ability.

Together with controllable parameters, pulse power and pulse duration the beam parameter product determines the maximum welding depth and permissible changes in the distance of the focus position and on-meeting place.

The beam parameter product is not constant throughout the whole power density. The reason for this is the thermal induced lens effect (thermal lens) inside the rod, which detunes the resonator. The more the beam quality increases, the more sensitive the resonator reacts to changes in the thermal lens.

These effects increase by growing beam quality (focusing ability). Figure 2.17 depicts beam parameter products for different laser systems.

\(^1\) Good focusing ability means, apart from a small focus diameter, a high depth of field.
Both pulse lasers are operated without light wave guide (LWG) and show the changes depending on the pump power of the beam parameter product due to a thermal induced lens effect of the laser rod. In connection with an LWG (step-index) these beam alterations at the place of operation do not occur any longer, the beam parameter product stays constant over the whole power density.

![Beam parameter product](image)

**Fig. 2.17** Beam parameter product (BPP) of different lasers vs. pumping power [35]

A laser beam intensity distribution the laser unit output can be referred to as a Gaussian approximation. This beam is characterized by a transversal distribution of the power density \( I(r,z) \), which corresponds to a Gaussian bell-curve. Figure 2.18 shows a 2-dimensional distribution of intensity of a Gaussian beam.

The radial intensity distribution of a Gaussian beam vertically to its distributing direction can be described mathematically by the exponential function (2.10).

\[
I(r,z) = I_0(z) \cdot e^{-\frac{r^2}{(4(z)/z)^2}} \quad (\text{W/mm}^2)
\]  

(2.8)

by the sizes
2 Characterisation of Laser Beam Qualities

$I_0(z)$: max. power density at $r = 0$ (W/mm$^2$)
$r$: beam radius (mm)
$d(z)$: beam diameter (mm)
$z$: Position at the optical axis where the beam waist is $z = 0$ (mm)

Graph 2.18 shows a plot of the intensity distribution of a Gaussian beam with common methods of defining the beam diameter. For Gaussian calculations the $I/e^2$ is used.

![Graph 2.18 Intensity distribution $I(r,z) = 0$ of a Gaussian beam TEM$_{00}$][156]

The fundamental waveform TEM$_{00}$ has a Gaussian-shaped intensity distribution $I(r)$ or $I(x,y)$ with beam radius $r$ and beam diameter $d = 2w$.

$$I(x, y) = I_0 \exp \frac{-s(x^2 + y^2)}{d^2} \quad (2.9)$$

The x-y-level is vertical to the propagation direction z and $r = (x^2 + y^2)^{1/2}$ is the radial coordinate. Power $P$ depends on the maximum intensity inside the beam $I_0$:
2 Characterisation of Laser Beam Qualities

\[
P = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y) \, dx \, dy = \frac{\pi}{8} d^2 I_0. \tag{2.10}
\]

The maximum power density \( I_0 \) at optical axis \( r = 0 \) is:

\[
I_0(z) = I_0 \left( \frac{d_0}{d(z)} \right)^2. \tag{W} \tag{2.11}
\]
described in the centre of the beam waist at \( z = r = 0 \).

For the fundamental waveform the beam parameter product is calculated out of the diameter \( d_0 \) and the divergence angle \( \theta \) as follows:

\[
\frac{d_0 \theta}{4} = \frac{\lambda}{\pi} \Rightarrow \quad d_0 = \frac{4 \lambda}{\pi \theta}. \tag{2.12}
\]

For higher transversal waveforms in a laser resonator the beam diameter \( d_0 \) as well as the divergence angle are higher by factor \( M \) than at the fundamental waveforms TEM\(_{00}\). In this case the beam parameter product is determined:

\[
\frac{d_0 \theta}{4} = M^2 \frac{\lambda}{\pi}. \tag{2.13}
\]

Size \( M^2 \) is called diffraction number. It is a measure for the beam quality \( K \) of a laser beam:

\[
K = \frac{1}{M^2}. \tag{2.14}
\]

While the diffraction number \( M^2 \) rises in proportion to the divergence angle \( \theta \) the beam quality inverse decreases \( \theta \). High beam quality has \( K = 1 \), while larger divergence angles result in \( K < 1 \). Figure 2.19 shows schematically the distribution of a Gaussian beam \( (M^2 = 1 \text{ and } K = 1) \) in comparison to a radiation field without diffraction limited beam quality \( (M^2 > 1 \text{ and } K < 1) \), assuming the same position and size of beam waists.
2 Characterisation of Laser Beam Qualities

The beam diameter $d(z)$ of a Gaussian beam increases with the place on the optical axis $z$ and depends on the waist diameter $d_0$ and the Rayleigh-length $z_R$:

$$d(z) = d_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}, \quad (\text{mm}) \tag{2.15}$$

$d_0$ : beam waist diameter (mm)

$z$ : place on the optical axis (mm)

$z_R$ : Rayleigh-length (mm)

The Rayleigh-length $z_R$ is the distance on the optical axis after which the beam cross-section doubles and the power density halves. The depth of field can be defined as double the Rayleigh-length. At a great distance ($z \to \infty$) the Gaussian beam results in a linear magnification of the beam diameter. So, for the divergence angle $\theta$ (= far field divergence) there is:

$$\theta = \frac{d(z \to 0)}{z} = \frac{d_0}{z_R}, \quad (\text{rad}) \tag{2.16}$$
The beam diameter \( d(z) \) of a Gauss-distribution is defined by the place where the power density decreases to \( I(r,z)/I_0(z) = e^{-2} \approx 14\% \). Having inserted the beam parameter product the following equation for Rayleigh-length \( z_R \) is a measure for focus depth:

\[
z_R = \frac{d_0^2}{4 \cdot q^2} \quad (\text{mm})
\]  

(2.17)

In Figure 2.20 Gaussian beam is shown with its distribution of the power density \( I(r,z) \) mentioned above and its propagation behaviour towards \( z \)-direction.

Fig. 2.20 Sizes of a Gaussian beam, propagation behaviour and intensity distribution in 3 and 2-dimensional views
The 2-and 3-dimensional diagrams are calculated with equations 2.8, 2.9, 2.11 and 2.15 using special vector and matrix functions (MATLab®, surf and mesh) (Appendix 13.6.1).

Even though the output beam of a Nd:YAG-laser is polarized generally, the alteration of the polarization by using an light waveguide (LWG) should be mentioned. Research has shown that an SI-light wave guide destroys most of the linear polarization. Figure 2.21 shows the change in polarization after an LWG.

![Diagram showing change of linear polarization](image.png)

**Fig. 2.21** Change of the linear polarization by a SI-light wave conductor [35]

The pulse energy of a linear polarized YAG-laser was measured directionally with an analyser before and after passing a light wave-guide. An almost completely polarized laser light was identified at the resonator output. Measurements after the LWG still showed a 30% share of linearly polarized laser light, i.e. by an LWG not only the distribution of the power density is homogenized but also the original direction of polarization.
2.4.3 Focusing of Laser Beams

The power density $I$ of the unfocused laser beam at the resonator output is only $0$ to $200$ W/mm$^2$ and is too small for the material processing of metals such as cutting and welding. Only by focusing the beam with a processing optics the required power density of $10^3$ to $10^5$ W/mm$^2$ can be achieved.

As optical glass is translucent for the wavelength of Nd:YAG Lasers, highly corrected lens systems can be applied. These optics guarantee high image-quality and permit process-observation also during processing.

For these, achromatic optics with several lenses for 3 wavelength ranges are usually used. The lenses are corrected for chromatic aberration and coated against laser light. A Gaussian beam, as described in chapter 2.4.1 is imaged by a lens (or lens-system) in a second Gaussian beam. For this image beam the same mathematical descriptions apply as for the object beam. As the beam parameter product remains unchanged beyond this image, every mathematical formula for a focused beam can be applied. In order to differentiate a focused laser beam from a laser output beam an "F" shifted downwards is added to the indices of the characteristic beam quantities (Table 2.6).

<table>
<thead>
<tr>
<th>Name</th>
<th>Parallel beam</th>
<th>Focused beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam- or focus diameter</td>
<td>$d_0$</td>
<td>$d_{of}$</td>
</tr>
<tr>
<td>Angle of divergence</td>
<td>$\theta$</td>
<td>$\theta_F$</td>
</tr>
<tr>
<td>Rayleigh-length</td>
<td>$Z_{R0}$</td>
<td>$Z_R$</td>
</tr>
</tbody>
</table>

If the laser beam is focused with a lens, focal propagation develops on the focal plane. The size of the focus diameter $d_{of}$ depends on the system peculiar size of the incident beam: Divergence angle $\theta$ and beam diameter $d_{in}$, the distance $z_0$ of the processing optics of the beam waist of the unfocused beam and the focal length $f$ used (Figure 2.22).
The position of the focus-radius has moved towards the lens by distance $\Delta f$:

$$
\Delta f = z_i - f = (z_0 - f) \frac{f^2}{(z_0 - f^2) + z_R^2} \quad \text{(mm)}
$$

Two different simplifications, depending on the place $z_0$ of the lens, can be developed from this relation:

**I. Near field approximation:**

If the processing optics is within the Rayleigh-length ($z_0 < z_R$) of the parallel beam, the formula is simplified as follows:

$$
d_{0F} = f \quad \text{(mm)}
$$

The focus diameter only depends on the beam divergence $\theta$ of the parallel beam and the applied focus length $f$.

**II. Far field approximation:**

If the processing optics is positioned outside the Rayleigh-length ($z_0 > z_R$) of the parallel beam, the equation is:
The focus diameter decreases in proportion to the beam waist diameter of the laser beam and the lens-distance.

For an objective focal length of \( f = 100 \text{ mm} \) and a beam diameter \( d_0 = 9 \text{ mm} \) the focus diameter \( d_{0f} \) depends on the lens-distance \( z_0 \) for different beam divergences \( \theta \) and the scopes of both approximations shown in figure 2.23.

\[
d_{0f} = d_0 \cdot \frac{f}{z_0} \quad \text{(mm)} \quad (2.21)
\]

The focused laser radiation, depending on power density, can result in overheating the molten metal leading to splashes and material ablation. Therefore, it is necessary for the focus position to vary above a material-specific critical power density. Through beam guiding and -shaping devices with homogenizing effects, such as beam wave-guide or transmissive facet-optics a more evenly beam profile, compared to a raw beam, can be achieved. The distance of the focusing optics of the waist beam of Nd:YAG lasers, which are used without laser light cable, rarely exceeds the value of 1000 mm. So the focus diameter can usually be determined by means of near-field approximation.
2.4.4 Laser Beam Expansion

As a Gaussian beam is imaged again as a Gaussian beam through lenses, the beam parameter products consequently is a constant:

\[
q' = \frac{1}{4} \cdot d_o \cdot \theta = \frac{1}{4} \cdot d_{os} \cdot \theta_p = \text{const.} \quad (\text{mm x mrad}) \quad (2.22)
\]

The result of this equation is that by extending the focal angle a smaller focal spot can be achieved. This angle-extension can be achieved by an increased beam diameter on the processing optics. Either the distance \( z_o \) between laser and processing optics can be extended or an expansion telescope can be built into the beam path. An expansion telescope consists of a dispersing lens and a convex lens (collimator lens). It forms the input beam into a beam, the beam diameter of which is increased by the expansion factor \( \beta \).

\[
\beta = \frac{f_1}{f_2}
\]

\( f_1 \): focal length of collimator lens
\( f_2 \): focal length of dispersing lens

Due to the constant of value \( q \) the divergence has to decrease by the same factor \( \beta \). If the expanded laser beam is focused by a following optics, the focus diameter decreases by the expansion factor. By means of near-field approximation this is:

\[
d_{os} = \frac{\theta}{\beta} \cdot f \quad (\text{mm}) \quad (2.24)
\]

Exchanging the dispersing lens, focusing can easily be adjusted to the processing geometry given. The focus position therefore moves in relation to the optical focus of the point of observation. This permits a defined alteration of the focus position (de-focusing). The power density can specifically be adjusted to the processing task.
2.4.4.1 Beam Shaping, Collimation and Focusing after a Light Waveguide

Having passed the light wave-guide, a divergent beam bundle emerges from the fibre end. The divergent beam bundle is then collimated with a plano-convex lens ($f_c$) and then focussed by a second plano-convex lens ($f$). In Figure 2.24 the beam path of the beam bundle leaving a fibre end surface is described.

Both lenses image the fibre face (core diameter $d_c$) onto the processing space. As a result the imaging relation is given by the focal length of both lenses:

$$\beta = \frac{f}{f_c}$$  \hspace{1cm} (2.25)

$f_c$: focal length of collimation lens
$f$: focal length of processing optics

The achievable focus diameter is then determined by:

$$d_{\text{ef}} = d_c \cdot \beta$$ \hspace{1cm} (mm)  \hspace{1cm} (2.26)
The beam quality $q^*$ at the transmitting cable output is constant and remains constant after being focused on the work piece. The advantages of a high beam quality in laser material processing are:

- Larger working distance
- Smaller seam welds and cutting joints
- Higher processing velocities
- Greater/larger distance tolerance between optics and work piece

The depth of field $s$ indicates the size of the field below and above the focus plane after the power density has decreased to 50%. Depth of focus is double the Rayleigh-length $z_R$,

$$s = 2 \cdot z_R = 2 \cdot \frac{d_{0f}^2}{4 \cdot q^*} \quad \text{(mm)} \quad (2.27)$$

In the following, the effects of beam quality $q^*$ on focal diameter $d_{0f}$ and the focal depth 2 x $z_R$ are shown (Figure 2.25, 2.26, 2.27).

A greater focal length $f$ increases the focus diameter $d_{0f}$ and the depth of focus $s$ at a constant beam parameter product $q^*$ (Figure 2.25):

![Figure 2.25 Beam propagation for $q^* = \text{const.}$](image)

A better beam quality $q^*$ will be achieved:
2. Characterisation of Laser Beam Qualities

- The same focus diameter $d_{0f}$ at a greater working distance and greater depth of focus (Figure 2.26)

$$q^*_1 < q^*_2$$

![Diagram of beam propagation for $q^*_1 < q^*_2$ and $f = \text{const.}$]

- Smaller focus diameter $d_{0f}$ at the same working distance and smaller depth of focus (Figure 2.27)

$$q^*_1 > q^*_2$$

![Diagram of beam propagation for $q^*_1 > q^*_2$]

Fig. 2.26 Beam propagation for $q^*_1 < q^*_2$ and $f = \text{const.}$.

Fig. 2.27 Beam propagation for $q^*_1 > q^*_2$

The better the beam quality, the better the focal qualities of the laser beam. Higher beam quality $q^*$ results in smaller spot diameter and reduced depth of focus. This leads to an increased intensity at the material to be processed.
Figure 2.28 shows the industrial processing optics of an Nd:YAG-lasers with fibre beam delivery and CCD-camera for focus position monitoring. Modern processing optics have a modular construction being cooled by air/ventilation or water, according to the power required.
3 Joining by Welding

In this chapter different welding processes are presented, explained and compared. Further, the effects of different welding processes and their intensity distributions at the hardening gradient in the joint cross-section and heat impact zones are discussed. In general Laser beam welding processes can be divided into the two areas, heat conductance and depth welding (key-hole welding).

An important aspect is the comprehension of the physics of the absorption of electromagnetic waves in material, material surfaces and their interaction with it. Using the optical constants $n$ (refraction index) and $k$ (extinction coefficient) and the Fresnel equations, the reflectivity $R$ and thus the absorption $A$, in dependence of the laser beam incident angle can be determined. For polarised light, this is effective for the perpendicular and parallel coordinates.

This should allow the estimation of the effects of a changing incidence angle on the work piece to be welded. Knowledge of these effects had impact on the construction of the work piece and the applied clamping technique.

The limitations and differences of conventional joining technologies as compared to laser beam welding are then evaluated.

The findings and results from chapter 3 are applied in the chapters 5, 6 and 9. The structure of this chapter is summarized in Figure 3.i.
Subchapter 3.1
Operating principle of welding

Effect of the heat source

Subchapter 3.2
Interaction of laser beams with matter

Principle of laser beam welding
SHADOW-welding

Subchapter 3.3
Absorption of laser radiation

The optical constants $n$ and $k$

Subchapter 3.4
Restrictions and differences to conventional joining methods

Subchapter 3.1/3.2/3.3/3.5 are used in chapter

Chapter 5 - Fine welding station
Chapter 6 - Characterisation of handling systems deviation

Fig. 3.i The subchapter block diagram
Joining by welding achieves the cohesion of materials using heat or force. This is made possible by welding materials, welding powder/flux or paste.

The energy required for welding is supplied from outside. Supplying thermal energy usually enables and/or supports the joining process.

Typical forms of heat production are chemical reactions, effects of electrical current, friction, effects of radiation see Figure 3.2, which, in positive substance joining and
welding with or without pressure, lead to the processing groups of fusion or pressure welding.

### 3.1 Operating Principle of Welding

According to its physical course a difference is made between pressure and fusion welding. Pressure welding is carried out using force with or without filler materials. Welding is enabled by limited local heating, even up to fusing. Fusion welding is joining with a limited local fuse mass without force/strength with or without filler material.

Figure 3.3 shows the causality-combination between thermal and mechanical energy, which, according to its productional- and technical realization, permit dividing the weld method into causality-principles for pressure and fusion welding.
3.1.1 Effect of the Heat Source

During welding, and related thermal methods, the quantity of heat leads to the development of temperature fields which, depending on the power density (Figure 3.4) of the method, has an effect on the on-glaze cross-cut, the seam shape and the distribution of the temperature field.

![Diagram showing comparison of power density at select melting weld methods]

Fig. 3.4 Comparison of the power density at select melting weld methods

The heat source applied achieves a number of material alterations of the welding joints during welding and component-deviation. Large material alterations only appear at fusion-melted joints. Every alteration is disadvantageous for the component. This is caused by the extreme temperature-time-course characterizing the welding process.
The thermal source used causes a number of changes in the weld material and mechanical changes in the work piece. These changes occur mostly in fusion welding methods and are always detrimental to the work piece.

The reason lies in the characteristic extreme temperature-time constant (Figure 3.6a) for such welding techniques.

- High heating velocity (100 to 1000 K/s)
- High cooling velocity (values up to 600 K/s)
- Short austenitizing period (some seconds)

High power densities, as achieved by beam processes, achieve small on-glaze zones and therefore require very precisely prepared joints and very small weld gaps, often press fit. The critical heat affected zone (HAZ) increases with reducing power density, and inevitably welding velocity, and the hardness gradients reduce with the temperature gradient, corresponding to the cooling velocity (Figure 3.6b).
The temperature-time-course in welding is the reason for:

- Material alterations
- Dimension alterations of the welded joint (construction) resulting from residual stresses caused by differences in temperature.
3.2 Interaction of Laser Beams with Matter

3.2.1 Principle of Laser Beam Welding

Laser beam welding is a fusion welding method and only differs from other fusion welding methods in the type of energy supply. The energy required for laser beam welding is penetrated into the material as electromagnetic radiation for the required weld metal volume, as quickly as possible, with corresponding power, thus reducing the heat load of the component in many application cases. Figure 3.7 shows chronological phases of laser beam welding.

![Diagram showing different chronological phases of laser beam welding](image)

Fig. 3.7 Different chronological phases of laser beam welding [35]

During the opening phase of the laser beam welding process, four, chronological phases (absorption – keyhole welding), according to power density, can be observed.
1. Absorption

The required power density for laser beam welding is achieved by focusing the laser beam radiation on the work piece by focal optics. In case of metals the radiation is then absorbed in a thin layer (<1 μm) on the metal surface and converted into heat. The transport of the energy into the material takes place by heat conduction.

2. Heating

The temperature achievable on the material surface is a function of the power density and the penetrating duration and is reduced by reflection- and heat conduction losses. These losses can specifically be reduced by both modifying (e.g. oxidation) the surface of the material and optimising the geometry of the work piece.

3. Heat conduction welding

On achieving the melting temperature a melt bath is produced on the surface in proportion to the penetrating duration, which, in spot welding, solidifies after pulsing thus determining the welding geometry. This method is called heat conduction welding as the geometry of the melt in this case is considerably determined by the heat conduction (Figure 3.8a).

4. Penetration welding

The welding process changes if, within the duration of penetrating, the evaporating point is achieved and the repulse pressure of the escaping vapours deforms the melt surface. During material melting a vapour-capillary (keyhole) is formed. The laser beam can deeper penetrate into the material through this keyhole. The welding depth is limited by the distribution of the beam and the interaction of radiation and metallic fume inside the capillary (Figure 3.8b).

The two fundamental fields of laser welding are (Figure 3.8):

- heat conduction welding – spot- and CW-welding
- keyhole or penetration welding – spot-and CW-welding
3 Interaction of Laser Beams with Matter

Heat conduction welding and penetration welding is possible with lasers operated in continuous mode as well as operated in pulsed mode.

The absorption behaviour of metals when penetrated by laser radiation and the influence of laser beam parameters on the welding process and the resulting welding geometries are presented in the following chapters by spot welding serving as an example.

Conduction welding offers less perturbation to the system because laser radiation does not penetrate into the material being welded. As a result, conduction welds are less susceptible to gas entrapment during welding. With keyhole welding, intermittent closure of the keyhole can result in porosity.

Fig. 3.8 Range of laser welding processes, a) conduction welding and b) penetration welding

Nd:YAG lasers: 1500 W, f = 100 Hz
fibre 400 µm, spot: 300 µm, f = 150mm
vs = 1.2 m/min, aspect ratio: 0.5

Fibre Laser: Weld seam 1, 700 W,
fibre 50 µm, spot: 100 µm, f = 300 mm
vs = 9 m/min, aspect ratio: 2.6
3 Interaction of Laser Beams with Matter

3.2.2 Stepless High Accurate and Discrete One Pulse Welding (SHADOW)

Laser welding methods, due to joining dynamics, can be subdivided as follows:

Stationary beam:

- **Spot welding**: Joining is by single welding spots.
- **Simultaneous welding**: This technique is similar to spot welding. The focus of the joining geometry has been adapted to the joint geometry. It is possible to produce weld seams using a line focus, for instance, by one single laser pulse without apparent motion between laser beam and component.

Moving beam:

- **Spot seam welding**: A seam is produced by stringing single spots together.
- **CW-welding**: A continuous seam is produced by a CW-laser (continuous wave-laser)

A seam weld of several millimetres is produced by one single pulse lasting \( \tau_h \) higher 10 ms through processing velocity \( v_s \) bigger 10 m/min. In order to use SHADOW, a beam source with the following specifications is required [44]:

- Wavelength <1100 nm
- Pulse peak power <3...5 kW
- Beam parameter product <20 mm x mrad
- Focus diameter <300 \( \mu \)m
- Pulse duration <50 ms
- Rayleigh-length >0.5 mm
For SHADOW-methods flashlight pumped as well as diode-pumped Nd:YAG Lasers are used. The required chart velocity can be provided by linear axis, rotational axes or scanners. The joint geometry can be of different forms, as long as accessibility from one side is guaranteed. This results in a minimum cycle time $t_z$.

$$t_z = \frac{P_p \cdot \tau_H}{P_{AV}}$$

$P_p =$ peak power, $P_{AV} =$ average peak power, $\tau_H =$ Pulse duration

The advantages of SHADOW compared to spot seam welding are:

- Shorter processing time
- Less thermal load: In spot seam welding every single pulse causes heating up and cooling off. In spot welding, with equal seam length, more material is melt open because 60 % of the single welding spots are overlapping, thus reducing the distortion of components.
- Improved input coupling of laser radiation: In industrial production regimes the surface conditions of the materials can vary on account of oxide layers and contamination through oil or roughness, influencing the absorption of the laser radiation in particular in case of low absorbing materials such as copper base alloys.

In SHADOW only, during the launching-phase laser radiation is coupled in at the solid phase. The material melts after some 100 $\mu$s. Coupling then takes place reproducibly into the liquid phase of the metal. In spot seam welding, however, each pulse is coupled into the solid phase of the metal.
3.3 Absorption of Laser Radiation

In case of material processing using laser radiation, the result of the process considerably depends on the laser beam efficiency coupled into the work piece. The power, absorbed in thermal joining methods such as cutting, joining and surface processing, leads to heating and phase transitions inside the work piece which can then be used for material processing. The ratio of absorbed power $P_{abs}$ to the incidenting laser power $P_L$ is called coefficient of absorption $A$.

\[ A = \frac{P_{abs}}{P_L} \]  \hspace{1cm} (3.2)

The coefficient of absorption considerably depends on the wavelength $\lambda$ of the laser light used for processing. But also surrounding conditions (processing gas, surfacing, surface quality (roughness, geometry), quality of the work piece (thickness), alterations due to laser radiation (local heating, laser-induced plasma) have an influence on the coefficient of absorption. In the borderline case of low absorbed power and ideal surfaces, absorption can be described by wavelength dependent optical constant index $n$ and attenuation index $K$. As measuring the coefficient of absorption is very difficult, it is most of all determined indirectly via measuring the transmitted ($P_{trans}$) and reflected ($P_{refl}$) radiation and balancing the energy,

\[ P_{abs} = P_L - P_{trans} - P_{refl}. \]  \hspace{1cm} (3.3)

Transmission coefficient $T$ and Reflection coefficient $R$ are defined as follows:

\[ T = \frac{P_{trans}}{P_L} \quad \text{and} \quad R = \frac{P_{refl}}{P_L}. \]  \hspace{1cm} (3.4)

The simple relation between absorption-, transmission-, and reflection-factor results from equations (3.3) and (3.4):
Making use of equation 3.5 the coefficient of absorption can be determined by measuring reflection factor and transmission factor.

If work pieces are thick enough, every material becomes opaque/non-transparent to electromagnetic radiation. For metals this thickness, the optical penetration depth \( \delta \), for the wavelength used in laser material processing \( \lambda = 1.06 \, \mu m \) and \( \lambda = 10.6 \, \mu m \), only fractions of \( \mu m \). In this case the equation (3.6) is simplified:

\[
A = 1 - R
\]

The reflection factor of metals has the same information as the coefficient of absorption.

Absorption can be divided into two major fields:

- Volume absorption \( \delta \geq t \)
- Surface absorption \( \delta \ll t \) \((t: \text{thickness of work piece})\)

As for material processing usually a surface absorption can be assumed.

Should as example a volume of a certain material to be melted at a speed \( v_s \) by the thermal conduction method, the power to be required is given by equation 3.7.

\[
P_{\text{abs}} = P_L A = (wdv_s) \cdot \left\{ \rho[c(T_M - T) + h_M] + P_v \right\}
\]

\( w \) is the seam width and \( d \) the weld depth. The first bracket term represents the time-unit related volume, the second term the material and process energy requirement with the melt enthalpy \( h_M \).

This allows a general relationship between laser power, material characteristics and attainable process data to be found.

\[
P_L \propto [wdv_s \cdot f(\text{material, process}) + P_v]
\]
where absorptance as material and wavelength dependant proportionality factor. If \( w \times d \) approximately represents the seam cross section \( F \), the proportionality from equation 3.8. gives

\[
P_L \propto Fv_s. \tag{3.9}
\]

The heat input per unit described by equation (3.10) is suitable as characterizing quantity.

\[
E_s = \frac{P}{v_s} \tag{3.10}
\]

This linear dependency of the seam cross-section on the energy input per unit length can also be found experimentally in other parametric areas to very high powers and/or low speeds.

Methods using a high power density produce a very small heat affected zone and lead to a very little distortion of component.
3.3.1 Electro-Optical Properties of Matter

Interaction of light and matter happens through charged particles such as electrons. Only light electrons, arising from the frequency $\omega$ and/or wavelength $\lambda$ of laser beam radiation, are able to follow the electromagnetic fields of the laser beam. The electrons are interacting with themselves, with positively charged atoms in the crystal lattice and with microscopic missing places left in a crystal lattice construction. The energy transmission taking place in this interaction is absorption energy, which can macroscopically be measured by an increase in temperature.

In case of gas and some solid or liquid dielectrics the electrons are attached to lattice atoms. The incidenting light stimulates the electrons to vibrate towards lattice atoms. The energy absorbed through vibration is emitted by the radiation of the atom or converted into kinetic or vibration energy by an impact. This usually leads to an increased temperature of the work piece.

The optical properties are determined by two quantities in this thesis:

Vibrations of electrons versus lattice atoms can be described by vibration frequency $\omega$. The atom-shocks and interacts among themselves, described by shock frequency $\nu_e$.

In case of metals the electrons, interacting with laser radiation, are no longer attached to individual atoms. The electrons form a gas of charged particles (plasma), which keeps together the crystal lattice built up by positively charged lattice atoms. The whole electron gas can oscillate versus the crystal lattice. The typical frequency is called plasma frequency $\omega_p$. The plasma frequency depends on the density of the electron gas,

$$\omega_p = \sqrt{\frac{e^2}{\varepsilon_0 m_e \rho}}$$  \hspace{1cm} (3.11)

($e$: elementary charge; $\varepsilon_0$: dielectric constant in vacuum; $m_e$: electron mass)

Influenced by laser radiation, this vibration is stimulated and the energy of this vibration is converted into heat by shocks from self-oscillating crystal lattices (electron-phonon-coupling) or by lattice imperfections. These shocks are also described by typical shock frequency $\nu_c$. 


Not only the optical characteristics of metals are dominated by the electronic system, but also the electric conductivity $\sigma$ and the heat conductivity $\lambda_h$ are described by quantities such as $\omega_p$ and $\nu_c$. This is also expressed by the close connection between reflection coefficient factor and the property of conducting electricity (Hagen-Rubens-relation).

$$R = 1 - 2\sqrt{\frac{2\varepsilon_0\omega}{\sigma}}$$  \hspace{1cm} (3.12)

### 3.3.2 The Optical Constants

In order to combine the absorption with the optical constant, the simplest case of the vertical incidence has to be observed. In this case absorption is independent of polarization as there is no direction of propagation indicating vertically in any direction, and the reflection factor $R$ can simply be expressed by $n$ and $k$.

$$R = \frac{(1 - n)^2 + k^2}{(1 + n)^2 + k^2}$$  \hspace{1cm} (3.13)

$R$ = reflectivity, $n$ = refraction index, $k$ = imaginary part of refraction index

This relation results from the limit conditions for electromagnetic fields between air $n=1$, $k=0$ and the work piece. The material constants $n$ and $k$ are frequency dependent and so are reflection and/or absorption. So the model idea, described above, comes to:

$$k = \left(\frac{1}{2} \cdot \left(-e + \left(e^2 + f^2\right)^{1/2}\right)\right)^{1/2}$$  \hspace{1cm} (3.14)

and

$$n = \left(\frac{1}{2} \cdot \left(e + \left(e^2 + f^2\right)^{1/2}\right)\right)^{1/2}$$  \hspace{1cm} (3.15)
$e = 1 - \left( \frac{\omega_p}{\omega} \right)^2 \frac{1}{1 + \left( \frac{\omega_p}{\omega} \right)^2}$

$f = \left( \frac{\nu_c}{\omega} \right) \left( \frac{\omega_p}{\omega} \right)^2 \frac{1}{1 + \left( \frac{\nu_c}{\omega} \right)^2}$ (3.16)

e is the frequency independent, static, relative dielectric constant of the work piece.

The coefficient of absorption has been found for various metals as function of the wavelength in figure 3.9. In addition, the wavelength of laser radiation, of laser types relevant for material processing, has been marked. It shows that there is less absorption for CO₂-laser radiation. One of the possibilities to increase the absorption of metals is to illuminate the work non-vertically using the dependence of the absorption coefficient from the direction of polarization [69].

Fig. 3.9 Dependence of absorption (A) from the wavelength for different materials [69]

The polarization, indicating the plane on which the vector of the electrical field oscillates vertically to the direction of propagation, belongs to the complete characterization of the laser light. Inclining the laser beam perpendicularly to the work piece surface it results in a special plane, a plane of incidence, which is set by the direction of propagation of the laser beam and the vector perpendicular to the surface.
If the electrical field of the light oscillates parallel to the incident plane, the beam is called parallel polarized. If it oscillates vertically, it is called polarized vertically. Non-polarized light consists of statistically distributed amounts of vertically and parallel polarized light [69]. If $\phi$ is the angle between direction of propagation of the laser beam and the surface vector angle of incidence, Fresnel's Form comes to the following connection:

\[
R_s = \frac{a^2 + b^2 - 2a \cdot \cos \phi + \cos^2 \phi}{a^2 + b^2 + 2a \cdot \cos \phi + \cos^2 \phi}
\]  
(3.17)

\[
R_p = R_s \frac{a^2 + b^2 - 2a \cdot \sin \phi \tan \phi + \sin^2 \phi \tan^2 \phi}{a^2 + b^2 + 2a \cdot \sin \phi \tan \phi + \sin^2 \phi \tan^2 \phi}
\]  
(3.18)

(Index $s$ for polarized vertically and $p$ for parallel polarized)

\[
a^2, b^2 = \frac{1}{2} \left( \left( n^2 (1-k^2) - \sin^2 \phi \right) \left( 4n^4 k^2 \right)^{1/2} - \sin^2 \phi \pm n^2 (1-k^2) \right)
\]  
(3.19)

For non-polarized light the average quantity has to be taken and applied to 3.14 und 3.15

\[
R = \frac{R_s + R_p}{2}
\]  
(3.20)
3.4 Restrictions and Differences to Conventional Joining Methods

In precision mechanics, in particular electronic and optical precision mechanics, joining techniques are required on account of increasing miniaturization and compact constructions, which have a high potential of being automated with an exact control of the penetrated process energy.

The advantages of laser systems in material processing are contactless material processing and small heat-affected zones compared to conventional welding processes, except for electron beam welding. Compared to electron beam welding laser beam welding offers the advantage of welding within the surrounding atmosphere. Pulsed solid-state lasers with an average output power of up to 400 W are mainly used for spot- and seam welding. It is mainly used for electrical bonding and the mechanical joining of filigree components. The user can specifically influence the process by a number of adjustable processing parameters.

The currently usual joining techniques in precision mechanics, competing with welding by solid-state lasers, are resistance- and arc-welding, welding with micro plasma and soldering. This method, however, has one major disadvantage. The thermal load on small and sensitive components is rather high and it cannot or only to some extend be used for areas which are difficult to access. In resistance welding components are mechanically loaded to such a degree by the pressure of the electrodes that using this welding process is restricted. Requiring electrical bonding for weld current circuit additionally restricts using this method for joint geometries. Table 3.1 shows a comparison of laser welding to other welding processes.

The irritating facts about brazing are the thermal load on components and the environmental damage by soldering flux. Detailed descriptions of conventional welding and brazing techniques can be gathered from literature [70]. Being a non-material contact joining method, adhesive bonding of small and sensitive components offers a number of advantages to material contact methods. The components to be joined are not exposed to any thermal or mechanical load. Great disadvantages, however, are insufficient aging stability, instability towards aggressive materials (e.g. acids, lye) and gas.
### Table 3.1 Comparison of laser welding to other welding processes [14]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LB</th>
<th>EB</th>
<th>GTA</th>
<th>GMA</th>
<th>RW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joining efficiency</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>High aspect ratio</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Small heat affected zone</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>High processing speed</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Bead profile</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Weld at atmospheric pressure</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Weld reflective metals</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Combine with filler</td>
<td>0</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Automate process</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Capital cost</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Operating cost</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Reliability</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Fixturing</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

+, advantageous; -, disadvantageous; 0, neutral; LB, laser beam; EB, electron beam; GTA, gas tungsten arc; GMA, gas metal arc; RW, resistance welding

In electronics and fine mechanics the components require increasingly high strength joining technologies to replace the conventional cluing or soldering processes. Laser welding can be an alternative because of its flexibility and the ability to provide short cycle times.
Chapter 4 gives a short introduction into the construction and function of commercial laser diode beam assembleys.

The disadvantages of modern systems are discussed and a possible solution for a novel Laser Diode Beam Assembleys (LDBA) is developed.

Solid-state laser diodes with multi-quantum well structure are used as the active beam source of a LDBA. Here, the principle mode of operation of the laser diode is explained and the temperature dependency of the output power as function of the excitation current discussed.

Gradient Index Optics (GRIN-optics) are very compact and efficient components used for focusing or collimation in optical fibre techniques. Through a radial, in near approximation parabolic refractive index characteristic, the laser beam is continuously deflected and thus collimated. The characterisation of the laser beam collimation ability of a laser diode with a beam direction deviation within a GRIN lens, was carried out using a Ray-tracing simulation.

This led to the awareness, that the beam direction deviation of the laser diode could only be corrected by a modification of the laser diode body.

For the precise and reproducible positioning of sensitive components, a special soft­working clamp technique was used. Industrial clamping tools were modified to the different clamping requirements. It was also necessary for new type clamping for laser diode and GRIN-lens to be developed. The structure of this chapter is summarized in Figure 4.i.
Subchapter 4.1
Commercial laser diode beam assembly

Subchapter 4.2
Semiconductor lasers
- Fundamental basics of laser diodes
- Temperature dependence during operation
- MQW laser diode packages and beam deviation

Subchapter 4.3
Gradient index optics for laser diode beam assembly

Subchapter 4.4
Characterisation of beam propagation using Ray-Tracing

Subchapter 4.5
Modification of laser diode (correction of beam direction deviation)

Subchapter 4.6
Precision clamping technique for fine machining
- Precisions clamping, terms and data
- Hydro clamping device
- Precision collets and slit inter-sockets

Subchapter 4.7
Construction with respect to laser beam welding
- Concepts and definitions
- Laser specific influences on weld seam quality
- Laser welding seam imperfections

Subchapter 4.1 - 4.7 are used in chapter

Chapter 5 - Fine welding station
Chapter 10 - LDBA manufacturing

Fig. 4.1 The subchapter block diagram
4.1 Commercial Laser Beam Assembly Systems

These systems collimate and focus the divergent laser radiation of the laser diode by means of special optics and optical fibres (Figure 4.1).

Owing to beam direction deviations of the laser diode and the mechanical construction of common beam assembly systems, the optical quality of focusing and collimating is restricted and are thus not suitable to assignments which require high quality radiation. In addition, these systems are limited by size and chemical resistance to aggressive fumes, gas and humidity. Various applications such as spectroscopy, medical technology or laser measuring technology require beam sources of smaller dimensions, be resistant to aggressive media and have better beam qualities.

![Collimation tube](image)

**Fig. 4.1** Laser diode pigtait with collimation tube [76]

In order to achieve smaller dimensions while improving the beam quality, it is required to access the laser light emitting chip. In addition, the optics for focusing and collimating the laser beam/radiation must be adjusted within the μm-range towards x,y and z-direction to the laser chip. Positioning (adjustment) should not alter considerably on account of thermal fluctuation or ageing processes. Furthermore, the individual components have to be designed in a way that their future function will not be impaired by the laser process.
4.2 Semiconductor Laser

Shortly after the first laser had been realized in 1961 there was a report on semiconductor lasers. At first only pulsed operation at low temperatures was achieved. CW-operated lasers also working at ambient temperatures were developed later on. Semiconductor lasers are of great economic interest, a large number having already been used in consumer goods such as digital music recorders and CD-ROMs as mass storage for PCs and laser printers. Compared to other lasers, the most important qualities are:

- Small dimensions ranging within micro- and millimetres
- Immediate stimulation by small electrical currents and voltages
- High efficiency over 50 %
- Immediate modulation opportunities via stimulating current with frequencies over 10 GHz.
- They can be integrated into electronic components and wiring, wave guides and further elements.
- Production by semiconductor technology enabling low cost mass production
- Small beam diameters which can be coupled immediately into the glass fibre for optical telecommunication

On account of the small resonator, radiation becomes highly divergent through diffraction resulting in beam direction deviation which is rather disadvantageous. Almost parallel ray beams are produced by suitable lenses or collimation optics.

4.2.1 Fundamental Basics of Laser Diodes

According to Figure 4.2a the output power increases in proportion to the increasing current. The radiation efficiency is relatively low in this area of spontaneous emission. If the optical gain exceeds the losses in proportion to increasing current and increasing power laser operation will start if a fixed current threshold $I_{th}$ is reached. Radiation efficiency with power will increase heavily in the area of the stimulated emission. The
external quantum efficiency $\eta$ defined in equation 4.1 is differentially formulated for the steeply ascending laser characteristic line,

$$\eta = \frac{e}{E_{ph}} \frac{d\Phi_e}{dI_F}.$$  \hspace{1cm} (4.1)

Where are

$\Phi_e$: Intensity [W]; $I_F$: forward current [A]; $E_{ph}$: energy of photon [J]; $e$: electromagnetic charge [As].

A differential quantum efficiency of $\eta_{ext} = 32\%$ per mirror end surface results from the characteristic line for 25 °C.

![Characteristic diagrams of a semiconductor laser](image)

**Fig. 4.2** Characteristic diagrams of a semiconductor laser: a) Principle, b) Measured curves for GaAlAs/ GaAs-Lasers by the author

The single laser diode has high losses thus requiring a current density of $j_{th} \approx 10^5$ A/cm$^2$ for laser operation. Such lasers can only be pulse operated.

Sophisticated structures enable reduction of the current threshold density down to $j_{th} < 500$ A/cm$^2$ thus enabling a continuous operation at ambient temperature.
4.2.2 Temperature Dependence during Operation

Figure 4.2b shows that current threshold $I_{th}$ increases if the temperature rises and the characteristic line slopes down gently, i.e. if the differential external quantum efficiency decreases. The current threshold shows to be exponentially depending on the temperature. This connection was empirically determined.

$$I_{th} = I_0 e^{T/T_0}$$ \hspace{1cm} (4.2)

The following quantities were found for the typical temperature $T_0$:

- GaAlAs-Laser: 120 K to 230 K
- InGaAsP-Laser: 60 K to 80 K

The mode spectrum of a laser diode progresses to a longer wavelength if the temperature rises. The enveloping characteristic line is displaced similar to the band-gap with GaAs,

$$\frac{d\lambda}{dT} = 0.24 \text{nm/K}$$ \hspace{1cm} (4.3)

The peaks of the individual longitudinal modes are displaced if temperature, refraction index and crystal length increase.

$$\frac{d\lambda}{dT} = \lambda \alpha + \frac{\lambda}{n} \cdot \frac{dn}{dT}$$ \hspace{1cm} (4.4)

$\alpha$ is the linear expansion coefficient of the crystal resulting in the following Figures:

$$\frac{d\lambda}{dT} \approx 0.12 \text{nm/K}$$ \hspace{1cm} (4.5)

with GaAs and $\approx 0.08 \text{nm/K}$ with InGaAsP.

Only 10% of the total effects are contributed by the length change of the crystal.
4.2.3 MQW Laser Diode Packages and its Beam Deviation

The HL63 14MG/24MG are 0.63 µm band AlGaInP laser diodes with a multi-quantum well (MQW) structure. They are suitable as light sources for laser pointers and optical equipment for amusement. The laser chip is on a cooling body being protected and shielded by a protective gas atmosphere. The cooling body forms a unit together with the basic body. Surplus heat energy is expelled outwards.

The pins guarantee the current supply of the laser diode as well as data acquisition of the monitor diode for controlling the output power of the laser diode. The emitting laser radiation gets outside through a window ($t = 250 \mu m$) (Figure 4.3).

![Laser diode package (side view)](image)

Features [158]:

- Visible light output: 635 nm
- Single longitudinal mode
- Optical output power: 3 mW (CW)
- Low operating current: 30 mA
On account of a rotationally symmetric construction the laser diode packages can be easily handled, can be clamped into devices and can be positioned without difficulty. Two symmetric notches and a groove (1.0 x 0.4 mm) on either side mark the beam propagation direction of fast and slow axis. Due to their construction semiconductor-laser diodes are very sensitive to electrostatic charges. Minimal static discharges can cause destruction or impair the function.

![Fig. 4.4 Laser diode package (top view)](image)

There are two internal circuits mode, style A and Style B, where PD is the photo diode and LD is the laser diode (Figure 4.5).
Due to the inner construction and refraction-determined radiation characteristics of the laser diode there are deviation from the ideal beam propagation ($\theta = \varphi = 0^\circ$) (Figure 4.6A). The lateral, non-centric alignment and orientation of the laser chip inside the diode (Ø 5.6 mm laser diode package, steel with gold plating) can be another cause of beam deviation with regard to the base area. That means the laser diode does not radiate at the surface vector toward the base surface of the laser diode.
Angle deviation $\theta$ and $\varphi$ for a common spatial beam propagation are ranging from $-0.5^\circ$ to $5^\circ$. By pre-selection the laser diodes with the least beam direction deviation are selected particularly.

A further possibility of beam direction compensation is the tilting of the laser diode in direction and degree against the deviation of the beam. A big disadvantage that results from this is the negative effect on required parallelism of the laser diode base to GRIN-lens.

By adjusting the incorrect beam direction (Figure 4.7-2b) to the surface vector of the basic body of the laser diode, the beam direction deviation can be further reduced or minimised. By processing the base surface special mechanical, the surface vector verges into the incorrect beam. Processing (removing the LD-housing) by use of a can opener (see Appendix 13.11) and a cutting tool can be produced as a precise and sensitive processing method (Figure 4.7-4).
4.3 Gradient Index Optics for LDBA

For the beam collimation of the laser diode pigtail, a GRIN-lens system is favoured. Two significant advantages of GRIN-lens technology are the very good optical qualities and the small physical size. This allows the laser diode pigtail to be constructed in a highly compact and efficient manner.

The way a GRadient INdex (GRIN)-lens works may be explained best by considering a conventional lens: An incoming light ray is first refracted when it enters the shaped lens surface because of the abrupt change of the refractive index from air to the homogeneous material. It passes the lens material in a direct way until it emerges through the exit surface of the lens where it is refracted again because of the abrupt index change from the lens material to air (Figure 4.8 right). A well-defined surface shape of the lens causes the rays to be focussed on a spot and to create the image. The high precision required for the fabrication of the surfaces of conventional lenses aggravates the miniaturization of the lenses and raises the production costs [77].

GRIN-lenses represent an interesting alternative since the lens performance depends on a continuous change of the refractive index within the lens material. Instead of complicated shaped surfaces, plane optical surfaces are used. The light rays are continuously bent within the lens until eventually they are focussed on a spot. Miniaturized lenses are fabricated down to 0.2 mm in thickness or diameter. The simple geometry allows a very cost-effective production and simplifies the assembly of such products. Varying the lens length implies an enormous flexibility at hand to meet the lens parameters as, e.g., the focal length and working distance to your special requirements without high research and development efforts and costs. For example, appropriately choosing the lens length causes the image plane to lie directly on the surface plane of the lens so that sources such as optical fibres can be glued directly onto the lens surface [83].
GRIN-lenses are produced by silver and lithium ion exchange in special glasses. In contrast to the thallium technology, which is conventionally used for the fabrication of GRIN-lenses, this unique key technology, where the special shape of the refractive index profiles is to be realized precisely, is non-toxic and bears no health and environmental risks for producer and user of such products. Refractive index changes up to 0.145, which are similar to those attained via thallium ion exchange, achieved via silver ion exchange. Embedding silver ions into glass or, alternatively, removing them from it, allows focusing and diverging lenses to be produced with numerical apertures up to 0.6 and acceptance angles up to 70° for the visible and infrared spectral range. Both processes are performed in rods and slabs resulting in rod lenses and cylindrical lenses with plane optical surfaces. This large scope of focusing and diverging lenses in rod and cylindrical geometry provide the user compact GRIN-lens systems and subassemblies as, e.g., micro-optical telescopes, complete endoscopic imaging systems, anamorphic beam shaping optics for diode lasers, and micro-optical scanners, in addition to single high-performance lenses. With such competence in optical design it is possible for the manufacturer to fit the system to user requirements [82].
4.3.1.1 Technical Details of the Optical Design with GRIN-Lenses

A radial refractive index profile of nearly parabolic shape realizes a continuous cosine ray trace within a GRIN focusing lens, the period or pitch length $P$ of which does not depend on the entrance height and the entrance angle of the light ray (Figure 4.9).

Various imaging designs can be realized using the same index profile by choosing different lens lengths:

A quarter-pitch lens images a point source on the entrance surface of the lens into infinity or collimates it, respectively. This configuration is usually applied to the collimation of single-mode and multi-mode optical fibres and laser diodes. For high-power laser diodes, GRIN cylindrical lenses are used for the fast-axis collimation. Together with other GRIN components they are easily integrated to compact micro-optical systems.

A half-pitch lens images an object on the entrance surface inverted on the exit surface of the lens (magnification $M = -1$).

A 1- (2, 3, or more, respectively)-pitch lens images an object on the entrance surface of the lens identically on the exit surface (magnification $M = +1$). Those lenses are used in endoscopes as relay lenses, which transmit the image from the front part of the endoscope to the eye-piece [77].

A 0.23-pitch-lens images a point source within a defined working distance $s$ into infinity and/or collimates it (Figure 4.10).
The geometrical gradient constant \( g \) characterizes the steepness of the index gradient and with the lens length \( z \) it determines the focal length \( f \) and the working distance \( s \) of the lens:

\[
f = \frac{1}{n_0 g \cdot \sin(gz)}
\]  

(4.6)

Various magnifications \( M \) and working distances \( s \) can be realized by choosing an appropriate lens length \( z \). The refractive index profile has to fit an ideal shape most accurately to ensure an optimum imaging quality. For focusing lenses, the ideal shape is described by:

\[
n(r) = n_0 \text{sech} (gr)
\]  

(4.7)

where \( n_0 \) is refraction index at the centre of the profile, \( r \) is the radius and \( g \) is the gradient constant of GRIN-lens.

Definition \( \text{sech}(x) \):

\[
\text{sech}(x) = \frac{2}{e^{x} + e^{-x}}
\]

Definition range: \(-\infty < x < +\infty \quad x \in \mathbb{R}\)
Function \( \text{sech}(x) \):

being a function which deviates slightly from a parabola, with its maximum refraction index \( n_0 \) at the centre of the profile. The pitch length \( P \) results from the gradient constant \( g \),

\[
P = \frac{2\pi}{g}.
\]

(4.8)

By adapting the geometrical length of lens \( z_0 \), deviating imaging tasks can be solved. Typical focal lengths and working distances standard lenses are listed in the product specifications. Figure 4.11 shows the procedure of optically designing an imaging GRIN system using these parameters.
The distance between principal planes $P_1$ and $P_2$ indicates that GRIN-lenses have to be treated as "thick" lenses. However, that fact does not influence the outstanding image quality and isoplanatic property of GRIN-lenses. The maximum acceptance angle of a GRIN collimation lens or the maximum viewing angle of a GRIN objective lens, respectively, is determined by numerical aperture $NA$. As in fibre optics, it is derived from the maximum index change of the GRIN profile,

$$\sin(\varphi) = NA = \sqrt{n_0^2 - n_R^2} = n_0 \sqrt{1 - \text{sech}^2 \left( gd / 2 \right)} \tag{4.9}$$

$n_R$ is the refractive index at the margin of the profile, and $d$ is the diameter or the thickness, respectively, of the lens.
4.4 Characterisation of Beam Propagation by Means of Ray-Tracing

The imaging quality of a GRIN-lens considerably depends on the fluctuation of the gradient constants as well as the tolerance of the lens length \( z_l \), diameter \( d \) and working distance \( s \). Axle inclination and the lateral displacement of the light source, which is assumed to be a point, are not taken into consideration. Figure 4.12 schematically shows the collimation of an assumed point source at distance \( s \).

![Diagram of collimation by means of a GRIN-lens](image)

Typical values of tolerance of a GRIN-lens (stick lens):

- length of lens \( z_l \): ±3% (tolerance range due to the manufacturing process)
- diameter \( d \): ±0.02 mm
- distance \( s \): ±0.01 mm
- focal length \( f \): ±0.02 mm

The deviation of ideal collimation from to real collimation, in consideration of the tolerance range of the lens length, diameter and working distance, can be optimized by precisely positioning the light sources within working distance \( s \) as well as towards the x- and y-direction.

Today efficient RAY-trace programmes are applied for simulating and optimizing beam propagation through optical systems [78-82].
Table 4.1 Technical data regarding GRIN-lenses for LDBA construction [83]

<table>
<thead>
<tr>
<th>Types of GRIN-lenses</th>
<th>Focal Length</th>
<th>Pitch</th>
<th>Numerical Aperture</th>
<th>Working distance</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) 399712</td>
<td>0.96 mm</td>
<td>0.23</td>
<td>0.51</td>
<td>0.12 mm</td>
<td>1</td>
</tr>
<tr>
<td>B) 399724</td>
<td>1.85 mm</td>
<td>0.23</td>
<td>0.48</td>
<td>0.23 mm</td>
<td>1.8</td>
</tr>
<tr>
<td>C) 399732</td>
<td>0.97 mm</td>
<td>0.23</td>
<td>0.50</td>
<td>0.15 mm</td>
<td>1.5</td>
</tr>
</tbody>
</table>

As an example the beam track for three different GRIN-lenses is simulated by means of a Ray-tracing programme (WIN-Lens). A spot light source, which is exactly within working distance s, is imaged into infinity and collimated. The GRIN-lens is assumed without tolerance of its theoretical dimensions.

A) When the point source, a Laser diode was placed at an object distance of 0.1088 mm at the object plane, the GRIN-lens (399712) images into infinity or collimates as shown below (Fig. 4.13).

![Fig. 4.13 Ray tracing showing collimation of Ideal setup of Laser Diode – GRIN-lens (399712) optical system](image)

B) When the point source, a Laser diode was placed at an object distance of 0.1689 mm at the object plane, the GRIN-lens (399724) images into infinity or collimates as shown below (Fig. 4.14).
When the point source, a Laser diode was placed at an object distance of 0.0857 mm at the object plane, the GRIN-lens (399732) images into infinity or collimates (Fig. 4.15).

Assuming an ideal GRIN-lens, it can be taken that light from a divergent propagated point source can be collimated to a perfect parallel beam. Different apertures, focal and working distances result in different beam diameters at the GRIN-lens output.
4.4.1 Tilting of a Laser Point Source

Differences in the quality of collimation at assembly of LDBA are caused by lateral positions tolerances of the laser diode related to the input surface of the GRIN-lens. The lateral position differences can be corrected by an x-y adjustment (xyz-micro-axes system) of the laser diode. This has no significant influence on the collimation. Is, however a tilt of point source in relation to the GRIN-lens input surface, that is discussed in chapter 4.5. Figure 4.16 illustrates the difference in collimation quality of a tilted and non-tilted point source in front of the input plane $E_{GRIN}$. The planes $E_{LD}$ and $E_{GRIN}$ are not parallel.

![Diagram of collimation quality comparison](image)

Fig. 4.16 Difference in collimation quality between tilted and non-tilted point source

On an example of the GRIN-lens type A (Table 4.1) with following technical data:

- Focal length $f = 0.96$ mm
- Pitch = 0.23
- NA = 0.51
- Diameter = 1 mm
- Working distance = 0.12

The results of a tilt are simulated in Figure 4.17. A value for the tilt is the linear shift of point source $\Delta s$ from the mid-axis. Due to the small diameter, the large aperture and the small working distance, the GRIN-lens type A allows a compact assembly of a laser diode pigtail for the LDBA.
Fig. 4.17 Different Ray-Tracing representation due to inclination of GRIN-lens Type A
4.5 Modification of a LD with Respect to Pulsed Laser Fine Welding

Hi-end-application place high demands on beam quality and focusing-ability of laser radiation thus making it necessary to correct the astigmatism of the laser diode. Astigmatism comprises beam direction failure and the parallel displacement of the laser beam through the output window and the non-centric positioning of the chip on the basic body of the diode. Easy access to the laser chip is required if corrections have to be made. In addition, the angle of the laser diode base surface towards emitting direction has to be adjusted. It is well known through beam waveguide technology that laser diodes were glued to the entrance surface of a beam waveguide. Since direct access to the laser chip is restricted by the housing with output window, it is removed by means of a special opening tool (Appendix 13.11) (Fig. 4.18).

After having removed the housing, the laser diode is adjusted three-dimensionally by means of a handling system beaming evenly at quadrants I-IV of the 4-quadrants diode thus guaranteeing the surface vector of the 4-quadrants diode to be congruent to the direction of emission of the LD. Wave vector $\vec{k}$ marks the direction of emission of the LD.
As a result of this alignment the laser diode inclines by angles $\varphi$ and $\theta$ (angle of beam direction failure). By careful ablation of the small, rotationally symmetric surface area of the laser diode basic body surface vector $\vec{n}_{LD}$ and wave vector $\vec{k}$ are matched (Figure 4.19). As processing method turning is applied. The height of ablation depending on the diode beam quality ranges between 0.1–0.2 mm. In order to remove the last bits of the housing the ablation depth reaches up to the cooling body of the laser diode chip.
4.6 Precision Clamping Technique

Clamping tools or clamping devices carry out important functions and assignments during material processing by laser beams such as laser beam welding, for example. They are used for fixing components and for positioning the joining position in relation to the laser beam. It is very important to observe the required accuracy taking account of component tolerances. It is also important to keep the position accuracy required by the process regarding the tolerances of the device.

Function of the clamping device taking laser beam welding as an example:

- Defined fixing of components prior to and during welding
- Positioning of the joining position in relation to the laser beam
  Decreasing of the joining gap by pressing the components to be joined against each other. (e.g. I-butt)
- Decreasing and/or avoiding of distortion during welding
- Heating up of components is stopped and/or heating is expelled by heat conduction

The following criteria must be observed when constructing a weld joint:

- Clamping tools at the welding position must be accessible
- Clamping surfaces should have a good heat conduction
- Components should be clamped as quick and easy as possible
- When selecting the material for the welding device it is important to notice if it resistant to laser radiation
- Clamping forces should not deform the component
4.6.1 Precision Clamping of Work Pieces by means of a special Clamping Device

The following chapter explains the applied clamping devices and their elements which enable the fixing of the joining components during the alignment procedure and eventually during the laser welding procedure. Precision devices used in tool manufacturing were used here. A few modifications to force transmission elements and new constructions of special devices, in consideration of the laser weldability of the components (LDBA) and their careful clamping, expand the bandwidth of the clamping opportunities.

4.6.1.1 Terms and Data

Clamping means securing a defined positioned work piece on a device in every processing condition during processing. The working direction, the kind and number of clamping elements are determined as follows:

- The forces arising during processing must neither displace, nor inadmissibly deform the work piece nor cause the work piece to vibrate
- The size and the working direction of the clamping force have to be determined in a way so as to reduce deformation of both work piece and device
- Clamping and de-clamping must be done quickly and safely
- If possible, the clamping force should be supported by a solid surface

According to the way the clamping force influences the process, a difference is made between

- direct clamping
- indirect clamping
In case of rigid clamping, pressure is released as soon as the clamping is removed, whereas, in case of elastic clamping, the clamping force is effective over the whole period of clamping. In case of direct clamping the work piece is clamped directly by means of the applied clamping element. In most cases of indirect clamping a number of elements are used for force transmission.

For the devices described below, elastic and indirect clamping as well as rigid and direct clamping have been applied.

### 4.6.1.2 Hydro-Clamping Device (HD-CD)

Explanation and features of Figure 4.20:

- accuracy of concentricity <5μm with 3 x D
- axial length adjustment
- exact centric clamping
- motionless clamping
- inter-socket diameter reduction

![Fig. 4.20 Hydro clamping device HSK A63](image)

On account of its light weight, moderate dimensions (Figure 4.21 and Table 4.2) and extensive attachments of precision slit inter sockets the hydro-clamping device can be adapted easily to an X-Y transport thus guaranteeing a reproducible and careful clamping
of the joining components. Due to the open design (gateway drilling \( \Theta \) 7 mm) it is possible to guide the beam path on the longitudinal axis through the hydro-clamping device.

![Diagram of Hydro-Clamping Device](image-url)

**Fig. 4.21** Schematic drawing of Hydro-Clamping Device (HD-CD) HSK A63

The following Table 4.2 shows the main dimensions of the Hydro-Clamping Device.

<table>
<thead>
<tr>
<th>D1 Clamp ( \Theta )</th>
<th>D2</th>
<th>D3</th>
<th>A</th>
<th>I2</th>
<th>I3</th>
<th>I5</th>
<th>V</th>
<th>G</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSK A 63</td>
<td>12</td>
<td>32</td>
<td>50</td>
<td>86,5</td>
<td>61</td>
<td>37</td>
<td>45</td>
<td>35</td>
<td>10</td>
</tr>
</tbody>
</table>
4.6.1.3 Precision Collets and Slit Inter-Sockets

Collets and slit inter-sockets are used for picking up and clamping cylindric work pieces. As a power transmission device with a clamping element such as screw fastening, they form a die chuck (Figure 4.22).

![Fig. 4.22 Collet with work piece stop](image)

The clamping element operates the collet 1 either by shear force on surface $A_1$ or by tensile force on surface $A_2$. The slit collets is pushed into the cone of basic body 2, the inner diameter of the collet increases, the work piece is picked up first and clamped afterwards. When the collet is inserted, friction arises between basic body and collet with a friction index $\mu_1$. The collet picks up the work piece and takes it to the stop pin 3. If the work piece touches the stop pin the collet is drawn further in until the work piece is clamped. More friction arises between collet and work piece with a friction index $\mu_2$.

As for the friction angle there is:

$$\rho_1 = \arctan \mu_1$$

$$\rho_2 = \arctan \mu_2$$

Tension force $F_{sp}$, depending on resulting force $F_{erz}$, angle of inclination $\gamma$, friction angle between collet and basic body $\rho_1$ and friction angle between collet and work piece $\rho_2$, can be derived from the following equation:
\[ F_{sp} = \frac{F_{erz}}{\tan(\gamma + \rho_1) + \tan \rho_2} \] (4.12)

At this collet there is no relative movement between collet and work piece. Therefore, no friction arises between collet and work piece when it is drawn in.

Slit inter sockets with a truth of running of ±2 μm are applied to increase the clamping diameter. The truth of running of the system (hydro-clamping device + inter socket) is ±5 μm. By slight modification the inter sockets, particularly adjusted to the hydro-clamping device (HD-CD), can also be adjusted to non-conventional component diameters. The modification can be carried out by means of sinking process.

The slit inter sockets are special importance because they are the main clamping element for the clamping tools listed in the table below.

The following Table 4.3 illustrates the clamping tools applied for producing an LBDA.
Table 4.3 Summary of clamping devices for LDBA alignment and manufacturing

<table>
<thead>
<tr>
<th>Clamping tools</th>
<th>Assistant clamp or alignment tools</th>
<th>Location of clamping tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>LD-clamping</td>
<td><img src="image1" alt="LD-clamping" /></td>
<td><img src="image2" alt="LD-clamping location" /></td>
</tr>
<tr>
<td>GRIN-lens clamping</td>
<td><img src="image3" alt="GRIN-lens clamping" /></td>
<td><img src="image4" alt="GRIN-lens clamping location" /></td>
</tr>
<tr>
<td>Interface Coupler clamping</td>
<td><img src="image5" alt="Coupler clamping" /></td>
<td><img src="image6" alt="Coupler clamping location" /></td>
</tr>
<tr>
<td>Gas-Inlet holder and IC-clamping</td>
<td><img src="image7" alt="Gas-Inlet holder" /></td>
<td><img src="image8" alt="Gas-Inlet holder location" /></td>
</tr>
<tr>
<td>Precision collet</td>
<td><img src="image9" alt="Precision collet" /></td>
<td><img src="image10" alt="Precision collet location" /></td>
</tr>
<tr>
<td>Mini-rotation chuck for MD1</td>
<td><img src="image11" alt="Mini-rotation chuck" /></td>
<td><img src="image12" alt="Mini-rotation chuck for MD1 location" /></td>
</tr>
<tr>
<td>Hydro-Clamping Device</td>
<td><img src="image13" alt="Hydro-Clamping Device" /></td>
<td><img src="image14" alt="Hydro-Clamping Device location" /></td>
</tr>
</tbody>
</table>

For further and detailed information concerning clamping devices see Appendix 13.11.4.
4.7 Construction with Respect to Laser Beam Welding

Laser beam welding, as joint method, opens up a number of new constructional opportunities to form components, particularly in view to light construction and fine machining. Little heat input or the opportunity of joining where only one side is accessible, but also the opportunity of using it for a great number of materials and material combinations, are just some of the assets of laser beam technology. In order to use laser efficiently in industry and technology, the constructional opportunities of laser welding must be used resolutely, taking into account the specific requirements, for example on process tolerances, through suitable constructional measures.

The objective of constructing through laser welding is the forming of components and the selecting of material so that requirements placed on laser welded components by both function and quality can be performed reliably and economically. The interactions between construction, material and production process are summarized by the term „weldability“, as it is applied for conventional welding methods [71].

In order to point out the special requirements of weldability on laser beam welding, laser beam weldability is assumed in the following description. It comprises every coherence with regard to specific methods.

4.7.1 Concepts and Definitions

The coherence described in Figure 4.24 completely applies to laser beam welding as well.

A component can be processed by laser welding if the following points are fulfilled:

- the material is suitable for welding (weldability)
- the welding reliability of the construction is guaranteed
- a welding possibility is guaranteed during the manufacturing process
It is the primary assignment of the constructing engineer to guarantee for the welding reliability, i.e. the component must guarantee, by its construction, to bear the load/stress which is to be expected during the process. The welding reliability, being considerably influenced by the material, is to be known to the constructing engineer. Furthermore, the component has to be constructed in the way that, under the manufacturing conditions chosen, the intended welds can be performed professionally and economically (weldability) under the selected manufacturing conditions.

The main influencing factors to be considered and/or checked during construction, regarding load, are:

- the kind of stress: resting, cyclical, pulsatory
- the kind of load: tensile, pressure, bending, torsion
- outer influences: temperature, corrosion, wear/attrition/abrasion

The influencing factors by material and/or filler material:

- weldability and mechanical-technological qualities of the laser welded seam resulting from laser welding process
Apart from these influencing factors, further boundary conditions, which are important to
the functional qualities of the laser-welded component, have to be taken into account in
order to guarantee for a high quality and a reliable manufacturing process. These are:

- the coating of the material (e.g. oxide layer, zinc layer)
- tolerances (handling system)
- seam and edge preparation
- accessibility (processing head, handling system)
- seam guidance (dynamic of handling system)

The advantages and potential of laser beam welding are in the considerable differences to
conduction welding methods. The most important difference is the concentrated local
energy deposition with high process velocity and thereby very low heat input per unit
length. In addition, laser radiation can be positioned very precisely by a suitable handling
technique. All together, these qualities open up a number of new constructional
opportunities, such as:

- favourable mechanical-technological qualities
- joints with one-sided accessibility
- new seam variants, e.g. Sting seam at the T-butt
- reformable welding seam, (inside high pressure remodelling), tailored blanking

Apart from various new constructive opportunities, which are opened up by laser
welding, production technical advantages can considerably contribute to using lasers
economically. In particular, these are:

- high process velocity and thus productivity
- high weld seam quality
- low heat influence / distortion, destruction of components.
4.7.2 Laser Specific Influences on the Quality of Weld Seams

Special energy deposition in laser welding leads to little fusion deposition with large penetration and high gradients of temperature inside the weld zone. These characteristics require more time in the preparation and positioning of the work piece thus influencing weld imperfections and the mechanical-technological qualities of the weld seam.

4.7.2.1 Laser Welding Seam Imperfections

The microstructure of the seam, as of all metal weld seams, is supposed to be as fine-grained as possible. Further qualities of the seam depend on its alloy constituent. The melts of the joint components are combined in the weld seam. If they consist of the same material, the characteristics may correspond with those of the base material. If joint partners consist of different material or if filler material is used, an alloy is produced. Alloy qualities can be specially produced.

Technical norms distinguish between outer and inner seam imperfections. The butt weld, for instance, shows outer and inner seam imperfections typical of Figure 4.25 in laser welding.

![Diagram of laser welding seam imperfections](image)

**Fig. 4.25 Overview of laser welding seam imperfections**

- Weld shape imperfections such as penetration and root depression are weakest points where the weld can tear.
• Melt ejection is produced if the melt is ejected from the seam on account of overheating resulting in holes and irregularities thus decreasing the strength and gas tightness of the seam.
• Seam concavity and root suck-back decrease the weld cross section thus the decreasing stability.
• Misalignment of edges at an I-butt joint at a butt joint also decrease the weld cross section.
• Minimum hollows at the end of the joint, so-called final craters, decrease the weld cross-section as well. They are produced if the laser beam is switched off too soon.
• The oxidation of top and under weld bead reduces the corrosion resistance of stainless steels.

4.7.2.2 Influence of Joint Configuration, Seam- and Edge Preparation

The technical specification of the edge preparation requires considering the proceeding specific qualities of laser welding analogous to other weld methods. If the demands on positioning, clamping technique or edge preparation are not observed, laser specific weld seam imperfections might be produced (Figure 4.26). In particular the dimensions of the laser beam of some tenth millimetres – and the size of the weld bead volume – some millimetres towards weld width, have to be observed. The deep-penetration weld effect and the more favourable force flow let the square butt weld at the butt or fillet joint seem more favourable for laser-welding.
While butt joints, on account of their possible simultaneous melting-on of both work piece edges, are more favourable, from the energy point of view, disadvantages might occur through the formation of cracks at microstructure- or not fully penetrated joints or miss-positioning [73]. In contrast, overlap joints inside a component are disadvantageous on account of their power diversion. However, an overlap joint can be realized by rather a simple clamping technique offering much better joint tolerances and beam position deviation. In this case only variations in the focus position above the track bear weight.

Gaps and misalignments of edges, tolerable on account of their beam technical boundary conditions, are limited to approx. 3 \% of the plate thickness, within the range of plate thickness used for rough production. The seam quality is not reduced without using filler material.

Preparing the components for laser welding is very important as maintaining the accuracy achieved by material processing is one major potential of the process. Therefore, laser welding is only applicable, from the economical point of view, if production flows, regarding exact production, are re-organized. Best preconditions for laser welding are revolved and milled edges.

By means of clamping technique the joining parts have to be positioned in that way that the joint is completely held by the fusion bead over the full length of the weld seam. A technical zero-gap with a maximum tolerance of 0.1 mm is required for welding without filler material. The required tolerances may be much smaller according to application (fine welding), e. g. in precision welding (2 - 20 \mu m). Larger gap widths lead to
inadmissible seam concavities. Assuming constant welding parameters adjusted gap widths are to be observed in case of welding with filler material with low tolerances, independent of the component thickness. Tack welds are required especially in case of unfavourable clamping and precise positioning of the joint components, because gap expansions occur due to thermal expansion during heating-up particularly at the end of the joint, which lead to inadmissible root suck-back at constant welding parameters. The dynamic behaviour of the welding gap (welding gap expansion), with regard to the layout of a suitable clamping device, depends on the individual fixation (restraint) towards welding direction and on removing the fixation from the weld centre. If it is not possible to observe the tolerances or if it is too cost-intensive, filler material can be used for welding in order to avoid suck-back at the weld seam.

The influence of contaminations on the work piece, which has to be welded, considerably depends on the shape of the weld, the laser efficiency and the process velocity. The higher the heat input per unit length, the lower the result of contaminations such as scale, oil or lacquer on the seam quality [74].
5 Laser Fine Welding Station with Pulsed Nd:YAG-Lasers

In chapter 5 the concept of the Laser Fine-Welding Station is developed and specified on the basis of the technical qualification profile. The Laser Fine-Welding Station consists of a handling system for the positioning of the process optics, a numerical control program FineWeld for laser welding, a cartesian micro-handling system for high-precision on-axis positioning of the laser diode beam assembly components and a monitoring and measurement program FineScan.

The LabView program FineScan was developed in a diploma thesis project for fully automatic steering and measurement data acquisition. A special adaptation of the positioning routine and data acquisition was used for the positioning procedure of the output coupler on the laser diode beam assembly.

An industrial Nd:YAG-laser system with laser beam processing optics (LBPO) was specified and built. The optical construction of the laser cavity and the excitation mechanic of the pump source, the numeric aperture of the process fibre and the optical construction of the LBPO led to the determination of the process parameters min. spot diameter (beam waist diameter), Rayleigh-length, intensity distribution and pulse peak power.

The Nd:YAG-laser fine welding station finds usage in chapters 6, 7, 8 and 10. The structure of this chapter is summarized in Figure 5.i.

Starting out from the technical qualification profile, the following chapter goes into the special conception and the construction of semi-automatic laser fine welding stations with pulsed Nd:YAG Lasers. A specially developed control system (FineWeld) and special software for controlling and data acquisition (FineScan) support high precision positioning and precise laser fine welding of rotationally symmetric components (Ø 1 – 20 mm) by pulsed laser beams. Modified collets and recently developed special clamping tools are used as clamping device.
Subchapter 5.1

Technical qualification profile

Subchapter 5.2

Concept of laser fine welding station

Subchapter 5.3

Setup of laser fine welding station (Nd:YAG)

Control and handling system

Description of FineWeld

Micro handling system

FineScan GUI user interface

Pulsed Nd:YAG-lasers with processing optics (LBPO)

Characteristic data HL204P

Optical arrangement

Laser light cable

LBPO for focusing

Laser beam processing optics (LBPO)

Subchapter 5.1 - 5.3 are used in chapter

Chapter 6

Chapter 7 and 8

Chapter 10 - LDBA manufacturing

Contribution by the author

Background work

Fig. 5.1 The subchapter block diagram
5.1 Technical Qualification Profile of Fine Welding Station

The qualification profile of the laser fine welding station is closely combined with the requirements for the weld seam quality (Figure 5.1). Selecting and integrating a suitable laser system (laser, beam delivery, processing optics), handling systems (axes, controller) and clamping technique (clamping tools and devices) for laser fine welding, in consideration of laser weldability, are explicitly adjusted to the processing task.

In this chapter the quality profile of a fine welding system (laser system, handling system and beam monitoring) is developed. This quality profile simultaneously serves as the basis for constructing a welding station, selecting suitable components and developing software for controlling and data acquisition.

The following technological requirements are to be placed on a laser welding station:

- Positioning of processing optics towards X,Y,Y-direction - 20 μm, tilt -15° to +70°
- Positioning of components to be welded towards X,Y,Z-direction < 1 μm
- Rotation of joint partners for spot welding with angles ranging between 0° to 180°
- Rotation of joint partners towards seam and spot welding (0° to n·360°)
- Positioning of clamping tools towards X,Y,Z-direction, 5 - 10 μm
- Positioning of beam monitoring optics towards X,Y,Z-direction, 5 - 10 μm
- Clean-room-atmosphere (class 1000) to protect all systems, units and the LDBA manufacturing process
- Electrostatic protection (ESP) for protecting the laser diode during adjustment

For detailed information see schematic construction and assembly of the handling systems in Figure 5.2 and Appendix 13.1.
The following requirements are to be placed on the control and data acquisition software:

- **FineWeld**: Controlling of linear axes for the positioning of processing optics and both the rotational axes ($R_1$ u. $R_2$) and the laser.

- **FineScan**: Controlling of micro axes (X,Y-direction) with variable step width (rough and fine scan) for precisely positioning the adaptive optics (fibre, lenses) by means of data acquisition by intensity-detector PDA-55 and CCD-camera beam profiler.

### 5.2 Concept of Laser Fine Welding Station

Starting out from the technological quality profile, a modular construction of the welding station is achieved and realised. Standardized mechanical, electronic and optical components and group of components are created here.
Based on the quality profile, individual components are selected, adjusted and integrated into one functional unit. Two Cartesian handling systems, consisting of translational and rotational axes, are set up and employed on account of a better positioning accuracy of the laser radiation on the joints of the components to be welded and less investment costs (compared to robot kinematic).

Figure 5.2 shows the schematic construction and assembly of all manual and programmable motional axes (translation, rotation and tilting).

The construction can be divided into two decoupled fields, thus being independent from each other.

- 1. translation (X,Y,Z-direction) and inclining of the laser beam processing optics
- 2. + 3. + 4. Rotation table with micro-axis, clamp device and beam monitoring for fine alignment and final laser welding.
Uncoupling the translational axes for the focus positioning of the processing optics and handling of the components during the fine alignment procedure and during the laser welding procedure enable positioning rotationally symmetric components within micrometers and welding by laser radiation. 2D-beam profilers and an intensity sensor are deployed (integrated) for supporting the fine alignment procedure of all optically active components of the LDBA.

The handling systems for focus positioning and the fine alignment of LDBA-components support and guarantee the laser fine welding procedure of the following joint and weld seam configuration with diameters ranging from 2 – 20 mm:

- Butt weld
- Fillet weld
- Overlap weld
5.3 Setup of the Laser Fine Welding Station with Nd:YAG-Lasers

Following norm EN ISO 11145 (1994) and considering laser reliability/safety, a semi-automatic laser fine welding system with pulsed Nd:YAG Lasers (HL 204P) is set up and put into operation. Every protective measure for producing highly sensitive optoelectronic and mechanical components are given by a class 1000 clean-room atmosphere. Figure 5.4 shows the schematic description of a laser fine welding station including its subsystems and components [75].

Handling systems are adapted by special carrying shelves of section aluminium (see Appendix 13.3) (Figure 5.5). The carrying shelves with handling systems are surrounded by a protection cabin in which a clean-room atmosphere is produced by a flow box. Floor and work surface are protected by electrostatic protective measures (earthed protective mats) against electrostatic charge.

There are also protective measures for the operator to be used (wrist straps and straps around the ankles). Directing external laser radiation to the working head inside the welding cabin is guaranteed by flexible beam wave guides. External power supply is made available for the operation of the handling systems.
For assessing the component quality (edge and surface quality), the operational test and the sight check a stereomicroscope (x135 magnification) with CCD-camera is used. First, superficial sight checks of the laser weld seams are carried out with this system.

---

1. Handling system LBPO (T₁), 2. Rotation table with micro-axes (R₁), 3. x,y,z- clamping-device (M₂), 4. x,y,z-manipulation beam monitoring CCD-sensor M₁, 5. micro axis system with mini-rotation axis (R₂)

R₁: Rotation 0 – 180°, R₂: Rotation 0 – n·360°, T₁: Tilt -15 – 0 – +70°
M₁: Manual translation stage (monitoring), M₂: Manual translation stage (Hydro Tool)

Fig. 5.5 Front-view of laser fine welding station with Nd:YAG lasers
5.3.1 Control and Handling System for Focus Positioning

For precise and reproducible focus positioning, a semi-automatic handling system consisting of a Cartesian x-y-z order of linear servo and manual axes is used (Figure 5.2). The exact adjustment towards x-direction (parallel to specimen) is carried out by a manual translational axis with micrometer screw. A manual tilting device enables the tilting of the laser beam processing optics within angles ranging between $-15^\circ$ to $+70^\circ$. The FineWeld-programme controls the positioning of the laser beam processing optics towards z- and y-direction with an accuracy of 5 μm. In z-direction towards specimen surface, the effective spot diameter can be adjusted.

In addition, FineWeld takes over the control of the rotation table and mini-rotational axis during the tack and continuous spot welding procedure. The rotation table is only used for the tack weld process. Figure 5.6 shows the interactions between the application program FineWeld, the handling system (x-axis, y-axis and rotation axis) and the controller driver ISELDRV.EXE. The FineWeld program interacts with the ISELDRV via interrupt call.

![Fig. 5.6 Software and Hardware structure with ISELDRV.EXE](image-url)
The main driver and the interface between the application program FineWeld and the operating system are a MS-DOS program (ISELDRV.EXE). It is installed on a Pentium Computer with the operating System WIN 95. To guarantee reliable data exchange between application program and the driver program it is stored as a resident program in the main memory. The data exchange between application program and driver is carried out via interrupt calls. Using interrupt calls for communication is a normal method in MS-DOS.

Technical Data of the AT-Bus Interface Card

- Four PID-controllers with a sample time of 0.35 ms and 12-Bit-D/A-Converter to control up to four servo axes via +/- 10 V-signals.
- TTL or RS422 interface for encoders.
- 32-Bit position, velocity and acceleration registers.
- 14 opto-electronic inputs (end switches, reference switches)
- opto-electronic outputs.
- 50-pole RIBBON plug.
5.3.2 Description of FineWeld (GUI)

The program GUI (Graphical User Interface) of FineWeld is subdivided into five windows: Servo Controller, Linear Axes, Table Rotation (RF-1 axis), Laser Welding and Rotation Axis MD-1 (Figure 5.7).

![Program GUI FineWeld (Object Pascal) for controlling the handling system and process parameters](image)

Fig. 5.7

Controller functions:

1. `ncGetVxInstallState`: Checks the install state of the controller
2. `ncGetDrvInstallState`: Checks the install state of the controller driver
3. `ncInitDrv`:Initialises of the controller driver
4. `ncReset`: Resets the controller
5. `ncReference`: Executing of a reference drive for the linear and rotation axis.

Servo-driven linear axes (y- and z-axis) and manual driven (x-axis):

- **x-Position (manual)**: Changes the working distance of the LBPO (μm) in positive and negative directions parallel to specimen to be welded.

- **y-Position (integer)**: Changes the height of the LBPO (μm) in positive and negative directions.

- **z-Position (integer)**: Changes the working distance of the LBPO (μm) in positive and
negative directions in beam propagation direction.

- Move: Execution of linear and rotation movement.

**Servo driven rotation table RF-1 (integer):** Rotation of the rotation table in a range of 0° to 180° for tack welding procedure (Appendix 13.4.2).

**Servo driven midget rotary axis MD-1 (integer):** Changes the rotation speed (°/s) and direction (+ left, - right) of the mini-rotation axis, range of rotation ±n x 360° (Appendix 13.4.2.1).

**Set Velocity:** Sets the new rotation speed and direction.

**Laser Welding:** Start switches the Nd:YAG lasers on and off.

**Shielding gas:** Opens and closes the valve for the shielding gas supply.

### 5.3.3 Micro Handling System and Rotation Table with Mini Rotation Axis MD-1

The rotation table built out of section aluminium rectangular sections of a light construction type with a tower for clamping- and measuring-devices, is adapted on a rotation unit with a servomotor by a rotary plate (Figure 5.8). The rotation unit guarantees smooth rotation around the axis of the rotation table within a range of 0-180°. To counteract the tilting and vibration of the rotation table during a turn, the rotation axis was set immediately next to the mass centre of gravity of the construction. In addition, a reduction ratio of 1:100 was selected for the rotation unit, which results in a higher torque.

Lateral moving of the mass gravity centre, resulting from positioning by a micro-handling system, does not impair the precision quality of the rotation table.
The rotation table with its Cartesian 3-axis handling system, orthogonal platform for mini-rotational axis, as well as clamping- and measuring devices adapted to the tower, are the central unit of a laser fine welding system.

All the components to be welded are exactly positioned to each by means of the desired beam profile and power measurement and are laser-welded then being supported by precision clamping devices.

In order to position the rotational axis of the rotation table exactly vertically, the laser beam of an HeNe-lasers is guided to the centre of the rotation unit via two corner reflectors and a pin aperture. A fixing device with reflection mirror is fixed in the centre of the rotary disk (Appendix 13.1). By equalizing the level differences of the rotational unit by precision foil, the laser-output beam is reflected back along its transmission line.

The rotational axis is now vertical. All of the following components such as the micro-handling system with its mini-rotational axis are adjusted at the rotational axis by the
HeNe-laser beam. Thus the mini-rotational axis, even if it is off-axis while being adjusted, can be re-positioned to on-axis very easily.

A micro-handling system consists of 3 linear micro stages with an position accuracy of 50 nm, being adapted to a Cartesian x-y-z handling system by a 90° angle bracket (Figure 5.9). The second angle bracket is fixed to the z-axis thus serving as a platform for the mini-rotational axis.

![Diagram](image)

**Fig. 5.9** Three-axis motorised micro stage assembly with 90° angle bracket [148]

By this system of linear-axis a mini-rotational axis can be adapted to the orthogonal platform of the z-translational axis and may be driven precisely in three ordinates in space. The complete micro-handling system again is fixed on the rotation table, including the tower for measuring and clamping devices. The complete handling unit can now be turned within a range of 180° without affecting the adjusted components.

The rotation table is turned incrementally by FineWeld offering any step size and velocity.
Graphical User Interface of FineScan

GUI FineScan has been developed to automatically determine the maximum intensity of optical light sources and to control motion controller MM4005 in LabView and has since been used with success. Data are recorded by a data acquisition card (NI PCI-6024E) with a sensor connected to the card via connector block (SCB-100) (Appendix 13.5.2.1/2). Motion controller MM4005 supports both manual mode by keypad (see Appendix 13.7.4) and programmable mode for carrying out complex, user-defined tracks. The motion controller, particularly during external mode, converts control signals from a second computer (programme) into processing commands for the micro handling system.

Mathematical algorithms in Rough Scan Mode and Fine Scan Mode determine the maximum intensity of a beam source with variable step width. The determined intensity data are stored in Excel files thus being available to other programmes for further processing.

Devices used (see Appendix 15.5):

- **PCI-Data Acquisition Card:** NI PCI-6024E
- **Connector Block:** SCB-100
- **Sensor/Detector:** Amplified Silicon Detector PDA 55
- **Motion Controller:** Motion Controller MM4005

The GUI of FineScan is subdivided into five registers (see Appendix 13.5, 13.8).

- **Manual Motion (MM4005)**
- **Measurement**
- **Rough Scan Result**
- **Fine Scan Result**
- **Load Data**

These five registers cover full functionality of data acquisition, automatic and manual motion control.
5.3.5 Pulsed Nd:YAG Lasers with Processing Optics

The laser system used for laser micro processing is an Nd:YAG Lasers (HL 204P) pumped by flash light, which can be operated either in spot weld or continuous mode (pulse trains).

The laser system consists of the components mentioned in Figure 5.10.

The main components of the laser system are (Figure 5.11)

- The cavity with laser and excitation lamp.
- The resonator consisting of rear mirror and output coupling mirror.
The output coupling mirror is partially transmitting for laser light. The cavity is cooled with de-ionized water.

![Diagram of laser components](image)

**Fig. 5.11** Main laser components (resonator) [150]

### 5.3.5.1 Characteristic Curves of HL 204P

The characteristic curves on the following pages show typical courses for the lasers HL 204P. The courses may in single cases differ slightly from those indicated here.

![Graph showing pulse energy vs. pulse duration](image)

**Fig. 5.12** HL 204P: Pulse energy vs. pulse duration [150]
5 Laser Fine Welding Station with Pulsed Nd:YAG-Lasers

Fig. 5.13 HL 204P: Pulse power vs. pulse duration

Fig. 5.14 HL 204P: Average power vs. adjusted pulse power
5.3.5.2 Optical Arrangement

The optical arrangement contains every component for guiding the laser light within the laser device up to the coupling optics. The laser light cable is connected to the coupling optics. The components of the optical arrangement are compiled and arranged according to the respective processing task (Figure 5.16, 5.17).
5.3.5.3 Laser Light Cable

The length of the laser light cable depends on the distance between laser device and processing optics. Laser light cables with dimensions according to standard lengths are delivered together with the laser device.

**Purpose** The laser light cable is a flexible transmission medium for laser beams. It permits spatial separation between laser and machining station.
Standard lengths of the laser light cable:

**Standard lengths**  4m, 6m, 10m, 15m, 20m

The specified values are usable lengths, measured from the outlet at the laser device.

**Bending radius**  The bending radius of the laser cable must be smaller than 200 mm.

**Installation**  Ensure that the laser light cables are installed without tensile stress and buckles.

**Structure**  In the interior of the laser light cable there is a light guide, which guides the laser beam from the laser device to the processing optics. The light guide is surrounded by a plastic tube and a steel case. The steel case protects the light guide from mechanical stress. It limits the bending radius of the laser light cable.

The steel case is surrounded by an external plastic tube protecting the laser light cable against environmental effects. A safety circuit integrated into the laser light cable switches off the laser automatically if the light guide is damaged or the laser light cable has been removed from the laser or the processing optics.
Table 5.1 Technical data laser light cable [150]

<table>
<thead>
<tr>
<th>Section</th>
<th>HL 62P</th>
<th>HL 124P, HL204P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre core diameter</td>
<td>200μm</td>
<td>400μm</td>
</tr>
<tr>
<td>Standard lengths</td>
<td>4m, 6m, 15m, 20m</td>
<td>Extensions in steps of 5m available up to 50 m</td>
</tr>
<tr>
<td>Minimum permitted bending radius</td>
<td>200mm</td>
<td></td>
</tr>
<tr>
<td>Cable diameter</td>
<td>12.5mm</td>
<td></td>
</tr>
</tbody>
</table>

The laser light cable is monitored over the whole length. The laser device switches off immediately and no more laser light may be emitted if a fault occurs in the cable. The fit of the two optical plugs is monitored as well. If an optical plug is loosened, the laser device immediately switches off. The electrical plug (3) connects the integrated safety monitoring of the laser light cable to the safety circuit of the laser device. The cable adapter (4) allows the monitoring cable to be connected when the counterpiece is terminated by a round plug.
5.3.6 Laser Beam Processing Optics for Focusing

The processing optics (Figure 5.20) focuses the laser light onto the processing point. The high power density required for the material processing is generated thereby. Processing optics consist of modules according to the requirements of the respective task. Further information is to be found in the operator manual for the processing optics.

Main characteristics of the processing optics type LBPO are (Figure 5.20):

- Collimation focal length 100mm or 200mm, thus producing the outside diameter of the optics of approx. 40mm or approx. 70mm
- Beam guidance straight (0°) or bent (90°)
- With or without monitoring optics
- Objectives for cutting and welding application

Fig. 5.20 Laser Beam Processing Optics (LBPO) for fine welding applications [150]
If components and modules are adjusted and combined according to the processing task, there will be three possible configurations of the laser beam processing optics (LBPO). For each combination (collimation focal length, focal length and fibre-core diameter) the Rayleigh-length, working distance and imaging scale was calculated in Table 5.2.

| Table 5.2 Technical data for configuration of laser beam processing optics |
|---------------------------------------------------------------|-----------------|------------------|
| Collimation focal length \( (f_c = 200 \text{mm}) \)         | 100mm | 150mm | 200mm |
| Focal length \( f \)                                       |       |       |       |
| Ø Fibre-core diameter                                       |       |       |       |
| 200 \( \mu \text{m} \)                                      | 100/(0.08) | 150/(0.16) | 200/(0.31) |
| 300 \( \mu \text{m} \)                                      | 150/(0.16) | 230/(0.41) | 300/(0.7) |
| 400 \( \mu \text{m} \)                                      | 200/(0.31) | 300/(0.7) | 400/(1.25) |
| 600 \( \mu \text{m} \)                                      | 300/(0.7) | 450/(1.59) | 600/(2.8) |
| Working distance (mm)                                      | 80    | 127   | 187   |
| \( \beta = f/ f_c \)                                       | 0.5   | 0.75  | 1     |

\* Rayleigh-length [mm]

To pass the LBPO on to the different work tasks, a compromise between power density and Rayleigh-length has to be found. Through changes to the collimation, focal length and fibre diameter, the minimal attainable spot diameter at the beam waist can be calculated. Input of these optical values takes direct impact on the working distance and Rayleigh-length.

To laser beam weld rotational symmetric components in thermal conduction mode, a maximal power density of \( 10^5 \text{ W/cm}^2 \) (7kW pulse power, spot diameter 300\( \mu \text{m} \)) should be attained. In consideration of the handling concept and the accessibility of the components, short focal lengths (\( f = 100 \text{mm}, \text{Rayleigh-length} < 400\mu \text{m} \)) with a small spot diameter and short work distance appear not to be possible. At focal lengths > 150 mm a large working distance from 187 mm increases the difficulty of precise positioning the laser beam to the component. Considering the combinations mentioned in Table 5.2, beam guidance is realized by a light waveguide (Ø 400\( \mu \text{m} \)) with the following, focusing processing optics (\( f = 150 \text{mm} \)) thus achieving a focus diameter of 300\( \mu \text{m} \), with a depth of field (Rayleigh-length x 2) of 1.4mm and a processing distance (optics – component-surface) of 127mm.
Additionally a laser distance sensor for highly accurate distance measuring is adapted on the top of LBPO (Laser Beam Processing Optics) (Fig. 5.21). The function of this distance sensor is to enhance the focus positioning process.

Fig. 5.21 Laser Beam Processing Optics (LBPO) with laser distance sensor
Figure 5.22 schematically shows the modular constructed processing optics LBPO-42. The individual components and modules have particularly been selected for laser fine welding of LDBA.

1. Fibre (Ø 400 μm), 2. Collimation (f = 200 mm), 3. 90° Beam splitter,
4. Protection filter, 5. Ocular, 6. Objective (f = 150mm), 7. Protection glass
8. Laser sensor for distance measuring

Fig. 5.22 Illustration and description of the Laser Beam Processing Optics (LBPO)
6 Characterisation of Handling System Deviation and Determination of Spot Weld Diameter and Rayleigh-Length

In chapter 6 the beam parameters minimal laser spot diameter und Rayleigh-Length were theoretically calculated using the system specifications of the Laser Beam Processing Optics \((f_{\text{col}}, f_{\text{ foc}})\) and the process fibre diameter. These results were compared to the experimentally acquired dimensions and evaluated. The basis for the calculations are the determined associations in chapter 2.

The mechanical deviations of all relevant handling systems from the theoretical ideal drive and positioning accuracies were experimentally determined. Taking into account the experimentally determined Rayleigh-length, the effects of machinal deviations on the focal positioning can be accurately evaluated. This led to prediction of the robustness of a laser beam weld on the example of the LDBA.

The results find usage by the laser beam weld process of the LDBA in chapter 10.

The structure of this chapter is summarized in Figure 6.i.

In order to guarantee reproducible and high quality laser welds, all laser and processing parameters must remain stable. The pulsed Nd:YAG lasers system HL 204P used here, has an active power control which compensates the effects of aging of the flash lamps on laser parameters providing stable values for the applied laser parameters. In order to evaluate the processing limits and processing reliability of the laser fine welding system with its installed handling system, typical deviation of the linear- and mini-rotational unit are checked by measuring the deviation from the ideal circle movement.

In particular, the spot weld diameter depending on pulse power and forward feed distance towards x-direction is determined. Important data may so be acquired regarding process reliability and the constructional forming of joint geometries.
Subchapter 6.1
Determination of minimum laser spot diameter and Rayleigh-Length

Subchapter 6.2
Determination of linear and rotation axis deviation for laser beam processing optics

Subchapter 6.1 - 6.2 are used in chapter

Chapter 10 - LDBA manufacturing

Contribution by the author

Background work

Fig. 6.1 The subchapter block diagram
6.1 Determination of Minimum Laser Spot Weld Diameter and Rayleigh-Length

The ability of focusing laser radiation is described by beam quality factor $M^2$. It indicates the divergence angle of the laser beam in a ratio to the divergence of an ideal Gaussian beam with equal diameters at the beam waist. Determining $M^2$, the beam diameters have to be measured longitudinally to the beam waist [139 - 141]. By customizing the curve to the ray trajectory, the diameters of the beam waist, beam divergence and $M^2$ are determined. ISO-standard 11146 [138] describes different methods of determining the diffraction (dimension) figure.

As determining the diffraction figure does not say anything about the minimal, real spot weld diameter, the real spot weld diameter depending on distance $z$ to the surface of a test body, with a step width of 200µm is taken down and measured. This is achieved by removing the black surface of photographic paper through single pulse shots with defined laser parameters. The diameters of the spot welds correspond approximately to the real beam diameters at the prevailing positions on the z-axis.

At a distance of 126 mm from the protection glass front of the processing optics the minimal spot diameter is $336 \pm 10$µm (Figure 6.1). The spot diameters were determined
by measuring the spot weld ablation results (Figure 6.2) with a microscope. In comparison, the beam diameter, which is theoretically to be expected according to equation 2.23 for a fibre with a core diameter of \(400\mu m\) and an image relationship of 0.75 of the processing optics \(f_{LR/	ext{pol}}/f_c = 3/4\), is \(300\mu m\). For verifying the spot diameters at positions 1 and 2, one single laser pulse was directed onto black Kapton film and measured, as shown in Figure 6.2.

![Fig. 6.2 Single spot weld ablation results](image)

The diameter of the beam waist at position 1 correlates very well with the diameter measured in Figure 6.1. The ablation of photographic material within the concentric field of the spot is caused by heat conduction. This field is not affected on metallic surfaces on account of higher melting temperatures.

The Rayleigh-length is another important typical quantity for laser beam propagation. The Rayleigh-length is the distance between position \(z_o\) of the beam waist and position \(z_{Ray}\) where the beam diameter \(d(z_{Ray})\) has increased to \(d_o \cdot \sqrt{2}\). As shown in Figure 6.1, the measured beam diameter is \(475 \pm 10\mu m\) if the Rayleigh-length is 1.05mm thus resulting in a depth of field of \(2.1mm\). The quantity theoretically determined for the Rayleigh-length of the processing optics is 0.7mm.

The difference between the theoretical Rayleigh-length and actual measured results (1.05 mm) are explained by the inaccuracy of the measuring equipment, the resultant value of the beam diameter being only an approximation. Especially in the case of pulse excavations as in Figure 6.2, a slightly increased spot diameter was noticed.

The exact local beam dimensions along the transmission path can only be measured with the use of a special focus monitor.
6.2 Determination of Linear and Rotation Axis Deviation for LBPO Handling

Linear and rotational axes, in a mathematical sense, do not carry out ideal translational or rotational movements. The real position of linear axes deviates more or less from the adjusted quantity, according to drive type (spindle) and applied controlling. Rotational axes normally do not carry out circular track movements but only approximate these movements.

In order to assess the effects on focus positioning, resulting from deviation from the ideal linear and rotational movement, the z,y-translational axes (Figure 5.2) are measured for position accuracy and the mini-rotational axis is measured for concentricity.

The z- and y-axes are moved with a defined step width of 200 µm within a symmetric positioning range of ±2 mm around the working distance of 126 mm (focus positioning) of the processing optics (Figure 6.3, 6.4). Every position alteration is recorded by an inductive sensing element (Digital Comparator).

![Graph showing linear servo-axis deviation in Z-direction for focus positioning with LBPO](image)

**Fig. 6.3** Linear servo-axis deviation in Z-direction for focus positioning with LBPO
The maximal positioning accuracy in Figure 6.3 and 6.4 of the focusing in z and y axis by the servo control is 9 μm and 18 μm respectively. In view of the theoretical Rayleigh-length of 750μm and a spot diameter of 300μm, the deviations have no significant effect on the welding results.

Deviation from the ideal circle movement of the mini-rotational axis are also recorded and analysed by Digital Comparator (precision inductive sensing element) for a 360° rotation. For this, a polished test body is measured at different positions within step angles of 10° (Figure 6.5). The maximum deviation of roundness of the test body is 3 μm.
The Encoder of the rotation axis MD1 generates 1000 steps per revolution. Internal flank multiplication using the phase shifted A and B channels, a resolution of 0.09°. The concentricity is given as $30 \pm 10 \, \mu m$.

Measuring starts approx. 1 hour after the Digital Comparators had been started in order to minimize possible measurement fluctuations on account of temperature drifting. The temperature inside the fine welding station before and during data acquisition is 19°C. Significant heat extensions of the test body are not to be taken into account.
Summarizing, the quantities of positioning accuracy $\Delta y$ and $\Delta z$ of the y-z translational axes for focus positioning are in a range of 8-20 µm. The quantity of accuracy of the manual tilting micro stage translation axis (Figure 5.21) $\Delta x$ amounts to 2 µm. In addition, the maximum deviation of the rotational axis of an ideal circle movement amounts to
\[ |\Delta \text{rot}_{\text{max}}| \sim 50 \, \mu \text{m} \] (Figure 6.6 and Figure 6.7). Figure 6.8 summarises and illustrates all linear and rotational deviation which can influence the welding process.

A change in the working distance in z-direction caused by concentric deviation in the rotation axis and excenter adjusted components lead to a shift in the focus position and a change in the spot diameter on the component surface. To achieve sufficient process stability, the shift distance \( \Delta z \) should be around \( \pm 400 \, \mu \text{m} \).

![Diagram of focusing lens, working distance, focus position, \( f_0 \) focal length, \( z_\text{f} \) Rayleigh-length](Fig. 6.8 Linear and rotational deviation in comparison to the Rayleigh-length)

In comparison to the Rayleigh-length of 1050 \( \mu \text{m} \) all deviation in z-direction can be neglected. The lateral shift \( \Delta x \) is, compared to the size of the component, also negligible.
7 Focusing and De-focusing Procedure of a Laser Beam

In chapter 7 the focus positioning using laser triangulation sensors described and technically implemented. A laser reflex sensor mounted off-axis to the laser beam processing optics was adapted for the precise and reproducible focal positioning at laser beam welding. The sensor calibration was carried out in works (pre-calibrated Scheimpflug condition). As the sensor was required to be operated off-axis, the characteristics curves for different angles had to be determined.

To support exact laser focal positioning, the laser reflex sensor is used in chapters 8 and 10. The structure of this chapter is summarized in Figure 7.i.

![Diagram](image_url)

**Fig. 7.i** The subchapter block diagram
The focusing and de-focusing of the laser beam by means of processing optics cause a displacement of the focus position regarding the surface of the work piece. An ocular (x10-magnification) with cross-hairs is applied to position the focus precisely. If the focus position (1) is on the surface of the work piece, it is called focusing. If the focus is within (-) or outside (+) the surface of the work piece, it is called de-focusing. If the cross hairs is within the focus area, the surface of the material is imaged sharply (reference point). From this point negative and positive de-focusing can be adjusted to a precision of 10 µm.

Displacement can be carried out either by an adjusting ring at the LBPO (Figure 7.1) or by a program-controlled movement of the z-axis of the LBPO-handling system with FineWeld software. Three calibrated scales on the LBPO mark the adjusting-length for each focal length applied (\(f_{LBPO} = 100, 150\) und 150 mm). The maximum adjusting-length is ± 8 mm. Focus displacement \(\Delta z\) is to be determined as follows:

\[
\Delta z \propto \frac{f_{LBPO}}{f_c} \cdot f_D (scale)
\]  

\(f_{LBPO}\) = focus length focusing optics [mm]  
\(f_c\) = focus length collimation optics [mm]  
\(f_D\) = displacement of the adjusting ring [mm]
7.1 Focus Positioning Supported by Laser Beam Distance Sensor

For precise and reproducible focus positioning the processing optics have been extended by a commercial laser sensor for focus distance measuring with the laser serving as guide laser at the same time. The following chapter describes the construction and the mode of action of a laser distance sensor, working on basis of the laser triangulation principle, as well as the adaptation to the processing optics.

7.1.1 Laser Reflex Sensor with CMOS-Line Array

Laser triangulation is a measuring method by which the distance of a point on the surface of an object is determined by a reference plane. This makes the triangulation method a guide laser similar to a mechanical comparator. The distance determined corresponds to a one-dimensional measured quantity.

Figure 7.2 shows the principle of laser triangulation. A laser beam is directed onto a work piece. The light is scattered at the place of incidence. This scattering light is measured for observing the place of incidence. If there is an ideal mirroring/reflecting surface, there will be no diffuse scattering light but only a directed reflection. Objects such as these are not suited to be measured by laser-triangulation. In general, the scattering behaviour depends on the material quality of a work piece, its surface structure and the wavelength of the laser. The scattering behaviour is represented by a polar scattering diagram. The luminous spot at the place of incidence is imaged on a detector (CCD-line array) under a predetermined angle to the incidence direction. This angle, regarding the scattering diagram, has to be selected so that the intensity, sufficient for detection, is detected by the objective. The position sensitive detector yields a signal depending on the position of the imaged spot.
Focusing and Defocusing Procedure of a Laser Beam

Working distance: 40 – 160 mm

CMOS-Line array

Objective

Working distance

Laser beam

Reflected radiation

Fig. 7.2 Representation of laser triangulation sensor and principle

The position of the spot on the detector depends on the position of the work piece towards z-direction. A signal, in proportion to the distance of the measuring object (z-direction), is produced out of the measured spot position, the known image geometry and the incidence direction (Chapter 7.2).

7.2 Scheimpflug Condition

Objective and detector have to be arranged so that the spot is imaged (focussed) on the detector level as sharply as possible for various distances of the measuring object. For this, the CMOS-line array is tilted in relation to the optical axis (Scheimpflug condition). This is a sensor default setting. In Figure 7.3 the required geometrical arrangement is explained in detail. This system of coordinates has been selected so that the v-axis is parallel to the optical axis of the objective and the u-axis on the objective level directs towards the z-axis. The zero point of the uv-system of coordinates is in the centre of the objective. The laser beam, directed towards the work piece, is tilted toward the v-axis. If
the laser beam reaches the work piece at point $P_1$, the resulting spot will be imaged in the detector plane point $P_1'$.

Accordingly, the same applies to $P_2$ and $P_2'$. As $P_2$ is further away from the objective than $P_1$, the distance between $P_2$ and the objective is shorter than the distance between $P_1$ and the objective (Figure 7.3). The detector (CMOS-line array) has to be tilted toward the $v$-axis to achieve sharp imaging for $P_2$. The laser beam towards incidence direction is described by the equation as follows:

$$u = m_Lv + u_0 \quad (7.2)$$

$u, v$ coordinates (Figure 7.3)
$m_L$ gradient of straight line
$u_0$ position of laser beam at $v = 0$
$f$ focal length of objective

If $v$ and $u$ are the coordinates of a point $P$ on the work piece, the coordinates of $v'$ and $u'$ of the appropriate image point $P'$ result from the following relations:

$$v' = \frac{v}{v/f + 1} \quad (7.3)$$

Fig. 7.3 Imaging geometry for laser triangulation
7 Focusing and Defocusing Procedure of a Laser Beam

\[ u' = \frac{v'}{v} \]  \hspace{1cm} (7.4)

Function (7.3) results from the existing image equation \( 1/b + 1/g = 1/f \), with \( b \) image distance, \( g \) object distance. Equation (7.4) results from relation \( B/G = b/g \) with \( B \) image height and \( G \) object height. The straight line coordinates are eliminated by equations (7.2), (7.3) and (7.4) to determine the equation of the curve with image point \( P' \). The result is:

\[ u' = (m_L - u_o / f)v' + u_o \]  \hspace{1cm} (7.5)

Function (7.5) describes a straight line. For a sharp image of points \( P_1 \) and \( P_2 \) in Figure 7.3 the detector has been aligned to this straight line. This equally applies to every other point along the direction of incidence of the laser beam. For \( v' = 0 \) this straight line crosses the \( u \)-axis near \( u = u_o \), i.e. in the same position as the incident laser beam. The slope of the detector has to be selected so that the direction of incidence, the \( u \)-axis on the objective level and straight line, which the detector has been aligned to, (equation 7.5), all cross one point. This rule is called „Scheimpflug condition“ and had been announced by Theodor Scheimpflug in 1907. This rule emphasises the general validity of the lens equation.

7.3 The Laser Sensor CP24MHT80 and its Adaptation at the LBPO

The laser sensor (CP24MHT80) uses a high-resolution CMOS line array and DSP technology, virtually eliminating material, colour and brightness related measurement value differences.

<table>
<thead>
<tr>
<th>Working Distance</th>
<th>40 mm</th>
<th>160 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Spot Size</td>
<td>0.5 x 1.2 mm</td>
<td>1 x 2.5 mm</td>
</tr>
</tbody>
</table>

The measurement range is calibrated accurately to 10 µm. Integrated analogue output can be configured for voltage 0...10V (10...0V) or current 4...20mA (20...4mA) via Teach-in or PC control.
The parameterization and initialisation of the sensor is done through the control panel at the sensor (Figure 7.4, 7.5). Current and voltage signals get from the signal output to the interface box (Appendix 13.10.2) where they are measured. The laser sensor has been equipped with an RS232 interface for communicating with a PC or a controller.

Fig. 7.4 Laser sensor CP24MHT80

Fig. 7.5 Panel of laser sensor CP24MHT80 [157]
Using the RS-232 interface and junction plug (Figure 7.6) S232W2 the functions of the sensor as well as the sensor conditions can be activated and measured quantities be observed. The interface works as software handshake procedure.

![Fig. 7.6 Laser sensor connection via plug adapter S232W2 with PC](image)

A pnp error output disables a pulse if there is no object recognized within the adjusted field of operation or if there is a failure. A red F-LED indicates the switched error output. If the measuring range of the sensor is exceeded, it will be indicated by a yellow LED. The laser sensor is integrated with a small tailored metal sheet above the LBPO parallel to the optical axis $z$. Tilting enables the angle/s to be adjusted within a range of $35^\circ$-50$^\circ$ (Figure 7.7).

![Fig. 7.7 Laser beam processing optics with laser distance sensor](image)
The sensor characteristic (Figure 7.8) depicts the linear behaviour of the output voltage in the operating field as a function of the working distance.

The sensor characteristics were determined using a precision slide on a vibration isolated table. A specimen was driven over a defined distance (120 mm) with respect to a triangulation sensor. The specimen was illuminated at angles of 0° (curve 1) and 42° (curve 2) by the sensor. The parallax from curve 2 is explained by an increased reflection on the specimen. The measurement range was 10 ±2 μm and is sufficient for the focal positioning. A great advantage of this system is the high accuracy of DSP-technology and the elimination of measurement accuracy characteristics of material, colour and brightness of the specimen. A triangulation sensor with a wide working range was used, due to the construction of the LBPO (laser beam processing optics) and the focal length of 150 mm (Appendix 13.10.2).
8 Process Characterisation of Pulsed Nd:YAG Laser Spot and Seam Welding

Chapter 8 discusses and compares the heat conduction and the keyhole welding with respect to the advantages and disadvantages by the welding of sensitive components. It was shown that with regard to the LDB welded components, that the heat conduction method using pulsed solid state laser is the more process-reliable. The effects of pulse-forming and modulation on the insertion behaviour of the laser beam on the work piece and the welded seam are also discussed. In the framework of a experimental parameter study a set of process-reliable laser and process parameters (process window) were developed. This parameter set finds usage in the welding procedures of the LDBA in chapter 10. The structure of this chapter is summarized in Figure 8.i.

![Subchapter block diagram](image-url)

Fig. 8.i The subchapter block diagram
Laser welding applications are becoming increasingly complicated. The trend towards smaller and cheaper products often results in the need to make high quality welds using less than suitable materials or active components, which are sensitive against heat. Successful laser welding of these components requires the development of a weld schedule with a reasonable process window. The use of pulsed Nd:YAG lasers with support for pulse shaping can help to significantly increase the process window and improve weld quality.

The development of new laser systems has led to an improved control over laser parameters and therefore also the processes. This means a considerably better pulse to pulse repeat accuracy and more control and influence of the actual pulse form. Improvements in laser technology also increase interest in the usefulness of pulse forming, modern laser systems allow almost any pulse form of high complexity to be generated. The user can program the pulse shape as an X-Y curve point for point, adapted to the pulse period and power. The most advanced laser uses a real-time power feedback mechanism, which controls the discharge current based on the measured optical laser output. This way the laser is able to produce the same shape over and over again, independent from lamp age, laser temperature or other external influence [106 – 111].

### 8.1 Conduction Welding versus Keyhole Welding

In laser welding, the materials are heated to temperatures above the melting point by the absorption of laser light. On removal of light the materials cool down and solidify. The resulting weld shape is determined by the peak power (pulse shape) of the laser pulse, the spatial intensity distribution, pulse energy, repetition rate, material characteristics and surface conditions. Within the set of parameters, the peak power, pulse shape and pulse energy can be programmed by the operator to change the weld shape. The spatial distribution is determined by selection of beam delivery system. In most cases a flat-top profile is used, provided by a stepped index fibre with the added benefit that the
spot size does not change with the laser power. Figure 8.1 illustrates the spatial intensity distribution of a Gaussian beam after a step index fibre and with free propagation [109].

The pulse energy determines the maximum amount of material that can be melted. The peak power of pulse amplitude determines how fast power is applied. Peak power is an important factor in determining weld shape.

There are two modes of welding with pulsed Nd:YAG Lasers, so-called conduction welding and keyhole welding. When welding with lower peak powers the weld shape is determined by heat conduction and convection from the surface of the material. Consequently the weld becomes both wider and deeper at the same time. This type of weld does not splash, is very reproducible and suitable for welding thin materials. Conduction welds are not suitable when deep welds are needed.

At high peak power a keyhole is generated. A small amount of material is evaporated from the weld area and a small hole is created. The walls of the hole reflect the laser light internally and therefore absorption is strongly increased. Keyhole welding is a less stable process than conduction welding, but results in deep high aspect ratio welds, often needed to create hermetic seams, or to meet strength requirements [112 – 125].
8.2 The Use of Pulse Shaping and Modulation

There are many potential uses for pulse shaping to improve weld quality, enlarge the process window or improve the cycle time. When discussing the influence of laser parameters on the weld, it can be said that the surface of materials is of importance. Contaminants on the surface such as oil, coatings, oxides and surface texture determine the amount of light that is absorbed.

By creating a laser pulse with a first segment that heats, but does not melt the surface, a reproducible environment for the actual weld pulse can be created. The result is a much more consistent weld quality with reduced sensitivity to differences in the materials [84] [85].

8.2.1 Comparing Effect of Pulse Shape in Stainless-Steel

In general are three classes of pulse shapes, the rectangular pulse, the up-sloped pulse and the down-sloped pulse. The rectangular pulse is the standard pulse shape employed in most of the steel welding processes. It generally gives the least penetration for a given energy and is prone to produce inclusions when used in the keyhole-welding mode.

The up-sloped pulse starts with a peak power, which is lower than that of the square pulse. The amplitude is gradually increased with time, which results in the deepest weld penetration of the three shapes compared. The reason for the deepest penetration is that the highest peak power is employed once the keyhole is already established. With the multiple reflections in the keyhole the absorption is high and most of the energy becomes absorbed. The result is that the keyhole penetrates deeper, resulting in about 50% more penetration than using simple square shapes of the same energy [128 – 130]. The downside to this pulse shape is the abrupt termination of the pulse at high peak power. Just such as the square pulse, the weld will solidify quickly leaving a hole near the tip of the weld [86].

The down-sloped pulse starts with the highest peak power, which is gradually reduced towards the end (Figure 8.2). The pulse has the same average peak power as the square
pulse, but still produces a slightly deeper weld. Of more importance is that the weld solidifies much slower giving the keyhole time to close. The ideal pulse shape is somewhere between the up-slope and down-slope pulse. Obviously the ideal shape depends largely on the requirements of the application and the material to be welded [87].

![Up-slope and down-slope pulse](image)

**Fig. 8.2** Up-slope and down-slope pulse

## 8.3 Characterisation of Pulsed Laser Seam Welding Parameters

The inherent complicated pulsed laser parameters of pulsed mode Nd:YAG Lasers permit a wide range of experimental conditions to be applied. These lasers also have the ability of pulse shaping at pulse repetition rates of up to several kHz and with durations varying from 0.3 to 20ms. This flexibility gives control of thermal input with a precision not previously available. It also allows control of penetration, melt pool shape and size, the onset of boiling, keyhole formation and explosion ejection. Pulsed mode YAG-lasers are
particularly suited to industrial applications such as precision spot and seam welding of small electromechanical and mechanical components [88]. Many studies have been carried out on pulsed Nd:YAG lasers welding applications [89-96]. Unfortunately, these studies always focus on the general experimental work, without giving a systematic analysis of the processing parameters. It can therefore be said that the effects of pulsed laser process parameters on material processing are still not fully understood.

8.3.1 Single Shot and Overlap Processing Theory for Pulsed Laser Welding

Pulsed mode laser material processing is characterised by an interaction of either a single pulse or multiple power pulses with the laser beam and the work piece. Therefore the processing theory for pulsed laser welding processes consists of both the single shot and the overlap theory.

In Chapter 2.4.1 various diagrams (Figure 2.13, 2.14 and 2.15) are showing pulsed laser power output for a series of variable and constant energy pulses.

A set of pulsed laser parameters is defined below:

- \( P_p = \) average peak power (kW)
- \( E_p = \) pulse energy (J)/pulse duration (ms)
- \( P_D = \) average peak power density (kW/m\(^2\))
  - average peak power (kW)/spot area (m\(^2\))
- \( P_M = \) mean laser power (kW)
  - pulse energy (J) x pulse repetition rate (Hz)
- \( t_p = \) pulse duration (ms), \( E_p = \) pulse energy (J), \( P_{RR} = \) pulse repetition rate (Hz)
- \( T_F = \) pulse to pulse time (ms), \( C_D = t_p/T_F = \) duty cycle

During laser material processing by a single shot of pulse power, three heating modes are observed: heating, melting and vaporisation. These are the combined effects of the peak power density and the interaction time between beam and work piece surface. The peak
power density determines thermal input rate onto the treated material area during the interaction time which is equal to pulse duration, because there is no relative motion between laser beam and work piece. As illustrated in Figure 8.3 the weld dimensions depend on the peak power density, pulse duration and welding speed $v_s$.

Pulsed laser seam welding consists of the execution of a series of periodic single spot welds overlapping each other and forming a welding seam. The formation and the percentage of overlap as well as the weld quality depend on the combination of various pulsed laser parameters (mean power, welding speed, pulse energy, pulse duration, spot diameter and average peak power density) [88].

Due to the partial overlapping of spot welds and the refilling process of preceding fusion zones, pores can effectively be reduced. The relevant equations are formulated as follows:

Assuming a one-dimensional overlapping, the percentage of overlap $P_O$ can be calculated in x-axis direction as follows:
Process Characterisation of Pulsed Laser Spot and Seam Welding

\[ P_o = \frac{(D - D^*)}{D} \cdot 100\% \]  
(8.1)

where \( D = d + v_s \cdot T_p \) and \( D^* = v_s \cdot t_p \)  
(8.2, 8.3)

Substituting the expression for \( D^* \) and \( D \) in equation 8.1, the overlap percentage can be calculated,

\[ P_o = \left[ 1 - \frac{v_s \cdot t_p}{d + v_s \cdot T_p} \right]. \]  
(8.4)

It can be seen from equation 8.4 the percentage of overlapping depends upon the pulse duration \( t_p \), the pulse to pulse time \( T \), welding speed \( v_s \) for a given mean power \( P_M \) and spot size \( d \).

Nd:YAG lasers pulse train can be considered as a transformation of a continuous wave (CW – duty cycle 100 %) power. Figure 2.13 illustrates a transformation of a CW laser power into the pulsed mode. The relationship between the parameters can be expressed by following mathematical equations, where \( D \) is the spot diameter:

\[ P_M = E_p \cdot P_{rr} \]  
(8.5)

\[ P_M = \frac{E_p \cdot t_p}{T_p} = P_p \cdot C_D \]  
(8.6)

\[ P_M = P_D \cdot D \cdot t_p \cdot P_{rr} \]  
(8.7)

From equation 8.5 it can be observed that for a given laser power \( P_M \), there can be various combinations of \( E_p \) and \( P_{rr} \) and the relation in inversely proportional. The Nd:YAG lasers used for pulsed LDBA welding has the ability to vary duty cycle. This may have significant effects on weld quality and thermal heat input of the LDBA.

The question arises how to select a set of parameters to provide efficient and effective pulsed laser welding concerning LDBA manufacturing.

Equation 8.8 is essentially correct for any power pulses, including rectangular pulses as used for LDBA manufacturing:
The energy of a single pulse, $E_p$, varies linearly with the pulse duration $t_p$ if the duty cycle and the mean power $P_M$ is maintained constant. Conversely, for selected values of $P_M$ and $t_p$ the duty cycle decreases with increasing pulse energy. Moreover Equation 8.8 can be written as:

$$C_D = \frac{t_p}{T_p} = t_p \cdot P_{RR} = \frac{t_p \cdot P_M}{E_p}$$

(8.8)

The duty cycle decreases with increasing $P_M$, if the spot size $D$ and the mean power $P_M$ are kept constant. Due to earlier experiments regarding pulsed laser spot welding of precision devices, it has been shown that short duty cycles can improve spot weld quality and reliability [97]. It has been stated that for spot welding by single power pulse, that the most important parameters are the average peak power density $APPD$ and the pulse duration $t_p$. For pulsed laser seam welding, other processing parameters have to be taken into consideration, e.g. mean laser powers $P_M$ and the travel speed $v_S$ [88]. To achieve a suitable $APPD$, the laser spot size has to be carefully selected with regard to the low mean power available.

In the following described experiments, spot-welds with pulse periods $t_p$ (0.3 ms, 0.4 ms u. 0.5 ms, $P_{RR} = 100$ Hz and 5 pulses) and with different power levels were carried out. Stainless steel (1.4920) was chosen as material. From the resultant depths of the spot welds as a function of laser pulse power, the minimum required pulse power for different spot diameters can be ascertained (Figure 8.4 and 8.5). The spot welds depicted in Figure 8.4 were carried out at the beam focal point. The spot welds in Figure 8.5 were carried out with a spot diameter of $400 \mu$m. This diameter occurred at the half of the Rayleigh-length (Figure 6.1).
Fig. 8.4 Depth of weld as a function of pulse power for a 330 μm spot ($P_{RR} = 100\text{Hz}$)

Fig. 8.5 Depth of weld as a function of pulse power for a 400 μm spot ($P_{RR} = 100\text{Hz}$)
With increasing pulse power and period, the weld depth increased in linear approximation (Figure 8.5). Larger spot diameters resulted in reduced area energy density and thus smaller weld depths. The threshold pulse powers required for measurable weld depths are therefore lower for smaller spot diameters as for larger.

It is observed that for a given mean power and focal spot size of 330 μm, the appropriate zone of acceptable spot welds quality by pulsed laser welding is between the duty cycles of 3-5 %. The advantage of short duty cycles causes less thermal heat input into the material than larger duty cycles. The strategy of multiple pulses on the same position is that after the first pulse absorption conditions are increasing. Due to this increased absorption behaviour the coupling efficiency of laser radiation is much higher compared to a single pulsed spot weld.

As the manufacture of the LDBA requires no weld depths greater than 400 μm, no greater pulse power than 1600 W is required at a pulse period of 0.3 – 0.5 ms (Figure 8.7).
Figure 8.8a-d illustrates the results of a series of overlapping spot welds. By changing the velocity, the degree of spot overlapping can be adjusted in range of 0-100% from the spot area.

![Parameter: 1500 W, f=100 Hz, Duty C. 4%, focus situation z= 0 overlap: 10% vs: 30 mm/s shielding gas: Ar (20 l/min)]

![Parameter: 1500 W, f=100 Hz, Duty C. 4%, focus situation z= 0 overlap: 40% vs: 20 mm/s shielding gas: Ar (20 l/min)]

![Parameter: 1500 W, f=100 Hz, Duty C. 4%, focus situation z= 0 overlap: 85% vs: 5 mm/s shielding gas: Ar (20 l/min)]

![Parameter: 1500 W, f=100 Hz, Duty C. 4%, focus situation z= 0 overlap: 95% vs: 1.7 mm/s shielding gas: Ar (20 l/min)]

Fig. 8.8a-d Series of overlapping spot welds with different velocities $v_s$
Figure 8.9a-d illustrates the results of a series of overlapping spot welds. By changing the shielding gas pressure, the quality of the weld bead was greatly influenced. A stable and uniform weld bead was obtained with the parameter set in Figure 8.9d. Due to the high shielding gas flow in Figure 8.9a-c the weld bead was not stable and irregular.

Parameter:
1500 W, f=100 Hz, Duty C.
7%, focus situation z=-0.2mm
overlap: 85 %
v_g: 5 mm/s
shielding gas: Ar (50 l/min)
nozzle orientation: 45°

Parameter:
1500 W, f=100 Hz, Duty C.
7%, focus situation z=-0.2mm
overlap: 85 %
v_g: 5 mm/s
shielding gas: Ar (40 l/min)
nozzle orientation: 45°

Parameter:
1500 W, f=100 Hz, Duty C.
7%, focus situation z=-0.2mm
overlap: 85 %
v_g: 5 mm/s
shielding gas: Ar (30 l/min)
nozzle orientation: 45°

Parameter:
1500 W, f=100 Hz, Duty C.
7%, focus situation z=-0.2mm
overlap: 85 %
v_g: 5 mm/s
shielding gas: Ar (20 l/min)
nozzle orientation: 45°

Fig. 8.9a-d Series of overlapping spot welds with different shielding gas pressure
9 Threshold for Conduction Welding

In chapter 9 the single shot and overlap processing theory is developed. Depending on the pulse frequency, spot size and feed rate, an overlap factor of single laser spots from 0 – 100% can be process-reliably set. On the basis of the Fresnel equations and Lambert-Beers laws, a mathematical model construct in heat conduction mode can be carried out. In the following, the threshold for heat conduction welding in dependence of the laser power, incidence angle and polarisation axis can be calculated for iron and comparatively for aluminium.

Results show that a change in the incidence angle of the laser beam affects the welding speed only marginally, so long as the incidence angle lies under the characteristic Brewster angle. The structure of this chapter is summarized in Figure 8.i.

The development of laser material processing requires extensive empirical research and the development of accurate and robust mathematical models. Many of these models have concentrated on various aspects of cutting [98, 99, 100], welding [101, 102, 103, 104] and drilling [105, 106]. All models of different laser machining processes involve the understanding and modelling of the fundamental physical and chemical laser absorption mechanisms. Photon-matter interactions are complex. The mechanisms determining energy coupling into the matter represent a key issue for understanding of laser material processing and improving the efficiency and reliability of this technology.

The objective of this chapter is to determine the threshold for conduction welding regarding laser seam welding of stainless steel with respect to Fresnel absorption as a function of the angle of incidence [144 – 146].
Subchapter 9.1
Single shot and overlap processing theory for pulsed laser welding

Subchapter 9.2
Threshold for conduction welding

Lambert & Beer law
Fresnel equations and reflection at metal
Modelling in conduction laser welding

Calculation of threshold for conduction welding

Conclusion

Subchapter 9.1 - 9.2 are used in chapter

Chapter 10 - LDBA manufacturing

Fig. 9.i The subchapter block diagram
9 Threshold for Conduction Welding

9.1 Lambert & Beer Law

The Lambert-Beer law gives the decrease in light intensity as a function of propagation distance $z$ in the form of an exponential law. According to Lambert & Beer’s law for homogenous media:

$$I(z) = I_o e^{-\alpha z}$$  \hspace{1cm} (9.1)

where $\alpha = \frac{4\pi \cdot nk}{\lambda_0}$ is the absorption coefficient and $\lambda_0$ is the vacuum wavelength [119].

The reciprocal of $\alpha$ is called the absorption length $l_a$, and is the distance after which the intensity is reduced by a factor of $1/e$.

In inhomogeneous media, $n$ and $k$ depend on position and may in certain crystals even depend on the direction of propagation. In that case $\alpha$ must be replaced by $\alpha(z)$ and integrated along the propagation path (equation 9.2).

$$I(z) = I_o e^{\int -\alpha(z) dt}$$  \hspace{1cm} (9.2)

The optical constants $n$ and $k$ can be calculated from complex dielectric permittivity.

$$\varepsilon = \varepsilon_1 - i\varepsilon_2$$  \hspace{1cm} (9.3)

using the following equations:

$$n^2 = \left(\varepsilon_1 + \sqrt{\varepsilon_1^2 + \varepsilon_2^2}\right)/2$$  \hspace{1cm} (9.4)
$$k^2 = \left(-\varepsilon_1 + \sqrt{\varepsilon_1^2 + \varepsilon_2^2}\right)/2$$  \hspace{1cm} (9.5)

However the law is valid for following assumption. The centre of absorption does not interact. There is no non-linear effect or $\alpha$ is a constant. Furthermore there is no saturation and the material is homogeneous.
9.2 Fresnel Equation and the Reflection at Metal

In the generalized Maxwell description, materials are characterized by the three parameters \( \varepsilon \) (dielectric constant) \( \mu \) (magnetic permeability) and \( \sigma \) (electrical conductivity). In particular, the conductivity leads to a damping and absorption of electromagnetic radiation. Normally metals show a very large conductivity. Therefore the Fresnel equation can be simplified for reflection at the metal after inserting the complex refractive index. In this way the following reflectivities can be found:

\[
R_s = \frac{(\cos \theta - n)^2 + k^2}{(\cos \theta + n)^2 + k^2}
\] (9.6)

\[
R_p = \frac{(1 - n \cos \theta)^2 + (k \cos \theta)^2}{(1 + n \cos \theta)^2 + (k \cos \theta)^2}
\] (9.7)

Where \( \theta \) is the incident angle, \( n \) is the refraction coefficient, \( k \) is the material extinction coefficient. It can be seen the reflectivity of parallel rays \( (R_p) \) and perpendicular rays \( (R_s) \) are different; p-rays are more easily absorbed by materials than s-rays do [119].

9.3 Threshold for Conduction Welding

The threshold for conduction welding when the work piece moves with the speed \( v \) relative to the stationary laser beam sent the absorbing power \( AP \) to the surface can be obtained from following approximation to the heat equation [146]. The coordinate is as shown in Figure 9.1 and \( r = (x^2+y^2+z^2)^{1/2} \) [118].

\[
T(r) - T_s = \frac{Ap}{2\pi Kr} \exp\left(\frac{v(x+r)}{2k}\right)
\] (9.8)
Equation 9.8 is the exact for the point source of strength $AP$ and has a singularity at $r = 0$. It can be used to estimate the threshold for welding for a Gaussian beam of radius $w$, by taking for $T = T_m$ at $r = w \sqrt{2}$

$$\text{And } x = 0 \text{ and } P = \int_0^\infty I(r)2\pi r dr = 2\pi \int_0^\infty \left( \exp\left[\frac{-2r^2}{w^2}\right]r dr \right)$$

From this results:

$$V_m = -\frac{2\sqrt{2}K_x}{w} \ln\left[\frac{(T_m - T_0) * 2\sqrt{2}\pi K w}{AP}\right]$$

Where
- $K = \text{ Thermal conductivity of the material (W/mK)}$
- $K_x = \text{ Thermal diffusivity of the material (m}^2$/s$)$
- $w = \text{ Diameter of the Gaussian beam (m)}$
- $T_m = \text{ Melting point (K)}$
- $T_0 = \text{ Room temperature (K)}$
- $AP = \text{ Absorbed power (W)}$
- $V_m = \text{ Critical welding speed of the work piece (m/s)}$.

The minus sign in front of the equation (9.10) means that the absorbed power (AP) should be greater than $(T_m - T_0) * 2\sqrt{2}\pi Kw$ or this equation can be written from this condition as
\[ P_{\text{min}} \geq \frac{(T_m - T_o) * 2\sqrt{2\pi \kappa w}}{A_{\text{min}}} \]  

Hence the minimum power of laser welding should be evaluated before using equation (9.20). The problems for using equation (9.20) are the thermal conductivity and thermal diffusivity because these values depend on the temperature. We did not know exactly which temperature should be applied to these thermal parameters.

However when we compared or the numerical values of Steel at \( A = 0.1 \) and Aluminium at \( A = 0.03 \) given by Cline and Anthony [127]:

\[ V_{(Al)} = \frac{-2.7 \times 10^{-4} w}{w \ln \left( \frac{2.2 \times 10^{7} w}{P} \right)} \], \hspace{1cm} (9.12)\]

\[ V_{(Steel)} = \frac{-2.7 \times 10^{-5} w}{w \ln \left( \frac{5.7 \times 10^{6} w}{P} \right)} \]. \hspace{1cm} (9.13)\]

Where \( w \) and \( v \) are given unit in \( m \) and \( m/s \) respectively.

When (9.12) and (9.13) are compared with (9.10), thermal conductivity (\( K \)) and thermal diffusivity (\( k \)) are calculated and compared with the values from data sheet as shown in Table 9.1.

<table>
<thead>
<tr>
<th>Metal</th>
<th>From [122] [123] and [124]</th>
<th>[121]</th>
<th>[122]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( (W/m-K) )</td>
<td>( (m^2/s) )</td>
<td>( (W/m-K) )</td>
</tr>
<tr>
<td>Steel</td>
<td>42.48</td>
<td>8.84 x 10^{-5}</td>
<td>40</td>
</tr>
<tr>
<td>Al</td>
<td>139</td>
<td>9.54 x 10^{-5}</td>
<td>110</td>
</tr>
</tbody>
</table>

* At liquid phase.
** From \( T = 1810 - 3800 \) K (from melting point at 1810 K)
*** From \( T = 1810 - 3500 \) K (over melting point)
$ At 900 K (near melting point at 933K). No information for liquid phase.
$$ At 1073 K (over melting point)
$$ At melting point.
n/a No information in liquid phase.

From the comparison, thermal physical properties of Iron should be the value in the liquid phase. However for Aluminium, only thermal conductivity is corresponding with the
value in the liquid phase. Therefore thermal physical values of each metal have to be applied at the temperature near the melting point.

9.3.1 Modelling in Conduction Laser Welding

The objective of this chapter is to calculate the profile of the critical welding speed as a function of incident angle by using threshold for conduction welding model (equation 9.10). However $AP$ or $P$ in equation 9.10, 9.11 and 9.12 are not constant. $AP$ or $P$ should be the absorbed power from material. Therefore in this report the reflectivity from the Fresnel equations is applied to obtain the $AP$ is a function of incident angle $\theta$ by the following equation:

\[ R = \frac{R_s(I) + R_p(I)}{2}, \quad (9.14) \]

\[ AP = (1-R(\theta)) \times \text{Laser Power} \quad (9.15) \]
\[ AP = (1-R_s(\theta)) \times \text{Laser Power} \quad (9.16) \]
\[ AP = (1-R_p(\theta)) \times \text{Laser Power} \quad (9.17) \]

Assumptions for modelling are included following:

The mode of welding is conduction welding according to the welding speed equation 9.10. It implies that laser power should not be higher than the threshold of $10^6 \text{W/cm}^2$ for steel, otherwise the keyhole-welding mode will occur. Laser beams with the Gaussian intensity distribution (also from the assumption of equation 9.10. Type of laser is a pulsed Nd:YAG lasers because in the calculation of reflectivity, the refractive index is for the wavelength 1.06 $\mu$m.

From the comparison in Table 9.1 thermal conductivity ($K$) and thermal diffusivity ($k$) in formula 9.20, it is assumed that these parameters at near melting point. The reason for choosing the physical parameters at near, not at, melting point or at liquid phase is because at melting point the absorptivity increases abruptly [126]. At the liquid phase, the Fresnel absorption can therefore be neglected. However, this chapter studies laser welding at absorptions at any incident angle. Hence modelling is carried out with the metal in the solid phase, i.e. temperature near melting point.
Substrates used are stainless-steel (1.4301) and Aluminium because of the ease of finding physical properties values $V_m$ from numerical formula in (9.12) and (9.13).

### 9.3.2 Calculation

At programming, the reflectivity $R(s)$ and $R(p)$ are first calculated from incident angle $\theta$, over a range of $0^\circ$ to $90^\circ$ according to equation 9.6 and 9.7. The absorbed power $(AP)$ is calculated from equation (9.14) and (9.15) as a function of incident angle. Finally, each value of $AP$ at each incident angle $\theta$ is substitute in the equation (9.10) to calculate the critical welding speed of each material.

From the modelling the welding process can be optimised by selecting the incident angle, which gives the minimum welding speed. At this point the maximum absorption occurs (most metals show increase power absorption abruptly near their melting points). This angle is called the Brewster angle.

From mathematical model, profiles of welding speed in steel work pieces are calculated in the different value of laser power (800, 1200, and 1500 Watt) and the different size of beam diameter (0.4 and 0.33 mm).

From formula (9.6) and (9.7) Brewster's angle depends on index of refraction of each material [126]. Figure 9.2, 9.3 shows the reflectivity of steel and Aluminium as function of the incident angle.
If the profile is considered before Brewster's angle, the minimum power for laser conduction welding can be calculated by using equation (9.11) \( P_{\text{min}} \geq \frac{(T_m - T_i) \times 2 \sqrt{2} \pi kW}{(1 - T_m)} \) and
maximum reflectivity. For $R_{\text{max}}$ it is applied the value at the zero incident angle not the angle after the Brewster angle. The result for suitable power of each material are presented in Table 9.2.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Minimum Power (W) For beam diameter 0.4 mm.</th>
<th>Minimum Power (W) For beam diameter 0.3 mm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>$\approx 600$</td>
<td>$\approx 460$</td>
</tr>
<tr>
<td>Al</td>
<td>$\approx 650$</td>
<td>$\approx 490$</td>
</tr>
</tbody>
</table>

From the value in Table 9.2, it means that laser power applied in the model (800, 1200 and 1500 W) are appropriate.

From the formula (9.10), the critical welding speed depends on laser power. Hence the results from programming the different value of laser power for each material are shown in the following.

Figure 9.4 and 9.5 shows the results of modelling by using Nd:YAG-lasers power of 800 Watt on steel with beam diameters of 330 $\mu$m and 400 $\mu$m.
Fig. 9.5 Profile of welding speed of steel from Nd:YAG lasers welding (laser power 800 W $\lambda=1.06 \mu m$ beam diameter 0.4 mm) with Fresnel absorption $R$

Figure 9.6 and 9.7 shows the results of modelling by using Nd:YAG lasers power 1200 W on steel for beam diameters of 330 $\mu m$ and 400 $\mu m$.

Fig. 9.6 Profile of welding speed of steel from Nd:YAG lasers welding (laser power 1200 W $\lambda=1.06 \mu m$ beam diameter 0.3 mm) with Fresnel absorption $R$
Threshold for Conduction Welding

Fig. 9.7 Profile of welding speed of steel from Nd:YAG lasers welding (laser power 1200 W \( \lambda = 1.06 \mu \text{m} \) beam diameter 0.4 mm) with Fresnel absorption R

Figure 9.8 and 9.9 shows the results of modelling by using Nd:YAG laser power 1500 Watt on steel for beam diameters of 330 \( \mu \text{m} \) and 400 \( \mu \text{m} \).

Fig. 9.8 Profile of welding speed of steel from Nd:YAG lasers welding (laser power 1500 W \( \lambda = 1.06 \mu \text{m} \) beam diameter 0.3 mm) with Fresnel absorption R
9 Threshold for Conduction Welding

Fig. 9.9 Profile of welding speed of steel from Nd:YAG lasers welding (laser power 1500 W $\lambda$=1.06$\mu$m beam diameter 0.4 mm) with Fresnel absorption $R$

9.3.3 Conclusion

1. Change of incident angle does not materially affect welding speed if the process is carried out under Brewster's angle. Therefore a changing incident angle over a range of 60° is not a critical parameter in laser welding.

2. For the optical system, material changes to welding speed come from laser intensity. An increase of beam power or reduction of beam diameter will therefore result in speed increases and deeper weld penetration. According to Lambert & Beers law, the shorter the wavelength, the more energetic the photons are. Photons with shorter wavelengths are more easily absorbed by the materials than photons with longer wavelengths. Hence welding speed also can be increased by reducing the wavelength.

3. For the physical thermal properties, heat diffusion will have most affect on welding speed. However, higher thermal diffusion properties result in higher probabilities to reach keyhole-welding modes.

4. Parallel polarised radiation is absorbed considerably better than vertically polarized radiation.
10 Manufacturing of Laser Diode Beam Assembly

This chapter discusses the difficulties arising in the manufacturing process of devices in which opto-electronic, micro-optical and precision mechanical components are assembled and joined by laser fine welding. The production of a laser diode beam assembly (LDBA) is used for demonstrating new solutions of these problems. Main difficulties occur in the alignment of the optical function components of this system. Regarding the LDBA, the first component in the assembly device is a laser diode, which has tolerances in the direction of its light emission. Because of this, the alignment of the components following this light source have to be carried out in such a manner that the light propagation through the LDBA device is kept parallel to the beam path of the optical axis. This leads to a necessary angular displacement related to the symmetrical axis of the LDBA. Therefore a previously developed laser fine welding system has been enhanced by a fine scan system for enabling the optical alignment of the LDBA [97][142].

Chapter 10 describes and discusses the construction and manufacturing procedures of a novel laser diode beam assembly. The LDBA is characterised by a corrected beam direction deviation, optimised beam characteristic and a compact build. The LDBA consists in the main of a modified laser diode pigtail, an interface connector and an output coupler. The LDBA can also be filled with a protective gas via a gas inlet on the interface connector.

The combination of modular construction and a new, adapted manufacturing procedure allows the laser beam weld technique in heat conductive mode to successfully produce high-precision positioned jointing in temperature-sensitive work-pieces. In total, 6 weld seams had to be carried out on the LDBA in a rigidly process sequence. A full-automatic adjustment of the output coupler using a two-dimensional area scan (FineScan) allowed a positioning of the output coupler in micrometer ranges. This allows the smallest manufacturing tolerance induced beam direction deviation to be corrected. The chapter goes on to discuss and evaluate the effects of the laser weld process on the adjustment and alignment of single components and of the function of the highly heat-sensitive laser diode. The chapter closes with an economics review on the joint technology laser beam welding using the example electro-opto-mechanical laser diode beam assembly (LDBA). The review was carried out with reference to the contemporary commercially available solid state and gas lasers. The structure of this chapter is summarized in Figure 10.i.
<table>
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<td>Subchapter 10.3</td>
<td>Modification of joint configuration of LD-pigtail</td>
</tr>
<tr>
<td>Subchapter 10.4</td>
<td>Pigtail alignment procedure and pulsed laser fine welding</td>
</tr>
<tr>
<td>Subchapter 10.5</td>
<td>The interface connector</td>
</tr>
<tr>
<td>Subchapter 10.6</td>
<td>Seam welding of laser diode pigtail and interface connector</td>
</tr>
<tr>
<td>Subchapter 10.7</td>
<td>2D-area scan set-up and output coupler alignment procedure</td>
</tr>
<tr>
<td>Subchapter 10.8</td>
<td>Laser fine welding of interface connector and output coupler and</td>
</tr>
<tr>
<td>Subchapter 10.9</td>
<td>Welding of gas inlet and interface connector</td>
</tr>
<tr>
<td>Subchapter 10.10</td>
<td>Consideration of economic efficiency of laser beam welding systems (Example - LDBA Production)</td>
</tr>
</tbody>
</table>

Fig. 10.1 The subchapter block diagram
10.1 LDBA Design and Alignment Procedure

As a new joining technology, laser beam-welding offers a multitude of enhanced constructive possibilities in device design. Not only the low energy input or the possibility of one-sided access jointing, but also the application to a great variety of materials and material combinations are important advantages of this technology. The prerequisite for laser fine welding is to design the component shape and to make the material selection in such a manner that functional and quality requirements of the weldable components are guaranteed. Moreover, the manufacturing process has to be carried out with high accuracy and reliability. For a high repetition accuracy of alignment, it is necessary to clamp the components in specially designed precision clamp tools. Table 10.1 depicts the complete LDBA alignment and assembling procedure, subdivided in components construction, assembling, welding procedure and intermediate stage.

Tab. 10.1 Schematic procedure of LDBA alignment and assembling
Weldability and welding seam quality (mechanical properties, gas-tightness) depend strongly on the optimised process parameters, laser parameters, material composition, precise structural design of the components (edge preparation and gap tolerance) and the use of a precision handling system. To meet these conditions, a diode laser diode beam assembly (LDBA) was designed consisting of a laser pigtail, Interface Connector (IC), focusing output coupler and gas inlet (Figure 10.1). Different fibre focusing optics can be aligned as replacement for the focusing output coupler.

![Exploded drawing](image-url)

Fig. 10.1 Exploded drawing of the diode Laser Diode Beam Assembly (LDBA)
These components consist of different material compositions (high-grade steel 1.3920, 1.4547, see chapter 13.11.2) with different sensitivities to the local melting process caused by pulsed laser welding. The most sensitive device in the LDBA is the laser diode, a small active laser device. Its main body consists of steel covered with 1 micron thick gold plating. The LDBA and its components are constructed in such a way that all alignment procedures can be carried out with high accuracy. Due to the LDBA construction and component joint configurations, all influences from clamping during the alignment procedure and after the laser welding process cause fewer mismatches on the alignment.

The Butt joint configuration makes design and alignment of optical components much easier as well as avoids time-consuming focusing procedures of the welding head. In particular, the fillet joint configuration is sensitive to deviation during the welding process, which can lead to a mismatch of the components to be welded. The small number of welds positions and reduction in the complexity of joint forms allow a fast and accurate positioning of the components relative to each other. The laser pigtail and gas inlet are mounted self-centring on the interface connector without the need for an adjustment effort (Figure 10.1).

By the use of three joint forms so chosen as not to influence each other during weld, any interference of the alignment results during and after welding can be neglected. In the case of the assembly of laser pigtail and gas inlets, a weld joint thermal movement can be practically excluded. The precision manufacture of the components leads to no seam openings being expected. The vertical construction form of the LBDA and the butt-joint weld arrangement of pigtail to IC and output coupler to IC, a one-sided access laser weld can be carried out without a high focusing effort on the working optics.

<table>
<thead>
<tr>
<th>Pairs of components</th>
<th>Connection flange</th>
<th>Joint configuration</th>
<th>Alignment Degree of difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pigtail</td>
<td>Flange A and B (Beam profiler)</td>
<td>Butt and overlap (fit)</td>
<td>high</td>
</tr>
<tr>
<td>Pigtail + (IC)</td>
<td>Flange 1</td>
<td>Butt weld (fit)</td>
<td>less</td>
</tr>
<tr>
<td>Gas inlet + IC</td>
<td>Flange 2</td>
<td>Fillet weld (fit)</td>
<td>less</td>
</tr>
<tr>
<td>Output Coupler + IC + Pigtail</td>
<td>Flange 4 (FineScan)</td>
<td>Butt weld</td>
<td>medium</td>
</tr>
</tbody>
</table>
Table 10.3 Technical details of LDBA (construction drawings see Appendix 13.11.3)

<table>
<thead>
<tr>
<th>Components</th>
<th>Drawing No.</th>
<th>Weight (g)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser diode (LD)</td>
<td>2000-73-01</td>
<td>0.25</td>
<td>Steel + gold plating</td>
</tr>
<tr>
<td>GRIN-lens holder</td>
<td>2000-73-04</td>
<td>0.55</td>
<td>1.3920</td>
</tr>
<tr>
<td>GRIN-lens mount</td>
<td>2000-73-05</td>
<td>0.35</td>
<td>1.3920 + gold plating</td>
</tr>
<tr>
<td>Gas-Inlet</td>
<td>2000-73-03</td>
<td>0.14</td>
<td>1.4546</td>
</tr>
<tr>
<td>Interface Connector (IC)</td>
<td>2000-73-02</td>
<td>6.80</td>
<td>1.4546</td>
</tr>
<tr>
<td>Output Coupler (OC)</td>
<td>2000-73-07</td>
<td>1.80</td>
<td>1.4546</td>
</tr>
</tbody>
</table>

The 4 main steps in manufacturing of LDBA are (chronological order):

- Laser diode Pigtail alignment and laser welding by use of a beam profiler
- Alignment and laser welding of laser diode pigtail and IC
- Alignment and laser welding of Gas-Inlet and IC
- Alignment of Output Coupler and IC by means of FineScan and final laser welding

10.2 Pigtail Construction and Manufacturing

Using the knowledge and findings in the previous chapters and taking into account the negative impacts of small positing deviations of laser diode and GRIN-lens on the beam collimation, a laser diode pigtail was constructed. This also covered any defects in clamp surety in component construction affecting positing accuracy.

The laser diode pigtail consists of a laser diode (without casing) with corrected beam projection, a GRIN-lens holder and a mounted GRIN-lens.
The body of the laser diode consists of steel with a 10 μm gold plate surface. The GRIN-lens holder was manufactured from good machinable stainless-steel (1.3920) with low thermal distortion coefficient and good weldability. The GRIN-lens mount was also of stainless steel. To improve the solderability of the GRIN-lens into its mount, the lens mount was plated with 3 μm thick gold plating. A necessary prerequisite for high-quality welded seams was the cleaning of all joint connections with acetone or Isopropanol. In the further course of the LDBA production a GRIN-lens was used with the following technical data:

Focal length $f = 0.96$ mm, Pitch = 0.23, NA = 0.51, Diameter = 1mm, Working distance = 0.12 mm.

### 10.3 Modification of Joint Configuration of LD-Pigtail

So that the effects of weld shrinkage induced length contractions on collimation alignment remained minimal, the GRIN-lens holder was modified at weld positions 2, 3 and 4 with respect to laser weldability. Figure 10.3 shows the laser diode pigtail with the modified joint geometry. The wall thickness in the welding groove area was now 0.3mm.
The joint geometry in the weld positions 1 to 4 in Table 10.4 is shown with the relative laser beam direction. All following laser welds were carried out with angles under 90° to the symmetrical axis of the laser pigtail.

**Table 10.4 Joint configuration and welding directions of laser diode pigtail**

<table>
<thead>
<tr>
<th>1) overlap joint</th>
<th>2) overlap joint</th>
<th>3) butt joint</th>
<th>4) butt joint</th>
</tr>
</thead>
</table>

![Diagram](image)

This allows non-productive and time-consuming focal position adjustment of the laser beam process optics to be eliminated.

The functional surface 3 served two purposes. During welding (spot and seam welding) of the laser pigtail, a pressure of about 10 N was applied to this surface. This prevented a displacement of the GRIN-lens holder during welding.

At the following welding of the laser pigtail to the Interface Connector, this functional surface allowed the pigtail to self-centre to the IC-flange (dotted line flange 3 in Figure 10.3) and is welded at position 3 with flange 3 of the interface connector.

In the following FEM-simulation, the influence of the pressure of the GRIN-lens holder-centring surface 3 (Figure 10.4) and mechanical deformation of the laser diode was more deeply investigated [159]. The pressure at the centring ring was taken as 10 N.
The mechanical deformation on the outer boundary of the GRIN-lens holders reached a maximum of 0.845e-04 mm. This relatively small value had no significant affect on the alignment results and was neglected.

Figure 10.5 shows the different areas of deformation of the laser diode during mechanical fixing, due to the pressure caused by the GRIN-lens holder (surface 3, Figure 10.3). The largest deformation (0.214 – 3.84e-5 mm) lay in the outer area of the laser diode. This is also the bearing surface for the GRIN-lens holder. A local deformation peak is found on the right-angled notch on the base. This marginal deformation led to no adverse effect on the beam characteristics of the laser diode and could also be neglected in the course of further production.
Fig. 10.5 Deformation of laser diode due to the influence of pressure strength
10.4 Pigtail Alignment Procedure and Pulsed Laser Fine Welding

The following alignment procedure regarding pigtail manufacturing is carried out in the alignment area of the rotation table and laser beam process optics (Figure 10.7).

![Diagram](image)

**Fig. 10.6** Set-up with Rotation table for pigtail alignment and welding

The focusing procedure of the laser beam is monitored by means of an application microscope. Further a laser distance sensor adapted on the top of LBPO allows fast and precise focus positioning.
The laser diode is fixed in a special clamp tool, which can be rotated by the precision mini rotation axis and be moved by means of linear precision axes in x,y and z directions. The GRIN-lens mount including the GRIN-lens is fixed by means of a hydro clamp tool inserted into a GRIN-lens clamp tool. The GRIN-lens is positioned in front of the laser diode. During the alignment process the laser beam intensity distribution is measured and monitored by a beam profiler. The active photosensitive surface of the sensor has an area of 40.6 mm² (6.5(H) x 6.25(V) mm – 752 x 582 usable pixels).

Figure 10.8 shows a characteristic 2D-intensity distribution of a collimated laser diode beam at a given distance, referred to as distance alignment. During the alignment of the GRIN-lens, the distance between photosensitive chip of the beam profiler and the GRIN-lens was 218.5mm is commensurate with a beam width of 4140 µm.
After the GRIN-lens holder and laser diode adjustment process was finished using the measured beam width of 4140 μm, they could be joined together at the chosen positions.
by spot welds in a heat conduction mode. The GRIN-lens holder was now fixed to hold the laser diode (butt weld – $W_1$).

During the spot-welding processes, a clamping ring assured a technically zero distance between laser diode and GRIN-lens holder by exerting pressure on the laser diode surface.

Figure 10.12 shows the joint situations before laser spot and seam welding. The technical gap between laser diode and GRIN-lens holder amounted to 5 $\mu$m.
Figure 10.13 shows the joint conditions after laser spot welds and final seam welding with a spot overlap of 90%. Discrete spot welds fix the components local before a complete seam weld is performed.
Figure 10.14a shows the welding result on the butt joint. The technically zero distance between the components prevented any collapse on the seam upper surface of the joint. The seam showed no expulsions of material, no pores or micro-cracks. Figure 10.14b shows the result at a side offset (lateral mismatch) of LD and GRIN-lens holder of 120 μm. The possible impact of an insufficient clamping during and after the spot-welding process (Figure 11.15a) can result in a lateral dislocation with additional angular displacement of the GRIN-lens holders. The result of this dislocation, the collimated beam profile from the laser diode would not be projected centrally on the photosensitive surface of the beam profiler.
Additionally, the beam path would not be parallel to the z-axis (Figure 10.10). The collimated beam would not be free from interference and would be projected to the edge of the photo-sensitive surface (Figure 10.15a).

The GRIN-lens is manually moved inside the GRIN-lens holder to a defined position Δd, where the beam intensity distribution and beam width are optimised. To avoid longitudinal contraction between GRIN-lens mount and GRIN-lens holder, the latter is equipped with a welding groove. The length deviation results from the decrease in volume of the weld pool during the change from the liquid phase to the solid phase at W3 (Figure 10.10).

Figure 10.16 shows the characteristic beam width deviation due to the defined displacement of the GRIN-lens in z-direction.

![Graph showing beam width deviation due to GRIN-lens displacement](image)

**Fig. 10.16** Beam width deviation due to GRIN-lens displacement

A physical length deviation in z-direction of 5μm in the alignment distance between the laser chip and the surface of the GRIN-lens causes a change in the optical beam-width of nearly 120μm. The movement in longitudinal position of the GRIN-lens holder during welding at position W3 (Figure 10.10) can be eliminated by a constructional change of the GRIN-lens holder. Before the GRIN-lens was welded to the GRIN-lens holder at position
W₃, a spot-weld sequence at a number of points at position W₂ (welding groove – overlap weld) (Figure 10.17a) were carried out.

The GRIN-lens holder and GRIN-lens were then spot welded at the top (welding direction 1 - overlap weld 0°).

![Diagram of joint arrangement of GRIN-lens holder and GRIN-lens](image)

**Figure 10.17** Joint arrangement of GRIN-lens holder and GRIN-lens

Weld direction 1 (0°) had the advantage over direction 2 (45°) that a time-consuming adjustment of the weld optic was not necessary. Further, the concentricity accuracy of 47 µm of the Mini-Rotations axis caused no negative effects on the focal position and therefore also no negative effects on the welding results. Figure 10.18a shows the results of the spot weld process.

![Results in laser tack (a) and spot seam welding of GRIN-lens holder and GRIN-lens mount (b)](image)

**Figure 10.18** Results in laser tack (a) and spot seam welding of GRIN-lens holder and GRIN-lens mount (b)
A circular weld as in Figure 10.18b is fully possible. However, this welding led to a sustained heating of the silver solder used to fix the lens into the lens mount. This led to a subsequent dislocation of the GRIN-lens within the GRIN-lens mount.

Figure 10.19 shows the GRIN-lens mount with silver-soldered GRIN-lens. After the solder process, a thin layer of flux and silver solder exists on the output surface of the GRIN-lens, which has to be removed.

![Fig. 10.19 Soldered GRIN-lens](image)

Figure 10.20a shows the weld results between GRIN-lens mount and GRIN-lens holder. Through melting of the edge of the GRIN-lens holders, the thermal loading of the GRIN-lens mount could be reduced to a minimum. The weld also shows no pores or micro-cracks.

![Fig. 10.20 Welding result of GRIN-lens mount and GRIN-lens holder](image)
10.5 The Interface Connector (IC)

The interface connector (IC) is a specially developed device, which is manufactured from stainless steel. It is designed to link the pigtail (flange 1) with the output coupler (flange 4). The IC is constructed so that the welding processes at flange 1 and 4 can be carried out in a butt joint configuration except for the fillet joint configuration of the gas inlet (flange 2). This construction allows precise alignment of pigtail, output coupler and gas inlet (flange 2) with a technically zero gap. Flange 3 is a special surface plane for optical filters and diaphragms.

Fig. 10.21 Schematic cross-section of interface connector with flanges

In particular fillet joint configurations are sensitive to deviation during the welding process, which can reduce the welding seam quality. The IC fulfilled different tasks.

Function of Interface Connector in LDBA construction:

Fig. 10.22 Schematically representation of IC function
10.5.1 Seam Welding of Laser Diode Pigtail and Interface Connector

The first step of the alignment process is to insert the pigtail in the Interface Connector (flange 1). The IC is then precisely fixed in a chuck.

![Gas nozzle](image1.png)

Parameter:

**Fig. 10.23** Set-up for laser seam welding of LD-pigtail and IC

The tack weld procedure is carried out at 8 points (distance 45°) on the flange side 1 with minimum pulse power. A continuous welding seam is then performed on the fly with a revolution of 380° using Argon shielding gas. The spot welds have a weld overlap of 85%. Figure 10.24 shows the precise butt joint arrangement of the interface connector.

![Interface Connector](image2.png)

**Fig. 10.24** Precise joint arrangement of IC and GRIN-lens holder
and GRIN-lens holder. The precise pass surfaces A and B support an exact positioning and alignment for the LD-pigtails and of the Interface connectors.

The end surfaces of GRIN-lens holder and Interface Connectors are provided with a chamfer (150μm x 200μm) (Figure 10.25a).

![Fig. 10.25 Welding results of pigtai and Interface connector](image)

Figure 10.25b shows the weld result on the Butt joint. Because of the clamped components, a small seam collapse occurred on the upper surface the consistent form of the weld seam pattern showed no material expulsion or indications of surface cracks. As the weld process starts and stops on the fly, no burning on seam begin or end occurred.
10.6 2-D Area Scan Set-up and Output Coupler Alignment Procedure

For the fine alignment procedure of the output coupler to the interface connector (IC) it is necessary to find the optimised position relative to each other. This position depends strongly on the angular deviation of the pigtail. For instance an angular deviation of $0.5^\circ$ to $1^\circ$ causes an eccentricity of $\sim0.5$mm to 1mm during the output coupler - interface connector alignment procedure (Figure 10.26). There exist two main cases of output coupler alignment. In case 1 the angle deviation $\alpha$ is zero, as a result $\Delta s$ is zero. In case 2 an angular deviation $\alpha$ causes an output coupler shift $\Delta s$, which is not equal to zero. In comparison to case 1 this joint configuration is more difficult, because the welding laser beam has to have its tilt angle changed during each revolution of the LDBA.

In comparison to optimal joint configuration of case 1, the misalignment of joint configuration of case 2 is very sensitive to welding failures. To correct pigtail angle deviation, the relative position of the output coupler to the interface connector has to be displaced away from the symmetric axis. Therefore it is necessary to know the exact position where the output intensity is at maximum $I_{MAX}(x,y)$. For this reason the 2D-intensity distribution of the output beam is measured and the position of the maximum intensity $I_{MAX}(x,y)$ is determined. This is realised by a system which consists of a motion-controller, a micro-handling system, a photo detector

![Diagram](image)
Manufacturing of Laser Diode Beam Assembly

(PDA55), and a computer with a PCI-Multi I/O card and specially developed FineScan software. The PDA55 is a silicon photo detector designed for detection of light signals in a frequency range from zero to 10 MHz.

The software FineScan controls the micro-handling system via motion controller and provides the data-acquisition for each pixel during the area scanning process (area of 2 mm²).

FineScan offers a rough scan and fine scan mode depending on the step width as well as a manual motion control mode. The x-y micro-stages manipulate the motion of the interface connector in the x-y-plane (Figure 10.28).

The measurement process is divided into two steps. First a low-resolution scan seeks the area where a maximum of light intensity is located. Secondly a high-resolution scan is applied to determine the exact maximum position.

The scanning field data (intensity distribution) is detected for each pixel by a Silicon photo detector and stored as an ASCII-File. Evaluating the detected 2-D intensity distribution, FineScan generates the position coordinates of the maximum intensity and the motion instructions for the handling system. During the area scan process, the output coupler of the LDBA (Figure 10.27) is clamped by the clamping tool in a fixed position.

Figure 10.28 shows a measured 2-dimensional intensity distribution of a laser diode after a fine scan process (resolution of 32 x 32 measuring point by a lateral step width of 50µm) in different representations.
Fig. 10.28 2-Dimensional intensity distribution with contours (a) and 3-dimensional representation (b).

To complete the alignment procedures, the values found from Figure 10.28 are driven to with an accuracy of $0.5\mu m$. At this position, the output coupler is then fixed to the Interface coupler by spot-welding.

Fig. 10.29 Precise joint arrangement of IC and Output coupler

Figure 10.29 shows a cross-section through the Interface connector and the Output connector. The offset of $100\mu m$ resulted from the 2D-area scan optimisation. Through this scan optimisation the potential beam alignment failures of the LDBA were corrected.
10.6.1 Laser Fine Welding of Interface Connector and Output Coupler

Figure 10.30 shows the alignment area of the welding station and the set-up for output coupler adjustment.

The second step of alignment is to insert the output coupler into the clamp tool and to move it close to the flange 4 of the interface connector. Subsequently FineScan performs the 2-dimensional area scan with variable step width and provides the intensity distribution of the laser pigtail radiation. The position of the maximum intensity \( I_{\text{MAX}}(x,y) \), which is calculated out of the intensity profile, is converted directly into instructions to the micro-handling system. The spot weld procedure is carried out at various positions around the interface connector (IC) (Figure 10.30b, 10.31). As opposed to spot weld procedures, by seam welding of the output coupler breakage can occur caused by stresses in the mirror. The pulse power threshold for such a breakage was found to be 1700 W at \( P_D = 0.4 \text{ms} \).
Finally, a continuous welding seam is performed at a 380° revolution of the LDBA. The result of a high quality laser fine welding seam is shown in 10.32 including crosscut. For this welding seam flange the following laser and process parameters in Figure 10.32 are used.

The consistent form of the weld seam pattern showed no material expulsion or indications of surface cracks. As the weld process starts and stops on the fly, no burning on seam beginning or end occurred.
10.7 Welding of Gas-Inlet and Interface Connector

To refill the Interface Connector with shielding gas it was necessary to construct a Gas Inlet (see construction drawing Appendix). The Gas-Inlet which is adapted to the drilling (2) of the Interface Connector is laser welded less than 45° (fillet weld).

A special clamping tool supports the alignment procedure of the Gas-Inlet to the Interface Connector. It is essential for a reliable laser weld, that axis 1 covers axis 2 exactly. The fillet weld joint configuration is very sensitive against misalignment of the two rotation axes 1 and 2. The difference $\Delta s$ between the axis 2 (rotation axis of the clamping tool) and axis 1 (rotation axis of Interface Coupler and Gas-Inlet) cause an eccentricity. This eccentricity is proportional to $\Delta s$.

Figures 10.34 and 10.35 show the welding results of the Interface Connectors and of the Gas-Inlets. The consistent form of the weld seam pattern showed no material expulsion or indications of surface cracks. An ultrasonic test showed no inner seam failures such as inclusions or pores.
Fig. 10.34 Results regarding Gas-Inlet and Interface Connector fillet welding

A crosscut of IC-Gas-Inlet weld shown in Figure 10.35 illustrates the penetration depth of 400 μm.

Parameter: $P=1500 \text{ W}, f=120 \text{ Hz}, P_d=0.4 \text{ ms}$
$z=0 \text{ μm}$,
$v_s=4 \text{ mm/s}$, $Ar(20l/min)$

Fig. 10.35 Crosscut of IC and Gas-Inlet fillet weld
10.8 Laser Diode Beam Assembly (LDBA)

The LDBA is a compact laser diode beam source (Figure 10.36b), constructed of high-grade mechanical, optical and opto-electronic parts. This assembly is optimised with special regard to the beam propagation direction. Figure 10.36a shows the LDBA in a section cross-cut.

![LDBA Cross-Cut and Complete System](image)

A leak test using Helium showed a complete loss rate of $5.0 \times 10^{-9}$ l/min (Figure 10.37) for the LDBA. Due to the less leakage rate, a filling of the LBDA with shielding gas is possible. This gas protects the laser diode from oxidation and increases the lifetime.

![Helium Leakage Test Unit](image)
On the basis of the LDBA, combined fibre system solutions can be developed. Here the output beam of the LDBA is coupled into a multimode fibre via a popular SMA or FC fibre collimation package.

Figure 10.38 shows a LDBA with a SMA connected collimation package (SMA F230SMA-A, NA = 0.55, f = 4.5mm, diameter 0.9mm) and a SMA-fibre. This simplifies fibre coupled detection and measuring system.
10.9 Results and Discussion

The new developed LDBA consisted of 6 different components, joined together by laser welding. Optical, mechanical and optoelectronic components were used. For the mechanical parts; GRIN-lens holder, GRIN-lens mount, Interface Coupler, Gas-Inlet und Output Connector, an acid-resistant stainless steel was used.

The basis of the LDBA was a modified laser diode with its case removed and an angular deviation corrected. The small working distance of 0.12 mm to the laser chip allowed the beam collimation to be carried out with a GRIN-lens [77]. To produce the optimal position of GRIN-lens to laser chip, both parts were clamped by special tools and with the help of a high-precision Cartesian handling system positioned to each other.

Finite element simulations were made of the mechanical loads on the GRIN-lens holder and laser diode caused by the clamping tools. The results showed that maximum mechanical deformation appeared in the area of the notch in the base of the diode and amounted to not more than \(0.214 - 3.84e^{-5}\text{mm}\). The mechanical deformation on the outer boundary of the GRIN-lens holders reached a maximum of \(0.845e{-4}\text{mm}\). These values are small enough to be neglected.

During adjustment, the intensity distribution in the axis was recorded with a beam profiler. The laser diode was manually adjusted until the entire beam cross section was imaged on the Beam profiler sensor surface. At a working distance of 210mm (Laser chip – Sensor Beam Profiler) the beam width was set to 4100\(\mu\text{m}\). At this distance the best collimation of the laser beam was observed.

As first step after adjustment, the laser diode and GRIN-lens holder were tacked at different points of the rotation-symmetric butt joint. The GRIN-lens was then set to the beam value of 4100\(\mu\text{m}\) in Z-axis. Tacking the GRIN-lens mount and GRIN-lens on a welding groove joint prevented a de-adjustment in Z-axis. The GRIN-lens mount and the GRIN-lens holder was then tacked on the lap joint. In the final step, the LD and the GRIN-lens holder were rotation symmetrically welded. Welding over the tacking and the notch in the LD showed no negative effects on weld quality. The assembly of LD, GRIN-lens holder and GRIN-lens was now referred to as laser diode pigtail.

The first step in the assembly of the LDBA was the insertion of the laser pigtail into the receptacle in the interface connector, which was then tacked at 6 positions in circumference. A complete round weld was then carried out on the GRIN-lens holder.
flange. In the second step the output coupler was clamped in position on the interface connector. The output coupler is a concave mirror fitted in a ring mount that can correct the smallest angle deviation of the laser pigtail through lateral movement on the interface connector.

The 2D-position optimising of the output coupler was carried out using FineScan. FineScan offers coarse and fine scan options with variable step widths. By evaluation of the stored intensity data from the PDA55 Photo detector, the intensity maxima could be driven to at an accuracy of 1 µm. At this optimal position, the output coupler was tacked onto the interface connector. Finally, a complete round weld was carried out.

In the last production step of the LDBA, the gas-inlet was clamped with special tools in position and was welded to the interface connector.

The user has now a high-value, compact and beam direction optimised laser diode beam assembly source for advanced applications. The weld suitable construction of the LDBA and matched laser and process parameters allowed the thermal loading of the components to be considerably reduced. The weld seams on the LDBA showed a high quality. The total leakage rate of the LDBA was determined to be 5.0x10⁻⁹ l/min in a helium leakage test.

Due to the semi-automatic manufacture and the complex adjustment procedures (manual and automatic) of the LDBA using beam profiler and photo detector, the average production time of an LDBA was ca. 1 hour. The effective time \( t_{\text{proc}} \) to laser weld all LDBA parts was determined as being \( t_{\text{proc}} \leq 1 \) min.

Through determined automation in clamping, component positioning, focusing and adjustment, the average production time could be reduced to 20 – 30 min. An optimised tack weld process to fix all parts of the LDBA prior to the main welding process could be realised using two simultaneously working Laser Beam Process optics. These optics will require to be physically opposed to each other, to neutralise the effects of shrinkage tension in the LDBA parts. This would repress negative effects on the adjustment and focusing results (2D-intensity profile and intensity distribution).

An adaptive online process monitoring and control system with integrated power monitoring could compensate for small instabilities in the laser process and the resulting divergences in weld quality.
10.10 Consideration of the Economic Efficiency of Laser Beam Welding Systems taking the LDBA Production as an Example

The increasing use of lasers, not only as special tools in industrial fine mechanics but increasingly competing with conventional welding methods, requires resulting costs to be sufficiently transparent. Experience has shown that the decision to introduce laser technology is usually in favour of laser if

- new production opportunities can be developed by using lasers
- or the quality achieved through laser processing is higher than the quality achieved through conventional processing
- or the production costs through laser processing are lower than the costs through conventional processing

The economic efficiency of the method is a central criterion for all of the three cases mentioned above. The following economic consideration will assist the evaluation of the costs of welding. It is not possible to show a similar valuation of alternatives, as the criteria of assessing new production techniques are individual company aims. Order and trend of higher costs are demonstrated here, taking as example a welding method for producing an LDBA. The costs of the individual groups were determined in 2007.

One handling system (rotation table) for adjusting the components and relevant clamp- and measuring techniques is assumed for both the system based on a CO₂-laser and the Nd:YAG lasers. Different modifications in beam guidance and focusing can only be mentioned marginally. The calculation of operating and investment costs is based on a system configuration set up and used successfully for producing an LDBA.

- Laser beam system
- Chill device
- Gas supply
- Handling system for beam positioning (handling technique)
- Micro handling system
- Beam guidance, processing optics for collimating and focusing
- Control and safety systems
- Clamping technique
Although laser systems for the industrial scale manufacture of one individual component essentially consist of the same components used in a multi-purpose system, they can hardly be put in a cost survey since special developments in motion technique, clamping technique and special systems of component transport have to be considered.

As the production costs are an essential criterion in selecting the appropriate welding method, a detailed statement of the individual costs shall serve the user as a basic comparison of the costs.

The costs for Nd:YAG lasers, CO₂ lasers and also fibre lasers, which increasingly enable new applications, are listed.

Costs include a laser system consisting of laser unit, cooling unit, standard processing optics and clamping technique. The cooling unit and optics for CO₂ lasers generally have to be procured separately, but are calculated as being a lump sum. These units are usually elementary parts of a solid-state laser system. If required, laser beam guidance via light wave-guide can be obtained from the laser manufacturer. Costs for special handling units and operating personnel have not been taken into consideration as these changes according to operation. Operation and production are also determined by clock times, number of working shifts, changing and adjusting times so that the costs can be calculated based on an 85 % availability of the laser during a one shift operation with 1600 hours a year.

Experience with high power lasers has shown that availability can be up to 95 %. High investment costs for a laser system also require high availability and operation in several shifts for various applications.

The statement of costs in Table 10.4 refers to a pulsed Nd:YAG solid state laser with average output power of 300W, a CO₂-laser with an output power of 2 kW and fibre laser (Single Mode) of 400W. On account of a high pulse output power, the processing results, but not processing velocity, of standard applications of seam welding can be compared to the results achieved by CO₂-lasers. These scale in good approximation with average output power of the laser systems. The purchase price is rather to be considered as a guideline representing the efficiency class of the laser system.
### Table 10.5 Statement of costs

<table>
<thead>
<tr>
<th>Statement of costs</th>
<th>CO₂-Laser</th>
<th>Nd:YAG lasers</th>
<th>Fibre Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Investment costs</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laser</td>
<td>160.000,-</td>
<td>85.000,00</td>
<td>75.000,00</td>
</tr>
<tr>
<td>Cooling (Water)</td>
<td>16.000,-</td>
<td>7.000,00</td>
<td>1.000,00</td>
</tr>
<tr>
<td>Beam guidance</td>
<td>7.500,00</td>
<td>6.000,00</td>
<td>3.500,00</td>
</tr>
<tr>
<td>Optic (Focusing)</td>
<td>12.000,-</td>
<td>9.000,00</td>
<td>7.000,00</td>
</tr>
<tr>
<td>Standard handling system</td>
<td>40.000,00</td>
<td>40.000,00</td>
<td>40.000,00</td>
</tr>
<tr>
<td>Micro handling system</td>
<td>22.000,00</td>
<td>22.000,00</td>
<td>22.000,00</td>
</tr>
<tr>
<td>Clamping technique</td>
<td>2.800,00</td>
<td>2.800,00</td>
<td>2.800,00</td>
</tr>
<tr>
<td><strong>Total Investment</strong></td>
<td><strong>260.300,00 €</strong></td>
<td><strong>171.800,00 €</strong></td>
<td><strong>151.300,00 €</strong></td>
</tr>
<tr>
<td>Deduction (5 years)</td>
<td>52.060,00</td>
<td>34.360,00</td>
<td>30.260,00</td>
</tr>
<tr>
<td>Tax costs/ year (11%)</td>
<td>13.000,00</td>
<td>8.590,00</td>
<td>7.565,00</td>
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<tr>
<td>Maintenance/ year (3% of Investment)</td>
<td>7.800,00</td>
<td>5.150,00</td>
<td>No maintenance</td>
</tr>
<tr>
<td>Fix machine costs/ year</td>
<td>72.860,00</td>
<td>48.100,00</td>
<td>37.825,00</td>
</tr>
<tr>
<td>Fix machine costs/ Hours (1920 h)</td>
<td>37,90</td>
<td>25,05</td>
<td>19,70</td>
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<tr>
<td>Laser gas</td>
<td>1.80 €/h</td>
<td></td>
<td></td>
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<tr>
<td>Flash lamps</td>
<td></td>
<td>1.50 €/h</td>
<td></td>
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<tr>
<td>Electrical energy</td>
<td>8.60 €/h</td>
<td>7.40 €/h</td>
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<tr>
<td>Protection gas (welding)</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Total costs/ hour</strong></td>
<td><strong>48,30 €</strong></td>
<td><strong>33,95 €</strong></td>
<td><strong>21,80 €</strong></td>
</tr>
</tbody>
</table>

If there is already a cooling unit available, the item „cooling“ can be dropped as long as the existing cooling unit guarantees the required temperature stability and provides the appropriate technical connected loads of the laser system. The only essential maintenance work is changing the output window of the laser, maintaining the vacuum pumps and ventilators. Maintenance work on a solid-state laser usually is changing the flash lamps (every 200 – 500 hrs of operation) and the ion-exchange cartridge (once a year). Thus the lump sum for maintaining, as stated in the Table 10.5, is a little less than the calculated for solid-state lasers.
Since analysing the operation costs of CO₂-lasers and solid state lasers (Nd:YAG and fibre laser) shows that the costs per hour of each of the three systems are determined by the depreciation (fixed costs) (with pure operation costs hardly making a difference) reducing the fixed costs is the main objective. The fibre laser system is maintenance-free thus reducing the fixed costs considerably.

By selecting the right laser system for the application planned, it is possible to reduce costs. The maximum average power of the laser system should be adjusted to production rates and specific clocking rates, thus achieving a high overall performance in practice. If process overhead cycle time, for example, are high on account of handling and preparation of joint geometries, a pulsed laser system with low average output power is less expensive than a CW-laser with corresponding output, which is only required for a short time. By distributing the laser beams appropriately at several processing levels, the overall performance of laser systems can be increased, reducing certain costs.
11 Conclusion and Outlook

11.1 Conclusion

The increasing miniaturization and compact constructions in mechanical, electronic and optical precision engineering require joint techniques providing high automating capability and reproducibility with precise control of the penetrated energy. Laser beam welding processes with their inherent potential of controlling the energy input give rise to new applications with respect to the manufacturing of optical active and compact laser diode beam assemblies. In electronics and fine mechanics the components require increasingly high strength joining technologies to replace the conventional gluing or soldering process. Alternative joining methods for commercial laser diode beam assemblies often reach their limits in terms of product quality and reliability. Here the precise laser fine welding of rotationally symmetric, optomechanical components with different joining and seam configurations is of great importance.

The objectives of this thesis, examined by the author, are as follows: The first objective was the development of a semi-automatic laser fine welding station (pulsed Nd:YAG-lasers) with an automatic micro-alignment solution for optomechanical components. For the time being, there are no commercial laser systems available guaranteeing high quality and reproducible fine adjustment for laser production of small optomechanical components. Therefore a semi-automatic laser fine welding system, based on a laser processing system according to EN ISO-standard, was developed as lab-prototype (test rig) and was successfully applied for micro-alignment and the production of the new laser diode beam assembly (LDBA).

The second objective in the course of this work is the construction and manufacturing of new laser diode beam assembly (LDBA), taking into account the laser weldability of the components. The LDBA consists of a laser diode pigtail with GRIN lens for beam collimation. Beam deviation was reduced by modification of the laser diode casing using a special alignment technique (hexapod manipulation). For the first time, a pulsed laser weld process could be successfully carried out on thermal and electrostatic sensitive devices. The welding procedure, the adapted clamping technique and the optimised laser and process parameters allowed the thermally induced distortional positioning changes of the separate components to be minimised.
Compared to commercial laser diode beam assemblies, the LDBA possesses a row of individual characteristics. The robust construction and high manufacturing quality allows operation under high thermal cyclic modes and demanding environments (Moisture, aggressive gas atmospheres).

The effects of laser weldability on the function of active and temperature-sensitive components are investigated. Further, the relative position deviations from the adjustment results, caused by shrinking stress due to the laser welding process, are also covered. Special safety devices and a class 1000 flow box allow the production to be carried out under clean room conditions. The ESD-safety devices installed inside the flow box reduced the danger of destructing sensitive components through electrostatic discharging.

A system for data acquisition and data processing (FineScan) was set up and was integrated into the production procedure to support the precise alignment of the optical components of the LDBA.

After considering the relevant technical basics of laser welding techniques, various kinematic systems were reviewed and investigated as to their paths accuracies. The results showed that scanner systems, as compared to robot and portal systems, displayed the best path accuracy (0.02-0.05mm) and reproducibility (0.01-0.05mm). It was however evident that the path accuracy and reproducibility of portal systems sufficed for precision usage when such systems were used in combination with a rotation axis construction. The rotation axis allowed the precision path movements and the portal system ensured the target position of the components to be addressed.

Based on the foundation of a technical qualifying profile, a half-automatic beam weld station using a pulsed Nd:YAG lasers systems was built and successfully used on the example production of an LBDA.

The modular constructed beam guiding and focusing system of the LBPO is adapted from a Cartesian axis system. The LBPO achieves a theoretical spot diameter of 300μm and a Rayleigh-length of 0.75mm from a collimation focal distance of 200mm and a focal length of 150mm. The focal positioning was carried out by use of an adapted ocular on the LBPO and a laser triangulation sensor CP24MHT80.

Using a servocontroller and the Software FineWeld, the LBPO could be driven in all 3 coordinates. FineWeld also modulated the pulsed Nd:YAG lasers and controlled the rotation table and the mini rotation axis.
A second, autarkic Cartesian handling system consisting of three high-precision micro-axis was adapted to the rotation table. For adjustment and position optimising of the LDBA components, two measurement systems were incorporated into the Laser weld station. They were an intensity sensitive 2D measurement system with a photo detector PDA-55 and a beam profiler. The program FineScan controlled a 3-axis Motion Controller that carried out the 2D scan procedure via a Cartesian micro-axis system. The data acquisition and analysis was also carried out by FineScan.

As the characterised beam parameters differed from the theoretical values, the minimal spot diameter and the Rayleigh-length was determined experimentally. At a working distance of the LBPO from 126mm, the spot diameter was 336±10µm. The Rayleigh-length could be determined as 1.05mm. This gave a focal depth area of 2.1mm by a spot diameter of 475±10µm.

To assess the influence of operation on positional accuracy, the linear unit and the mini-rotation table were measured for accuracy deviation. The inaccuracy of the linear unit to the focal position was from 10-20µm. The maximal inaccuracy of the mini-rotation table was 50µm. It was therefore determined that the inaccuracies could be considered to be small. The maximal positional uncertainty of focus in X-ordinate could be given as 70µm or 7% of the Rayleigh-length. In the Y and Z-ordinates, the positional inaccuracy was between 10-20µm.

Commercial beam assemblies on the basis of laser diodes show a row of disadvantages in the beam propagation and quality. To mention are the limited beam direction quality of the assembly, the relatively large dimensions and the poor flexibility. Further, the beam direction faults can only be corrected with difficulty and heavy expenditure. Laser diodes especially show a great sensitivity to electrostatic charges and temperatures over 50°C. This can lead to complete loss of the functions of laser and monitor diode. This would lead to failure of the LDBA.

Laser diodes of Semiconductor basis emit a small-band wavelength spectrum with powers up to 50mW. The emitted beam shows an elliptical and divergent character due to the construction on the laser chip and the sharp change in refraction index between semiconductor and air. The beam also emits with an angle deviation to norm, which can reach some degrees.

An optimising of the beam characteristics was reached through reducing the distance to the emitting laser chip. The housing of the Laser diode was removed and the angular
deviation determined using a 4-quadrant diode. The base surface of the laser diode was then mechanically lathed, taking into account the angular deviation.

For beam collimation, a special lens on the basis of GRIN-technology was used. The compact construction and the good optical characteristics make GRIN-lens suitable for the complex usage. Assuming the laser diode chip as light point source to be at a working distance of 0.12mm to the GRIN-lens input surface, a number of RAY-Trace simulations were carried out. It could be shown that small tilts of the laser diode to the input surface of the lens led to a non-orthogonal beam exit. The beam was, however, still collimated.

For the LDBA, a GRIN-lens with the following technical details was used: ($f = 0.96 \text{ mm}$, $\text{pitch} = 0.23$, $\text{NA} = 0.51$, $\text{diameter} = 1\text{mm}$ and working distance $0.12\text{mm}$). Because of the small size and for easier handling of the GRIN-lens, it was soldered into a special (stainless-steel) GRIN-lens mount.

For the precise positioning and fixing of all LDBA components, a suitable optimised clamping technique was indispensable. For the production of the LDBA, high-precision industrial clamping techniques were used, modified according to clamping assignment and joint geometry. For the specialised clamping requirements for the laser diode, the gas inlets and the GRIN-lens, new clamping elements were developed and successfully deployed.

The great number of variable parameters influencing the pulsed seam welding process and thus influencing the welding result are typical for laser beam welding, in particular of heat conduction welding by means of pulsed solid state lasers operating in the spot or seam welding regime. The most important parameters which could be identified are mean laser power, pulse energy, pulse duration, welding velocity, beam dimensions as well as the temporal and spatial intensity distribution and the average peak power density of the laser radiation. For material processing by a single shot of pulse power, three heating modes are observed, heating, melting and vaporisation. These are combined effects of the peak power density and the interaction time (pulse duration) between the beam and the material. The pulsed seam welding process consists of the production of a series of periodic spot welds partially overlapping to form a fusion zone. The percentage of overlap and thermal heat input can be controlled by the beam dimension, duty cycle and welding velocity.

Trials in spot-weld mode for diameters of $330\mu\text{m}$ und $400\mu\text{m}$ were determined as function of the pulse power. It could be shown that with relatively short pulse periods
(duty cycles 3-5 %), weld depths in the order of some 100µm could be realised. Thermal absorption in the component was moderate by short pulse periods (0.3-0.5ms) and middle powers up to 1600W. This is a necessary precondition for the welding of sensitive components without greater thermal loading.

The theoretical threshold for conduction welding with regard to laser seam welding of stainless-steel (1.4301) was investigated, with respect to Fresnel absorption as a function of the incidence angle.

The calculations for the focal diameter of 330µm and 400µm at different powers and angles of incidence have shown that parallel polarised light is more effectively absorbed as vertically polarised. This led to a decided increase in welding speed. The absorption maximum was reached at the Brewster angle for parallel polarised light. This is dependent on the material characteristics.

Further, the effective welding speed increased with power density at the work piece. The use of non polarisation supporting glass fibres leads to the laser beam having a poor wave plane at the fibre exit. It can therefore be taken as a good approximation that an arithmetic mean of parallel and vertical polarised light is existent.

The new developed LDBA consisted of 6 different components, joined together by laser welding. Optical, mechanical and optoelectronic components were used. For the mechanical parts; GRIN-lens holder, GRIN-lens mount, Interface Coupler, Gas-Inlet und Output Connector, an acid-resistant stainless steel was used.

The basis of the LDBA was a modified laser diode with its case removed and an angular deviation corrected. The small working distance of 0.12mm to the laser chip allowed the beam collimation to be carried out with a GRIN-lens (DATA). To produce the optimal position of GRIN-lens to laser chip, both parts were clamped by special tools and with the help of a high-precision Cartesian handling system positioned to each other.

Finite element simulations were made of the mechanical loads on the GRIN-lens holder and laser diode caused by the clamping tools. The results showed that maximum mechanical deformation appeared in the area of the notch in the base of the diode and amounted to not more than (0.214 – 3.84e-5mm). The mechanical deformation on the outer boundary of the GRIN-lens holders reached a maximum of 0.845e-04mm. These values are small enough to be neglected.

During adjustment, the intensity distribution in the axis was recorded with a beam profiler. The laser diode was manually adjusted until the entire beam cross section was

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imaged on the Beam profiler sensor surface. At a working distance of 210mm (Laser chip – Sensor Beam Profiler) the beam width was set to 4100μm. At this distance the best collimation of the laser beam was observed.

As first step after adjustment, the laser diode and GRIN-lens holder were tacked at different points of the rotation-symmetric butt joint. The GRIN-lens was then set to the beam value of 4100μm in Z axis. Tacking the GRIN-lens mount and GRIN-lens on a welding groove joint prevented a de-adjustment in Z-axis. The GRIN-lens mount and the GRIN-lens holder was then tacked on the lap joint. In the final step, the LD and the GRIN-lens holder were rotation symmetrically welded. Welding over the tacking and the notch in the LD showed no negative effects on weld quality. The assembly of LD, GRIN-lens holder and GRIN-lens was now referred to as laser diode pigtail.

The first step in the assembly of the LDBA was the insertion of the laser pigtail into the receptacle in the interface connector, which was then tacked at 6 positions in circumference. A complete round weld was then carried out on the GRIN-lens holder flange. In the second step the output coupler was clamped in position on the interface connector. The output coupler is a concave mirror fitted in a ring mount that can correct the smallest angle deviation of the laser pigtail through lateral movement on the interface connector.

The 2D-position optimising of the output coupler was carried out using FineScan. FineScan offers coarse and fine scan options with variable step widths. By evaluation of the stored intensity data from the PDA-55 Photo detector, the intensity maxima could be driven to at an accuracy of 1μm. At this optimal position, the output coupler was tacked onto the interface connector. Finally, a complete round weld was carried out.

In the last production step of the LDBA, the gas-inlet was clamped with special tools in position and was welded to the interface connector.

The user had now a high-value, compact and beam corrected laser diode beam source as LDBA available to him. The weld suitable construction of the LDBA and matched laser and process parameters allowed the thermal loading of the components to be considerably reduced. The weld seams on the LDBA showed a high quality. The total leakage rate of the LDBA was determined to be 5.0x10⁻⁹l/min in a helium leakage test.

LDBAs are versatile in use. They can be combined with commercial optics and fibre components to form new systems.
The laser beam output of the LDBA was therefore focused in simple manner with an SMA-fibre collimation package in an SMA fibre. Fibre measurement systems can therefore be constructed in relatively short time periods.

The laser systems, handling systems, clamp material and process control sensors are capital intensive and cause high overheads. For economical use, a high-value output through laser welding and a high capacity utilisation highly necessary. For these reasons, laser welding is mainly carried out in the automobile industry, the automobile sub-supplier area and in large volume production.

The economics of laser beam welding process and the quality of the weld joints are decided through the production environment and laser weldability. The productivity and weld quality is influenced considerably by the constructive form of the joint geometry and seam preparation.

In spite of the high investment and overheads, laser beam welding offers an economic advantage when the whole product and production process is taken into account. First through this procedure is it possible to methodically construct and produce in a manner suitable for laser beam welding, and therefore take advantage of the full capability. The exact knowledge of the limiting boundaries of laser use will lead in future to laser weld usage in a large number of productive areas.

11.2 Outlook

In years to come there will be a great demand for OEM Laser Diode Beam Assembly. There will be a growing number of high-quality applications, demanding improved beam quality and availability. A trend towards economical, autarkic Laser Diode Beam Assembly for various applications is perceptible. Future fields of application will be medical technology, spectroscopy and measuring technology.

New laser applications offer additional potential in microelectronic-, electronic-production and the production of flat screens. The applications of laser are driven ahead by the progressing miniaturization of mass-produced articles such as cell phones, notebooks and devices for consumer electronics. New materials and a combination of materials, considering laser weldability, will increasingly be applied.
Material combinations such as copper and stainless steel can be welded by Single-Mode Fibre lasers even today. High brightness reduces the flux of the melting bath vertical to the sheet material surface on account of small melting bath dimensions next to the gas capillary.

The industrial application of highly efficient laser beam sources with improved beam quality, and at the same time parameter control and availability for producing optomechanical and electronic components, will constantly increase.

Additional successful application, with regard to laser weldability of miniaturized components, considerably depends on the development of existing and established laser systems. There is a clear trend towards laser fine welding for the production of miniaturized components rather than applying solid state lasers with flexible beam guidance and beam shaping.

Here, processing optics with automatic focusing are of special importance. In particular, scanner optics are very flexible instruments for adjusting the focus position and adjusting the intensity distribution to process requirements in laser welding technology.

Pulsed solid state laser systems with high beam quality, improved energetic efficiency and high availability, such as fibre lasers and diode-pumped disc lasers, develop a large number of variable laser parameters providing process control and process stability.

The effectiveness of a laser system also becomes more and more important considering the global increasing cost of energy.

The high brightness of modern solid state lasers result in a considerably increasing energy density within the focussed laser beam, which can immediately be used for reducing the heat input per unit length. It is possible to reduce the required output efficiency or to increase the processing velocity by achieving the predetermined depth of welding. Considerably slimmer welding seams are produced thus involving small component distortion and reducing the heat-affected zone.

On account of the improved process control of laser parameters of pulsed beam sources and the availability of high efficient laser systems, there are new technological opportunities in micro-joining technology which support welding technology instead of adhesive or soldering joints. In the future, materials will just be chosen for functional requirements on account of the development of new laser joining techniques and joining strategies, because less restriction by laser weldability are expected.
At the same time the laser develops new fields of application by applying new bio-compatible materials such as nitinol.

If global economic conditions are favourable, the market for laser welding systems will grow. This applies in particular to the market and application of micro processing systems. Even well established applications such as laser beam welding have not yet become saturated. Two central trends in processing technology, such as flexibility and automation are important advantages of laser compared to other tools.

It is not a question of which system will be successful in the future. An integral way of viewing things, mainly considering the applications that are to be carried out, quality and technical conditions (laser weldability) and considering business aspects will be inevitable.
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<td>Using the EK2000</td>
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</tbody>
</table>
13 Appendix

13.1 Construction Drawings and Components of the Laser Welding Station

Fig. 13.1-1/2 Front view - Fine Welding Station with pulsed Nd:YAG Lasers
The optical set up shown in Figure 13.1-3 ensures the correct, perpendicular orientation of the rotation table with micro axis system if input beam and reflected beam are adjusted parallel.

Fig. 13.1-3 HeNe laser for rotation table adjustment

Fig. 13.1-4 Side view-Fine Welding Station with pulsed Nd:YAG Lasers and Inspection Microscope
Technical Drawings (Laser Fine Welding Station) pp. 257 - 264

- Fine Welding Station
- Assembly Carrier
- LBPO Translation Unit
- Rotation Table
Assembly Carrier

2000-71-01
## 13.2 List of Devices and Materials for Pulsed Laser Fine Welding Station

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Description</th>
<th>Location</th>
<th>Number</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>MAYTEC 80x80-2080</td>
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<td>4</td>
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<td>Gray Filter</td>
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<td>Thorlabs XY-Translator w. Micrometer Dr.</td>
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<td>Srews M5x12mm</td>
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<td>Connector strips</td>
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<td>75</td>
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<td>Newport Linear Actuator 850F</td>
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<td>Connector Interface Box</td>
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<td>Digital Inductive Comparator</td>
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<td>Plexi-glass 1mm (16m2)</td>
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</tbody>
</table>
13.3 Aluminium Profile for Construction of Fine Welding Station

**Table 13.2-1 Aluminium Profile**

<table>
<thead>
<tr>
<th>Extruded profile as per DIN 17615</th>
</tr>
</thead>
</table>

Alluminium alloy: Al Mg Si 0,5 F25
Material No. 3.320672 (low temperature annealed)

**Mechanical Data**
(Values give in the direction of the press flow)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength in RM</td>
<td>min 250 N/mm²</td>
</tr>
<tr>
<td>Elongation</td>
<td>min 200 N/mm²</td>
</tr>
<tr>
<td>Stress point A₅</td>
<td>min 10 %</td>
</tr>
<tr>
<td>Stress point A₁₀</td>
<td>min 8 %</td>
</tr>
<tr>
<td>E-Module</td>
<td>about 70.000 N/mm²</td>
</tr>
<tr>
<td>Brinell hardness</td>
<td>HB 25/187,5 = 75</td>
</tr>
<tr>
<td>Coeffizent of elongation</td>
<td>23,8 x 10⁻⁶/K</td>
</tr>
</tbody>
</table>

Surface as per DIN 17611:
E6/EV1-dull finish and anodized colours
Coat thickness ca. 10 micron
Coat hardness 250-350 HV
Special colours upon request
The surface area - subject to technical procedure - can show optical changes.

**Profile tolerance**
(Excerpt from DIN 17615, part 3)

Nominal dimensions:
The dimensions deviation depends on the precision with which the tooling is manufactured, the tooling wear and the variation during the extrusion process.
For one manufacturing set-up the variation within one profile is 0.0004 inches

<table>
<thead>
<tr>
<th>Dimensions range in mm</th>
<th>Tolerance in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>from</td>
<td>to</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>45</td>
<td>60</td>
</tr>
<tr>
<td>60</td>
<td>90</td>
</tr>
<tr>
<td>90</td>
<td>120</td>
</tr>
<tr>
<td>120</td>
<td>150</td>
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</tbody>
</table>

**Table 13.2-2 Aluminium profile data**

**Flatness of profiles surface**
13 Appendi

Straightness tolerance of the edge in longitudinal direction

At a certain length $l_1$ the given tolerance $h_1$ is not to be exceeded. For each incremental length of $l_2 = 300$ mm the deviation $h_2$ is not to exceed $0.3$ mm

<table>
<thead>
<tr>
<th>Lengt $l_1$ m</th>
<th>to 1</th>
<th>to 2</th>
<th>to 3</th>
<th>to 4</th>
<th>to 5</th>
<th>to 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tol. $h_1$ in mm</td>
<td>0.7</td>
<td>1.3</td>
<td>1.8</td>
<td>2.2</td>
<td>2.6</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Flatness tolerance (Twist tolerance)

<table>
<thead>
<tr>
<th>Width $b$ Dim. range</th>
<th>Flatness tolerance at length</th>
</tr>
</thead>
<tbody>
<tr>
<td>from</td>
<td>to</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>50</td>
<td>75</td>
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<td>75</td>
<td>100</td>
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<td>100</td>
<td>125</td>
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<td>125</td>
<td>150</td>
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<tr>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>200</td>
<td>300</td>
</tr>
</tbody>
</table>

Parallelism tolerance (Angular tolerance)

The parallelism tolerance (angular tolerance) refers to unequal sides to the shorter side of the angle, i.e. it is
measured from the longer side.

<table>
<thead>
<tr>
<th>Width $B$ from</th>
<th>Width $B$ to</th>
<th>Parallelism tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>100</td>
<td>0.008 x b</td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>0.006 x b</td>
</tr>
</tbody>
</table>

**Strength values for profile connection with MayTec-Connectors**

Torque tightening values for connector setscrew

<table>
<thead>
<tr>
<th>Profile group</th>
<th>Setscrew special execution</th>
<th>max. torque value</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 mm H-slot</td>
<td>M6 x 8</td>
<td>8.5 Nm</td>
</tr>
<tr>
<td>20 mm F-slot</td>
<td>M8 x 10</td>
<td>20.0 Nm</td>
</tr>
<tr>
<td>30 mm F-slot</td>
<td>M10 x 12</td>
<td>30.0 Nm</td>
</tr>
<tr>
<td>40 mm E-slot</td>
<td>M10 x 12</td>
<td>40.0 Nm</td>
</tr>
<tr>
<td>45 mm E-slot</td>
<td>M10 x 12</td>
<td>40.0 Nm</td>
</tr>
<tr>
<td>50 mm E-slot</td>
<td>M10 x 12</td>
<td>40.0 Nm</td>
</tr>
<tr>
<td>60 mm E-slot</td>
<td>M10 x 12</td>
<td>40.0 Nm</td>
</tr>
</tbody>
</table>

The max. tightening torque values are only valid for the MayTec setscrew and can not be reached by the usual comercial quality standard.

All values given have been tested with pre-tension of the connectors and maximum torque value and refer to the connection of two identical profiles.

**Tension load**

<table>
<thead>
<tr>
<th>Profile group</th>
<th>max. tensile strength</th>
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<td></td>
<td>Connector Standard Universal</td>
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<tr>
<td>20 mm H-slot</td>
<td>---</td>
</tr>
<tr>
<td>20 mm F-slot</td>
<td>5.000 N</td>
</tr>
<tr>
<td>30 mm F-slot</td>
<td>5.000 N</td>
</tr>
<tr>
<td>40 mm E-slot</td>
<td>10.000 N</td>
</tr>
<tr>
<td>45 mm E-slot</td>
<td>15.000 N</td>
</tr>
<tr>
<td>50 mm E-slot</td>
<td>15.000 N</td>
</tr>
<tr>
<td>60 mm E-slot</td>
<td>15.000 N</td>
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</tbody>
</table>

**Slide load**

| Profile group | max. slide strength | max. |
### Flexure load

**T-Nuts**

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<th>Connector</th>
<th>flexure strength</th>
</tr>
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<td>Connector</td>
<td>E-connector</td>
</tr>
<tr>
<td>slot</td>
<td>pcs</td>
</tr>
<tr>
<td>40 x 40</td>
<td>E</td>
</tr>
<tr>
<td>80 x 80</td>
<td>2</td>
</tr>
<tr>
<td>40 x 160</td>
<td>4</td>
</tr>
<tr>
<td>80 x 80 Winkel</td>
<td>3</td>
</tr>
<tr>
<td>80 x 80 Winkel</td>
<td>4</td>
</tr>
<tr>
<td>80 x 80</td>
<td>6</td>
</tr>
<tr>
<td>80 x 160</td>
<td>8</td>
</tr>
<tr>
<td>45 x 45</td>
<td>E</td>
</tr>
<tr>
<td>45 x 90</td>
<td>2</td>
</tr>
</tbody>
</table>

**Application**

Fastening element for screw-type connections

Fixing with compressing spring

**Detail of Profile Group 40, E3-Nut**

**heavy**

- Kernbach D12 für Gewinde M14
- Kernbach D5 für Gewinde M10

**Description** | **Profile 40 x 40, 4E**
---|---

<table>
<thead>
<tr>
<th>Description</th>
<th>Profil 80 x 80, 8E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength cm$^4$</td>
<td>lx = 166,0  ly = 166,0</td>
</tr>
<tr>
<td>Widerstandsmoment cm$^3$</td>
<td>Wx = 41,4  Wy = 41,4</td>
</tr>
<tr>
<td>Weight kg/m</td>
<td>5,9</td>
</tr>
</tbody>
</table>

**Detail of Profile Group 40, E3-Nut**

**heavy**

![Profile Diagram]

**Table:**

<table>
<thead>
<tr>
<th>1.11.040040.43.60</th>
<th>1.11.040040.43.61</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength cm$^4$</td>
<td>lx = 12,0  ly = 12,0</td>
</tr>
<tr>
<td>Widerstandsmoment cm$^3$</td>
<td>Wx = 6,5  Wy = 6,5</td>
</tr>
<tr>
<td>Weight kg/m</td>
<td>2,0</td>
</tr>
</tbody>
</table>
13.4 Handling System and Devices for Manipulation

13.4.1 Ball Screw Feed Axis LF5 for Processing Optics Manipulation

<table>
<thead>
<tr>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>• aluminium shaft profile W 225 x H 75 mm, anodized</td>
</tr>
<tr>
<td>• clamping surface and profile bottom side plan-milled</td>
</tr>
<tr>
<td>• 4 precision steel shafts Ø 12 h6, material Cf53, hardness 60 ± 2 HRC</td>
</tr>
<tr>
<td>• aluminium slide blocks WS 5/70, 2 x WS 5/70 (70 mm long) or WS 5/200 (200 mm long), adjustable free of clearance, central lubrication</td>
</tr>
<tr>
<td>• ball screw pitch 2.5/4/5/1 0/20 mm</td>
</tr>
<tr>
<td>• profile sealing by abrasion-resistant sealing lips</td>
</tr>
<tr>
<td>• aluminium die-cast end plates</td>
</tr>
<tr>
<td>• 2 limit and/or reference switches, repeatability ± 0.02 mm</td>
</tr>
<tr>
<td>• driving steel collar with sealed angular contact ball bearings</td>
</tr>
<tr>
<td>• prepared either for flange-mounted direct drive modules or lateral belt drive modules</td>
</tr>
</tbody>
</table>

Order Key: 234 311 0057

Fig. 13.3-1 Ball screw Feed Axis

<table>
<thead>
<tr>
<th>Aluminium profile LES 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment of inertia I_x 2381.854 cm$^4$</td>
</tr>
<tr>
<td>Moment of inertia I_y 206.925 cm$^4$</td>
</tr>
<tr>
<td>*Centre of gravity 53.39 mm</td>
</tr>
<tr>
<td>Cross section surface 42.49 cm$^2$</td>
</tr>
<tr>
<td>Material Al/MgSi0, 5F22</td>
</tr>
<tr>
<td>Anodization E8/E81</td>
</tr>
<tr>
<td>Weight with steel shafts 13.8 kg/m</td>
</tr>
<tr>
<td>Weight with steel shafts and spindle 15.2 kg/m</td>
</tr>
</tbody>
</table>

Fig. 13.3-2 Technical Data Aluminium Profile

<table>
<thead>
<tr>
<th>Nominal torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revolutions (1/min) 2.5 4 5 10 20</td>
</tr>
<tr>
<td>300 15 15 16 17 18</td>
</tr>
<tr>
<td>1500 19 19 19 20 21</td>
</tr>
<tr>
<td>3000 23 24 24 25 26</td>
</tr>
</tbody>
</table>

Fig. 52 311 0057
**Deflection**

Fig. 13.3-3 Deflection LF5

Fig. 13.3-4 Ball Screw Feed Axis LF5 for processing optics manipulation
Features

- aluminium shaft profile W 75 x H 75 mm, anodized
- clamping surface and profile bottom side plan-milled
- 2 precision steel shafts Ø 12 h6, material C153, hardness 60 ± 2 HRC
- aluminium slide blocks WS 5/70, 2 x WS 5/70 (70 mm long) or WS 5/200 (200 mm long), clearance-free adjustable, central lubrication
- ball screw pitch 2.5/4/5/10/20 mm
- profile sealing by abrasion-resistant sealing lips
- aluminium die-cast end plates
- 2 limit and/or reference switches, repeatability ± 0.02 mm
- driving steel collar with sealed angular contact ball
- bearings prepared either for flanged mounted direct drive modules or lateral belt drive modules

Order key: 234 011 0069

Fig. 13.3-5 Axis LF5

<table>
<thead>
<tr>
<th>Aluminium profile LF 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment of inertia $I_x$</td>
</tr>
<tr>
<td>Moment of inertia $I_y$</td>
</tr>
<tr>
<td>Moment of resistance $W_x$</td>
</tr>
<tr>
<td>Moment of resistance $W_y$</td>
</tr>
<tr>
<td>Moment of resistance $W_z$</td>
</tr>
<tr>
<td>Cross-sectional area</td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Anodization</td>
</tr>
<tr>
<td>Weight with steel shafts</td>
</tr>
<tr>
<td>Weight with steel shafts and spindle</td>
</tr>
<tr>
<td>Max. deviation from the straight line</td>
</tr>
<tr>
<td>Max. torsion</td>
</tr>
<tr>
<td>Convex, concave</td>
</tr>
</tbody>
</table>

Fig. 13.3-6 Technical Data Aluminium Profile
Deflections:

Fig. 13.3-7 Deflection LF4

Fig. 13.3-8 Scale Drawing LF4
13.4.2 Index Rotation Table RF-1 and Midget Rotary Axis MD1

**Features**

- reduction assembly kit 1:52 and/or 1:100
- reduction 1:24 (standard)
- weight: 14.6 kg

**Options:**

- reduction assembly kit 1:52 and/or 1:100
- electromagnetic brake [60 Nm]
- stepping motor drive with encoder
- CNC control via amphenol

---

**Fig. 13.3-9 Index Rotation Table**

<table>
<thead>
<tr>
<th>Item</th>
<th>Assembly kit</th>
<th>RF 1 with servo motor drive</th>
<th>RF 1 with stepping motor drive</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>269077 0001</td>
<td>RF 1 with servo motor drive</td>
<td>RF 1 with stepping motor drive</td>
<td>Features</td>
</tr>
<tr>
<td></td>
<td>For reduction 1:52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Item no.:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>269050 0240</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>For reduction 1:100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Item no.:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>269051 0500</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 13.3-10 Technical Data**

<table>
<thead>
<tr>
<th></th>
<th>Stepping motor</th>
<th>DC-servo motor</th>
<th>AC-servo motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction ratio</td>
<td>1:24 1:52 1:100</td>
<td>1:24 1:52 1:100</td>
<td>1:24 1:52 1:100</td>
</tr>
<tr>
<td>Drive rotation</td>
<td>[rpm]</td>
<td>[rpm]</td>
<td>[rpm]</td>
</tr>
<tr>
<td>Operating moment</td>
<td>[Nm]</td>
<td>[Nm]</td>
<td>[Nm]</td>
</tr>
<tr>
<td>Operating moment</td>
<td>[Nm]</td>
<td>[Nm]</td>
<td>[Nm]</td>
</tr>
<tr>
<td>Nominal torque</td>
<td>[Nm]</td>
<td>[Nm]</td>
<td>[Nm]</td>
</tr>
<tr>
<td>Nominal holding torque</td>
<td>[Nm]</td>
<td>[Nm]</td>
<td>[Nm]</td>
</tr>
<tr>
<td>Min. increment</td>
<td>[arcmin]</td>
<td>[arcmin]</td>
<td>[arcmin]</td>
</tr>
</tbody>
</table>
13.4.2.1 Midget Rotary Axis MD 1 (Mini-Rotation Axis)

Features:

- play-less timing belt drive with stepping, or DC servo motor-reduction 1:20
- shaft with through hole Ø12mm
- reception flange with internal cone SK 20
- weight: according to design from 1.35 kg upwards

Optionen:

- "closed" design
- additional mounting plate
  (vertical mounting possible)
- CNC control via Sub-D

Mounting plate (vertical mounting of the closed design)
Item no.: 277 026
Accessory:
3-jaw Chuck Ø 65mm
ITEM: 261 060 2065
Collets Fitting
Collets SK-20 for tools Ø 3 – 10mm, with mounting ring

Order Key:
261 010 011

Fig. 13.3-12 Midget Rotary Axis MD1

<table>
<thead>
<tr>
<th></th>
<th>Stepping motor MS 045 HT</th>
<th>DC servo motor MV 030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction ratio x x</td>
<td>1:20</td>
<td>1:20</td>
</tr>
<tr>
<td>Drive revolution x</td>
<td>0 - 60</td>
<td>0 - 120</td>
</tr>
<tr>
<td>Operating moment x</td>
<td>8 (Nm)</td>
<td>3 (Nm)</td>
</tr>
<tr>
<td>Manual torque x</td>
<td>0 (Nm)</td>
<td>0 (Nm)</td>
</tr>
<tr>
<td>Nominal holding torque</td>
<td>14 (Nm)</td>
<td>7 (Nm)</td>
</tr>
<tr>
<td>Max. incremental turning torque (Nm/m)</td>
<td>3.5 (Nm/m)</td>
<td>7 (Nm/m)</td>
</tr>
</tbody>
</table>

Fig. 13.3-13 Technical Data MD1
Fig. 13.3-14 Scale Drawings MD1 [149]
13.5 Technical Data Control PC and Servo Controller

13.5.1 Servo Control PC

- Casing:
  - Stable Sheet steel- system carrier for PC- components
  - Powder- coated Aluminium-Half-shell casing
  - Dimensions B x H x T = 475 x 186 x 410 mm

- Configuration:
  - Processor: `586 (min.100MHz)
  - RAM: 8 MB
  - Hard disk (optional): min. 1 GB
  - Graphics board: PCI, 2 MB
  - Floppy-disk: 3.5" 1.44 MB
  - Interface: 2 serial, 1 parallel
  - Power supply: 200 W

Servomotor-Control board UPMV 4/12

- Four independent axis processors
- 32-Bit Set value register, acceleration register
- 32-Bit Position detection
- Programmable 16-Bit PID-Controller, Sampling time 0.35 ms
- 12-Bit D/A-Output (± 10 V Speed -Set value)
- Eight Signal inputs for Reference-/Zero point switching (optically isolated)
- Signal input Fault Output stage (optically isolated)
- Signal input Enable Limit switch (optically isolated)
- Signal output Stage switch -off (optically isolated)
- Signal output Enable Limit switch (optically isolated)
- Connected via 50-pole Flat band-Connector
Power unit for DC-Servomotors

- Casing
  - Robust Sheet steel- system carrier for Power supply and electronics
  - Powder-coated Aluminium- shell casing (anthracite)
  - Dimensions B x H x T = 475 x 186 x 410 mm
  - Integrated fan unit to force-cool the output stage
  - Front side operating elements *Emergency stop, Power* and Mains switch
  - Wiring of the Signal in /- outputs from Servomotor and Control processor via connectors at the rear.

- Power block PB 600-C
  - 600 VA-Toroidal transformer with Temperature monitoring
  - Electronic Switch-on current limiting via the output voltage
  - Auxiliary voltage I + 24V/2A
  - Auxiliary voltage II + 24V/1A (safety circuits)
  - Safety circuits with *Emergency stop* - and On-switch -input
  - Integration of external emergency stop systems (Remote)
  - Closed sheet steel casing L x B x H 220 x 150 x 140 mm
  - Connections via connector sets

- Servomotor-Power board UMV 10
  - 4-Quadrant -Amplifier 70 V/8 A
  - 18 kHz PWM-Switching frequency
  - Efficiency up to 85%
  - Set value ± 10 V (Current control)
  - Safety circuits for: Over voltage, Over current, Over temperature
  - Front side Displays for Operation, Faults
  - Euro-Format 160 x 100 mm, 9-TE-Front plate

- Emergency stop- system
  - Relay chain with two separate limit switch inputs per motor-output, + 24 V switched
  - Shorting the limit switch monitor function through key switch
• Shorting the limit switch monitor function through software controlled inputs
• Display of limit switch operating conditions
• Integration of external command system
  (Emergency stop, safety switch contact, main switch)
• Signal input to function monitor the Servomotor-Control board
  (Operational readiness of the control processors)
• +24 V-Supply voltage through Isel-Power block
13.5.2  System Description

13.5.2.1  Overview Circuit Plan

Fig. 13.5-1 Overview of the circuit connections
13.5.2.2  Control PC for Laser Fine Welding Station

Fig. 13.5-2 Servo controller and Control PC (side view)

a)  Servomotor-Control interface UPMV 4/12 [149]

b)  NI6025E – Multifunction DAQ card [155]

The Control processor consists of a compact '586-Processor with hard disc, floppy-disk, PCI-Graphics board and power supply. The robust Sheet steel casing provides a high grade of system operational safety, ensuring compliance with the relevant EMC Regulations (Noise immunity) and therefore permits use of the Controller in Industrial Environments.

Features of NI6025E – Multifunction DAQ card [147]

• 16 analog inputs at up to 200 kS/s, 12 or 16-bit resolution
• Up to 2 analog outputs at 10 kS/s, 12 or 16-bit resolution
• 8 digital I/O lines (TTL/CMOS); two 24-bit counter/timers
• Digital triggering
• 4 analog input signal ranges
• NI-DAQ driver simplifies configuration and measurements
Fig. 13.5-3 Rear view – Control PC for data acquisition and axis controlling
13.5.2.2.1 SCB-100 - Shielded Connector Block for Data Transmission

The SCB-100 shielded connector block is a shielded board with 100 screw terminals that connect to the AT-MIO-64E-3 or other products using the 0.005 series shielded D type I/O connector. The terminal block has 100 screw terminals for easy connection to signal wires. A cold-junction compensation temperature sensor is included for use with thermocouples. The SCB-100 also has a strain-relief bar for securing wires or cables.

![SCB-100 - Shielded connector block](image)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cold-Junction Compensation Temperature Sensor</td>
</tr>
<tr>
<td>2</td>
<td>Switches S4, S5 and S6</td>
</tr>
<tr>
<td>3</td>
<td>100-PIN I/O Connector</td>
</tr>
<tr>
<td>4</td>
<td>Signal Accessory LED</td>
</tr>
<tr>
<td>5</td>
<td>Switches S1, S2 and S3</td>
</tr>
<tr>
<td>6</td>
<td>Screw Terminals</td>
</tr>
<tr>
<td>7</td>
<td>Breadboard Area</td>
</tr>
<tr>
<td>8</td>
<td>Board Mount Screws</td>
</tr>
</tbody>
</table>

Fig. 13.5-4 SCB-100 – Shielded connector block
Signal Connection

To connect the signal from the PDA 55 to the SCB-100, the following Steps have to be performed:

1. Disconnect the 100-pin cable from the SCB-100, if connected.
2. Remove the grounding screws on either side of the top cover and open the top cover.
3. Configure switches to the signal types you are using (Fig. 13.5-4)
4. Adjust the strain-relief hardware
   - Loosen the strain-relief screws and slide the signal wires through the front panel strain-relief opening.
   - Remove the top strain-relief bar.
   - Add insulation or padding if necessary.
   - Connect the wires to the screw terminals by stripping ¼ in. of insulation, inserting the wires into the green terminal and tightening the screws.
   - Reinstall strain-relief

Close the top and connect the terminal block to the 100-pin connector
a) Servomotor-Interface UPMV 4/12

![Servomotor-Interface UPMV 4/12](image)

Fig. 13.5-5 Servomotor-Interface UPMV 4/12

- J1 - Jumper field base address
- J2 - Jumper field interrupt
- X1 - Output connector

b) Multi-I/O- board

The Multi-I/O- board with 16 inputs and 8 outputs (as PC-Insertion board) is specially developed to the requirements of Binary data acquisition respectively of Data exchange. The PC-board is 250 mm long and can be used in any PC or Industrial processor with a 16-Bit ISA-Bus connector.

Through a settable adjustable base address is a combination as also a number of Multi-I/O- boards in cascade possible.

![Multi-I/O- board](image)

Fig. 13.5-6 Multi-I/O- board
13.5.2.3 Servo Controller Power Unit

The Power unit is a compact assembly for the operation of up to four brush fitted DC-Motors. The Main parts are four Power output stages UMV 10 with output power of 70 V/8A, and a 600 VA-Power block. The latter provides all necessary supply voltages and safety relevant inputs for the function elements of the servo-controllers.

![Servo Controller Power Unit](image)

**Fig. 13.5-7** Servo Controller Front View [149]
Power unit for DC-Servomotors

a) Servomotor-Power board UMV 10
b) Power block PB 600-C
c) Interface module
d) DC-Power supply NT-24
e) Connector

a) Servomotor. Power board UMV 10

Fig. 13.5-8 Servomotor-Power board UMV 10

b) Power block PB 600-C

The Power block PB 600-C is a compact current supply for power units/controllers. The Power block provides an unregulated Intermediate link voltage, operating voltages for the power output stage and also two separate +24 V-Fixed voltage outputs. Further, it takes over the Power block control and monitoring functions of safety relevant components and the Emergency stop-Switching of the motor voltage.

The Power block is type tested and is subject to manufacturing control through VDE (VDE 0160-Test certificate 6224).
c) Interface-module

The Interface-module serves as auxiliary adapter to the 37-pole Sub D-Connector on the Multi-I/O-board.

Through a 1:1 connection line, the signal inputs and outputs of the Multi-I/O-board are led to the relevant connector of the Interface-modules by user-friendly Screw-Terminal Connectors.

The module also includes LED-bar displays and input and output status displays.

The module requires a DC voltage supply of +24 V. This is provided through the built-in DC-Power supply NT-24.

d) DC-Power supply NT-24

The Modular power supply serves to supply voltages to the external signal inputs and outputs of the Servocontrollers.

The Power supply is mounted inside the Controller casing and switch on via the voltage supply of the Power blocks. Output power is stabilised at a fixed voltage +24 V/2.6A. This allows smaller units (e.g. Valves, relay, Sensors) to be directly operated without additional external power supplies.
e) Connector

Connects external components (e.g. Motors, Signal inputs and outputs).

13.5.2.4 Connection and Commissioning

All connectors the external units (Motors, signal inputs and outputs) are at the rear of the unit.

(1) 220V power plug
(2) Key switch
(3) Remote-connector
(4) Interface- module with signal input X2
(5) Monitoring Limit switch

(6) Signal input X1

(7) 4 Servo motor outputs

(8) Voltage supply motor brake

(1) Mains voltage-Input

The servo controller unit power supplies require alternating voltage 230V/50Hz at a total current flow of nominal 4A.

(2) Key switch

(3) Remote Connector

Over the remote connector the Servo controller can be linked into the supervisory Emergency stop system, respectively external operating elements. A 6-pole Screw-Terminal-Connector is available.

1 – 2 potential free Switch contact (Closer contact - Output)

3 – 4 Emergency stop- system (Opener contact - Input)

5 - 6 In-Switch (Closer contact - Input)

- Potential free switch contact (1 – 2)
  This switch contact is closed when the power output stage is supplied with voltage (safety relay and switch relay active). At an interruption in the safety system, the contact is opened.

- Emergency stop- system (3 – 4)
  This input serves to connect from external safety systems, e.g. EMERGENCY STOP-Switch, safety switches. If no external EMERGENCY STOP is required, these contacts must be shorted.

  The terminals carry the safety circuit voltages. Take care to use potential free elements when installing, as otherwise a short-circuit in the safety system may occur. (use switch elements according to EN 418)

- Main switch (5 – 6)
  This contact set is wired parallel to the front side main switch. As soon as this contact set is close, voltage is supplied to the output stages, when all safety relevant conditions have been met.
According to machinery safety regulations, the connection of an external main switch is permissible only when the front panel main switch is disabled by appropriate measures (covering the switch etc.)

(4) **Interface- module with Signal input X2**

Over this 37-pole Sub D-Connector the Signals and outputs are led to the Multi-I/O-board and Power unit.

Pin connection of the Sub D-Male plug

<table>
<thead>
<tr>
<th>Table 13.5-1 Signal Assignments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal</strong></td>
</tr>
<tr>
<td>Analog-Input ± 10V</td>
</tr>
<tr>
<td>GND (24 V-Supply-Current)</td>
</tr>
<tr>
<td>GND (24 V-Supply-Current)</td>
</tr>
<tr>
<td>Relay-Output A1.2</td>
</tr>
<tr>
<td>Relay-Output A1.4</td>
</tr>
<tr>
<td>Relay-Output A1.6</td>
</tr>
<tr>
<td>Relay-Output A1.8</td>
</tr>
<tr>
<td>PWM-Out (Emitter)</td>
</tr>
<tr>
<td>+ 24 V-Supply-Current</td>
</tr>
<tr>
<td>Counter-Input</td>
</tr>
<tr>
<td>Signal-Input E1.3</td>
</tr>
<tr>
<td>Signal-Input E1.1</td>
</tr>
<tr>
<td>Signal-Input E1.7</td>
</tr>
<tr>
<td>Signal-Input E1.5</td>
</tr>
<tr>
<td>Signal-Input E2.2</td>
</tr>
<tr>
<td>Signal-Input E2.4</td>
</tr>
<tr>
<td>Signal-Input E2.6</td>
</tr>
<tr>
<td>Signal-Input E2.8</td>
</tr>
</tbody>
</table>

All signal connections from Interface module and Multi-I/O-board are identical, so that a screened standard line (1:1 Wiring) can be used to connect the units.
13.6 FineWeld Program Source Code and Controller INI-File

unit Unit1;

interface

uses
Windows, Messages, SysUtils, Classes, Graphics, Controls, Forms, Dialogs,
Servo32, StdCtrls;

type
 TForm1 = class(TForm)
 Button1: TButton;
 Button2: TButton;
 Button3: TButton;
 Button4: TButton;
 Button5: TButton;
 Button6: TButton;
 Button7: TButton;
 Button8: TButton;
 Button9: TButton;
 Button10: TButton;
 Edit1: TEdit;
 Edit2: TEdit;
 Edit3: TEdit;
 Label1: TLabel;
 Label2: TLabel;
 Label3: TLabel;
 Label4: TLabel;
 Label5: TLabel;
 Label6: TLabel;
 Label7: TLabel;
 Label8: TLabel;
 procedure Button1Click(Sender: TObject);
 procedure Button2Click(Sender: TObject);
 procedure Button3Click(Sender: TObject);
 procedure Button4Click(Sender: TObject);
 procedure Button5Click(Sender: TObject);
 procedure Button6Click(Sender: TObject);
 procedure Button7Click(Sender: TObject);
 procedure Button8Click(Sender: TObject);
 procedure Button9Click(Sender: TObject);
 procedure Button10Click(Sender: TObject);
 private
 { Private-Deklarationen }
 public
 { Public-Deklarationen }
end;

var
 Form1: TForm1;

implementation
procedure TForm1.Button1Click(Sender: TObject);
const ss: array [0 .. 80] of AnsiChar = 'bspservo.ini';
var
ret: LONG;
s: string;
ps: Pointer;

begin
ret := ncInitDrv(@ss);
{s := Format('Rückgabewert: %d', [ret]);
ShowMessage(s);}
end;

procedure TForm1.Button2Click(Sender: TObject);
var
ret: LONG;
s: string[80];

begin
ret := ncGetDrvInstallStateO;
{s := Format('Rückgabewert: %d', [ret]);
ShowMessage(s);}
end;

procedure TForm1.Button3Click(Sender: TObject);
var
ret: LONG;
s: string[80];

begin
ret := ncGetVxDInstallStateO;
{s := Format('Rückgabewert: %d', [ret]);
ShowMessage(s);}
end;

procedure TForm1.Button4Click(Sender: TObject);
var
ret: LONG;
s: string[80];

begin
ret := ncResetO;
{s := Format('Rückgabewert: %d', [ret]);
ShowMessage(s);}
procedure TForm1.Button5Click(Sender: TObject);
var
  ret: LONG;
  s: string;
  ss: array [0 .. 100] of AnsiChar;
begin
  ret := ncGetVxDVersion(@ss, 100);

  s := Format('Rückgabewert: %d Version: %s', [ret, ss]);
  ShowMessage(s);
end;

procedure TForm1.Button6Click(Sender: TObject);
var
  ret: LONG;
  s: string[80];
begin
  ret := ncSetHandMode(17);

  s := Format('Rückgabewert: %d', [ret]);
  ShowMessage(s);
end;

procedure TForm1.Button7Click(Sender: TObject);
var
  ret: LONG;
  s: string[80];
begin
  ret := ncReference(NC_REF_X or NC_REF_Y or NC_REF_Z);

  s := Format('Rückgabewert: %d', [ret]);
  ShowMessage(s);
end;

procedure TForm1.Button8Click(Sender: TObject);
var
  ret: LONG;
  s: string[80];
  status: NCSTATUS;
begin
  ret := ncGetStatus(@status);
  if ret <> 0 then
    begin
      s := Format('Rückgabewert: %d', [ret]);
      ShowMessage(s);
    end
else
  begin
    if status.StatusAX and ISMOVING <> 0 then
      begin
        ShowMessage('Anlage in Bewegung');
      end;
    s := Format('Status: AX: %.4x, BX: %.4x, CX: %.4x, DX: %.4x', [ret,
    ShowMessage(s);
  end;
end;

procedure TForm1.Button9Click(Sender: TObject);
var
  ret: LONG;
  s: string[80];
  pos: NCPOS;
beg{n
  pos.X := StrToInt(Edit2.Text)*3600;
  pos.Y := StrToInt(Edit1.Text);
  pos.Z := StrToInt(Edit3.Text);
  ret := ncMoveLineRel(@(pos));

  {s := Format('Rückgabewert: %d', [ret]);
   ShowMessage(s);}
end;

procedure TForm1.Button10Click(Sender: TObject);
var
  ret: LONG;
  s: string[80];
beg{n
  ret := ncSetVel(StrToInt(Edit4.Text)*3600);
  s := Format('Rückgabewert: %d', [ret]);
  ShowMessage(s);
end;
end.
Load in FineWeld procedure TForm1:
procedure TForm1.Button1Click(Sender: TObject);
const ss: array [0 .. 80] of AnsiChar = 'bspservo.ini';

"ISEL AUTOMATION MOTOR DRIVE 3.00"

;Remark=12_Bit_interface for 3-axes motion control

**HARDWARE SETTINGS**

Ressourcen=50%
Software Interrupt=78h
Hardware Interrupt=IRQ11
Base address=300h
Axes_number=3
Axes_typeX=Linear axis
Axes_typeY=Linear axis
Axes_typeZ=Linear axis
Axes_typeA=Rotation axis
Control structur=No_TTT_Structur
Movement_directionX=Standard
Movement_directionY=Standard
Movement_directionZ=Not_Standard
Movement_directionA=Standard
Active_level_switch=Low
Port_address_positivEnd_switchX=30Ch
Bit_number_PositivEnd_switchX=0
EnableDisable_PositivEnd_switchX=Disable
Port_address_NegativEnd_switchX=30Ch
Bit_number_NegativEnd_switchX=0
EnableDisable_NegativEnd_switchX=Disable
Port_address_PositivEnd_switchY=30Eh
Bit_number_PositivEnd_switchY=5
EnableDisable_PositivEnd-switchY=Enable
Port_address_NegativEnd_switchY=30Eh
Bit_number_NegativEnd_switchY=1
EnableDisable_NegativEnd_switchY=Enable
Port_address_PositivEnd_switchZ=30Eh
Bit_number_PositivEnd_switchZ=2
EnableDisable_PositivEnd_switchZ=Enable
Port_address_NegativEnd_switchZ=30Eh
Bit_number_NegativEnd_switchZ=6
EnableDisable_NegativEnd_switchZ=Enable
Port_address_PositivEnd_switchA=30Eh
Bit_number_PositivEnd_switchA=3
EnableDisable_PositivEnd_switchA=Enable
Port_address_NegativEnd_switchA=30Eh
Bit_number_NegativEnd_switchA=7
EnableDisable_NegativEnd_switchA=Enable
Port_address_Referenz_switchX=30Ch
Bit_number_Referenz_switchX=0
Mode_Referenz_switchX=Standard
Direction_Referenz_switchX=Standard
Distance_Referenz_switchX=500
Port_address_Referenz_switchY=30Eh
Bit_number_Referenz_switchY=5
Mode_Referenz_switchY=Standard
Direction_Referenz_switchY=Not_Standard
Distance_Referenz_switchY=1000
Port_address_Referenz_switchZ=30Eh
Bit_number_Referenz_switchZ=6
Mode_Referenz_switchZ=Standard
Direction_Referenz_switchZ=Standard
Distance_Referenz_switchZ=100
Port_address_Reference_switchA=30Ch
Bit_number_Reference_switchA=3
Mode_Reference_switchA=Standard
Direction_Reference_switchA=Standard
Distance_Reference_switchA=500
EnableDisable_WatchDog_Reference=Enable
Velocity_controller=available
Port_address_Keyswitch=30Ch
Bit_number_Keyswitch=5
EnableDisable_Keyswitch=Disable
Active_level_Keyswitch=High
Port_address_Input_Port1=310h
EnableDisable_Input_Port1=Disable
Port_address_Input_Port2=311h
EnableDisable_Input_Port2=Disable
Port_address_Input_Port3=312h
EnableDisable_Input_Port3=Disable
Port_address_Input_Port4=313h
EnableDisable_Input_Port4=Disable
Port_address_Output_Port1=310h
initial_value_Output_Port1=00000000b
EnableDisable_Output_Port1=Disable
Port_address_Output_Port2=311h
initial_value_Output_Port2=00000000b
EnableDisable_Output_Port2=Disable
Port_address_Output_Port3=312h
initial_value_Output_Port3=00000000b
EnableDisable_Output_Port3=Disable
Port_address_Output_Port4=313h
initial_value_Output_Port4=00000000b
EnableDisable_Output_Port4=Disable
Movement_Output_Port_use=Disable
Port_address_Movement_Output_Port=314h
Minimum_Value_Movement_Output_Port=00h
Maximum_Value_Movement_Output_Port=FFh
Delay_time_Movement_Output_Port=0.1
Encoder_Line_numberX=1000
Encoder_Line_numberY=1000
Encoder_Line_numberZ=1000
Encoder_Line_numberA=1000
Axes_gear_ratioX=64042
Axes_gear_ratioY=2534
Axes_gear_ratioZ=5107
Axes_gear_ratioA=259200

SOFTWARE SETTINGS

Maximum_axes_accelerationX=42693869
Maximum_axes_accelerationY=1013600
Maximum_axes_accelerationZ=2042400
Maximum_axes_accelerationA=181440000
Reference_acceleration_ratioX=10.0
Reference_acceleration_ratioY=10.0
Reference_acceleration_ratioZ=10.0
Reference_acceleration_ratioA=10.0
Maximum_axes_velocityX=2304793
Maximum_axes_velocityY=68400
Maximum_axes_velocityZ=137700
Maximum_axes_velocityA=10368000
Segment_velocity=25000
Trace_velocity=25000
TeachIn_velocity=25000
Fast_velocity=100000
Initial_Reference_velocityX=10000000
End_Reference_velocityX=5000000
Initial_Reference_velocityY=25000
End_Reference_velocityY=2500
Initial_Reference_velocityZ=500000
End_Reference_velocityZ=2500
Initial_Reference_velocityA=10000000
End_Reference_velocityA=500000
Circle_velocity_Reduction_factor=1
Trace_velocity_Reduction_factor =1
X_Axes_dead_time=0.0043
Y_Axes_dead_time =0.0099
Z_Axes_dead_time =0.0062
A_Axes_dead_time =0.0163
Tracking_Tolerance=200%
Positive_SoftwareEnd_switchX=+1296000
Negative_SoftwareEnd_switchX=-1296000
Positive_SoftwareEnd_switchY=+2000000
Negative_Software_switchY=-2000000
Positive_SoftwareEndschalterZ=+2000000
Negative_Software_switchZ=-2000000
Positive_Software_switchA=+1296000
Negative_SoftwareEnd_switchA=-1296000
Controller_KpX=50
Controller_KiX=50
Controller_KdX=1000
Controller_TdX=0
Controller_IIX=2048
Controller_KpY=50
Controller_KiY=50
Controller_KdY=1000
Controller_TdY=0
Controller_IiY=2048
Controller_KpZ=100
Controller_KiZ=50
Controller_KdZ=2000
Controller_TdZ=1
Controller_IIZ=1024
Controller_KpA=50
Controller_KiA=50
Controller_KdA=1000
Controller_TdA=0
Controller_IIA=2048

13.6.1 3D and 2D-Plot of Gaussian Intensity Distribution

% 3D, 2D-Plot of Gaussian Intensity Distribution and Beam Propagation
% calculated for 10(z=0)=10, 10(z=2zr)=10/2 and 10(z=2zr)=10/5
% 
% x=(-2:0.1:2);
y=(-2:0.1:2)';
v=ones(length(x),1);
l=10/2
X=v'*x;
y=Y'*v';
f= l.*exp(-2.*(X.^2+Y.^2));
figure
surf(x,y,f)
mxf = max(max(f));
mif = min(min(f));
axis([-3.3,-3.3,mif,mxf])
xlabel('x-axis');
ylabel('y-axis');

% grid in x-direction
% grid in y-direction
% grid help vector
% calculated for 10, 10/2 and 10/5
% grid matrix of x-values
% grid matrix of y-values
% Function values
% 3-D plot
% max. function values
% min. function values
% axis adjustment
13.7 High-Performance Handling Components

13.7.1 High-Performance Low-Profile Ball Bearing Linear Stages

- Precision ball bearing movements
- Non-influencing lock (except 4 in.)
- Reversible for left or right-handed applications
- Compatible with Newport manual and motorised actuators
- Stackable for low profile multi-axis positioning

Models 423, 433, and 443 feature exceptional performance, usability, and value with precision ball bearing construction - hardened balls rolling between opposing pairs of hardened and polished stainless steel rods. For stability, repeatability, and exceptionally smooth motion, actuators bear upon a hardened carbide insert. Springs provide preload against the actuator tip to eliminate backlash.

A stable stainless steel actuator mounting system allows your choice of manual or motorised actuators to be attached in either a left or right-hand configuration. A non-influencing lock (also reversible for left-handed configuration) similar to that used on our top-of-the-line ultralight Series Stages provides positive stable positioning and guards against inadvertent adjustments. For higher load capacity, see 426 and 436 Series Crossed-Roller Low-Profile Stages, or our Double-Row Ball Bearing UMR Series Stages [148]
### Table 13.7-1 Technical data stages 423

<table>
<thead>
<tr>
<th>Stage</th>
<th>(M-423) Series 423</th>
<th>(M-433) Series 433</th>
<th>(M-443) Series 443</th>
<th>(M-443-4) Series 444</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Stage Travel [in. (mm)]</td>
<td>1 (25)</td>
<td>1.81 (46)</td>
<td>2 (50)</td>
<td>4 (102)</td>
</tr>
<tr>
<td>Angular Deviation (µrad)</td>
<td>&lt;200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Load Capacity, Centered [lb (N)]</td>
<td>35 (156)</td>
<td>47 (209)</td>
<td>58 (258)</td>
<td>58 (258)</td>
</tr>
<tr>
<td>Load Capacity, Vertical [lb (N)]</td>
<td></td>
<td>15 (67)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 13.7-2 Data manual and motorised drives

<table>
<thead>
<tr>
<th>Manual Drives</th>
<th>Description</th>
<th>423 (M-423)</th>
<th>433 (M-433)</th>
<th>443 (M-443)</th>
<th>444 (M-443-4)</th>
<th>Travel (mm)</th>
<th>Sensitivity (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AJS Series</td>
<td>Fine Adjustment Screw</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>13-50</td>
<td>0.6-0.75</td>
<td></td>
</tr>
<tr>
<td>SM-13</td>
<td>Micrometer</td>
<td>•</td>
<td></td>
<td></td>
<td>13</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SM-25</td>
<td>Micrometer</td>
<td>•</td>
<td>•</td>
<td></td>
<td>25</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>SM-50</td>
<td>Micrometer</td>
<td>•</td>
<td>•</td>
<td></td>
<td>50</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>HR-13</td>
<td>High-Resolution Micrometer</td>
<td></td>
<td>•</td>
<td>13</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM-13</td>
<td>Differential Micrometer</td>
<td>•</td>
<td></td>
<td></td>
<td>13</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>DM-13L</td>
<td>Differential Micrometer</td>
<td>•</td>
<td></td>
<td></td>
<td>13</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>DM-25L</td>
<td>Differential Micrometer</td>
<td>•</td>
<td>•</td>
<td></td>
<td>25</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Motorised Drives</td>
<td>Motorised Actuator</td>
<td>•</td>
<td>•</td>
<td>•</td>
<td>25-50</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>LTA Series</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12.5-25</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>CMA Series</td>
<td>Motorised Actuator</td>
<td></td>
<td>•</td>
<td>•</td>
<td>12.5</td>
<td>0.2-0.5</td>
<td></td>
</tr>
<tr>
<td>PZA12 Actuator</td>
<td>NanoPZ actuator, 12.5 mm travel</td>
<td>•</td>
<td>•</td>
<td></td>
<td>12.5</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>
13.7.2 XY-Translator Stages with Differential and Micrometer Drives

XY Translator with Differential Drives

Differential Adjusters Similar to DM22

- Coarse 0.4mm per Revolution – Fine
- 25μm per Revolution
- 0.5 per Revolution
- Compact design
- 1/4" (6.5mm) travel
- Backlash free design
- Compatible with Ø 1.00 lens tubes
- Compatible with cage plate assemblies

XY Translator with Micrometer Drives

Micrometer Drives Model 148-205 0.5mm Per Revolution 10μm Per Graduation

Compact Design
1/4" (6.5mm) travel
Backlash Free Design
Compatible with our Ø 1.00 Lens Tubes
Compatible with our Cage Plate Assemblies

The ST1XY translation stage utilizes hardened tool steel components on all moving parts; this ensures long-term, drift-free operation. The ST1XY is designed to connect with our extensive line of Ø 1.0 diameter lens tubes as well as our cage assemblies. This compatibility offers great flexibility in building optical systems. An #8-32 (M4) tap has been added to the bottom surface to allow direct mounting on our TR series 1/2" diameter posts [156]
13.7.3 850F-Series Linear Actuator

The 850F actuator incorporates a versatile design which can be configured with travel limits from as little as approximately 1/32 inches to 2 inches (9.8 mm – 50 mm), enabling it to be used on a wide variety of Newport translation stages and mirror mounts. Mechanical limit switches cut motor power preventing accidental over-travel. The actuator incorporates a manual actuation knob for coarse adjustment (with the motor power off).

To provide accurate motion, the actuator’s 3/16 inch diameter plunger is non-rotating. The standard gearbox ratio actuator can produce a maximum thrust in excess of 11kg, when operating continuously over many cycles, the maximum load is rated at 8kg. The actuator’s internal structure is a precision-rolled lead-screw with a pitch of 32.3885 threads per inch. The pitch of the lead-screw has been chosen to provide exactly 0.05μm encoder resolution when combined with the standard ratio.

<table>
<thead>
<tr>
<th>Table 13.7-3 Specifications Linear Actuator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base Material</strong></td>
</tr>
<tr>
<td><strong>Drive Mechanism</strong></td>
</tr>
<tr>
<td><strong>Drive Screw Pitch (mm)</strong></td>
</tr>
<tr>
<td><strong>Reduction Gear</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Feedback</strong></td>
</tr>
<tr>
<td><strong>Limit Switches</strong></td>
</tr>
<tr>
<td><strong>Origin</strong></td>
</tr>
<tr>
<td><strong>Motor</strong></td>
</tr>
<tr>
<td><strong>Cable Length (m)</strong></td>
</tr>
<tr>
<td><strong>MTBF</strong></td>
</tr>
<tr>
<td><strong>Weight [lb (kg)]</strong></td>
</tr>
</tbody>
</table>
Key Features:

- Up to 50 mm travel in a space saving design
- Non-rotating tip improves motion smoothness and has no wear
- Exceptional position sensitivity
- Adjustable limit switch prevents damage from over-travel
- Convenient manual positioning knob

Table 13.7-4 Specifications

<table>
<thead>
<tr>
<th></th>
<th>LTA-HS</th>
<th>LTA-HL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel (mm)</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Resolution (µm)</td>
<td>0.035</td>
<td>0.0074</td>
</tr>
<tr>
<td>Minimum Incremental Motion (µm)</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Uni-directional Repeatability (µm)</td>
<td>0.15 typical, 0.5 guaranteed</td>
<td>0.15 typical, 0.5 guaranteed</td>
</tr>
<tr>
<td>Bi-directional Repeatability (µm)*</td>
<td>0.6 typical, 2 guaranteed</td>
<td>0.6 typical, 2 guaranteed</td>
</tr>
<tr>
<td>On-Axis Accuracy (µm)</td>
<td>5 typical, 15 guaranteed</td>
<td>2 typical, 8 guaranteed</td>
</tr>
<tr>
<td>Maximum Speed (mm/s)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Axial Load Capacity (N)**</td>
<td>50</td>
<td>120</td>
</tr>
<tr>
<td>Side Load Capacity**</td>
<td>5</td>
<td>20</td>
</tr>
</tbody>
</table>
13.7.3.1 Connector Pin Assignments

<table>
<thead>
<tr>
<th>WIRE COLOR</th>
<th>PIN</th>
<th>CONNECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLACK</td>
<td>NC</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>4</td>
</tr>
<tr>
<td>WHITE</td>
<td>NC</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>8</td>
</tr>
<tr>
<td>SHIELD GND</td>
<td>NC</td>
<td>9</td>
</tr>
<tr>
<td>ORANGE</td>
<td>NC</td>
<td>10</td>
</tr>
<tr>
<td>GRAY</td>
<td>NC</td>
<td>11</td>
</tr>
<tr>
<td>YELLOW</td>
<td>NC</td>
<td>12</td>
</tr>
<tr>
<td>GREEN</td>
<td>NC</td>
<td>13</td>
</tr>
<tr>
<td>RED</td>
<td>NC</td>
<td>14</td>
</tr>
<tr>
<td>BLUE</td>
<td>NC</td>
<td>15</td>
</tr>
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<td></td>
<td>NC</td>
<td>16</td>
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<td>NC</td>
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<td></td>
<td>NC</td>
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<tr>
<td></td>
<td>NC</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>25</td>
</tr>
</tbody>
</table>

Fig. 13.7-5 Connector Pin Assignments

Fig. 13.7-6 Scale Drawing
13.7.3.2 Angle Brackets

Rigid, angled mounting brackets with slotted faces 30°, 45°, and 90° angle brackets.

![Fig. 13.7-7 Angle brackets](image)

The 360 Series Angle Brackets are rigid, angled mounting plates with slotted faces. The 30, 45 and 90 degree angles are accurate to within ±2 arc min. Model 360-90 is useful for building 3-axis linear stage assemblies and as a platform with rod mounted components. Brackets may be combined to provide stable compound angle supports. Pairs of 360-30 or 360-45 brackets bolted together on hypotenuse faces provide coarse-adjustable height platforms of exceptional rigidity [148].

![Fig. 13.7-8 Cartesian system with linear motorised translation stages](image)
13.7.4 General Description MM4005

The MM4005 is an advanced, stand-alone, integrated motion controller/driver. It can control and drive up to 4 axes of motion, in any stepper and DC motor combination. The MM4005 controller was specially designed to operate with Newport’s broad line motion devices.

![Minimum system configuration](image)

Fig. 13.7-9 Minimum system configuration

In this configuration all commands are received from the front panel. Programs can be generated and executed without using an additional computer.

A more common setup is shown in Fig. 13.7-9. The MM4005 drives multiple stages and is controlled by a remote computer [148].

Features

Many advanced features make the MM4005 the preferred choice for precision applications:

- Integrated controller and driver design is more cost effective and a space saving solution.
- Compact, rack-mountable or bench-top enclosure.
- Allows any combination of motor types (stepper and DC) and sizes.
- Supports closed-loop operation of stepper motors.
- Feed-forward servo algorithm for smooth and precise motion.
• Advanced multi-axis synchronisation (linear interpolation).
• Advanced motion programming capabilities with up to 100 nested loops and complex digital and analog I/O functions.

Specifications

Function
• Integrated motion controller and driver

Number of motion axis
• 1 to 4, in any combination or order of stepper and DC motors

Trajectory type
• Non-synchronized motion
• Multi-axis synchronized motion (linear interpolation).
• S-Curve or Trapezoidal velocity profile for non-synchronized and synchronized motion. The default configuration is S-Curve velocity profile.

Motion device compatibility
• Entire family of motorized motion devices, using either stepper or DC motors.

CPU type
• 5x86/100 Processor.

DC motor control
• 16bit DAC resolution.
• 10 MHz maximum encoder input frequency.
• PID with velocity feed-forward servo loop.
• 0.3 ms digital servo cycle.

Stepper motor control
• 1 MHz maximum pulse rate.
• Full, half and mini step capability.
• Open or closed-loop operation.
• PID with velocity feed forward closed-loop mode.
• 0.3 ms digital servo cycle.

Computer interfaces
• RS-232-C
• IEEE-488

Utility interface
• 8-bit opto-coupled digital inputs
• b-bit open-collector digital outputs
• 4 analog inputs, 12 bit resolution programmable input range (0-5 V, 0-10 V)
• External synchronisation Pulse Output from position acquisition.

Programming
• Remotely via the computer interface.
• From the front panel.

Program memory
• 30 KB, non-volatile.

Display
• Fluorescent backlit LCD.
• 40 mm x 130 mm, 6 lines by 30 characters.

Dimensions
• (134 x 483 x 395).

Power requirements
• Power supply with PFC (Power Form Corrector) 90 to 264V- 50/60 Hz
• Motors off – 100 VA max.
• Motors on – 570 VA max.
13.7.4.1 Modes of Operation

LOCAL Mode

In LOCAL mode, the MM4005 is operated through the keys on the front panel. The display and function keys allow the selection of menus and operations that can be performed without using an external computer.

![LOCAL Mode Diagram](image)

Fig. 13.7-10 Functions available in LOCAL Mode

Operations that can be performed from the front panel depend on whether the power to the motors is turned on or off. A motion, for instance, cannot be performed when the motors are turned off and a general controller setup should not be done when the motors are on.

SETUP can be activated only from LOCAL mode, Motors Off. In this mode, the user can set up the general operation of the controller and the parameter specific to every motion axis and motion device.

The programming mode can be activated in LOCAL Mode while motors are on or off. In programming mode, a motion program can be created or modified.

MOTION is a general mode of operation in which an axis is commanded to move. The most complex motions result from executing a program. The two other cases are when a manual JOG or a point to point move is executed.
REMOTE Mode

To operate in REMOTE mode, the controller must be connected through one of its interfaces (RS-232-C or IEEE-488) to a computer or terminal. In this mode, all commands are received remotely and the controller executes them as directed. The MM4005 command language consists of 129 commands.

The functions available in REMOTE mode are similar to the ones in LOCAL mode. The main difference is that the MOTOR off / MOTOR on cases are handled by the command interpreter so there is no need to distinguish between them. The controller will refuse to execute motion commands when the motors are turned off and will set the appropriate error flag.

Another difference between LOCAL and REMOTE is that the Setup mode is not available remotely. Some Setup parameters can be changed but the controller cannot be placed remotely into a setup mode.

Programming mode is enabled and disabled by specific commands. All valid commands sent in this mode are not executed immediately but stored as a part of a motion program. MOTION is a general mode of operation in which an axis is commanded to move. The most complex motions result from program execution. Other types of motion include manual JOG and a point to point MOVE.

HOME Search mode has the same meaning and functionality as in LOCAL mode. A home search cycle should not be interrupted. The controller exit this mode automatically and task completion.
13.7.4.2 Front Panel Description

A general view of the front panel is shown in Fig. 13.7-12. There three distinct areas, from left to right: power controls, a display and function keys, and a keypad.

![Front Panel Diagram](image)

**Fig. 13.7-12 MM4005 front panel**

**Power Stand-by**

This button is used for everyday controller power ON/OFF switching. To differentiate from the rear main power switch, this button is called Power Stand-by.

Motor ON/OFF
For convenience and safety reasons, the power to motors can be controlled separately.

13.7.4.3 Rear Panel Description

Before attempting to operate the MM4005, it must first be properly connected and configured.

![Rear Panel Diagram](image)

**Fig. 13.7-13 Rear panel of the MM4005**
Axis Modules

The MM4005 can accommodate up to four motor driver cards. Each motor driver card has a 25-pin D-Sub connector, mounted on a small panel visible from the rear of the controller, for attaching the motion device.

GPIO Connector

This 37-pin D-Sub connector is used for general purpose digital Input/Output signals. The MM4005 offers two separate 8-bit digital ports, one for input and one for output. A variety of commands are available for control and interface using these ports from within a motion program.

Power Inhibition Connector

This 9-pin D-Sub connector provides remote motor power interlock capability. One or more external switches can be wired to remotely inhibit the motor power in a way similar to the Motor off button on the front panel.

Auxiliary Connector

This 25-pin D-Sub connector has two active lines. One is for motor power status indication and the other for frequency generator output. The frequency generator is controlled by the motion program and has frequency range of 0.01 to 500 Hz.

Remote Control Connector

This 25-pin D-Sub connector provides two functions. The first is similar to the power Inhibition connector. The two active pins must be short-circuited for the motor power to be enabled. The connector’s second function is to provide inputs for the two analog ports. These ports are two independent 8 bit analog-to-digital converters. Programming commands allow the user to read and manipulate the information provided by these ports.

RS-232-C Connector

This 9-pin D-Sub connector provides an RS 232-C interface to a host computer or terminal. The port has a three-line configuration using a software (XON/XOFF)
handshake. The pinout enables the use of an off-the-shelf, pin-to-pin cable. The port provides internally the necessary jumpers to bypass the hardware handshake, if needed.

**IEEE-488 Connector**

This is a standard 24-pin IEEE-488 connector.

13.8 **FineScan Description**

The program “Centerposition” has been written to allow the determination of the mid-position of optical sources by use of software. A light source is driven in two axes and the local intensity measured. Using a mathematical algorithm, the mid-position of the light source is calculated. As an alternative, it is possible to determine the position of maximal intensity. The desired position can then be driven to. The so determined intensity values are then stored in Excel-compatible files.

The Program can be used on a Personal Computer running Windows 95 operating system or higher. LabView 6.0i or higher must also be installed on this PC. It is also possible to install a Runtime version to permit LabView applications to be run [153].

13.8.1 **The Build-up**

The light source to be scanned is fixed to the mount of a two-axis-positioning table. The source is moved along both paths and the light intensity measured at various points using a Thorlabs Silicon Detector PDA 55.
A sensor analogue output signal (0V to 10V) is transmitted to a data acquisition board (DAQ) via terminal block and screened cable.

The DAQ-Board from the company National Instruments is initialised via the Measurement & Automation Explorer (LabVIEW). The board is now recognised by LabVIEW, and communication built up between the RS323 interface and the Motion-Controller MM4005, being controlled by the "Centerposition" program.

Equipment used:

- **Data acquisition Board**: NI PCI-6024E
- **Connector Block**: SCB-100
- **Sensor/Detector**: Thorlabs Silicon Detector PDA 55
- **Motion Controller**: Motion Controller MM4005

### 13.8.2 Operating Instructions

#### 13.8.2.1 Manual Motion

With the Operating panel "Manual Motion" the axis table can be manually driven in the X or Y-Direction. The Operator field for manual Control is based on the original Newport Motion Controller MM4005.
To drive the three axis manually using the Mouse, the Button „START Manual Control >>“ must be activated. At this operation the button changes from green to red colour.

As long as the function is in this position, the axis drives are activated. The display situated to the right of the window now shows the actual intensity measured.

To move each axis 0.1mm in the desired direction, operate the corresponding buttons on the panel under the single arrow < (button n 1, 4, 7) or> (button n 3, 6, 9). To drive at a speed of 1mm, select first the double arrows <<>> (button n 2, 5, 8), whereby only the middle row may be activated. Operation of button „Home“ returns all axes to the positions set at the start of the controller.

The button „Read Position“ reads the actual position of each axis and sets the values in the corresponding fields right next to the buttons.

To leave this menu correctly, operate the red button „STOP Manual Control <<“ when driving is finished.

In this function it is often forgotten, the button „STOP Manual Control <<“
to operate, so it remains active despite a change of field. This is normally noticed by other program functions not reacting. Operation of the button to the condition „START Manual Control >>“ usually eliminates this problem.

This function is normally used to set the axis start positions before measurement begin. Here it is recommended to observe the maximal expected intensity, setting the observed maximal intensity display to not more as 80%. This allows room for unexpected higher intensities to be correctly displayed.

13.8.2.2 Measurement

The operating panel “Measurement” is the actual core function of the controller. In this function all inputs and information are contained pre, during and after scanning.

Fig. 13.8-2 Operating panel „Measurement“

The operating panel is constructed to follow the sequential run of the program. In the figure above, the four main working steps of the controller are illustrated.
The four main working steps are:

1. File
2. Rough Scan
3. Centre Calculation
4. Fine Scan

The Checkbox at the right Side serves to check the function, to be able to determine which working Step is being carried out. An Emergency stop function is included, to permit halting the system at any time.

### 13.8.2.2.1 File

In the upper part of the figure, the file dialog panel is shown. In this box the file name under which data is to be stored can be entered. Storage of scan data is initiated by operating the green Button „Enter“. To carry out a scan, the file name must be entered. Operation of the button opens a normal dialog window as usual with Microsoft windows applications. The file name is entered without extension, which are automatically added, being .rsv for Rough Scan Data and .fsv for Fine Scan Data. After successful input of the name, it appears in the box with a tick after the file name. If the tick symbol is not displayed, so can no measurement be made.

![Data Dialog](image)

**Fig. 13.8-3** Data Dialog

### 13.8.2.2.2 Rough Scan

In this section, the measurement values of the Rough Scan Fields and the step width are set.

![Rough Scan](image)

**Fig. 13.8-4** Rough Scan
The scan is always carried out over a quadrant table area having all sides of the same length. This length A can be chosen freely, it is recommended to keep the surface to be scanned as small as possible, scan time increasing to square of the side lengths.

Step width A field contains the value from point to point at which the area is to be scanned.

The field Points contains a calculated value showing how many points are to be scanned. The scan function is started by operation of button “Start“ During the process; the advance of the measurement function is shown in the lower right corner.

Operation of the register card „Rough Scan Results“ will allow the scan measurement processes to be followed. At end of the scan function, a tick is shown in the checkbox for “Rough Scan done”.

An early stop of the measurement process can only be carried out by operation of the emergency stop control. This is not recommended, as it will also end the program, and enter zero values for all non-scanned areas in the table.

It has been found that for the Rough Scan function, the field to be covered should be held not larger as needed. Ca. 100 point/fields are usually sufficient for Rough Scan operations.

Further, a smaller step width will allow a faster measurement from point to point. 100 points at a distance of 1 mm will require considerably more time as with a distance of 0.05 mm.

13.8.2.2.3 Centre Calculation

In this part of the menu, the method by which the middle of the following fine scan fields should be calculated is set. On this calculated value is the fine scan field set. This is only possible when a rough scan has been carried out and a tick is displayed in the checkbox after “Rough Scan done”.

![Fig. 13.8-5 Centre Calculation](image)

**The following options are possible in the program:**

With the Option „First Maximum“ the first maximal intensity value will be taken as that which as first displays a scan maximal value in the scan field.

With the Option „Binary“ the scanned field is set to digital 0 and 1 value. The value at which an intensity value is set to 1 is set by the „threshold“ value. From this binary field the middle value is calculated.

Die Option „Binary Filtered“ functions as the option Binary, with the exception that isolated high intensity points are ignored in the calculation.
With the Option „Manually“ a further window is opened, where a cross-point graticule can be led to where the middle should be set to. Operation of button „accept“ initiates this setting.

Through operation of button „Calculate“, the set option is used to calculate the middle. A further window displays the result as illustration in flashing pixel mode. Return from this window is through button „Back“.

In the Checkbox behind „Calculation done“ a tick is displayed.

The valid in all options given „Median Filter“(*1) smoothes the Rough Scan results. The single intensity values are compared to their background levels and corrected as necessary.

![Fig. 13.8-6 Centre Calculation](image)

The calculation process can be repeated indefinitely, after each calculation the middle values will be displayed again.

Before measurement, it should be considered that the calculation method „First Maximum“ will provide a generally good result as long as maximal intensity limits are correctly set. Smoothing by the Median Filter allows measurement failures to be satisfactorily corrected.

13.8.3 FineScan

The Fine Scan functions primarily just as the Rough Scan. However, the limiting of the fine scan field as compared to rough scan can be attained by one of two different methods.

![Fig. 13.8-7 FineScan – Length B and step width b](image)
The following program options are possible:

1. **Option „By Length“:**

If the Option „by Length“ is selected, the data can be input as by Rough Scan:

The scan is always carried out over a quadrant table area having all sides of the same length. This length B can be chosen freely, it is recommended to keep the surface to be scanned as small as possible, scan time increasing to square of the side lengths. Step width B field contains the value from point to point at which the area is to be scanned. The field Points contains a calculated value showing how many points are to be scanned.

2. **Option „Interactive“:**

If the Option „Interactive“ is selected, a further window opens and displays the Rough Scan data detected:

![Fig. 13.8-8 Interactive selection of the area](image)

The two displayed graticules can be moved over the scanned area and allow selection of that which is under the centres of the graticules to be chosen as scan area. With the button „accept“ the data is input.

With the Button „Start“ the scan process is started. During measurement, the progress made is displayed in the right lower corner.

Operation of register card „Fine Scan Results“ allows the scan of the field to be displayed during measurement.

At end of scan, a tick appears in a checkbox after „Fine Scan done“. 
An early stop of the measurement process can only be carried out by operation of the emergency stop control. This is not recommended, as it will also end the program, and enter zero values for all non-scanned areas in the table.

The option ,,Centre Axis“ in Fig. (13.8-7) offers the possibility to drive the axis to the maximal intensity point after Fine Scan. With this option active, the axis is therefore automatically driven to the maximal intensity point.

13.8.3.1 Rough Scan/ Fine Scan Results

It is possible during the scan process to follow the progress of measurement. Register card ,,Rough Scan Results“ or ,,Fine Scan Results“ activated allows the data in this display to be set in intensity values and so more easily seen.

13.8.3.1.1 Load Data

If data from previous measurements is required to be displayed, this is possible under register card ,,Load Data“.

![Fig. 13.8-9 Register card Load Data](image)

Through operation of button ,,File“, the File dialog box is opened and previous data can now be read in. In the upper part of the display, the paths and file names of the displayed data is shown.
End Program

With the red button „End Program“, the program “Centerposition” is normally ended.

13.8.4 Centre Position

13.8.4.1 Main program (Main. I)

The LabVIEW-Program „Centre Position“ to determine mid-positions of optical sources consists of one main part. This main program (Main. I) consists of four sequences, which are run through, in row.

The following sequences are processed in the Main program:

- **Sequence 0:** The RS232 Interface is opened to communicate with the Newport-Motion-Controller M4005.
- **Sequence 1:** The button/motor is initialised.
- **Sequence 2:** In this Sequence is the main control part.
- **Sequence 3:** The serial interface RS232 is closed.

![Fig. 13.8-10 Structuregram Main.VI](image)

The **Action sequence „0“**

Communication between PC and Controller is via a serial interface (PC) and an RS232-line. With the VI „RS232 Open“ it is possible to open a serial interface. (see Fig. 13.8-11) If a failure in communication in interface or PC and controller is detected, a fault message is issued at once. The set-up of the serial port baud rates and other characteristics can be found over the O.S system control function. (see Fig. 13.8-11).
Die Action sequence "1"

Here the input variables (Stop, table1M,) are set to FALSE to prevent unwanted conditions from arising. In this sequence the file name filed is filled with an empty string. The Sub VI „MO/MF“ permits a check right at the onset to find is the motor is in operational condition ON or not. Is the motor not operational, a fault message is issued through the Sub Vi.

Fig. 13.8-12 Sequence 1
The Action sequence

The main sequences to the determination of mid position of optical Sources are described in the second part.
In a „While“-loop seven „Case“ tests contained in the operator panel input are repeated (see Chapter 13.8.2).

- Enter Filename
- Manual Positioning
- Measurement/Rough Scan
- Calculations
- Fine Scan
- Load Data

The „While“-Loop is left by operation of End Program or Emergency Stop.

In the following part, the above named CASE tests are explained in detail.

Fig. 13.8-13 VI stop and end program
Fig. 13.8-14 Action sequence "2"
13.8.4.2 File entered

In the user window under the Register card "Measurement", if the Filename is input and the Enter- button operated, the CASE test will be set to True. Through File Dialog (1) a Dialog box (Windows) opens in which the path can be given, where the measurement results can be stored.

After closing the dialog box with OK or Enter, a tick is set to indicate a successful input. The file name is then given the ending .rsd (Rough Scan Data) or .fsd (Fine Scan Data). These files are then stored in the given paths, allowing the data to be recalled at any time.

Fig. 13.8-15 Enter File name
13.8.4.3 Manual Positioning

Here the manual control of the X-, Y- and Z-Axes are carried out. During runtime the buttons 1,3,4,6,7,9 (see 13.8.2.1) are tested of „True“. If positive, it is checked which button of which axis is activated.

Additionally the centre-positioned buttons tested. Is as example button 1 activated, the axis 1 will drive at low speed in the negative (left) direction. If button 2 is additionally activated, the axis will be driven at higher speed left. (see example Fig. 13.8-16)

![Diagram of manual positioning](image)

Fig. 13.8-16 Manual Positioning

While sending commands via RS-232 on the Controller, the following abbreviations should be understood:

As example, if button 1 only is pressed, command **1PR-0.10000** will be sent via RS232.
Is the button "Home" (Drive all axis to zero position) operated, commands "1PA0.0000", and "2PA0.0000", "3PA0.0000" are sent in sequence.
If the actual position is to be output, commands "1TP, 2TP, 3TP" are required.

![Diagram of 3 axes and command to output](image)

**Fig. 13.8-19** VI – ReadPos of axis 1

The actual analogue measurement value recording of the intensity is carried out by a LabVIEW provided SubVI: As input in SubVI „AI one pt“ the Unit number, the Channel number (Measurement & Automation Explorer) and the upper and the lower Limits of the measurement values are required.

→ Unit number = 1
→ Channel number = 0
→ Upper Limits = 10
→ Lower Limits = 0

![Diagram of measurement of intensity](image)

**Fig. 13.8-20** Measurement of intensity
Structuregram „Manual Positioning“

**Manual Positioning**

If button is pressed

<table>
<thead>
<tr>
<th>YES</th>
<th>If axis 1L or 1R is pressed</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>If axis 1L is pressed</td>
<td>NO</td>
</tr>
<tr>
<td>YES</td>
<td>If axis 1M is active</td>
<td>NO</td>
</tr>
<tr>
<td>YES</td>
<td>Send 1PR-1.0000 to RS232</td>
<td>YES</td>
</tr>
<tr>
<td>YES</td>
<td>Send 1PR-0.1000 to RS232</td>
<td>YES</td>
</tr>
<tr>
<td>YES</td>
<td>Button &quot;1L set to false&quot;</td>
<td>YES</td>
</tr>
<tr>
<td>YES</td>
<td>Button &quot;1R set to false&quot;</td>
<td>YES</td>
</tr>
<tr>
<td>YES</td>
<td>IF Home button is active</td>
<td>NO</td>
</tr>
<tr>
<td>YES</td>
<td>Send 1PA-0.0000, 2PA0.0000, 3PA0.0000 to RS232</td>
<td></td>
</tr>
<tr>
<td>YES</td>
<td>IF Home button ReadPos active</td>
<td>NO</td>
</tr>
<tr>
<td>YES</td>
<td>Send 1TP, 2TP, 3TP to RS232</td>
<td></td>
</tr>
<tr>
<td>YES</td>
<td>Measure the present intensity and display it on screen</td>
<td></td>
</tr>
<tr>
<td>YES</td>
<td>while button &quot;stop manual control&quot; is true</td>
<td></td>
</tr>
</tbody>
</table>

Enquiry if axis 2 (R or L) or axis 3 (R or L) are active? Sequence equal to axis 1

Fig. 13.8-21 Structuregram „Manual Positioning“
13.8.4.4 Measurement - Rough Scan

In this program part, the "Rough Scan" carried out over a previously given surface. Before the scan can be started, three input conditions have to be met. They are:

- The file name (path data)
- Manual control function must be "True"
- The start button for Rough Scan must be activated.

---

**Fig. 13.8-22 Structuregram ,,Measurement/Rough Scan**
With the preset step-width, the surface (Length A) is driven over and the intensity at the reached positions measured. The X-Axis (left to right) is driven first.

When a row has been scanned, the Y-axis is moved one step and the procedure repeated. This procedure is repeated until the entire Step Width set area has been covered and scanned. The actual progress position can be followed in an intensity graph (Result Measurement. For later use in e.g. calculation of middle (Calculation, Fine Scan) the measurement values are stored in array form. Rough Scan data is stored in a previous determined file name and can be recalled at any time. Operation of the EMERGENCY STOP switch is possible at any time during the run, putting the system in the EMERGENCY STOP-condition.

13.8.4.4.1 Calculation

After the measurement modes have been defined (First Maximum, Binary.) in the Operator field, to start calculations two further conditions are required:

- Button “Calculate” must be activated
- Rough Scan must be completed

In the related checkbox, the tick is displayed when the conditions are met.
Rough Scan data has been previously stored in 2-Dimensional array. This data is made available for the calculations. A generally available „Median Filter“ smoothes or adjusts individual intensity values to their background intensities If the option is used, the array data will be made available not filtered for the different calculation types. The different types are covered in chapter 3.2.3.
After calculation, the indices (Coordinates) of the middle points are ascertained and displayed in a window by flashing pixel (Calculated centre flashes) and transmitted to the Fine Scan function.

See Structuregram Fig. 13.8-23.
Appendix 337

Calculation

Type of calculation (First maximum, binary, binary filtered, manually)

IF calculate and rough scan confirmed?

Centre calculation done (checkbox true)

Call array of rough scan

Median filter ON?

Filtered data array of rough scan for centre calculation

Non-filtered data array of rough scan for centre calculation

Filtered data array of rough scan for centre calculation

Non-filtered data array of rough scan for centre calculation

Which type is chosen?

Calculation of centre - first maximum - threshold - manually -

Calculation of centre - binary filtered -

Calculation of centre - binary filtered -

Calculation of centre - binary filtered -

Output of centre coordinates

Output of centre coordinates

Output of centre coordinates

Output of centre coordinates

Fig. 13.8-23 Structuregram „Calculation”

13.8.4.4.2 Fine Scan

Two Options permit the user to refine the surface to be scanned:

- „By length“
- „Interactive“

Two necessary conditions again have to be met before Fine Scan can be carried out, the Middle calculation function checkbox must display a tick, and the button “Start” in Fine Scan must be activated.

In “By Length“-Mode, a quadrant table area around the calculated middle with the input step-width (a) and side length (A) is input.

In „Interactive“-Mode the area to be scanned is set through two co-ordinate graticules.

See operator instructions Chapter (13.8.2.2.3).

The movement of the axis drives are covered by the same routine (Chapter 13.8.4.4) except in Fine Scan. Data is stored and made available as required to the next Centre Axis routine.

The calculated middle position should be driven to after recalculation as in „Calculation“. The calculation routine is as in Chapter (13.8.4.4.1).
Fine Scan

Adjustment of grid size
"By length" or "Interactive"

Adjustment of length B of area scan

If button Start in FineScan is pressed and checkbox centre calculation active?

YES

case 1
A square area is located around the calculated centre
Move axis 1 (X) in left corner of area to be scanned
Move axis 3 (Y) in lower corner of area to be scanned
Wait until movement of axis 1 (X) is finished
Wait until movement of axis 3 (Y) is finished

Process of movements during fine scan is similar to procedure of rough scan
Save Data of FineScan and transmission of position array to centre axis

If centre axis active?

YES
New calculation of centre, respectively max. intensity.
The new calculation is similar to the previous.
Move axis 1 (X) in point of maximum intensity
Move axis 3 (Y) in point of maximum intensity
Wait until movement of axis 1 (X) is finished
Wait until movement of axis 3 (Y) is finished
Checkbox "axis centered" is active

NO

case 2
The area to be scanned is defined by means of 2 cursors in the intensity graph
Move axis 1 (X) in left corner of area to be scanned
Move axis 3 (Y) in lower corner of area to be scanned
Wait until movement of axis 1 (X) is finished
Wait until movement of axis 3 (Y) is finished

Fig. 13.8-24 Structuregram „Fine Scan“
13.8.4.4.3 Load Data from File

All previous data stored from Rough or Fine Scans can be opened for re-use here. Operation of the “File” Buttons in user mask „Load Data“ opens the desired data. The required path to the data should be previously defined, however. By the SubVI „Read File From Spreadsheet“, the numerical text files are read in sequentially and converted into a 2-Dimensional array. The array can now by optically displayed in an intensity graph. (see Operator instructions).

![Fig. 13.8-25 Read Data From File](image1)

![Fig. 13.8-26 Structuregram Load Data from File](image2)
Action sequence "3"

The last sequence closes the RS232-Interface. If an error occurs at closing the interface or communication between PC and Controller be detected, an error message will be given.

SubVI "RS232" to close the interface

Fig. 13.8-27 SubVI-RS232 close interface
13.9 Pulsed Nd:YAG Laser HL 204P

HL 204P/4: Front view and left side view

Fig. 13.9-1 HL 204P/4: Top view

Fig. 13.9-2 Space for service works at HL 204P/4
13.9.1 Laser Light Cable

The length of the laser light cable depends on the distance between laser device and processing optics. Laser light cables with dimensions according to the following table are delivered together with the laser device.

<table>
<thead>
<tr>
<th>Laser</th>
<th>Fibre core diameter</th>
<th>Length of the laser light cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>HL 62P</td>
<td>200 µm</td>
<td>4 m, 6 m, 10 m, 15 m, 20 m</td>
</tr>
<tr>
<td>HL 124P</td>
<td>400 µm</td>
<td>4 m, 6 m, 10 m, 15 m, 20 m</td>
</tr>
<tr>
<td>HL 204P</td>
<td>400 µm</td>
<td>4 m, 6 m, 10 m, 15 m, 20 m</td>
</tr>
</tbody>
</table>

Fig. 13.9-3 Length of the laser light cable

Standard lengths of the laser light cable:

**Standard lengths**: 4 m, 6 m, 10 m, 15 m, 20 m

The specified values are usable lengths, measured from the outlet at the laser device. Information about the lengths of your laser light cables is to be found in the documentation delivered together with your laser device.

**Bending radius**: The bending radius of the laser cable **must be smaller than 200 mm**.

**Installation**: The laser light cables have to be installed without tensile stress and buckles.
13.9.2 Connections

This section contains information about: External connections in the base of the laser device interfaces on the control unit and on the mains distribution.

13.9.2.1 External Connections in the Base

**Fig. 13.9-4** External connections

- **Power supply:** The laser device is supplied with electrical power via a mains cable. The mains cable is connected to the laser device.

- **Cooling water hoses:** Connections for supply and return 3/4 inch. The hoses are attached to the connections and sealed with 2 hose clamps each.

- **Ethernet interface for the operating PC:** The control system is connected to the operating PC by means of the Ethernet interface. The cable that connects the operating PC to the control unit must not be longer than 75 m.

- **I/O interface or field bus:** The I/O interface can be used to connect the laser device to an interface external control system (e.g. a PLC) and to control it from there.
The laser device can also be controlled by means of one of the following fieldbusses:

- Interbus – S
- Profibus – DP
- DeviceNet.

In this case the board with the I/O interface is replaced by a card the chosen fieldbus system. Information about pin assignment and data format is then to be found in the interface description of the chosen field bus system.

**ASV interfaces for safety**  Shutter interfaces are located on the ASV and ASV2 boards.

The circuits shutter interfaces are part of the safety devices of the laser device. They make it possible to set up safety circuits (SIK), e.g. for monitoring shielding covers at the workstation.

**EMERGENCY STOP interface**  The EMERGENCY STOP interface (X7) allows:

- further EMERGENCY STOP pushbuttons to be connected to the laser device or
- the laser device to be integrated in a higher-ranking EMERGENCY STOP circuit.

The higher-ranking EMERGENCY STOP circuit can be part of a system the laser device is a component of.

**Note**  When installing the cable to an external EMERGENCY STOP device, make sure that it cannot get pinched or rolled over.

**Interface for external control unit**  The contacts which are necessary to activate the function “Control ON”, “Control OFF” from an external device (e.g. an PLC) are provided on the interface X8 on the SUN board. In addition to that, the interface has contacts for connecting an external laser warning lamp and an external monitoring lamp.

**Interface for connecting**  The control panel for switching the control on and off is connected to interface X12. If operating the laser device without a control panel, you have to ensure that the signals generated by the control panel are applied to this interface by some other way.
13.9.2.2 Overview – Pulsed Nd:YAG Laser HL204P

Fig. 13.9-5 Overview laser components

Power data

The following values of laser power, pulse energy and beam parameter product are available at the processing station. By means of the laser power control these values will be reached even if the arc lamps show a loss in efficiency at the end of their life time.

<table>
<thead>
<tr>
<th></th>
<th>HL 62P</th>
<th>HL 124P</th>
<th>HL 204P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave length of the laser light</td>
<td>1064 nm</td>
<td>1064 nm</td>
<td>1064 nm</td>
</tr>
<tr>
<td>Maximum average power</td>
<td>60 W</td>
<td>120 W</td>
<td>200 W</td>
</tr>
<tr>
<td>Minimum pulse power</td>
<td>250 W</td>
<td>300 W</td>
<td>500 W</td>
</tr>
<tr>
<td>Maximum pulse power</td>
<td>3000 W</td>
<td>5000 W</td>
<td>8000 W</td>
</tr>
<tr>
<td>Pulse duration at max. pulse power</td>
<td>0.2 – 10 ms</td>
<td>0.3 – 10 ms</td>
<td>0.3 – 9.8 ms</td>
</tr>
<tr>
<td>Pulse duration at reduced pulse power</td>
<td>0.2 – 20 ms</td>
<td>0.3 – 20 ms</td>
<td>0.3 – 20 ms</td>
</tr>
<tr>
<td>Maximum pulse energy</td>
<td>30 J</td>
<td>50 J</td>
<td>75 J</td>
</tr>
<tr>
<td>Maximum pulse repetition frequency</td>
<td>200 Hz</td>
<td>300 Hz</td>
<td>400 Hz</td>
</tr>
<tr>
<td>Beam parameter product</td>
<td>16 mm mrad</td>
<td>16 mm mrad</td>
<td>16 mm mrad</td>
</tr>
</tbody>
</table>

Further performance characteristics can be seen in the Characteristic curves on the following pages.
Laser light cable: Number and the length of the laser light cables depends on the application of the laser device.

Processing optics: Number and arrangement of the processing optics depend on the machining task the laser device has to carry out.

Control Panel: The control panel is an optional part of the laser device. The functions of the control panel can also be carried out by an external control system such as a PLC. Detailed information can be found in the interface description.

Operating PC: The operating PC is usually a commercially available device. An industrial PC is delivered for special applications. If desired by the customer, the laser device can also be delivered without the operating PC.

Chiller: A chiller can optionally be included in the scope of delivery. Please refer to the manufacturer's documentation for information about the chiller.
13.9.2.3 Components of the Optical Arrangement

![Diagram of optical arrangement](image)

1. Laser beam, blocked
2. Mirror inside the beam guideway
3. Absorber
4. Laser beam, released
5. Mirror outside the beam guideway

Fig. 13.9-7 Central shutter (VZ) [150]

The exit of a laser beam can be released (B) or locked (A) by means of the central shutter. When the laser beam is released, it passes the central shutter as shown chart B. When the laser beam is locked, the central shutter guides the laser beam into an absorber (3), where it will be transformed into heat.

In dead condition the central shutter is locked. The central shutter has two functions:

**Operating function:** In the operating function the central shutter is controlled by operator-originated commands or laser programs as long as the safety circuit is closed.

**Safety function:** When the safety circuit is interrupted, the central shutter is immediately closed. This also happens when the command to open comes from the operator or from the running laser program.

Information about the functioning and the wiring of the central shutter is to be found in the interface description.
Shutter switch (VW1, VW2, ...)

A shutter switch is a beam switch with a safety function. Its design does not differ from that of a usual beam switch. The difference lies in the activation of the shutter switch by an ASV or ASV2 board. The shutter switch is integrated into a safety circuit via the ASV or ASV2 board. The shutter switch has two functions:

**Operating function** In the operating function the central shutter is controlled by operator originated commands or laser programs as long as the safety circuit is closed.
**Safety function**  When the safety circuit is interrupted, the shutter switch is immediately positioned so that the laser beam is guided into an absorber (see picture before, chart A). This also happens when the command to open comes from the operator or from the running laser program.

Information about functioning and wiring of the safety circuit is to be found in the interface description.

The number of shutter switches in one optical arrangement corresponds in general to the number of light paths. The shutter switches are arranged in one line. They are activated in such a way that at most one shutter switch is open (mirror in the beam guideway, see picture above, charts B and C). So it is ensured that in case of interrupted safety circuit, the laser beam is always guided into the absorber which is located at the end of the line.

**Beam switch (W1, W2, ...)**

![Diagram](image)

**Fig. 13.9-9 Beam switch [150]**

The laser can optionally be guided into one of two directions by means of a beam switch. If the mirror is in the beam guideway, the laser beam is deflected by 90° (B). If the mirror
is swivelled out of the beam guideway, the laser beam passes the beam switch straight (A). The beam switch can be controlled via operator commands or via laser program.

![Physical Splitter](image)

Fig. 13.9-10 Physical Splitter [150]

The physical splitter the laser beam into two beams. The ratio of power in the individual beams is constant. Each beam contains 50 % of the power. One beam continues in a straight line. The other beam is deflected by 90 % to the right or left.

![Physical Splitter with adjustable splitter ratio](image)

Fig. 13.9-11 Physical splitter with adjustable splitter ratio [150]

The physical splitter with adjustable splitter ratio contains a semi-transparent mirror with variable transparency over the angle of rotation. Accordingly, the splitter ratio depends on the angular position of the mirror. The proportion a of the deflected beam can be set to a value in the range from 20 % to 80 % on an actuator (arrow).
The deflection deflects the laser beam by 90% to the right or left.

The incoupling optics contains a lens which focuses the laser beam to the beginning of the light guide in the laser light cable. This results in low-loss incoupling of the laser beam into the laser light cable.
13.9.2.4 Selecting a light path

The positions of the mirrors in the controllable components of the optical arrangement (beam switches, shutter switches, shutters) determine the light path.

In the figure (Light path determined by VW2) above the mirror of shutter switch VW2 has been swiveled into the beam guidance. At this point, the laser is deflected by 90% and coupled into the laser light cable connected to this light path.

In the figure (Light path determined by VW1) the mirror of shutter switch VW1 has been swiveled into the beam guidance. At this point, the laser is deflected by 90% and coupled into the laser light cable connected to this light path.
13.9.2.5 Laser light cable

Purpose  The laser light cable is a flexible transmission medium for laser beams. It allows spatial separation between laser and machining station.

Structure  In the interior of the laser light cable there is a light guide, which guides the laser beam from the laser device to the processing optics.

The light guide is surrounded by a plastic tube and a steel case. The steel case protects the light guide from mechanical stress. It limits the bending radius of the laser light cable.

The steel case is surrounded by an external plastic tube which protects the laser light cable against environmental effects.

A safety circuit integrated into the laser light cable switches off the laser automatically, if the light guide is damaged or the laser light cable has been removed from the laser or the processing optics.
Table 13.9-3  Technical data

<table>
<thead>
<tr>
<th></th>
<th>HL 62P</th>
<th>HL 124P, HL 204P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fibre core diameter</strong></td>
<td>200 µm</td>
<td>400 µm</td>
</tr>
<tr>
<td><strong>Standard lengths</strong></td>
<td>4 m, 6 m, 15 m, 20 m</td>
<td>Extensions in steps of 5 m available up to 50 m</td>
</tr>
<tr>
<td><strong>Minimum permissible bending radius</strong></td>
<td>200 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Cable diameter</strong></td>
<td>12.5 mm</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 13.9-17  Laser light cable, components [150]

**Monitoring**

The laser light cable is monitored on the whole length. The laser device switches off immediately and no more laser light may be emitted if a fault occurs in the laser light cable.

The fit of the two optical plugs is monitored as well. If an optical plug is loosened, the laser device immediately switches off.

The electrical plug (3) connects the integrated safety monitoring of the laser light cable to the safety circuit of the laser device. The cable adapter (4) allows the monitoring cable to be connected when the counterpiece is terminated by a round plug.
Laying the LLK

Outside laser protection cabins the laser light cables have to be laid firmly.

For this can be used:
- cable clamps
- cable ducts
- other suitable auxiliary means for fixing cables.

Inside laser protection cabins which are monitored by a safety circuit, laser light cables may be laid freely and movably.

Control

Fig. 13.9-18 Control unit [150]

The control unit controls all functions of the laser device. Apart from this, it monitors numerous operational values and reports when a value is outside the permitted range.

The control contains interfaces to higher-ranking controls. They allow an external control of the laser device. For more information, please the interface description.

Controlling

The most important functions are:
- Switching the laser on and off.
- Controlling the optical arrangement.
- Executing and managing laser programs.
- Communication with external devices (e.g. PLC).

Monitoring

The control also monitors among others the following operational values:
- Laser power.
- Temperature of the coolants.
- Temperatures within the area of the laser and of the optical arrangement.
- Condition of the laser light cable.
- Safety contacts at the processing points.

**Messages**

If an operational value is outside the permitted range, the control system generates a monitoring message or a fault message.

A corresponding message is displayed on the monitor of the operating PC. When a malfunction occurs, the control stops the operating of the laser until the cause for the malfunction is eliminated.

**Configuration**

The control is compiled of electronics subassemblies as shown in the following figure.

The configuration of the control may differ in individual cases from the one indicated in the figure [148].

![Control unit description](image)

**Fig. 13.9-19** Control unit description [150]
### 13.10 Sensors, Detectors and Power Supply Drivers

#### 13.10.1 WINCAM-PCI

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Specification WINCAM-PCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurable Sources</td>
<td>CW and pulsed Sources</td>
</tr>
<tr>
<td>Measured Beam Powers</td>
<td>5 μW to 20 mW, for a 1 mm diameter Gaussian beam at 633nm, ND 4.0 filter installed</td>
</tr>
<tr>
<td>Electronic Dynamic Range</td>
<td></td>
</tr>
<tr>
<td>CW beams</td>
<td>32 dB (1, 600:1) for 20dB SNR, using electronic and CCD gain control</td>
</tr>
<tr>
<td>shutter</td>
<td></td>
</tr>
<tr>
<td>Pulsed, pulse-width &lt; 100 μs</td>
<td>10 dB (10:1) for 20dB SNR, using CCD gain control</td>
</tr>
<tr>
<td>Pulsed, pulse width &gt; 100 μs</td>
<td>10dB min. for &lt;100 μs pulse width, 32 dB max. for 16ms pulse width</td>
</tr>
<tr>
<td>Manual Dynamic Range</td>
<td>Up to 40 dB (10,000:1) using C-mount Neutral Density filters available from</td>
</tr>
<tr>
<td>All beams</td>
<td></td>
</tr>
<tr>
<td>SNR</td>
<td>24dB B (250:1) optical signal to noise ratio</td>
</tr>
<tr>
<td>(Signal-to-RMS Noise Ratio)</td>
<td></td>
</tr>
<tr>
<td>Imaged Beam Dimensions</td>
<td></td>
</tr>
<tr>
<td>WCAM 6</td>
<td>4.89 x 3.64mm (“1/3 inch” camera format)</td>
</tr>
<tr>
<td>WCAM 8</td>
<td>6.46 x 4.83mm (“1/2 inch” camera format)</td>
</tr>
<tr>
<td>Pixel Dimensions</td>
<td>external optics.</td>
</tr>
<tr>
<td>WCAM 6</td>
<td>6.5(H) x 6.25(V) mm pixels (752 x 582 usable pixels)</td>
</tr>
<tr>
<td>WCAM 8</td>
<td>8.6(H) x 8.3 (V) mm pixels (752 x 582 usable pixels)</td>
</tr>
<tr>
<td>Measurement Accuracy</td>
<td>1% +/- 1μm absolute accuracy, for beams &gt; 100μm</td>
</tr>
<tr>
<td>Measured &amp; Displayed Profile Parameters</td>
<td></td>
</tr>
<tr>
<td>X &amp; Y</td>
<td>Gaussian beam diameter</td>
</tr>
<tr>
<td>2-D plot (10, 16 or 256 colors)</td>
<td></td>
</tr>
<tr>
<td>3-D plot (10, 16 or 256 colors)</td>
<td></td>
</tr>
<tr>
<td>Displayed Profiles</td>
<td>Gaussian fit</td>
</tr>
<tr>
<td>Update Rate</td>
<td>25Hz max. for full screen.</td>
</tr>
</tbody>
</table>
**Data Analysis**

Pass/ Fail  
On-screen, in selectable Pass/ Fail colours

Averaging  
Beam diameter running average

Log data and statistics  
Up to 4096 samples. Min., Max., Mean, Standard

Deviations  
Units of mW (relative to a reference measurement provided by the user as an input to the software.)

Source to Sensor Distance  
1.0mm minimum, with ND filter removed.

Wavelength Range  
WCAM6 & WCAM8 350 to 1150nm, Silicon CCD Camera
WCAM6/NG & WCAM8/NG 190 to 1150nm (cover glass removed)
Third party cameras <190nm; 1.2μm to 20 μm; contact

Dimensions  
Across axis width x Height x along axis depth
Camera Head 148 x 90 x 22mm (5.8 x 3.5 x 0.9 inches)
(See drawing below) 200mm (8 inches with cable connected)

Mounting  
¼-20 & M6 threaded mounting holes

Camera Port Adapter  
Standard 1”x 32 TPI C-Mount internal thread

Weight, Camera Head  
340gm (0.75 lb)

Imaging Board  
Standard PCI with 9-pin & 15-pin D sockets
RCA type input for RS-170 & CCIR cameras.
WinCAM works with almost any third party camera
Standard RS-170 (NTSC), CCIR & Pyrocam camera
files are included. Custom files may be user-generated.

Camera Cable  
9 pin D-connectors 3m (10ft.) standard length.

---

**Figure 13.10-1** Schematic beam profiler [151]
13.10.1.1 WinCAM PCI Card Edge Connectors

![Diagram of WinCAM PCI Card Edge Connectors]

<table>
<thead>
<tr>
<th>RCA 75 Ohm</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-pin female D-Connector</td>
</tr>
<tr>
<td>Pin 1</td>
</tr>
<tr>
<td>Pin 2</td>
</tr>
<tr>
<td>Pin 3</td>
</tr>
<tr>
<td>Pin 4</td>
</tr>
<tr>
<td>Pin 5</td>
</tr>
<tr>
<td>Pin 6</td>
</tr>
<tr>
<td>Pin 7</td>
</tr>
<tr>
<td>Pin 8</td>
</tr>
<tr>
<td>Pin 9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>15-pin female D-connector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pin 1</td>
</tr>
<tr>
<td>Pin 2</td>
</tr>
<tr>
<td>Pin 3</td>
</tr>
<tr>
<td>Pin 4</td>
</tr>
<tr>
<td>Pin 5</td>
</tr>
<tr>
<td>Pin 6</td>
</tr>
<tr>
<td>Pin 7</td>
</tr>
<tr>
<td>Pin 8</td>
</tr>
<tr>
<td>Pin 9</td>
</tr>
<tr>
<td>Pin 10</td>
</tr>
<tr>
<td>Pin 11</td>
</tr>
<tr>
<td>Pin 12</td>
</tr>
<tr>
<td>Pin 13</td>
</tr>
<tr>
<td>Pin 14</td>
</tr>
<tr>
<td>Pin 15</td>
</tr>
</tbody>
</table>

Fig. 13.10-2 Connector Pin Assignments

Trigger Input: Connect to Pins 6 (TTL signal) and 15 (TTL Ground) [151]
13.10.1.2 WinCAM Software

![GUI WinCAM Software](image)

**Fig. 13.10-3 GUI WinCAM Software [151]**

1. Pull-down Menu Bar
2. Button Bar, access to frequently used functions
3. Status and enhanced diagnostics
4. WinCAM button, one of many – signal level
5. Main window
6. Help Hint; place the cursor on the region/item of interest & find a hint here
7. 3D-view
8. Thumbnail view area
9. Vertical Y axis profile
10. Horizontal X axis profile
13.10.2 PDA55 Switchable Gain, Amplified Silicon Detector

The PDA55 is an amplified, switchable-gain, silicon detector designed for detection of light signals from DC to 10 MHz. A five-position rotary switch allows the user to vary the gain in 10 dB steps. A buffered output drives a 50Ω load impedance up to 5 volt. The PDA55 housing includes a removable threaded coupler that is compatible with any number of Thorlabs 1” threaded accessories. This allows convenient mounting of external optics, light filters, apertures, as well as providing an easy mounting mechanism using the Thorlabs cage assembly accessories.

The PDA55 has an 8-32 tapped mounting hole with a 0.25” mounting depth and includes a 1 20 VAC power AC/DC supply. The PDA55-EC has an M4 tapped mounting hole and includes a 230 VAC AC/DC power supply.

<table>
<thead>
<tr>
<th>Detector</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Area</td>
<td>3.6 x 3.6 mm</td>
</tr>
<tr>
<td>Response</td>
<td>320 to 1100 nm</td>
</tr>
<tr>
<td>Peak Response</td>
<td>0.6 A/W @ 960 nm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>DC to 10MHz</td>
</tr>
<tr>
<td>NEP (960nm, 0dB)</td>
<td>1 x 10^-11 W/Hz</td>
</tr>
<tr>
<td>NEP (960nm, 10dB)</td>
<td>8 x 10^-11 W/Hz</td>
</tr>
<tr>
<td>NEP (960nm, 20dB)</td>
<td>5 x 10^-11 W/Hz</td>
</tr>
<tr>
<td>NEP (960nm, 30dB)</td>
<td>4 x 10^-11 W/Hz</td>
</tr>
<tr>
<td>Output Voltage (50:1)</td>
<td>0 to 5V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>0 to 10V</td>
</tr>
<tr>
<td>Output Impedance</td>
<td>50 ohms</td>
</tr>
<tr>
<td>Load Impedance</td>
<td>Hi-Z to 50 ohms</td>
</tr>
<tr>
<td>Gain Steps</td>
<td>0, 10, 20, 30, 40 dB</td>
</tr>
<tr>
<td>Gain Switch</td>
<td>5-Pos Rotary</td>
</tr>
<tr>
<td>On / Off Switch</td>
<td>Toggie</td>
</tr>
<tr>
<td>Output</td>
<td>BNC</td>
</tr>
<tr>
<td>Damage Threshold</td>
<td>100mW CW</td>
</tr>
<tr>
<td>Optical Head Size</td>
<td>0.5/7cm 10ns PW</td>
</tr>
<tr>
<td>Weight</td>
<td>60 grams</td>
</tr>
<tr>
<td>Accessories</td>
<td>SM1T1 Coupler</td>
</tr>
<tr>
<td>Storage Temp</td>
<td>-55 to 125 C</td>
</tr>
<tr>
<td>Operating Temp</td>
<td>-20 to 70 C</td>
</tr>
<tr>
<td>AC Power Supply</td>
<td>AC - DC Converter</td>
</tr>
<tr>
<td>Input Power</td>
<td>100-120VAC, (220-240VAC-EC version)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance</th>
<th>min</th>
<th>typical</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 dB Setting</td>
<td>Transimpedance</td>
<td>1.5 x 10. V/A</td>
<td></td>
</tr>
<tr>
<td>Trans. Gain (50:1)</td>
<td>0.75 x 10^5 V/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise (RMS)</td>
<td>0.28 mV</td>
<td>0.33 mV</td>
<td>0.44 mV</td>
</tr>
<tr>
<td>Offset</td>
<td>5 mV</td>
<td>6 mV</td>
<td>15 mV</td>
</tr>
<tr>
<td>10 dB Setting</td>
<td>Transimpedance</td>
<td>4.7 x 10. V/A</td>
<td></td>
</tr>
<tr>
<td>Trans. Gain (50:1)</td>
<td>2.35 x 10^5 V/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2.3MHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise (RMS)</td>
<td>0.30 mV</td>
<td>0.35 mV</td>
<td>0.40 mV</td>
</tr>
<tr>
<td>Offset</td>
<td>5 mV</td>
<td>8 mV</td>
<td>15 mV</td>
</tr>
<tr>
<td>20 dB Setting</td>
<td>Transimpedance</td>
<td>1.5 x 10. V/A</td>
<td></td>
</tr>
<tr>
<td>Trans. Gain (50:1)</td>
<td>0.75 x 10^5 V/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>700kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise (RMS)</td>
<td>0.36 mV</td>
<td>0.40 mV</td>
<td>0.46 mV</td>
</tr>
<tr>
<td>Offset</td>
<td>10 mV</td>
<td>10 mV</td>
<td>20 mV</td>
</tr>
<tr>
<td>30 dB Setting</td>
<td>Transimpedance</td>
<td>4.7 x 10. V/A</td>
<td></td>
</tr>
<tr>
<td>Trans. Gain (50:1)</td>
<td>2.35 x 10^5 V/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>170kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise (RMS)</td>
<td>0.46 mV</td>
<td>0.53 mV</td>
<td>0.60 mV</td>
</tr>
<tr>
<td>Offset</td>
<td>20 mV</td>
<td>20 mV</td>
<td>50 mV</td>
</tr>
<tr>
<td>40 dB Setting</td>
<td>Transimpedance</td>
<td>1.5 x 10. V/A</td>
<td></td>
</tr>
<tr>
<td>Trans. Gain (50:1)</td>
<td>0.75 x 10^5 V/A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>60kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noise (RMS)</td>
<td>0.74 mV</td>
<td>0.81 mV</td>
<td>1.0 mV</td>
</tr>
<tr>
<td>Offset</td>
<td>100 mV</td>
<td>20 mV</td>
<td>100 mV</td>
</tr>
</tbody>
</table>
Operation

- The PDA55 gain is adjusted using a small slotted screwdriver to turn the internal, gain-setting rotary switch. An access hole labeled GAIN is provided on the rear panel for this purpose. The gain is set to 0dB, when the slot is aligned counterclockwise as far as it will go. Each clockwise click of the switch increases the gain by 10 dB. Do not use excessive force when adjusting the gain switch.

- The PDA55 is switched on by the POWER toggle switch located on the rear of the optical sensor.

- The light to voltage conversion can be estimated by factoring the wavelength-dependent responsivity of the silicon detector with the transimpedance gain as shown below:

  (e.g. output in volts / watt = transimpedance gain (V/A) x responsivity (A/W))

- The maximum output of the PDA55 is 10 volts for high impedance loads (5V for 50: loads). Adjust the gain so that the measured signal level out of the PDA55 is below 10 volts (5 volts with a 50: load) to avoid saturation. If necessary, use external neutral density filters to reduce the input light level.

- For maximum linearity performance when measuring focused beams, fibre outputs, or small diameter beams, do not exceed a maximum intensity of 1 0mW/cm^2.

- Because of the finite gain-bandwidth performance common to all amplifier circuits, the bandwidth of the PDA55 goes down with increased gain settings.

<table>
<thead>
<tr>
<th>Gain Switch position</th>
<th>Gain (dB)</th>
<th>Transimpedance Gain (V/A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.5 x 10^5</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>4.7 x 10^5</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>1.5 x 10^5</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>4.7 x 10^5</td>
</tr>
<tr>
<td>5</td>
<td>40</td>
<td>1.5 x 10^5</td>
</tr>
</tbody>
</table>

Gain Settings

Fig. 13.10-4 Detector Responsivity [156]
Maintaining the PDA55

There are no serviceable parts in the PDA55 optical head or power supply. The housing may be cleaned by wiping with a soft damp cloth. The window of the detector should only be cleaned using optical grade wipes. If you suspect a problem with your PDA55 please call Thorlabs and technical support will be happy to assist you.

Fig. 13.10-5  Scale Drawing PDA55 [156]
13.10.2 Laser Sensor CP24MHT80

The sensor uses a high-resolution CMOS line array and DSP technology, virtually eliminating material, colour and brightness related measurement value differences. The Measurement range is calibrated accurate to 10µm. Integrated analogue output can be configured for voltage 0…10 V (10…0 V) or current 4…20 mA (20…4 mA) [157].

<table>
<thead>
<tr>
<th>Table 13.10-2 Optical and Electrical Data [157]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical Data</strong></td>
</tr>
<tr>
<td>Working Range</td>
</tr>
<tr>
<td>Measuring Range</td>
</tr>
<tr>
<td>Resolution</td>
</tr>
<tr>
<td>Resolution (Speed-Mode)</td>
</tr>
<tr>
<td>Linearity</td>
</tr>
<tr>
<td>Linearity (Speed-Mode)</td>
</tr>
<tr>
<td>Light Source</td>
</tr>
<tr>
<td>Wave Length</td>
</tr>
<tr>
<td>Service Life (T = +25°C)</td>
</tr>
<tr>
<td>Laser Protection Class (EN 60825-1)</td>
</tr>
<tr>
<td>max. Ambient Light</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 13.10-3 Mechanical Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Data</strong></td>
</tr>
<tr>
<td>Adjustment</td>
</tr>
<tr>
<td>Housing</td>
</tr>
<tr>
<td>Protection Mode</td>
</tr>
<tr>
<td>Connection</td>
</tr>
<tr>
<td>Protective Insulation, Rated Voltage</td>
</tr>
</tbody>
</table>
Fig. 13.10-6 Reflex Sensor CP24MHT80

Fig. 13.10-7 Connection diagram [157]

Legend

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
<td>Power supply +24V</td>
</tr>
<tr>
<td>-</td>
<td>Power supply (AC Voltage)</td>
</tr>
<tr>
<td>A</td>
<td>Switching output (1,2,3,...) / NO</td>
</tr>
<tr>
<td>X</td>
<td>Switching output (1,2,3,...) / NC</td>
</tr>
<tr>
<td>V</td>
<td>Contamination / Error output (NC)</td>
</tr>
<tr>
<td>E</td>
<td>Input (analog or digital)</td>
</tr>
<tr>
<td>T</td>
<td>Teach input</td>
</tr>
<tr>
<td>Z</td>
<td>Time delay (activation)</td>
</tr>
<tr>
<td>S</td>
<td>Stecking</td>
</tr>
<tr>
<td>TNO</td>
<td>RS-232 receiver path</td>
</tr>
<tr>
<td>TDO</td>
<td>RS-232 sender path</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>Test input</td>
</tr>
<tr>
<td>W</td>
<td>Trigger input</td>
</tr>
<tr>
<td>O</td>
<td>Analog output (1,2,3,...)</td>
</tr>
<tr>
<td>0</td>
<td>Ground for the analog output</td>
</tr>
<tr>
<td>EZ</td>
<td>Block discharge</td>
</tr>
<tr>
<td>XW</td>
<td>Valve output</td>
</tr>
<tr>
<td>XW+</td>
<td>Valve control output &quot;+&quot;</td>
</tr>
<tr>
<td>XW-</td>
<td>Valve control output &quot;-&quot;</td>
</tr>
<tr>
<td>SY</td>
<td>Synchronization</td>
</tr>
<tr>
<td>E+</td>
<td>Emitter-Line</td>
</tr>
<tr>
<td>G+</td>
<td>Grounding</td>
</tr>
</tbody>
</table>

Wire colors according to DIN IEC 757

<table>
<thead>
<tr>
<th>Color</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>BK</td>
<td>black</td>
</tr>
<tr>
<td>BN</td>
<td>brown</td>
</tr>
<tr>
<td>RD</td>
<td>red</td>
</tr>
<tr>
<td>OR</td>
<td>orange</td>
</tr>
<tr>
<td>YE</td>
<td>yellow</td>
</tr>
<tr>
<td>GN</td>
<td>green</td>
</tr>
<tr>
<td>BU</td>
<td>blue</td>
</tr>
<tr>
<td>VT</td>
<td>violet</td>
</tr>
<tr>
<td>GY</td>
<td>grey</td>
</tr>
<tr>
<td>WH</td>
<td>white</td>
</tr>
<tr>
<td>PK</td>
<td>pink</td>
</tr>
<tr>
<td>GY/YE</td>
<td>green/yellow</td>
</tr>
</tbody>
</table>
### Control Panel

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>03</td>
<td>Error Indicator</td>
</tr>
<tr>
<td>07</td>
<td>Selector Switch</td>
</tr>
<tr>
<td>12</td>
<td>Analogue Output Indicator</td>
</tr>
<tr>
<td>24</td>
<td>Plus Button</td>
</tr>
<tr>
<td>25</td>
<td>Minus Button</td>
</tr>
<tr>
<td>63</td>
<td>Analogue Output Current Indicator</td>
</tr>
<tr>
<td>+/-</td>
<td>Minus and Plus Key with LED</td>
</tr>
<tr>
<td>Run</td>
<td>Sensor operation</td>
</tr>
<tr>
<td>RES./SPEED Mode</td>
<td>Switch Resolution</td>
</tr>
<tr>
<td>TEACH</td>
<td>Measurement range</td>
</tr>
<tr>
<td>RS-232</td>
<td>Interface operation</td>
</tr>
<tr>
<td>U/I Mode</td>
<td>Analogue Output</td>
</tr>
</tbody>
</table>

**Fig. 13.10-8** Control Panel [157]

**Housing Dimensions, Dimensioned Picture:**

![Scale Drawing of Laser Sensor](image)

All dimensions in mm (1 mm = 0.03937 Inch)

**Fig. 13.10-9** Scale Drawing of Laser Sensor [157]
NC-File for Laser Material Processing of Laser Sensor Holder

;SPATH=/_N_WKS_DIR/_N_WENGLOR_WPD
N100 ; (================================================================================================)
N110 ; ( Andreas Bünting )
N120 ; ( Laser Sensor Holder for Fine Welding Station )
N130 ; (================================================================================================)
N140 ; ( Customer: Andreas Bünting )
N150 ; ( Machine: Vmax and Nd:YAG Laser )
N160 ; ( PEPS CAD /CAM System Version 5.3.12 )
N170 ; ( PostProcessor Version: 2.00 itec )
N180 ; (================================================================================================)
N190 ; ( Material: No Stainless steel )
N200 ; ( Thickness: 2mm )
N210 ; ( Issued: 07.03.2006 )
N220 ; ( )
N230 ; ( PostProzessor Version: 2.00 itec AG )
N240 ; ( UppDate vom 29.07.2006: )
N310 ; (================================================================================================)
N320 T1D1
N330 G17 G60 G90
N340 SOFT FFWON
N350 INIT_MACH ; Machine parameter
N360 INIT_TECH ; Process parameter
N380 G01 Z=H_SAFEPOS_Z F=V_POS_Z
N390 G64
N400 G04 F0.2
N1000 TRANS X=H_CUT_X Y=H_CUT_Y Z=H_CUT_Z + THICKNESS
N1010 G01 X105.00 Y10.58 F=V_START
N1020 LASER_ON
N1030 G01 G41 F=PROC_SPEED_GATE
N1040 G1 X104 Y10.576
N1050 G3 X103 Y9.576 I0 J-1
N1060 G3 X103 Y9.576 I2 J0
N1070 LASER_OF
N1080 G01 X116.37 Y67.89 F=V_POS
N1090 LASER_ON
N1100 G01 G41 F=PROC_SPEED_GATE
N1110 G1 X116.164 Y66.908
N1120 G3 X116.934 Y65.722 I0.978 J-0.208
N1130 G2 X126.502 Y62.796 I11.934 J-56.146
N1140 G3 X128.001 Y66.505 I0.749 J1.854
N1150 G3 X107.143 Y70.939 I-23.001 J-56.929
N1160 G3 X107.003 Y66.941 I-0.07 J-1.999
N1170 G2 X116.934 Y65.722 I-2.003 J-57.365
N1180 LASER_OF
N1190 G01 X71.00 Y115.58 F=V_POS
N1200 LASER_ON
N1210 G01 G41 F=PROC_SPEED_GATE
N1220 G1 X69.25 Y115.576
N1230 G3 X68.25 Y114.576 I0 J-1
N1240 G1 X68.25 Y112.076
N1250 G3 X70.75 Y109.576 I2.5 J0
N1260 G1 X71.25 Y109.576
N1270 G3 X73.75 Y112.076 I0 J2.5
N1280 G1 X73.75 Y117.076
N1290 G3 X71.25 Y119.576 I-2.5 J0
N1300 G1 X70.75 Y119.576
N1310 G3 X68.25 Y117.076 I0 J-2.5
N1320 G1 X68.25 Y114.576
N1330 LASER_OFF
N1340 G01 X9.00 Y115.58 F=V_POS
N1350 LASER_ON
N1360 G01 G41 F=PROC_SPEED_GATE
N1370 G1 X7.25 Y115.576
N1380 G3 X6.25 Y114.576 I0 J-1
N1390 G1 X6.25 Y112.076
N1400 G3 X8.75 Y109.576 I2.5 J0
N1410 G1 X9.25 Y109.576
N1420 G3 X11.75 Y112.076 I0 J2.5
N1430 G1 X11.75 Y117.076
N1440 G3 X9.25 Y119.576 I-2.5 J0
N1450 G1 X8.75 Y119.576
N1460 G3 X6.25 Y117.076 I0 J-2.5
N1470 G1 X6.25 Y114.576
N1480 LASER_OFF
N1490 G01 X-5.00 Y113.68 F=V_POS
N1500 LASER_ON
N1510 G01 G41 F=PROC_SPEED_GATE
N1520 G1 X-2.4 Y113.676
N1530 G3 X0 Y116.076 I0 J2.4
N1540 G1 X0 Y126.076
N1550 G2 X2.5 Y128.576 I2.5 J0
N1560 G1 X113.964 Y128.576
N1570 G2 X115.732 Y127.844 I0 J-2.5
N1580 G1 X134.268 Y109.308
N1590 G2 X135 Y107.54 I-1.768 J-1.768
N1600 G1 X135 Y56.063
N1610 G1 X150.14 Y32.219
N1620 G2 X149.337 Y28.748 I-2.111 J-1.34
N1630 G1 X103.107 Y0.369
N1640 G2 X99.683 Y1.169 I-1.308 J2.131
N1650 G1 X75 Y40.397
N1660 G1 X75 Y88.576
N1670 G1 X67.5 Y88.576
N1680 G2 X65 Y91.076 I0 J2.5
N1690 G1 X65 Y101.076
N1700 G3 X62.5 Y103.576 I-2.5 J0
N1710 G1 X2.5 Y103.576
N1720 G2 X0 Y106.076 I0 J2.5
N1730 G1 X0 Y116.076
N1740 LASER_OFF
N1750 TERMINATE(0)
N1760 M30
Output Graph

\[ a = \text{Analog Voltage Output} \]
\[ c = \text{Measuring Range} \]

<table>
<thead>
<tr>
<th>Working Distance</th>
<th>40mm</th>
<th>160mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Spot Size</td>
<td>0.5 x 1.2mm</td>
<td>1 x 2.5mm</td>
</tr>
</tbody>
</table>

Fig. 13.10-10 Output Graph [157]

Sensor Interface Box

The Reflex Sensor CP24MHT80 is connected via interface cable (S232-W) and Connecting line S80-2M to the interface box. This interface cable offers two connectors for a RS232 computer interface and provides direct connections to the interface connector box via Sub-D Plug.

Fig. 13.10-11 Sensor Interface Box [157]

A stable power supply unit (18 ... 30V) can be connected directly to the interface connector box. This interface box offers two analogue control and error outputs (4mm connectors) for measuring the sensor output voltage or current which is a linear function
of the distance $s$ (working distance of the laser sensor). The laser sensor is directly connected to the interface connector-box via interface cable (S80-2M). All outputs offered (Fig. 13.10-2) are connectable via Sub-D connector to the interface box.

![Laser sensor diagram](image)

**Fig. 13.10-12** Connector interface box

![Connecting line diagram](image)

**Fig. 13.10-13** Assignment connecting line

![Pin assignments diagram](image)

**Fig. 13.10-14** Pin Assignments Laser Sensor [157]
13.10.3 Inductive Digital Comparator 2000/2001

Extramess 2000

**Functions:**
- ON/OFF
- RESET (Zero setting the digital and analog displays) - 0 - (Set the analog display to zero)
- PRESET (Enter any numerical values)
- mm/inch switchable
- Reversal of counting direction RANG E (Switch the range and resolution)
- ABS (reference to electronic zero point)
- Battery charge status indicated
- Linearized inductive absolute measuring system
- Power supply via the integrated rechargeable batteries (40 hrs.) or main power adapter
- Rate measuring values are actualized 20 values/s
- Data output: either Opto RS232C or Digimatic

Extramess 2001

Features are identical to Extramess 2000, in addition:
- MAX / MIN memory, e.g. ideal to search for the reversal point

Dial Comparator can be remotely operated via the interface
- High contrast LCD with 6.5 mm high digits. Analog display has a 4 mm long pointer for better visual perception, ideal when checking concentricity and flatness as well as search for the reversal point when measuring bores
- Operating and display unit (bezel) can be rotated through 280°
- Measuring force spring is interchangeable
- Lower stop is adjustable
- Protection class IP54
- Operating temperature 5 - 40°C
- Scope of supply: Mains adapter, rubber bellows and spanner for preliminary stroke setting
- Factor can be set/adjusted
- Control output compatible to Dial Comparators with limit contacts
- Scope of supply: Mains adapter, rubber bellows and spanner for preliminary stroke setting

**Fig. 13.10-15 Inductive digital comparator**

**Table 13.10-4 Technical Data**

<table>
<thead>
<tr>
<th>Measuring ranges switchable mm (inch)</th>
<th>Resolution and readings mm/inch</th>
<th>Display range of analog display mm (inch)</th>
<th>Span of error G</th>
<th>Over-travel</th>
<th>Meas. force</th>
<th>Order no.</th>
<th>Order no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1.8 (.07&quot;) 0.0001/.00005&quot;</td>
<td>± 0.030 (.0015&quot;) 0.6</td>
<td>2.4</td>
<td>0.7 - 0.9</td>
<td>4346000</td>
<td>4346900</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8 (.07&quot;) 0.0005/.00002&quot;</td>
<td>± 0.015 (.0006&quot;) 0.6</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.8 (.031&quot;) 0.0002/.00001&quot;</td>
<td>± 0.006 (.0003&quot;) 0.3</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>1.8 (.07&quot;) 0.0001/.00005&quot;</td>
<td>± 0.030 (.0015&quot;) 0.6</td>
<td>2.4</td>
<td>0.7 - 0.9</td>
<td>4346100</td>
<td>4346910</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.8 (.07&quot;) 0.0005/.00002&quot;</td>
<td>± 0.015 (.0006&quot;) 0.6</td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.8 (.031&quot;) 0.0002/.00001&quot;</td>
<td>± 0.006 (.0003&quot;) 0.3</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* 1 Digit in any zero position
** Includes Adapter Bush 940
Inductive Digital Comparator

1. Operating buttons
2. Display
3. Mounting shank
4. Measuring spindle
5. Contact point 901H
6. Connection or mains power supply
7. Data output
8. Rotateable operating and display unit

Fig. 13.10-16 Description of Inductive Digital Comparator

Accessories:

Data Connection Cable:

Opto RS232C (2 m), SUB-D jack 9-pin Data Connection Cable Digimatic (2 m), flat plug 1 0-pin Software for 2001 for blocking/disabling individual operating functions, includes cable Cable to connect control output to an SPS

Fig. 13.10-17 Manual Lifer
13.10.4 APC Laser Diode Driver Kit

The LD2000 and EB2000 are integrated together to form the EK2000 Laser Diode Driver Kit. The EB2000 allows users to quickly set up the LD2000 with a laser and DC power supply without having to develop a custom PCB or extensive hand wiring. All of the LD2000 features are supported with convenient, easy to use connector interfaces. The LD2000 is a low-noise, stable laser diode current source that can be operated with laser diodes having a common laser anode and monitor photo diode cathode. The driver operates in an automatic power control (APC) mode using the built-in monitor photo diode integrated in the laser diode for feedback. On board trim pots are provided for controlling the laser power and current limit. Both functions can also be controlled via an external voltage source. The LD2000 supports a wide range of laser diodes with drive currents up to 100mA and photo diode currents from 20μA to 2mA. The LD2000 also has an external modulation input to support applications that require modulating the laser output [156].

13.10.5.1 Features

Constant power mode from 20 μA to 125 μA (factory configured, for other monitor currents see section 13.10.5.3)

- Laser drive currents from 0 to 100 mA
- Low Noise / Ultra Stable Laser Control
  Slow Start for diode protection
13.10.5.2 Using the EK2000

The EB2000 was to support all of the LD2000 features although for most applications, only a few of the component locations on the EB2000 will be used. The minimal configuration will include one LD2000, one EB2000, one DC Power Supply (see important note below), and a diode laser. A typical setup is shown in Figure 13.10-18 below:

![Figure 13.10-18 Set-up of diode laser with EB2000 and LD2000](image)

Table 1 lists the descriptions of all the components the EB2000 supports. A diagram of the EB2000 circuit board is provided in Figure 2. (Please refer to the LD2000 Application Notes for additional detailed information on the LD2000 operation).

![Figure 13.10-19 LDBA Constant Current Drive with EB2000 and LD2000](image)
**Minimal Configuration:** To set the LD2000 up for the simplest configuration (CW mode, no external modulation) follow the steps below:

1. Connect a DC power supply to P2.
2. Connect your laser to P1.
3. Install jumpers in P5 and P6 to enable the on-board trim pots (default position).
4. Install a jumper in P10 to disable the external modulation.
5. Install the appropriate value resistor in $R_{\text{FEXT}}$ (see LD2000 Application Notes).

The EB2000 is now set up to operate the laser in a CW mode using the LD2000 on-board trim pots to control the laser drive current.

**GENERAL**

The LD2000 is composed of three independent circuits; 1) slow start circuit, 2) limit current circuit, 3) output control circuit. Each is described below:

**Slow Start Circuit**

The slow start circuit is used to monitor the supply voltage and keep the laser output off until the power supply stabilizes. The slow start circuit uses a voltage reference and a comparator to monitor the supply voltage. An internal 2.5V reference is compared to the voltage at the ON/OFF pin (pin 17). When this voltage exceeds 2.5V, the laser is enabled. The comparator input (pin 17, ON/OFF) has an input impedance of 20 kΩ. This resistance is used with an external resistor (RPU on Evaluation Board) to form a voltage divider that sets the LD2000 dropout voltage. **For most applications a 15k resistor tied from the +12V power supply to the ON/OFF pin which disables the laser when the power supply drops below 4.5V is adequate.**

Note: the ON/OFF pin can also be used to disable the laser by pulling this pin low to 0V.

The slow start circuit uses an internal time constant formed by a 1 MΩ and a 1 F capacitor to yield a 50ms turn on delay. This can be extended by adding an external capacitor CDLY on the evaluation board.

**Limit Current Circuit**
The limit current circuit is a constant current source which can be set by the on-board trim pot or an external control voltage. This determines the maximum drive current that can be supplied to the laser. The transfer function for this control is 40mA/V. The current limit also determines the laser current when operating in the constant current mode.

**Constant Power Feedback Loop**

The constant power feedback loop circuit uses the laser monitor photo diode current (which is proportional to the laser output power) to regulate the laser output power. An internal transimpedance amplifier converts the photo diode current to a voltage used by the feedback circuit. The feedback loop varies the drive current to the laser such that the voltage derived from the photo diode monitor current matches an adjustable setpoint voltage (described below). The laser output can be adjusted by varying the setpoint voltage.

When the current limit is set higher than the laser current needed by the feedback loop the laser is operating in a constant power mode. If the current needed by the feedback loop is higher than the current limit, the laser drive current will be clipped to the current limit and the laser will then be operating in the constant current mode.

The photo diode transimpedance amplifier has an internal gain of 20k which yields a 50 A/V output. Since the maximum voltage of the feedback loop is 2.5V, this limits the maximum photo diode current to 125A. This upper limit can be easily increased by adding an external resistor (see Appendix B).

The setpoint voltage used by the feedback loop is the difference between the PD CURRENT SETPOINT voltage and the Analog Modulation Voltage as follows:

\[ V_{SETPOINT} = V_{PD \, CURRENT \, SETPOINT} - V_{ANALOG} \]

The control loop integrator has a time constant of approximately 60μs set by an 0.012μF integrating capacitor. The loop time constant can be extended by adding an external capacitor across CX1 and CX2 (pin 1 and pin 2 of the LD2000).
Note: all control signals are based on the photo diode current. The user must refer to the manufactures spec sheets of the particular diode that will be used to correlate this to the laser output power.

13.10.5.3 Using the LD2000

The LD2000 is packaged as a component which, with minimal external components, can be integrated into a system to make a complete laser diode driver system. We recommend using printed circuit board construction to achieve optimum results. The pin outs for the LD2000 are provided in Figure 1 and described below:

LD2000 PIN DESCRIPTION

<table>
<thead>
<tr>
<th>Pin</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2</td>
<td>CX1, CX2 - These pins are provided for connecting an external capacitor to the control loop integrator to extend the integrator time constant. This may be necessary to get maximum bandwidth when using TTL modulation. Connect the positive terminal of the cap to CX2.</td>
</tr>
<tr>
<td>3</td>
<td>ANALOG MODULATION - This pin is used with an external voltage signal source to provide analog modulation. The transfer function (referenced to the photo diode current) is -50μA/V (see note 1) with 0V being the laser completely on. The laser output decreases as this voltage increases with the laser being completely off at 2.5V. Connect this pin to ground when not using the analog modulation.</td>
</tr>
<tr>
<td>4</td>
<td>SLOW START - This output pin is high during the start up period and goes low when the laser is enabled. It can be used as a LASER EMISSION indicator. An external capacitor can be connected from this pin to ground to extend the slow start delay time. Note: this output will not drive an LED directly and must be buffered (contact the factory for more details).</td>
</tr>
</tbody>
</table>
5 PD CURRENT TRIMPOT - This pin is connected to the wiper of the on-board PD Current Trim pot. Connect this pin to the PD Current Setpoint to control the photo diode current with the on-board trim pot.

6 PD CURRENT SETPOINT - This pin controls the PD Current according to a transfer function of $50\mu$A/V with 0V being the laser is completely off (0 photo diode current). The laser output increases as this voltage increases.

7 REF OUT - This is a buffered 2.5V voltage reference.

8 PD AMP OUT - This is an analog voltage proportional to the photo diode current and

$$\text{VPD AMP} = \frac{V+}{2} - RF \times \text{PD}$$

where $RF = \text{PD AMP Transimpedance gain (internal 20k in parallel with \text{RFEXT})}$

9 V+ - Positive supply voltage (+8 to +12VDC).

10 GND - Power supply common.

11 LD A / PD K - Common laser diode anode, photo diode cathode.

12 PD A - Photo diode anode.

13 LD K - Laser diode cathode.

14 LIMIT SETPOINT - This voltage determines the maximum laser drive current according to the transfer function 40mA/V.

15 LIMIT TRIMPOT - This is connected to the wiper of the Limit Current trim pot. Connect this to the Limit Setpoint pin to use the on-board trim pot to set the current limit.

16 Not used. This must be tied to ground to operate the laser.

17 ON/OFF - This pin is used to externally turn the laser on and off through the slow start circuit and to set the low voltage dropout point. It has an internal 20k resistor to ground. Connect a 1.5K resistor to the power supply voltage to set the dropout voltage to 4.5V.

18 LIMIT OUT - This is an output voltage proportional to the limit current with a transfer function of 40mA/V. Use this pin to assist in setting the laser current limit.
Setting the Feedback Resistor

The LD2000 is configured at the factory for a maximum feedback gain. This gain setting is appropriate for lasers that have low monitor currents in the range of 20 to 120mA (e.g. TOLD9215).

For most lasers, the photo diode current is greater than 120 mA and the feedback gain will have to be reduced to drive the laser at full drive current. This can be done quite easily by following the procedure below:

1. Determine the appropriate feedback gain using the following calculation:

   \[ RF_{EXT} = \frac{20,000}{(8000 \times IMON - 1)} \text{ (ohms)} \]

   where: \( RF_{ext} \) is the external gain setting resistor to be added.

   \( IMON \) is the monitor current for a particular laser. (A)

Pick the nearest standard value resistor (1/4W, 5% or better). Table 1 lists some typical values for various lasers.

![Fig. 13.10-20 RFext vs. photo diode monitor current](image)

Install the \( RF_{ext} \) resistor into space RF EXT on the evaluation board.

Be sure to use adequate ESD preventative measures when handling diode lasers. A grounded wrist band and anti-static mat are required to prevent damaging the diode laser due to static discharge.
13.10.5.4 Operating Modes of EK2000

CW OPERATION
To operate the EK2000 in a CW mode, do the following steps:

Connect your laser diode to the pre-wired connector assembly.

Attach a suitable DC voltage supply across P2 on the Eval Board. A 1’ long prewired cable assy will be provided. Connect the + voltage to the red wire and the ground to the black wire. The power supply will be bypassed near the LD2000 with a 10μF tantalum capacitor (C1) and a 0.1 μF ceramic capacitor (C2).

Short P6 on the Eval Board to use the on-board PD Current Trim pot (factory default setting). Short P5 on the Eval Board to use the on-board Current Limit Trim pot (factory default setting). Short P10 on the Eval Board to set analog modulation to FULL ON (factory default setting). Short P9 on Eval Board to set ON/OFF to off position (factory default setting).

Turn both the PD Current Trim pot and the Current Limit Trim pot counter-clockwise 20 turns each to set these at their minimum operating points.

Turn the DC power supply on and use a voltmeter to monitor the LIMIT OUT (P8 on Eval Board).

Adjust the Current Limit Trim pot clockwise slowly while observing the LIMIT OUT to set the maximum operating current for your laser (refer to laser manufacturer’s data sheets). Note: this output is 40mA/V.

Remove the shorting jumper across P9. Using a calibrated power meter to monitor the diode laser output, slowly adjust the PD Current Setpoint trim pot clockwise to obtain the desired operating power level. The laser will begin to emit upon reaching the drive current threshold.

Analog Modulation
To operate the EK2000 analog modulation feature, follow the setup procedures for CW Operation to establish the laser operating conditions. Once the EK2000 has been setup
for your laser, remove the shorting jumper from P10 and apply a positive voltage from P10-VMOD to P10-GND to modulate the laser.

The analog modulation voltage has a negative transfer function characteristic. That is, at 0 volts, the laser is fully on, at 2.5 volts the laser should be fully off.

The linear operating range of the modulation is determined by the transimpedance gain of the PD amplifier, RF. The appropriate transimpedance gain for the laser can be calculated as follows:

\[ RF = \frac{2.5}{\text{IMON}} \]

Where \text{IMON} is the photo diode current specified by the laser manufacturer for the maximum operating output power. Note: the LD2000 includes an internal 20K resistor. RF is the net resistance of the internal 20K resistor with any external resistance added in parallel on pins 8 and 12. To calculate the external resistance \( (RF_{\text{ext}}) \) needed to operate at a particular monitor current \( (\text{IMON}) \), use the following equation:

\[ RF_{\text{ext}} = \frac{50,000}{(20,000 \times \text{IMON} - 2.5)} \]

**External Modulation Operation**

The laser output power can be controlled via an external modulation voltage while operating in the Constant Power Mode. The laser output is inversely proportional to the modulating voltage with 0V being the laser fully on and 2.5V turning the laser fully off.

To use the external modulation, do the following:
1. Set up the LD2000 for Constant Power (refer to Section 5.0).
2. Attach an external modulation source (e.g. function generator, D/A converter, etc.) to the analog modulation Input (P10).
3. Apply power to the EK2000 and adjust the modulation input amplitude and
frequency for the desired output.

4. The laser output will now be controlled by the external modulation voltage.

![Graph showing laser power vs. modulation voltage](image)

Fig. 13.10-21 Laser power vs. modulation voltage [156]

The graph above describes the characteristic of the modulation voltage. If the LD2000 is set up to match a particular laser, the solid curve would represent the output power of the laser as a function of the modulation voltage. A couple of notes of interest:

a. If the PWR Limit control is set below the maximum output power, the laser output will plateau (clip) at the PWR Limit level for modulations below the PWR limit.

b. If the total feedback gain, RF, is not optimized for the operating laser, the laser turn off point of the output will be different than 2.5V (usually somewhere below 2.5V since the default feedback gain is usually too high for most lasers).

c. If the feedback gain is too low for a laser (i.e. the maximum laser power can be reached at a point somewhere below the maximum setting of PWR Limit, than use care to set the PWR Limit control to the maximum desired operating power before applying the modulating voltage.
13.10.5.5 LD2000 Theory of Operation

The LD2000 uses the internal monitor photo diode provided on most low power diode lasers for feedback when operating in the Constant Power Mode. The following figure is a block diagram of the LD2000 laser driver:

![LD2000 Simplified Block Diagram - Constant Current Source](156)

The laser power is regulated through an integrating feedback loop. The setpoint of the feedback is determined by the PWR LIMIT control trim pot and the ANALOG MOD IN. An internal transimpedance amplifier converts the laser feedback current to a voltage that is used as the error signal for the feedback loop. Since all analog signal levels are based on a 2.5V internal reference, we will use this to derive the feedback gain setting resistor value:

The LD2000 has an internal transimpedance gain of 20K. Without a user installed feedback resistor, the transimpedance gain is:

$$RF = 20K$$

and $V_{\text{error}}$ is equal to:

$$V_{\text{ERROR}} = RF \times '\text{MON}$$
where \( \text{IMON} \) is the feedback monitor photo current. The total transimpedance gain should be set so that the photo current at the maximum laser power equals 2.5 volts.

Since \( \text{VERROR} \) has a maximum value of 2.5V, we can derive the value of an external feedback resistor needed to set the transimpedance for any laser:

\[
RF = 2.5V / \text{IMON}
\]

where \( RF \) is the transimpedance gain needed, and \( \text{IMON} \) is the monitor photo current for your laser.

\[
RF = RF\text{EXT} || 20K
\]

\[
RF = RF\text{EXT} * 20K / (RF\text{EXT} + 20K)
\]

solving for \( RF\text{EXT} \),

**EB2000 Component Description**

<table>
<thead>
<tr>
<th>Ref Des</th>
<th>Description</th>
<th>Pin EB2000</th>
<th>Pin LD2000</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Laser Connections</td>
<td>1</td>
<td>11</td>
<td>Laser Diode Anode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>12</td>
<td>Monitor Photo diode Anode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>13</td>
<td>Laser Diode Cathode</td>
</tr>
<tr>
<td>P2</td>
<td>Power Supply Hookup</td>
<td>1</td>
<td>9</td>
<td>Power Supply Positive +8 to +12VDC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>10</td>
<td>Power Supply Return</td>
</tr>
<tr>
<td>P3</td>
<td>Power Limit External Trim pot</td>
<td>1</td>
<td>7</td>
<td>CW Terminal (Vref 2.5V)</td>
</tr>
<tr>
<td></td>
<td>(5.0 K)</td>
<td>2</td>
<td>6</td>
<td>Wiper Terminal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>10</td>
<td>CCW Terminal (GND)</td>
</tr>
<tr>
<td>P4</td>
<td>Current Limit External Trim pot</td>
<td>1</td>
<td>7</td>
<td>CW Terminal (Vref 2.5V)</td>
</tr>
<tr>
<td></td>
<td>(5.0 k)</td>
<td>2</td>
<td>14</td>
<td>Wiper Terminal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>10</td>
<td>CCW Terminal (GND)</td>
</tr>
<tr>
<td>P5</td>
<td>On-Board Current Limit Trim pot</td>
<td>1</td>
<td>14</td>
<td>Jumper these 2 pins to enable on-board trim pot.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>P6</td>
<td>On-Board Power Limit Trim pot</td>
<td>1</td>
<td>5</td>
<td>Jumper these 2 pins to enable on-board trim pot.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>
| P7      | Photo diode Amplifier Output | 1 | 8 | The pins can be used to monitor the laser photo diode feedback current. The voltage sensed here will be determined by the transimpedance gain:
|         | Monitor      | 2 | 12 | (i.e. \( V = \text{IMON} * 20K / (RF\text{EXT} + 20K) \)) |
| P8      | Current Limit Monitor | 1 | 18 | LIMIT OUT |
|         |              | 2 | 10 | GND |
| P9      | ON / *OFF | 1 | 17 | ON / *OFF input |
|         | Shorting these two pins will disable the laser output. | 2 | 10 | GND. |
| P10     | Analog Modulation Input | 1 | 3 | ANALOG MOD |
|         | If external analog modulation is not required, these 2 pins must be jumpered together. | 2 | 10 | GND |
| C1      | Power Supply Bypass | 1 | 9 | + Cap terminal |
(10 F tantalum recommended) | 2 | 10 | - Cap terminal
--- | --- | --- | ---
C2 | Power Supply Bypass | 1 | 9 | Unpolarized
(0.1 F ceramic recommended) | 2 | 10 |
CDLY | Adding an external capacitor will extend the turn-on delay cycle. | 1 | 17 | The pad nearest the LD2000 has a positive potential. Attach the + lead of an electrolytic to this pad.

### Table 13.10-6 External Resistors [156]

<table>
<thead>
<tr>
<th>Ref Des</th>
<th>Description</th>
<th>Pin EB2000</th>
<th>Pin LD2000</th>
<th>Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF EXT</td>
<td>An external resistor can be added here to modify the transimpedance gain of the LD2000 photo diode feedback</td>
<td>1</td>
<td>8</td>
<td>Unpolarized</td>
</tr>
<tr>
<td></td>
<td>(Refer to the LD2000 Application Notes for a detailed description of the circuit.)</td>
<td>2</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A mounting location is also provided above the RF EXT to mount a trim pot (e.g. Bournes 3266 series, 1 M) to provide continuous adjustable transimpedance gain.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPU</td>
<td>A 1.5K resistor must be installed here in order to operate a laser.</td>
<td>1</td>
<td>17</td>
<td>Unpolarized</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
LD2000 Description Top View

![LD2000 Description Top View](image)

Fig. 13.10-23 LD2000 Description Top View [156]

![Strain Relief and ESD Protection for laser diodes](image)

Fig. 13.10-24 Strain Relief and ESD Protection for laser diodes

![LDBA Constant Current Drive](image)

Fig. 13.10-25 LDBA Constant Current Drive
13.11 LDBA Component Data, Materials and Drawings

13.11.1 Laser Diode Data

HL6354MG/55MG - Low Operating Current Visible Laser Diode

Description

The HL6354MG/55MG are 0.63µm band AlGaInP laser diodes with a multi-quantum well (MQW) structure. They are suitable as light sources for laser levelers, laser scanners and optical equipment for measurement [158].

Application

- Laser leveler
- Laser scanner
- Measurement

Features

- Visible light output: 635nm Typ (nearly equal to He-Ne gas laser)
- Single longitudinal mode
- Optical output power: 5mW CW
- Low operating current: 27mA Typ
- Low operating voltage: 2.4V Max
- Operating temperature: +50°C
- TM mode oscillation

Table 13.11-1 Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Item</th>
<th>TC=25°C</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical output power</td>
<td>TC=25°C</td>
<td>Po</td>
<td>7</td>
<td>mW</td>
</tr>
<tr>
<td>LD reverse voltage</td>
<td>TC=25°C</td>
<td>VR(LD)</td>
<td>2</td>
<td>V</td>
</tr>
<tr>
<td>PD reverse voltage</td>
<td>TC=25°C</td>
<td>VR(pD)</td>
<td>30</td>
<td>V</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>TC=25°C</td>
<td>Topr</td>
<td>-10 to +50</td>
<td>°C</td>
</tr>
<tr>
<td>Storage temperature</td>
<td>TC=25°C</td>
<td>Tstg</td>
<td>-40 to +85</td>
<td>°C</td>
</tr>
</tbody>
</table>
Table 13.11-2 Optical and electrical characteristics

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
<th>Test Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold current</td>
<td>Ith</td>
<td>18</td>
<td>18</td>
<td>27</td>
<td>mA</td>
<td>Po=5mW</td>
</tr>
<tr>
<td>Operating current</td>
<td>Iop</td>
<td>27</td>
<td>27</td>
<td>36</td>
<td>mA</td>
<td>Po=5mW</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>Vop</td>
<td>2.2</td>
<td>2.2</td>
<td>2.4</td>
<td>V</td>
<td>Po=5mW</td>
</tr>
<tr>
<td>Beam divergence parallel to the junction</td>
<td>ea</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>mA</td>
<td>Po=5mW</td>
</tr>
<tr>
<td>Beam divergence perpendicular to the junction</td>
<td>ea1</td>
<td>25</td>
<td>25</td>
<td>30</td>
<td>mA</td>
<td>Po=5mW</td>
</tr>
<tr>
<td>Lasing wavelength</td>
<td>Xp</td>
<td>630</td>
<td>630</td>
<td>640</td>
<td>nm</td>
<td>Po=5mW</td>
</tr>
</tbody>
</table>
| Monitor current               | IS     | 0.25| 0.25| 0.25| mA   | Po=5mW

The casing of commercial laser diodes can be removed with this special can opener (Figure 11.2) to have closer access for application optimising to the diode chip.

![Fig. 13.11-2 Laser diode hand-held can opener [156]](image)

The can opener works with following lasers T0-18, T0-46, T0-3, 5.6mm and 9mm.
13.11.2 Materials for LDBA Components

Material 1: Vacodil 46 – Material No.: 1.3920 [152]

Chemical Composition: Ni (46%), Mn (0.2%), Si (0.2%), C (<0.02%), Fe (53.59%)

Mechanical Properties:

- Tensile strength: 500MPa
- Yield point: 300MPa
- Vickers hardness: 140HV

Physical Properties:

- Average linear Extension:
  - 20 – 100°C: 7.9x10⁻⁶K⁻¹
  - 20 – 200°C: 7.7x10⁻⁶K⁻¹
  - 20 – 300°C: 7.4x10⁻⁶K⁻¹
  - 20 – 400°C: 7.3x10⁻⁶K⁻¹
  - 20 – 500°C: 8.6x10⁻⁶K⁻¹
  - 20 – 600°C: 9.7x10⁻⁶K⁻¹

Specific Resistance (20°C): 0.49μΩm

Density: 8.2g/cm³

Material 2: – Material No.: 1.4546 X5CrNiNb18-10 [152]

Chemical Composition: C (0.08%), Si (1%), Mn(2%), P (0.045%), S (0.03%), Cr (19%), Ni (9%), Nb (0.8%), Fe (68%)

Material 3: Material No.: 1.4301 X5CrNi18-10 / X4CrNi18-10

Analyse in %:

- C: 0.07
- Si: 1.00
- Mn: 2.00
- P: 0.045
- S: 0.030
- Cr: 17.00-19.5
- Mo: 8.00-10.5
- Ni: 9
- Fe: Rest
13.11.3  LDBA Component Drawings pp. 390 - 396

- Laser Diode
- Interface Connector
- GRIN-Lens Mount
- GRIN-Lens Mount-II
- GRIN-Lens Holder
- Gas-Inlet
- Output Coupler
13.11.4 Drawings of Clamping Tools pp. 398 - 403

- HD-Clamping Device
- Laser Diode Clamping
- GRIN-Lens Clamping
- Gas-Inlet Clamping Tool
- Beam Profiler Holder
Beam Profiler Holder

Dimensions:
- Width: 80 mm
- Height: 60 mm
- Depth: 45 mm
- Thickness: 20 mm
- Hole diameter: 10 mm
- Hole: M5 x 0.8 - 6H

Part No.: 2000-72-01