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Proof of principle non-invasive
Pulsed Electric Field study
(Measurement and Experiments)

by

Fahd A. Banakhr MIEEE, MIET and MInstMC

A Doctoral Thesis submitted in partial fulfilment of the requirements for the
award of Doctor of Philosophy of Loughborough University, UK

March 2013

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Abstract

Pulsed electric field (PEF) technology applied to food processing was firstly used in the late 1960s. The currently available systems use either conventional Blumlein generators or generators similar to those found in radar power sources to produce the required high voltage pulses. The liquid to be processed is passed through a number of treatment chambers or cells which each contain a pair of electrodes in contact with the liquid. An electric field is thereby applied to the liquid, leading to the technology being termed *invasive* and it can be used only with liquid food.

A novel and non-invasive PEF technology for use in the food processing industry is introduced and investigated in this thesis. The technology represents a novel way of performing PEF treatment. A proof of concept arrangement uses two ceramic cylinders mounted inside the non-invasive PEF cell with a gap of 3 mm between them. A displacement current of the order of mA passes through the non-invasive PEF cell during treatment, as compared with the kA of current usually produced during an invasive treatment. The low current is not only economic in electric energy but also maintains a low food temperature, which implicitly maintains food flavour.

In the thesis the electro-optic Kerr effect technique is used to perform accurately the PEF measurement and convincingly prove that strong electric fields are present. Two Kerr water cells were designed and used to determine the Kerr constant for water, since the data presented in the literature is unreliable. The first Kerr water cell uses a pair of Bruce profile stainless steel electrodes and the second a pair of parallel plate stainless steel electrodes. An electro-static solver (Maxwell software) was used to determine the electric field distribution and to calculate the electric field integral to accurately determine the Kerr constant for water.

Water samples containing the E-coli bacteria were prepared and filled in the non-invasive PEF cell by the Flavometrix Company. Eight PEF experiments were successfully performed during this research programme and the results show unequivocally that the novel non-invasive technique is effective in significantly reducing the initial concentration of E-coli bacteria. This opens the door for the future design of an industrial prototype.
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<tr>
<td>CB</td>
<td>Capacitor Bank</td>
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<tr>
<td>HV</td>
<td>High-Voltage</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>MV</td>
<td>Mega-Volt</td>
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<tr>
<td>ODE</td>
<td>Ordinary Differential Equation</td>
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<tr>
<td>PEF</td>
<td>Pulsed Electric Field</td>
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<tr>
<td>PFL</td>
<td>Pulse Forming Line</td>
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<tr>
<td>PFN</td>
<td>Pulse Forming Network</td>
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<td>SF6</td>
<td>Sulfur hexafluoride</td>
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<td>TG</td>
<td>Trigger Generator</td>
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<td>LiNbo3</td>
<td>Lithium Niobate</td>
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<tr>
<td>KDP</td>
<td>Potassium Dideuterium Phosphate</td>
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<td>E coli</td>
<td>Escherichia coli</td>
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CHAPTER ONE

INTRODUCTION
Chapter 1

1 Introduction to Pulsed Power technology and its application to industrial food processing

The present thesis is a blend of various technologies applied to perform research into the novel domain: of the non-invasive application of pulsed electric field impulses in food processing. The various technologies are related to pulsed power generators and the production of strong electric fields in water. These in turn need to be measured very accurately, with the difficulty in the measurement being that it needs to be performed near metallic objects. The application of the strong pulsed electric fields to process water containing microbes needs the introduction of some biophysical aspects of the novel technology. In what follows in this chapter, all these will be briefly introduced and discussed.

Over the last decade, the development of pulsed power systems has massively increased, and a wide variety of systems has been developed. The term ‘pulsed power’ (PP) expresses the technology of building up (electrical) energy over a relatively long period of time and subsequently releasing it very quickly, thus increasing the instantaneous power as shown in Figure (1.1). Pulsed Power is important in all applications where the load must be pulsed or performs better if it is pulsed. In general, a pulse is characterised by its shape i.e. by its rise and fall (decay) times and by the duration and flatness of its plateau region. The rise time of a typical voltage pulse duration is defined as the time that the voltage takes to rise from 10% to 90% of its final value. Both the fall and rise times depend on the evolution of the load impedance, which may vary with time, while the flatness of the plateau region is also an important requirement for driving some loads [1]. A scheme to produce high power electrical pulses is normally based on an energy source (usually a capacitor) that is charged slowly at a relatively low power and, by activating a closing switch, is discharged rapidly. Figure (1.2) illustrates the main components of a high power pulsed generator.

![Figure 1.1 the principle of pulsed power](image)

The green line shows the constant power used to charge the capacitor bank of a pulse generator. The yellow, orange and red lines illustrate the massive increase in power that can be obtained by releasing the energy using various conditioning techniques. Note that energy (the area under a line) is not conserved; a relatively low energy efficiency is to be expected in high-power generators.
There are two very different ways of energy storage in pulsed power systems:

- **Capacitive energy storage;** where the energy is stored in the form of electrostatic field energy
- **Inductive energy storage;** where the energy is stored in the form of magnetic field energy

Relatively slow pulsed power systems (μs, ns range) may be constructed using lumped components and described by simple lumped circuit theory. However, fast pulsed power systems (ns, ps range) are usually constructed with transmission lines and therefore need to be described by transmission line theory.

Practical pulsed power schemes involve the generation of very short voltage pulses (nanoseconds to milliseconds) with the possibilities of producing:

- Currents up to several mega amperes (~20 MA).
- Voltages up to several megavolts (~10 MV).
- Energy release up to several mega joules (tens of MJ).
- Power densities up to several hundreds of millions of watts per square centimetre
- Joule temperatures of millions of degrees Kelvin.

Figure (1.3) shows the largest pulsed power machine in the world (the so-called Z-machine) at Sandia National Laboratories (USA).

Fig.1.3 Z-machine at Sandia National Laboratories (USA).
1. INTRODUCTION

1.1 Brief history of Pulsed Power

The first stage in the development of pulsed power systems was during the Second World War for use in radar technology, when a massive development program was undertaken to develop pulsed radar requiring very short high power pulses. Later, developments continued with other applications, which led to the design and manufacture of several novel pulsed power machines.

At the beginning of the Cold War, when U.S. and Soviet scientist at Los Alamos National Laboratories and Arzamas 16 respectively began the race in the development of nuclear weapons, they also began to investigate the production of electrical energy by atomic fusion. The only possibility of reaching this goal was seen in the generation of super high magnetic fields of 1000 T and more, producing high magnetic pressures for plasma confinement. For the generation of such high fields a device called the Magnetic Flux Compression Generator was invented in the fifties by A. Sakharov in the Soviet Union and Clarence Maxwell Fowler in the U.S.A.

After U.S. President Reagan’s proclamation of the Strategic Defence Initiative in 1983, often called ‘Star Wars’, pulsed power technology offered extremely good financial incentives for the development of improved materials and electrical components with high energy and power densities. The United Kingdom and France both participated in this race, but with low budgets compared to those of the U.S. and the Soviet Union. The main topics investigated were electrical devices such as electromagnetic guns, laser weapons and high power microwave weapons. Engineers and scientists began to look elsewhere after the cold war ended, and the financial support for pulsed power was greatly reduced. With the trend to commercial applications, they had to learn very rapidly that its introduction of pulsed power into the commercial market depends strongly on the competitiveness of their products as compared with those already available using conventional technologies.

In 1997, the International Society of Pulsed Power Applications was founded in Germany and is specific to supporting the commercial side of the European Pulsed Power applications.

Since 2000, the Korean Electro Research Institute (KERI) has developed pulsed power technology and its applications, mostly based on power electronics. KERI activity covers components, military systems and industry applications. Moreover, it has developed several pulsed power supplies responding to industry needs.
1. INTRODUCTION

1.2 Applications of Pulsed Power Technology

Basically, there are two categories of pulsed power applications:

- Industrial applications
- Research and development

1.2.1 Pulsed power industrial applications:

The industrial applications of pulsed power are rapidly becoming widespread and include:

i) **Food processing**
   Pulsed electric field processing has been demonstrated by many researchers to be equivalent to pasteurization, in terms of its pathogen reduction for a wide range of liquid foods. Moreover, it offers considerable benefits in the preservation of taste, colour and nutritional value above other processing techniques that are often heat sensitive [2].

ii) **Sludge treatment**
   Sewage sludge is composed of organic materials, bacteria and mostly water. The bacteria contain digested organic materials and the objective of the sewage sludge treatment is to destroy the bacteria cell membranes. High voltage pulsed power can be used to generate an arc discharge (plasma) in the sludge, which will ensure that this happens [2].

iii) **Production of nano-powders**
   With the advent of nano-technology there has been a great demand for a mass production process for the manufacture of nano-sized powders for various industrial applications such as cosmetics, electrodes for MLCC (multi layer ceramic capacitors) and the production of silver fibre for anti-bacterial products. A pulsed power based electric wire explosion can be used to produce these nano-particles [3].

iv) **Medical waste treatment**
   Pyrolysis is a pulsed power based process in which waste is heated in an oxygen deficit, which results in the gasification of organic components and the melting of mineral compounds [4].

v) **Magneto-forming**
   This is a type of high velocity, cold forming process for electrically conductive metals, most commonly copper and aluminium. The work piece is reshaped by high intensity pulsed magnetic fields inducing a current in the work piece and a correspondingly repulsive magnetic field, rapidly repelling portions of the work piece. The work piece can be reshaped without any contact from a tool, although in some instances the piece may be pressed against a die or former. The technique is sometimes called *high velocity forming* or *electromagnetic pulse technology* [5].
1.2.2 Research and development

i) Inertial confinement fusion
Inertial confinement fusion is a process in which nuclear fusion reactions are initiated by heating and compressing a fuel target, typically in the form of a pellet that most often contains a mixture of deuterium and tritium. The heating can be achieved using laser or high power X-ray radiation generated by powerful pulsed power generators [6].

ii) Bioelectric
Bioelectric refers to the use of pulsed power and/or plasma technologies to manipulate cells, tissues and organisms. The application of intense pulsed electric fields with ultra short durations has been proven to target intracellular structures inside the cell nucleus without permanent damage to the cell membrane. Possible applications include the killing of cancer cells [7]

1.3 Repetitive pulsed power systems
Currently, the study of pulsed power technology is leaning towards compact repetitive systems, since important applications arise in defence systems, laser systems, high energy physics, water treatment, material processing and other industrial applications. Compact repetitive pulsed power systems can be improved by enhancing the peak and average power output, increasing the pulse repetition frequency and reducing the equipment size, all to meet the demands of widespread applications. However, almost all the components, switches and transformers need to be capable of withstanding large electric field stresses almost continuously, which requires special research and implementation of novel insulation technologies.

1.4 Pulsed Electric Fields for food processing (short history)
In recent years, methods of food preservation have changed considerably. Thermal processing is now the most commonly used method of increasing shelf-life and maintaining food safety by inactivating spoilage and pathogenic microorganisms. However, since consumers are increasingly aware of taste, colour, flavour, and nutrients that may all be spoiled by heat, there is a demand for alternative methods of food preservation. Modern non-thermal methods such as high-pressure and pulsed electric field deserve attention, because they can accomplish food preservation with short treatment times and no, or very little, heating of the medium [8].

The earliest application of electricity in food processing was the sterilization of milk, in the early 1900s. The milk was sterilized using alternating current in a process termed ‘electro-pure’ and microbial inactivation occurred as a result of ohmic heating. The principle of applying electric fields for the inactivation of microorganisms is not new. In early 1915 it was reported that electrically treated milk was being supplied to the city of Liverpool. In 1960 the use of high voltage pulses for the destruction of microorganisms was firstly suggested. Since then, their application for cell disruption in food materials was described and promoted by Dovenspeck in 1960 and has been further developed and expanded to the inactivation of microorganisms. In recent years, pulsed electric field technology has also been utilized in producing electroporation (a term defined and explained in detail in chapter 5) and electro-
fusion, both for food preservation [2]. ‘Pure Pulse Technologies’, a subsidiary of Maxwell Laboratories located in San Diego, California, owns several U.S. patents to preserve fluid foods such as dairy products, fruit juices, and fluid eggs by treatment with high voltage pulses. The patents comprehensively describe both batch and continuous systems, including treatment chamber characteristics, pulse flow network components, and specific switching arrangements to avoid electrode fouling [8].

Washington State University also has a comprehensive programme of food processing by the use of high intensity pulsed electric fields. The first results reported were obtained using a modified version of an electroporator to treat 0.1 ml of inoculated simulated milk ultra filtrate with 20 kV/cm electric pulses. Later the group designed and constructed 12 ml and 25 ml volume temperature-controlled static chambers [8].

Another leading group in this technology is at Ohio State University, where an integrated pilot plant system with sterilised packaging has been implemented. This system has been applied successfully to process fruit juice, verifying an appreciably extended shelf life. This pulsed electric field system has a treatment chamber, (which can have various configuration and field treatment zones), and a pulsed flow network capable of delivering energy at rates in the order of kHz [8].

There are other possible applications of pulsed electric field technology, for example some European groups have also shown interest in the determination of the inactivation mechanisms and kinetics of several microorganism in model and real foods.

During a PEF treatment, the food material is placed between two electrodes forming a treatment chamber and high voltage repetitive pulses are applied across the system in order to achieve membrane breakdown. The processing time or total duration of the treatment is defined as:

\[ t = n \tau \]  

(1.1)

where \( \tau \) is the pulse duration and \( n \) is the number of the pulses applied to the food. Equation (1.1) shows that the treatment time increases either with the number of pulses or with the pulse duration. It is important to observe that increasing the number of pulses, increases the total energy consumption, while with increasing the pulse duration increases the temperature of the food (see chapter 5) [3]. During treatment, the food material is in close contact with the electrodes and, therefore, is subject to an electric field. Assuming the sample is homogeneous (i.e. the permittivity constant across the sample), the average electric field strength \( E \) is as follows:

\[ E = \frac{V}{d} \]  

(1.2)

where \( V \) is the voltage across the food sample and \( d \) the distance between the electrodes [9]. From Equation (1.2) it can be seen that increasing the gap requires a higher voltage to obtain the desired electric field (i.e. a critical electric field corresponding to the membrane breakdown). The design of the treatment chamber (i.e. the geometry and the dimension of the electrodes) determines a more or less uniform distribution of the field inside the food. The more uniform is the electric field the more homogeneous will be the treatment. Besides the number of pulses and pulse duration (i.e. total treatment time), a PEF treatment is defined by
other electrical parameters such as: the pulse shape and the pulse repetition rate i.e. the number of pulses per second.

Later (in chapter 2) an analysis of the pulsed power generators used in the thesis will be presented. The main phenomenon induced by Pulsed Electric Fields in order to destroy bacteria is electroporation, a phenomenon discussed and analysed later (in chapter 5).

1.5 Challenges of Pulsed Electric Field Diagnostics

1.5.1 B dot probe
An increasing number of pulsed power generators, delivering short duration high intensity pulses, are used in high energy density physics (i.e. fusion) or for applications such as charged particle beam generation, high power microwave or industrial plasma processing. In general, the most commonly used sensor for measuring electric fields is the magnetic probe in the form of a small receiving loop (antenna). H. Whiteside [10] described the basic theory of the loop antenna, which is discussed in chapter (4). The major disadvantage of any magnetic field probe is that the current distribution is induced by both electric and magnetic time varying field components. The most used magnetic field probe is the so called B-dot probe shown in Figure (1.4) which is based on a small area wire loop having just one turn. When it is installed away from the current flow, the coils are sensitive to the oriented magnetic fields, but the response depends strongly on the coil axis orientation, exact area and distance to the current axis. Therefore, the major limitation is their sensitivity to magnetic fields created by other current distributions in space.

1.5.2 D dot probe
Another widely used electric field probe is the so called D-dot probe, which is a field coupled sensor that is also used to measure impulse electric fields. It has attractive features including non-intrusive installation, simplicity of construction, and potentially wide bandwidth [11]. D-dot probes (or sensors) are used in combination with passive integrators, low pass filters providing a broad band capability, but limited sensitivity.
1. INTRODUCTION

Figure 1.5 Typical D-dot sensor [11]

The D-dot probe has two elements that are sensitive to the same field but measure it in opposite directions. They have their own ground reference, which is located between the two elements as illustrated in Figure (1.6).

![Figure 1.6 Ground plane D-dot sensor mounted back to back](image)

The output signal of the sensor is

\[ V_o = Z_{D-dot} A_{eff} DCos(\theta) \]

where, the D-dot impedance is 100Ω

*\( A_{eff} \)* is the effective area of the sensor

*\( D \)* is the displacement vector (\( D = \varepsilon_0 E \) in air)

*\( \theta \)* is the angle between E and the normal to the sensor ground plane.

Moreover, a fast balun (*balanced-unbalanced*) transformer is normally used to match the D-dot probe output with a 50Ω coaxial cable.

Their main drawback for use as a diagnostic tool in a non invasive PEF application, is the fact that they cannot be placed close to metallic components.

1.5.3 High voltage V-dot sensor

A high voltage V-dot sensor was installed in the outer wall of the water/oil filled PFL. The sensor is capable of measuring accurately signals with duration of 4 to 5 µs and has a rise time of a few tens of nanoseconds. It is ideal therefore for the measurement of the TPFL1 and TPFL2 (more details in chapter 2).
1.6 Electro-optic sensors

Conventional means of measuring high voltages (and therefore indirectly obtaining the electric field) rely on measurement consuming a small amount of the power from the system. Instead of indirectly measuring the quantity of interest, measurement can be taken of the changes in properties of some material as a result of the surrounding electrical or magnetic field. The advantages of such a technique are its electrical isolation, immunity to Electromagnetic radiation interference, high sensitivity and small size. The techniques rely on various mechanisms by which a material rotates the polarisation of light passing through it (birefringence). As presented above B-dot and D-dot probes are difficult to use and the need arises to use electro-optic phenomena, and for the present research it was decided to develop a Kerr effect based sensor.

Electro optic effects are defined as those that follow from the application of a dc pulsed electric field, and are optical phenomena. The optical properties of certain materials are changed when an electric field is applied, by electric forces that distort the positions, orientations, or shapes of the molecules constituting the material. As shown in Figure (1.7), a field applied to an anisotropic electro optic material modifies its refractive indices and thereby its effect on polarised light, which takes one of two forms:

- The refractive index changes in proportion to the applied electric field, which is a ‘linear electro-optic effect’ known as the ‘Pockels effect’. In this form the substance used is a crystal such as Potassium Dideuterium Phosphate (KDP) and Lithium Niobate (LiNbO₃). This effect is very popular for use in electro-optic modulators for lasers. However, the cost of the crystals for use in a Pockels sensor is often prohibitively expensive.

- The refractive index changes in proportion to the square of the applied electric field, which is known as the ‘quadratic electro-optic effect’ or ‘Kerr Effect’. This occurs in liquids and gases such as Nitrobenzene, Water, CO₂.

![Electro-optic effect diagram](image)

Figure 1.7 an electric field is applied to an electro-optic material; the electro-optic effect requires a transverse light beam

According to [12], the changes in the refractive index are typically very small. Nevertheless, its effect on an optical wave propagating a distance much greater than a wavelength of light in the medium can be significant. For example, if the refractive index increases by $10^{-5}$ an optical wave propagating a distance of $10^5$ wavelengths will experience an additional phase shift of $2\pi$.
1.7 Thesis aims

The first aim of this thesis is to understand the control and use of fast high-voltage pulse generators. Such generators use a Tesla transformer charging pulse forming lines or simply they are based on a capacitor discharged through a pulse forming line.

The second aim is to use a pulsed power generator to produce strong transient electric fields. As the fields are generated close to metallic electrodes, standard methods for measuring electric fields produced by antennas are shown not to be easily applicable.

The third aim is therefore to develop specific electro-optic methods to very accurately monitor the time dependence of impulse electric fields produced by an antenna or by other arrangements.

The fourth and final aim is to apply very strong Pulsed Electric Fields to process water containing a microbe (Escherichia Coli) by using a proposed novel non-invasive method.

The overall structure of the Thesis is illustrated in the Figure (1.8) below.

Figure 1.8 The Thesis structure
CHAPTER TWO

PULSED POWER GENERATORS
Chapter 2

2. Pulsed Power Generators

The growing demand for pulsed power systems and particularly repetitive units is widely accepted, and is mostly related to industrial applications. As detailed in chapter 1, pulsed power represents a technology in which the energy is built up over a relatively long period of time and is released in a very short time, thus greatly increasing the instantaneous power. Repetitive pulsed power technology development is focused on areas requiring repetitive short pulses such as the generators in intense ion and electron beam or X-rays systems. In addition, repetitive pulsed-power components and systems are being developed to the point that their output parameters are comparable with those currently achieved in single-pulse systems. The range of voltages of interest is from hundreds of kilovolts to megavolts.

In the experiments presented in this thesis, two different types of high voltage pulse generators were used: a fast trigger generator termed TG70 and two repetitive Tesla transformer based pulsed forming line generators (PFL). In what follows these machines are described in detail.

2.1 Pulsed trigger generator TG70

The TG70 is a high voltage trigger generator that can in principle produce short rise time high voltage output pulses into as many as three parallel connected coaxial cables as shown in Figure (2.1). The trigger generator was developed by Physics International Company (nowadays L3 sciences [13]) and represents by far the best trigger generator unit worldwide, being used in many projects, mostly related to high voltage (Megavolt) Marx generators. The three cables can be charged to a maximum voltage of 70 kV and the peak pulse voltage at the output end of the cables can approach 140 kV for high impedance (‘open’) loads. The source of energy is a low-inductance energy-storage capacitor, which is DC charged up to 70 kV and then discharged into the cables by a triggered SF₆ pressurized gas spark gap (trigatron).

Figure 2.1 Schematic of the pulsed trigger generator TG70 [13]
Figure (2.1) shows a simplified electric scheme for the TG70, and Figure (2.2) shows an equivalent electrical scheme using lumped elements.

![Figure 2.2 Lumped element scheme of TG70](image)

As illustrated in Figure (2.1), the TG70 trigger generator system consists of:

1. **High voltage generator**
   
The high-voltage pulse generator comprise an annular phenolic cased capacitor contained within a cylindrical aluminium housing, with an SF₆ pressurized gas spark gap switch located at one end of the assembly. The components which comprise the HV pulse generator are:

   - Energy storage/discharge capacitor
   - Output spark gap switch
   - Trigger generator

2. **Control system (chassis)**
   
The remotely located control chassis consists of:

   - A gas control panel mounted on a rack panel that accepts sulphur hexafluoride (SF₆) gas at a regulated pressure, and distributes it to the TG70 housing and spark gap switch. This control panel consists of:
     1) Supply pressure gauge (A), see Figure (2.3(i)), which regulates the gas flow from the supply cylinder
     2) Pressure gauge for the required operating voltage (B) see Figure (2.3(i)), which regulates the gas flow to the spark gap

   - Electrical Controls

**TG 70 Functioning**

The following procedure explains briefly the functioning of the TG70.

1. The supply gas cylinder is a pressurised bottle of high grade gas, with the SF₆ measured by gauge (A).

2. The spark gap is pressurised from the supply cylinder, with the gas regulated and measured by pressure gauge (B). The spark gap pressure is chosen from the operating voltage versus SF₆ pressure curve presented in Figure (2.4). Both the
supply cylinder and the spark gap chamber are flushed with SF$_6$ to remove any impurities prior to being pressurised.

Figure 2.3 The complete TG70 system (i) the control unit consisting of (A) supply pressure gauge, (B) gas pressure gauge for setting the voltage, (C) TG-70 power button, (D) display screen, (E) charging switch, (F) H.V adjustment, (G) high-voltage button, (H) trigger button (ii) The high voltage generator consisting of (I) trigger unit, (J) oil tank.

Figure 2.4 operating voltage (kV) vs SF$_6$ pressure curve [13]

Note the self-breakdown line above the operation area

3- Ensure that the power button (C) of the TG70 is ON.
4- Ensure that the high voltage (HV) button (G) is on, otherwise the manual trigger (H) will not operate.
5- Initiate charging of the capacitor by means of the charging switch (E) in Figure (2.4).
6- Using the knob (F) and the display screen (D) set the voltage to the required level and then press the trigger button (H).
7- Close the high voltage (HV) button

**Output cables**

The three outputs from the TG-70 are made via coaxial cables type RG-218/U shown in Figure (2.5) below.

![Coaxial cable diagram]

Figure 2.5 TG-70 output coaxial cable [14]

The cables consist of a central copper conductor surrounded by a solid plastic (polyethylene) insulator, enclosed in a shield layer of woven metallic braid and protected by an outer insulating jacket. The cables are (30ft) 9.1 m long, which provides sufficient electrical transit time to ensure pulse doubling at the output end of the cable, and they have an impedance of 50 Ω.

**TG70 Modelling**

To better understand its operation and to be capable of implementing a crowbar switch (see chapter 5), a model of the TG70 was developed using LT Spice software. LT Spice is a spice based programme [15] developed for modelling electrical circuits, and consists of a schematic capture programme that allows users to create and edit circuits, and a waveform viewer for displaying the simulated wave forms.

**TG70 LT Spice modelling**

Figure (2.6) shows the basic arrangement of the circuit used for modelling the TG70 generator. As shown, the model consists of a 0.1 μF capacitor C1, which charges the three transmission line (T1, T2, and T3), that represent the RG218/U coaxial cables. Two transmission lines are terminated with a resistor (R2 or R3) of 10 kΩ to complete the circuit. Figure (2.7) shows the result of the TG70 modelling with a resistive load R1 of 58Ω having an inductance of 700nH.
If the load on the TG70 is capacitive, it is necessary to add a capacitor C2 in series with resistor R1, where the value chosen corresponds to the capacitance of the water cell described later in chapter (5). Figure (2.8) shows the circuit modelling for the TG 70 with a capacitive load, and Figure (2.9) shows the predicted output for a capacitive load which is the Kerr water cell 1 (more details is in chapter 4).
2. PULSED POWER GENERATORS

Figure 2.8 Circuit modelling for the TG 70 with a capacitive load

Figure 2.9 Predicted output of TG70 LT Spice modelling for capacitive load

Comparison between TG70 modelling and experiments
Figure (2.10) present a comparison between the predicted output voltage of the TG70 and an experimental result obtained when a 58 Ω resistor was attached at the end of one of the three output cables. Together with the cables, and as included in figure (2.6), this results in the inductance (L1) increasing to 700 nH.
Figure 2.10 Comparison between experimental and modelling result for the TG70 with resistive load

Figure (2.11) shows an experiment result with the TG70 powering a 1.12 nF capacitive load, connected in parallel with a resistive load of \( R = 1.135 \text{ k}\Omega \), and with inductance from the connecting cables of about 150 nH. Such capacitive loads are characteristic of the water cells used later when determining the Kerr constant of liquids, as detailed in chapter 4.

The voltage oscillations observed in Figure (2.11) are very useful, allowing a separate precise determination of the Kerr constant for each peak (as described later in chapter 5).
The very close comparison between theory and experiment allows using LT Spie modelling, allowed an understanding to be gained of all features of the later Kerr experiments, including electrical breakdowns.

2.2 Tesla Transformer systems

During the present work, two Tesla transformer based PFL systems were used termed: TPFL1 and TPFL2. The author participated only in the development of TPFL2, since TPFL1 was developed by a previous PhD student. However, for completeness, brief presentations are made for both systems.

This section is organised as follows: firstly a general introduction covers the history of Tesla Transformers. This is followed by short presentations of the other two components, the PFL and the closing switch. Finally, the two systems, TPFL1 and TPFL2, are briefly described with more details regarding the development of TPFL2.

In the present thesis Tesla transformers are used as a high voltage pulsed charging generator in two similar systems: the first termed TPFL1 in which the transformer charges a pulse forming line PFL coupled to a radiating antenna and a second termed TPFL2 in which the PFL is discharged using a very low inductance load. The two systems have the same principles of design but the second generator or TPFL 2 has been improved to be more powerful than the first generator TPFL 1. In general, Figure (2.12) illustrates the overall features of both systems.
2. PULSED POWER GENERATORS

![Diagram of Pulsed Power Generator System]

**Figure 2.12** Block diagram General design principle of (TPFL1&TPFL2)

### 2.2.1 Introduction and history of Tesla transformer

A Tesla transformer is an air core pulsed transformer, operated at very high power levels, or ultra high RF frequencies. The advantage of the air core transformer is that no magnetic core materials are used to channel the magnetic flux through the winding and ensure maximum flux linkage. The flux linkage is strongly dependent upon the physical proximity of all the turns of one winding with respect to all the turns of the other winding. Thus, the coupling coefficients of air core transformers tend to be lower than these of magnetic core transformers, mainly with high gain transformers. However, an important advantage of air core transformers is that they are not limited in either current handling capacity [16] or frequency by saturation of the magnetic materials or by the composition of the core.

In general, there are two types of high voltage air core pulse transformer, which can be operated up to megavolts [16]. The common type is the single layer helical wound transformer, and the second type is the spiral strip type. In the present work the former type is used for the Tesla high voltage generator, although, there are two common problems for this type of transformer. One of these is the turn to turn electrical breakdown between windings, which is the most common problem with helical transformers used in charging systems for pulse forming lines. Because the raise time of the voltage transient is fast (less than 10ns) and is generated by the discharge of the PFL that is fed into the output of a direct coupled transformer, the problem is serious. The capacitances between turns and from each turn to ground are normally sufficient to fast rising transients. Consequently, a voltage pulse approaching the fall amplitude of the transient can momentarily appear across the final turns of the secondary and cause a breakdown.

The revolutionary work of Tesla is well reported in a series of patents such as ‘System of electric lighting’ where the use of the air-core transformer generates high voltage at high frequency for the production of light. In another patent Tesla improved the circuitry described in ‘System of electric lighting’.

In 2005, P.Drude proved that the maximum output voltage is achieved in the secondary circuit of a Tesla transformer by tuning the primary and secondary circuit to resonate the same frequency and with a coupling coefficient of 0.6. In 1966 D. Finkelstein, presented the dual resonance condition under which complete energy transfer from the primary circuit to the secondary circuit takes place. He went on to show that for any coupling coefficient other than 0.6, the instant at which the complete energy transfer takes place is delayed. The design he proposed used a spiral-strip type secondary winding wound on an acrylic former, with the inter-turn insulation provided by multi-layered Mylar. Mylar film was also used to insulate the single-turn primary winding from the multi-turn secondary winding. De-ionised water insulated the transformer within its housing, thereby enabling it to withstand an output voltage up to 1 MV. The transformer was used with a variety of loads, including exploding wires and high-voltage water filled capacitors and also to test a water-filled spark gap.
F. M. Bieniosek in 1990, presented an analysis for a triple resonance transformer circuit i.e. three circuit in resonance, used to improve the output efficiency of the MEDEA II electron accelerator. The stray capacitance of the spiral secondary winding was comparable to that of the load capacitance, and as a consequence a significant quantity of energy remained stored in the stray-capacitance and was not delivered to the load. With the addition of a suitable inductor between the transformer secondary winding and the load, the circuit was made to operate in a triple resonance mode, thereby increasing the energy transfer efficiency to the load. Due to this design change, there was a reduction in the peak voltage across the secondary winding. A compact and repetitive Tesla transformer based pulsed accelerator was developed by G. A. Mesyats in 1991 and Yu. A. Andreev in 1997, separately at the Institute of Electro-physics (IEP) and the Institute of High Current Electronics (IHCE), both in Russia. The pulsed power source of these accelerators is based on a Tesla transformer integrated with an oil-insulated coaxial pulse-forming line with an open steel magnetic core to increase the coupling coefficient to almost unity. The secondary winding was wound on a conical former and the voltage step-up ratio was very high. This ensured that the charging voltage of the primary capacitor bank could be less than a kilo-volt, enabling low voltage capacitors and switches to be used in the primary circuit, which helped to reduce the cost and also in solving problems related to high-voltage in the primary circuit.

J. L. Korioth in 1999, proposed a design with a ‘super low’ inductance primary (SLIP), for use in dual resonant transformers, with the aim of making the primary set-up of capacitor bank and switch compact and of low inductance. One unit used two 6" long, 8" diameter coaxial cylinders, with twelve 2 nF primary capacitors and a hydrogen spark-gap switch placed between a slit in the conductive cylinders. The inductance was 200 nH and the resonant frequency about 2.1 MHz.

M. Denicolai in 2002, demonstrated that to achieve an optimal performance, a good way is to tune the primary and the secondary coil to resonate at same frequency and then to increase the coupling coefficient to 0.6. Also, in order to minimise the loss it is essential for the maximum voltage at the secondary to be obtained in the shortest possible time.

2.2.2 Tesla transformer theory
The basic Tesla transformer can be simply described as two inductively coupled and damped resonant circuits [17] as shown in Figure (2.13), where subscripts (P) and (S) identify the inductance (L), capacitance (C), and resistance (R) of the primary and secondary circuits respectively, and (M) denotes the mutual inductance between the two circuits. The resistances represent the resistive loss in the circuits, which in practice is mainly the time dependent loss in the primary circuit due to the spark-gap switch. A more accurate approach would be to treat the circuit parameters as distributed, as in a transmission line analysis, especially the stray-capacitance of the secondary winding. However, since the load capacitance is generally sufficient to lower the oscillation (LC) frequency to well below the self-resonant figure associated with the distributed reactance of the unloaded winding, the lumped parameter assumption can predict the transformer performance with sufficient accuracy for the present application.

Applying Kirchhoff’s law to the circuit of Figure 2.13 with the switch closed gives, for the primary circuit

\[
\frac{1}{C_P} \int i_p dt + R_p i_p + L_p \frac{di_p}{dt} + M \frac{di}{dt} = 0
\]  

(2.1)
and for the secondary circuit

\[
\frac{1}{C_s} \int i_s dt + R_s i_s + L_s \frac{di_s}{dt} + M \frac{di_p}{dt} = 0
\]  

(2.2)

Figure 2.13 A Tesla transformer inductively coupled primary and secondary circuits

For an instantaneous charge \(q_p\) and \(q_s\) on capacitors \(C_p\) and \(C_s\),

\[
i_{p,s} = \frac{dq_{p,s}}{dt}
\]  

(2.3)

Substituting into equation (2.1) and (2.2), rearranging and introducing the differential operator \(D\) yields

\[
\begin{bmatrix}
D^2 + \frac{R_p}{L_p} D + \omega_p^2 \\
D^2 + \frac{R_s}{L_s} D + \omega_s^2
\end{bmatrix}
\begin{bmatrix}
q_p \\
q_s
\end{bmatrix}
+ k \begin{bmatrix}
\frac{L_s}{L_p} D^2 q_s \\
\frac{L_p}{L_s} D^2 q_p
\end{bmatrix}
= 0
\]  

(2.4)

\[
\begin{bmatrix}
D^2 + \frac{R_p}{L_p} D + \omega_p^2 \\
D^2 + \frac{R_s}{L_s} D + \omega_s^2
\end{bmatrix}
\begin{bmatrix}
q_s \\
q_p
\end{bmatrix}
+ k \begin{bmatrix}
\frac{L_s}{L_p} D^2 q_s \\
\frac{L_p}{L_s} D^2 q_p
\end{bmatrix}
= 0
\]  

(2.5)
where
\[ k = \frac{M}{\sqrt{L_p L_s}} \]  
and
\[ \omega_p^2 = \left( L_p C_p \right)^{-1} \]
\[ \omega_s^2 = \left( L_s C_s \right)^{-1} \]

where \( \omega_p \) and \( \omega_s \) are the resonant frequencies of the uncoupled primary and secondary circuits, and \( k \) is the coupling coefficient (0 < \( k \) < 1). Equations (2.4) and (2.5) can be solved numerically (by a Runge Kutta method). By considering two special cases (i) in which the resistive loss in the circuit is neglected i.e. \( R_p = R_s = 0 \) and a complete analytical solution is possible and (ii) the primary and secondary resonant frequencies are matched \( \omega_p = \omega_s \) and a low-loss approximate solution is possible, which assists in determining the important parametric factors.

i) Lossless circuit \((R_p = R_s = 0)\)

Even though the lossless circuit is impractical, the analysis provides a maximum limit to the actual transformer performance. Substituting \( R_p = R_s = 0 \) into equations (2.4) and (2.5) and solving for \( V_s \) yields [18]

\[ V_s(t) = V_0 \frac{2k}{L_p \sqrt{L_p} \sqrt{(1-T)^2 + 4k^2 T}} \sin \left( \frac{w_p + w_s}{2} t \right) \times \sin \left( \frac{w_s - w_p}{2} t \right) \]  

(2.8)

where, \( T \) the tuning ratio \( = \frac{\omega_p^2}{\omega_s^2} \) and

\[ w_p = \omega_p \sqrt{\frac{(1+T) - \sqrt{(1-T)^2 + 4k^2 T}}{2(1-k^2)}} \]
\[ w_s = \omega_s \sqrt{\frac{(1+T) + \sqrt{(1-T)^2 + 4k^2 T}}{2(1-k^2)}} \]  

(2.9)

where, \( w_p \) and \( w_s \) are the angular resonant frequencies of the primary and secondary circuits when coupled. Their value are always real and clearly \( w_s > w_p \). From equation (2.8) it can be seen that the secondary voltage has a high oscillation frequency \( \frac{w_p + w_s}{2} \) which is amplitude modulated by a second and lower frequency oscillation \( \frac{w_s - w_p}{2} \).

Equation (2.8) shows that the maximum voltage across the secondary capacitance can be expressed as

\[ V_0 \frac{2k}{\sqrt{L_p \sqrt{L_p} \sqrt{(1-T)^2 + 4k^2 T}}} \]

which can be achieved only if both the sine terms in equation (2.8) are simultaneously equal to ±1, and can be stated as
\[
\begin{align*}
(w_s + w_p)t &= (2n+1)\pi \\
(w_s - w_p)t &= (2m+1)\pi 
\end{align*}
\]

where \(n\) and \(m\) are integers. The earliest time at which the maximum secondary voltage will occur is when \(m = 0\) and thus \(t = \pi / (w_s - w_p)\); substituting and rearranging equation (2.10) then yields

\[
\frac{w_s}{w_p} = \frac{1+n}{n}
\]  

(2.11)

and on substituting equation (2.9) into (2.11)

\[
k = \sqrt{\frac{(2n+1)^2(T+1)^2-(1-T)^2}{4T}}
\]  

(2.12)

The energy transfer efficiency \(\eta\) is

\[
\eta = \frac{\sqrt{\frac{1}{2}} C V_{\text{max}}^2}{\sqrt{\frac{1}{2}} C_p V_0^2}
\]

where \(V_{\text{max}}\) is the maximum voltage achieved across the secondary capacitance during the time period \(t \leq \pi / (w_s - w_p)\). Satisfying the condition of equation (2.10) gives

\[
\eta = \frac{4k^2T}{(1-T)^2+4k^2T}
\]

The complete energy transfer takes place, i.e. \(\eta = 1\), when \(T = 1\) or the resonant frequencies are matched. The maximum voltage across the secondary capacitance is then

\[
V_s = V_0 \sqrt{\frac{L_s}{L_p}}, \text{ when } k = \frac{1+2n}{2n^2+2n+1}
\]

To illustrate the dependence of the energy transfer efficiency on the coupling coefficient \(k\), equation (2.8) was used with \(T = 1\) (matched resonance). The results are shown in Figure (2.14).

It is evident from Figure 2.14 that with a coupling coefficient of less than 0.6, the energy transfer time is delayed. For a coupling coefficient of \(0.43 < k < 0.53\), the performance is poor, with almost 13% of the energy remaining in the primary circuit for \(T = 1\). There are other discrete values of \(k\) such as 0.385, 0.28, and 0.22, etc. for which complete energy transfer takes place if \(T = 1\) [19]. When corresponding results are plotted for \(T \neq 1.0\) the performance of the transformer becomes even worse.
2. PULSED POWER GENERATORS

Figure 2.14 Energy transfer efficiency and energy transfer time as a function of coupling coefficient $k$, for $T = 1$ and $T = 0.8$

### ii) Low-loss circuit

The lossless assumption is clearly a very rough approximation to reality, as any practical transformer will have losses in both the primary and secondary circuits. Ohmic resistance losses will be greatly enhanced by skin and proximity effects as the resonant frequency increases. In addition, the dielectric loss in the capacitors will increase with any increase in frequency, which will appear as an effective series resistance. Perhaps the major contribution will however come from time-dependent electrically breakdown phenomenon in the spark-gap switch.

With the quality factor of the primary and secondary circuits defined as

$$Q_p = \frac{\omega_p}{L_p} \frac{R_p}{Q_p}$$
$$Q_s = \frac{\omega_s}{L_s} \frac{R_s}{Q_s}$$

(2.13)

a simple expression for the secondary voltage across the secondary capacitance for a matched frequency circuit with resistive loss can be obtained as [20]

$$V_s = V_0 \sqrt{\frac{L_s}{L_p}} e^{-\frac{\omega t}{\tau}} \left[ \cos \left( \frac{\omega t}{\sqrt{1+\tau}} \right) - \cos \left( \frac{\omega t}{\sqrt{1-\tau}} \right) \right]$$

(2.14)

where $\tau = \frac{4Q_p Q_s (1-k^2)}{\omega (Q_p + Q_s)}$, the damping time constant, and $\omega = \omega_p = \omega_s$ is the angular frequency of the applied voltage. This approximation is quite accurate for $k < 0.6$ and $Q > 10$.

Using equation (2.14), the variation of energy transfer efficiency with coupling coefficient was plotted for different values of quality factor. It is evident from Figure (2.15) that the efficiency decreases with a decrease in the quality factor, with the decrease being greater for lower values of the coupling coefficient. Hence it is desirable to design a transformer with
matched resonance, a coupling coefficient of about 0.6, and a $Q_p$ of 20 or even higher as shown in Figure(2.15).

![Figure 2.15 Variation of energy transfer efficiency with the coupling coefficient for various values of Q (quality factor)]

2.2.3 General introduction to Pulse Forming Line

Physics and electrical engineering have many applications for short pulses ($10 \text{ ns} < t_p < 100 \text{ ns}$), which requires a good pulse shape, for example a fast rise time ($t_r$) and fall time ($t_f$). Among the different techniques for generating such pulses one of these is the pulse forming line which also can be used at extremely high pulsed power levels.

In general, the pulse forming method relies on the use of a single length of transmission line and a fast switch. Essentially, the pulse forming line consists of a transmission line, (sometimes a waterline or oil filled line) that is charged as a lumped capacitor (forming the secondary capacitance of the Tesla transformer) to store electrical energy and a high voltage switch to discharge this energy in the transmission line to the load.

The important feature of the transmission line is that its cross sectional configuration and the separation between the conductors must also remain constant along the length of the line. If a dielectric is inserted between the lines the dielectric constant must remain constant along the length of the line. Although different types of line can be envisaged, the simplest and most commonly used is the coaxial line, where two coaxial cylindrical conductors with finite length work as a transmission line, as shown below.
Figure 2.16 Coaxial transmission line

The electrical parameters of the coaxial transmission line are equally distributed along its length. With reference to Figure (2.16) these parameters (per unit length) for a coaxial line are [21]:

\[
C = \frac{2\pi \varepsilon_r}{\ln \left(\frac{R_{out}}{R_{in}}\right)}
\]

\[
\mu_r \ln \left(\frac{R_{out}}{R_{in}}\right)
\]

\[
L = \frac{\mu_r \ln \left(\frac{R_{out}}{R_{in}}\right)}{2\pi}
\]

and the characteristic impedance of the line is

\[
Z_0 = 60 \sqrt{\frac{\mu_r}{\varepsilon_r}} \ln \left(\frac{R_{out}}{R_{in}}\right)
\]

where \(\varepsilon_r\) is the relative permittivity of the dielectric material between the conductors.

\(R_{in}\) is the inner radius of the inner conductor of the transmission line.

\(R_{out}\) is the outer radius of the outer conductor of the transmission line.

A simple circuit diagram of a pulse generator based on single pulse forming line, which is similar to transmission line is shown in Figure (2.17).
2. PULSED POWER GENERATORS

Figure 2.17 Basic structure of a pulse forming line generator [21]

As shown, a DC power supply charges the transmission line, usually by:
- A resistor or inductor that has high impedance which limits the charging current to the maximum corresponding to the output power specifications of the supply.
- A capacitor, where the high impedance may not be necessary because the switch recovery time is at least as fast as the response time of the power supply.

Using switches such as spark gaps can latch into a permanently on state when fed by the current generated by the charging supply.

According to Figure (2.17), the line is charged when the switch is closed and it is subsequently discharged into the load $Z_L$. Assuming that the impedance of the load is resistive, a rectangular pulse is generated on the load. This pulse has a duration $t_p$ given by:

$$ t_p = \frac{Z_L}{v_p} $$

where, $v_p$ is the propagation velocity.

$$ v_p = \frac{c}{\sqrt{\varepsilon_r}} $$

Figure (2.18) illustrate the potential on a line at various times after the switch is closed.
As the switch is closed, the voltage on the load rises to a value determined by the initial supply voltage, the characteristic impedance $Z_0$ and the load impedance and is given by:

$$V_l = V \left( \frac{Z_l}{Z_l + Z_o} \right)$$

Since the impedances of the line and load are equal the voltage on the load will be $V/2$, and at the same time a voltage step $V_s$ is propagated away from the load towards the charging end of the line. This voltage step is given by

$$V_s = V \left( \frac{Z_l}{Z_l + Z_o} - 1 \right) = V \left( \frac{-Z_o}{Z_l + Z_o} \right)$$

When the voltage step reaches the charging end of the line, after a time $t_p$, it will be reflected with a reflection coefficient $\rho = +1$, because the output impedance of the charging supply is greater than that of the line. Thus the potential at the charging end of the line falls to zero and the voltage step propagates back towards the load. If the impedances of the load and the line are matched, the voltage step will be $\frac{-V}{2}$, which means that the line potential is reduced to zero (i.e. it is completely discharged). When the voltage step reaches the load the line is completely discharged. However, if the line and the impedance of the load are not matched, more reflections of the voltage step propagation will occur at the load, and the output pulse shape becomes more complicated than a single rectangular pulse.
2.2.4 Spark gap switches

In high voltage pulse generators closing or opening switches, such as spark gaps, are used with both capacitive and inductive energy storage systems. These switches are an important component of pulsed power circuitry and the system output performance is critically dependent on their characteristics. Closing spark gap switches depend on the functions they perform. In generators for example, it may be necessary to have a short switching time $t_s = 10^{-19} - 10^{-8}$ s [22]. Spark gap switches display an excellent voltage withstand capability (as high as a few MV), and a high charge transfer capability. In addition, their operation can be synchronized with other circuit elements by triggering them through a third electrode.

A gas switch can be considered to be electrically closed when under a high electric field stress the insulating gas between the electrodes becomes conducting and a plasma channel develops. This transition of the switch from the insulating to the conducting state can be explained in two ways, the Townsend model and the streamer model. Figure (2.19) is a diagram of switches similar to those used in this work.

![Figure 2.19 Schematic diagram of a spark gap switch [22]](image)

In (2.19(A)); (1,4) are the electrodes of the switch, (2) the pins, (3) SF6 gas at 4-5 atm. (5) switch housing. In part (B); (1) are the electrodes, (2,6) inner conductors, (3,5) the outer conductors, (4) SF6 gas at 4-5 atm. (7) insulators.

In table (2.1) the pulse rise time is calculated from the inductance of the spark gap by

\[ t_r = \frac{L}{Z_{\text{load}}} \]

<table>
<thead>
<tr>
<th>OUTPUT VOLTAGE (MV)</th>
<th>Inductance, L (nH)</th>
<th>$Z_{\text{load}}t_r$, ($\Omega \cdot \text{ns}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>90</td>
<td>116</td>
</tr>
<tr>
<td>1.0</td>
<td>135</td>
<td>169</td>
</tr>
<tr>
<td>2.0</td>
<td>248</td>
<td>305</td>
</tr>
</tbody>
</table>

Table (2.1) [22]
2. PULSED POWER GENERATORS

Two electrode switches are widely used in repetitive system generators with, pulse repetition rates of \(10^2 - 10^4\) Hz at voltages \(10^3 - 10^4\) V. The gas flow velocity should be sufficiently high to remove plasma from the gap within the pulse interval, but not too high so as to keep the discharge region at the cathode heated in order that initiating electrons will appear during the discharge initiated by the next pulse [22].

Most switches may be viewed as a set of capacitor plates separated by a dielectric. The dielectric properties can be made conductive in some manner, such as the ionization of a gas (thyatrons), injection of charge carriers into the conduction band (solid state), or injection of a conducting medium into the separating region (vacuum spark gaps) [22]. The readily available energy stored in the inter electrode capacitance is dissipated internally in the switch and is important for the rapid formation of a conducting plasma. In most cases a charge transport phenomenon through the previously insulating medium is required to maintain switch closure.

2.3 TPFL1

2.3.1 Tesla Pulse Forming Line (TPFL1)

This type of system is based on direct switching technology. The initial energy is fed to a capacitor bank as shown in Figure (2.20) that illustrates the design principle adopted for TPFL1.

![Figure 2.20 Block diagram of (TPFL1)](HV Power Supply) → [Capacitor Bank + Spark gap switch] → [Tesla transformer] → [PFL + Fast Switch] → [Antenna]

The design specification for the Tesla transformer used in TPFL1 is as described in [23]

1) Peak secondary voltage \(~ 500\) kV. This high voltage is required for the application in which very intense electric field are to be generated either by an antenna coupled to the PFL or inside the PFL. As the voltage increases, significant insulation is required in the transformer secondary circuit, and as a result this type of system is usually bulky. In order to limit the volume it was decided to operate both TPFL1 and TPFL2 systems at only 500kV.

2) Energy transfer efficiency \(\geq 80\%\); the higher the better, and the main factors affecting it have been identified, as is explained later.

3) Voltage gain \(\geq 17\). In order to minimise the electrical stress on the primary side it is desirable that the charging voltage of the primary circuit should be less than 30 kV.
2. PULSED POWER GENERATORS

4) Total secondary capacitance ~ 60 pF. The load capacitance is governed by the pulse forming line (PFL), as discussed later.

5) Charging time of secondary load capacitance < 500 ns. This is to assist the insulation on the high-voltage section of the system, as most dielectric materials show an inverse power relationship between breakdown strength and stress duration [24].

The transformer, like any practical Tesla design, is operated in a dual resonant mode, requiring a coupling coefficient of about 0.6 and matched primary and secondary circuit.

The maximum secondary voltage occurs in the second peak of the output voltage, with the charging time for the load capacitance this being the time from the instant of closure of the primary spark gap switch closure to the peak. This shows that the design specification requires the charging time to be < 500 ns, and the matched resonant frequency should therefore be more than 2 MHz.

A set of designed parameters for the Tesla transformer that satisfies the above conditions is given in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary circuit capacitance, $C_p$</td>
<td>24 nF</td>
</tr>
<tr>
<td>Primary circuit inductance, $L_p$</td>
<td>200 nH</td>
</tr>
<tr>
<td>Secondary circuit capacitance, $C_s$</td>
<td>60 pF</td>
</tr>
<tr>
<td>Secondary circuit inductance, $L_s$</td>
<td>85 μH</td>
</tr>
<tr>
<td>Mutual inductance, $M$</td>
<td>2.4 μH</td>
</tr>
<tr>
<td>Coupling coefficient, $k$</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Table 2.2 Proposed circuit parameters for Tesla transformer [23]

For an ideal case, with 100% energy transfer efficiency, the maximum voltage gain $V_G$ is, from equation (2.12)

$$V_G = \frac{L_s}{L_p} = \frac{C_p}{C_s} \approx 20$$

and to achieve a voltage of 500 kV across the secondary, the primary capacitor needs to be charged to 25 kV. In an actual circuit there will be resistive losses arising from the effective circuit resistance although other significant contributions are due to the discharge action of the spark-switch in the primary circuit, and the dielectric loss of the capacitors. These loss mechanisms provide the effective resistance terms in equation (2.13), and from Figure (2.15) it can be concluded that a quality factor of 20 or higher is desirable for the primary circuit.
Capacitor bank

The capacitor used for the primary capacitor bank (CB) satisfies the conditions:

- Rated voltage \( \geq 30 \text{ kV} \)
- Voltage reversal withstand capability 100% 
- Low dissipation factor < 2% 
- Low inductance

Ceramic capacitors are most appropriate to meet these requirements, and in addition they are less expensive than Mica capacitors. Morgan Electronics 2 nF, 30 kV ceramic capacitors with a dissipation factor of less than 1% at 1 kHz were therefore used.

As the inductance requirement is low on the primary side, twelve 2 nF capacitors were connected in parallel as shown in Figure (2.21).

![Capacitor bank (CB) arrangement](image)

Figure 2.21 Capacitor bank (CB) arrangement

Transformer winding fabrication

The primary of the Tesla transformer was wound on a cylindrical plastic mandrel of outer diameter 218 mm, with the copper sheet sandwiched and heat bonded between two 125 mm layers of Mylar–polyethylene laminate, to provide improved insulation. The primary winding arrangement is shown in Figure (2.22).

The helical secondary was wound on a plastic conical former with a coil height of 196 mm, as shown in Figure (2.23).
As the secondary winding experiences a high electric stress, it is immersed in transformer oil. A schematic view of the transformer together with the pulse forming line (PFL) is given in Figure (2.24).

The metallic base plate closes one end of the arrangement and also helps in grading the electric field. But it also has a detrimental effect, due to the induced eddy currents decreasing the effective inductance and thereby reducing the gain and energy transfer efficiency [25]. A similar effect is also noticed when the conductors of the PFL are placed at the other end of the transformer, and in order to minimise both effects the metallic parts were placed at least 25 mm away from the transformer windings.
Initial power supply for the systems

This part of the system is provided by a capacitor charging power supply followed by commercially available 1000 pps high voltage capacitors, and a pulsar trigger generator.

i) Capacitor charging power supply

This is a commercially available from TDK Lambda model 500A series shown in figure (2.25) designed to operate in two modes. In the most common format it is a constant current capacitor charging supply which will reliably charge HV capacitors and pulse forming networks (PFNs). The 500A can also operate as a constant voltage, continuous output DC power supply, with the addition of an external filter capacitor. The specifications for this charging supply is shown in Table (2.3)
2. PULSED POWER GENERATORS

<table>
<thead>
<tr>
<th>Input Voltage (VAC)</th>
<th>Current (PFC) 500A</th>
<th>Current (No PFC) 500A</th>
</tr>
</thead>
<tbody>
<tr>
<td>180-250 47-63Hz</td>
<td>3.5A</td>
<td>5A</td>
</tr>
<tr>
<td>90-140V 47-63Hz</td>
<td>7A</td>
<td>10A</td>
</tr>
</tbody>
</table>

Table 2.3 Specification of the capacitor charging power supply [26]

ii) Trigger generator

Model PG-103D is an all solid-state pulser employing IGBT topology. It is designed to trigger SG-series trigatron spark gaps and is capable of controlling up to four switches. A complete system consists of a control box, optical fiber link(s), trigger head(s), and trigger transformer(s). Since there is no direct electrical connection between the control box and trigger head, noise immunity is greatly enhanced. The number of channels is specified at the time of order, but the system may be subsequently upgraded at the factory with additional channels. Multi-channel systems offer internally programmable delays, which is useful with crowbar applications, for example. When properly configured and installed, the model PG-103D trigger generator will fire independent or multiple-channel switches with ratings to 100 kV and 500 kA.

![Figure 2.26 Front panel for the trigger pulsar][27]
A THD-01B trigger head connected to the pulsar. It is based on the switch requirements (trigger voltage and rise time) and also on the operational needs (repetition rate and isolation voltage). The THD-01B system utilizes a trigger transformer with exceptionally large DC isolation (primary-to-secondary hold-off potential). The primary application for the THD-01B head is high current, high charge-transfer switches. The trigger heads are enclosed in heavy-gauge steel boxes for increased immunity to EMI, RFI, and magnetic fields. Transformers and boxes have provisions for surface mounting and attachment. All trigger heads receive their fire command through an optical fiber link. These utilize industry standard ST™ connectors and multimode fiber (Avago 820-nm multimode HFBR-1412/2412 transmitter-receiver links).

**Tesla Transformer Winding design**

The inductance calculations for the Tesla transformer were performed using the filamentary technique discussed in detail elsewhere [23]. Most high-voltage transformers are designed with the low-voltage primary winding on the outside of a concentric secondary winding. For a low inductance primary circuit of 200 nH, a single-turn of copper sheet is used, with the following dimensions being decided on after a number of iterations:

- Diameter of winding 220 mm
- Width of copper sheet 150 mm
- Thickness of copper sheet 100 µm

The calculated self-inductance of the single-turn primary winding with these dimensions is 180 nH.
For the secondary winding, two types of design were considered:
   a) Helical winding
   b) Spiral winding

For a helical winding of copper wire, it is necessary to wind the wire on a conical former, both to ensure good insulation and to maximise the magnetic coupling with the primary winding. The details of a suitable winding being decided after a number of iterations are:

- No. of turns 31
- Wire diameter 0.95 mm
- Axial length of coil 196 mm
- Maximum diameter 185 mm
- Minimum diameter 116 mm

from which the calculated self-inductance of the secondary coil is 85 µH, the effective resistance is 2 Ω at 2 MHz and the stray-capacitance of the secondary winding is 28 pF.

For a spiral winding, the secondary coil is wound with copper sheet. The details of a suitable winding being considered after number of iterations are:

- No. of turns 25
- Copper sheet thickness 254 µm
- Diameter of the cylindrical former 74 mm
- Width of copper sheet 150 mm
- Insulation thickness between windings 0.5 mm

From which the calculated self-inductance of the secondary coil is 70 µH, the effective resistance is 21 mΩ at 2 MHz, and the stray-capacitance is 65 pF. Even though the spiral winding resistance is much lower than that of the helically wound coil, it has an inherent disadvantage in that its stray-capacitance is more than the load capacitance. The overall efficiency is thereby considerably reduced, as a significant amount of energy is used in charging the stray capacitance. On balance, the helically wound secondary winding is clearly the preferred option.

a) Primary circuit set-up

The primary circuit of the Tesla transformer is shown in Figure (2.1). The capacitor bank, CB is connected to the primary winding of the Tesla transformer through a short flat transmission line and a self-break spark-gap switch, as shown in Figure (2.29). A triggered spark-gap switch was not used, as the aim was to develop a simple and compact system, and the addition of a trigger mechanism would lead to a bulkier and more complex system.
b) Pulse Forming Line (PFL)

A PFL can be characterised by its conductor geometry and the type of insulating material used. For most high-voltage, fast pulse systems a coaxial geometry [28] is preferred, though other types of geometry like radial line resonators [29], [30] are also used in ultra-wideband transmitters, as well as in biconical structures [31]. The advantage of the coaxial PFL is that it may be readily integrated with the structure of the transformer to produce a highly compact design.

Various types of fluid can be used as the insulating material, though the support structures are usually made of solid insulators such as plastic. The types of fluids used include high-pressure gases, such as SF₆ pressurised to several atmospheres, de-ionised water, transformer oil, alcohol and glycerine. Deionised water, alcohol, and glycerine all have a high permittivity and are often used in either pure form or mixed together, although due to their polar characteristics the transmission loss increases considerably for RF signals. The transmission losses for gases are zero, but their permittivities are all very low and close to unity. A gas filled PFL will therefore have a relatively low energy storage density. Transformer oil offers the best choice as the dielectric medium for the present system, as its dielectric strength is high and it has a low dissipation factor.

For a coaxial PFL, in which end effects are neglected, the maximum electric field $E_{\text{max}}$ will be at the surface of the inner conductor, and for a voltage $V$ it is

$$E_{\text{max}} = \frac{V}{a \cdot \ln \left( \frac{b}{a} \right)}$$

where $a$ is the outer radius of the inner conductor and $b$ is the inner radius of the outer conductor. The aim is to produce a simple and compact design for the EMP generator, so that it is advisable to integrate the PFL with the Tesla transformer, i.e. to have the same outer diameter for both the PFL and single-turn Tesla primary. Since the single-turn Tesla primary has a diameter of 220 mm, the outer diameter of the outer conductor of the PFL must therefore also be 220 mm. With a wall thickness of 10 mm, the inner radius of the outer conductor is 100 mm. The partial breakdown strength of transformer oil is about 300 kV/cm, but this is dependent on the condition of the oil with regard to humidity and other contaminants. Assuming a factor of safety of $2 \ E_{\text{max}}$ was assumed to be about 150 kV/cm and
using equation (2.41), the outer radius of the inner conductor of the PFL should therefore be about 50 mm.

In the PFL and Tesla transformer arrangement shown in Figure (2.30) the conductors are made of aluminium. The spark gap end of the inner conductor of the PFL has a conical shape, to increase the leakage path and so reduce the probability of surface breakdown, since the inner (which was at a potential of more than 500 kV) and the outer (at ground potential) conductors of the PFL are both in contact with the plastic support. An electric field plot for the PFL using Maxwell 2D (www.ansoft.com) is shown in Figure (2.31), which confirms that the electric field is below 150 kV/cm near the inner conductor of the PFL. The probability of any breakdown is therefore avoided with the use of transformer oil as the dielectric medium, as its dielectric breakdown strength is 200 kV/cm.

The coaxial PFL will behave as a quarter wavelength resonator when switched to an antenna and its length $l$ is given as [32]

\[ 2l = \frac{c}{4f \sqrt{\varepsilon_r}} \]

For a resonant frequency of 100 MHz the physical length of the PFL should be 250 mm. However, loading by both the antenna and the effective reactance of the output switch will result in a resonant frequency somewhat lower than that predicted for an ideal quarter wavelength line. Therefore, the actual physical length of the PFL necessary for a 100 MHz resonance will need to be somewhat shorter, say about 175 mm.

Figure 2.30 PFL (without oil) mounted on the Tesla transformer; the conical secondary on top of which the inner conductor of the PFL is mounted can be seen.
Figure 2.31 2D electric field plot for PFL using Maxwell 2D FEM software package

The capacitance of the coaxial PFL is [32]

\[ C = \frac{2\pi\varepsilon_0\varepsilon_r l}{\ln\left(\frac{b}{a}\right)} \quad (2.42) \]

With a length of 175 mm the capacitance is about 31 pF and the stored energy \( E_{stored} \) is

\[ E_{stored} = \frac{1}{2} CV^2 = \frac{\pi\varepsilon_0\varepsilon_r V^2}{\ln\left(\frac{b}{a}\right)} \quad (2.43) \]

For an applied voltage of 500 kV, the stored energy is about 3.8 J. This small value of stored energy gives a very high power since the time of the discharge is 1 nano-second which is the aim of the machine.

c) Valentine Antenna

The Valentine antenna is a travelling wave high gain antenna improved to withstand very high amplitude pulses in a large frequency band. It is able to radiate high power pulses with a minimum of distortion. It is made of two copper strip curved along a specific profile as shown in Figure (2.32). It supports high voltage (HV) short duration pulses with a 25 kV
amplitude. The antenna has a high gain and is capable of radiating short pulses without dispersion within the 300 MHz – 2.5 GHz frequency band [33].

This antenna was designed at Pau University. It is capable of withstanding high voltage impulses up to 400 kV with a rise time of one nanosecond. Figure (2.33), illustrate the radiation principle of the Valentine antenna. The electric field produced is guided by the double strip line before being radiated. The radiation starts when the pulse reaches the zone where the double-strip line flares at the beginning of the exponential profile. The radiation is built during the propagation of the transient current on the antenna. The high frequencies are radiated first and the low frequencies towards the end of antenna. A part of the low frequencies is not radiated and returns to the generator. If the output of the generator is not matched, a second undesirable pulse will be radiated. The polarization of the radiated electric field is principally rectilinear and vertical for a vertical position of the antenna.

The antenna coupled to the TPFL1 has dimensions of a length of 400 mm and width of 78.09 mm, it is immersed in water with a cylindrical support having a diameter of 250.68 mm and its length is 990 mm.
2.4 TPFL 2

2.4.1 Tesla Pulse Forming Line (TPFL 2)
The TPFL 2 has a similar construction to TPFL1, but the high energy and load current required a scaled up design. The PFL is filled with water and is located between the Tesla transformer and the fast spark gap as shown in block diagram below.

![Block diagram showing general design principle of (TPFL2)](image)

**High-Voltage Tesla Transformer**

The design calls for a dual-resonance Tesla transformer having a coupling coefficient close to 0.6 and matched resonant frequencies for the primary and secondary circuits. The primary winding is a single-turn coil and the secondary winding a helical coil, wound on a conical plastic former, with the necessary high-voltage insulation achieved by immersing the secondary winding in oil. Figures (2.35) and (2.36) show the time dependence of the currents in the primary and secondary circuits, the output voltage on the PFL load and the overall electrical efficiency for a charging voltage of 32 kV. The maximum overall efficiency is in excess of 80%, a relatively high figure when compared with the efficiency of similar Tesla-based systems presented in literature. [34]

![The time dependence of the current in the primary circuit](image)
Numerical modelling used the following input data for the two windings [23]:

Primary inner radius: 170 mm  
Primary axial length: 150 mm  
Primary thickness: 0.1 mm  

Secondary inner radii (along the conical former):
- maximum 151 mm  
- minimum 91 mm  

Secondary axial length: 180 mm  
Secondary round conductor outer diameter: 1.2 mm  

The main parameters were calculated as:

- Primary winding self-inductance $L_p = 376.8$ nH  
- Secondary winding self-inductance $L_s = 181.7$ µH  
- Primary secondary winding mutual inductance $M = 5.0$ µH  
- Theoretical voltage multiplication factor $k_v = 21.9$
2. PULSED POWER GENERATORS

Primary circuit
As a small bonus, the two capacitors used in the present system each have a capacitance of 153 nF and not the 150 nF advertised in the GAEP catalogue and used in the design. The primary circuit was tested at a low charging voltage of about 3 kV, with the use of a nail switch. The nail switch has a simple construction, with the dielectric between the two plates of a parallel-plate transmission line being broken by the action of a nail pushed through by the fall of a weight along a tube. The characteristic resistance of such a switch is very low, between 5 and 10 mΩ, with the difference representing the error in the estimate of the ESR of the bank. The value found was 20±5 mΩ, from which the ESR of each of the two capacitors follows as 40±10 mΩ. The value used in the design was 80 mΩ while the data from GAEP for a frequency of 450 kHz suggest an ESR of 20 mΩ i.e., 50% lower.

Secondary circuit
Voltage measurement across the transformer secondary, using a conventional voltage probe, loads the transformer and make data interpretation very difficult. It was therefore decided to measure the current flowing in a short circuited secondary (Figure 2.37) to more reliably obtain data on the secondary circuit. The experiment, performed at the same low charging voltage (of about 3 kV) again used a nail switch, provided an estimate of all inductances of the system and the coupling coefficient, with the percentages indicating the differences between the calculated and the experiment measurement the design data being:

- Lp: -0.6% lower
- Ls: -2.6% lower
- M: -2.8% lower
- k: -1.1% lower

Further measurements demonstrated that some of these differences were the result of small differences in the transformer geometry between the design and the actual components.
2. PULSED POWER GENERATORS

TPFL2: an advanced and detailed presentation

In general, the characteristics of a PFL are determined by three factors: the geometry and topology of the conductors, the nature of the insulating material filling the line, and the physical dimensions. The common preference in most high-voltage, fast pulse systems is to use coaxial lines. The advantage of these PFLs is that they may be readily integrated into the structure of the transformer to produce a highly compact design. The best examples of this concept are the Russian high-voltage pulse generators described earlier.

Solid support structures within the PFL can be made using polymer type plastics, but the bulk insulating medium will be a fluid. Typical options include:

- De-ionised water
- Ethylene glycol
- Perfluoro-1,3-dimethylcyclohexane
- Transformer oil
- High pressure gases, e.g. SF₆ at several atmospheres

Water and ethylene glycol both have relatively high dielectric constants and breakdown strengths, and are therefore often used, either pure or mixed, in high-voltage pulsed power devices. However, both need a pump with an attached filter to maintain their properties and, due to the polar characteristics of their molecules, the transmission losses increase considerably at frequencies in the VHF range. Gases exhibit virtually zero transmission loss, but as their dielectric constants are close to unity, gas-filled PFLs will have relatively low energy storage densities unless very high pressures are used to increase significantly the internal breakdown strength. Transformer oil possibly represents the best choice, as it combines high dielectric strength with a low dissipation factor, and in comparison with high pressure gas it should be much easier to handle and contain. A more convincing demonstration will be provided later.

For completion, we mention the possible use of other dielectrics in the construction of a PFL, such as ceramic materials and various composite polymers. For integrating the PFL with the transformer however, a fluid represents a better choice.

There are three practical targets when designing a PFL, as summarised below.

A. Maximising the voltage

Maximising the voltage of a coaxial structure can be important for high-voltage transmission lines and special design PFLs. For a coaxial PFL, and ignoring fringing fields at the terminations, the maximum electric field \( E_{\text{max}} \) as shown previously in equation (2.41)

\[
E_{\text{max}} = \frac{V}{a \ln(b/a)}
\]

If the PFL volume is fixed i.e., \( b \) has a given value \( b_{\text{real}} \), and the natural breakdown field limits of the insulation material within the line is \( E_{\text{break}} \) then by introducing

\[
x = \frac{b_{\text{real}}}{a}
\]

the maximum voltage that can be applied is
2. PULSED POWER GENERATORS

\[ V(x) = \frac{b_{\text{real}} E_{\text{break}} \ln(x)}{x} \]

The corresponding value of \( x \) enabling the maximum voltage to be achieved is obtained from

\[ \frac{dV(x)}{dx} = \frac{b_{\text{real}} E_{\text{break}}}{x^2} (1 - \ln(x)) = 0 \]

as \( \ln(x) = 1 \) or \( a = \frac{b_{\text{real}}}{e} \approx 0.368 b_{\text{real}} \) and \( V_{\text{max}} = \frac{b_{\text{real}} E_{\text{break}}}{e} \).

**B. Maximising the energy density**

Maximising the energy storage density of a PFL is often the most important concern. This is related to the capacitance per unit length of the line \( C' \) which, in coaxial geometry is

\[ C' = \frac{2 \pi \varepsilon_r}{\ln(b/a)} \]

where \( \varepsilon_r \) is the relative permittivity of the insulation material filling the line, and \( \varepsilon_0 \) is the permittivity of free space \( (\varepsilon_0 \approx 8.85 \text{ pF/m}) \). Hence, the energy stored per unit length \( W' \) is:

\[ W' = \frac{1}{2} C' V^2 = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln(b/a)} V^2 \]

As before, by considering the breakdown field limitation of a line of given volume,

\[ W'(x) = \frac{\pi \varepsilon_0 \varepsilon_r}{x^2} \left( b_{\text{real}} E_{\text{break}} \right)^2 \ln(x) \]

the maximum value is found by solving

\[ \frac{dW'(x)}{dx} = \frac{\pi \varepsilon_0 \varepsilon_r}{x^3} \left( b_{\text{real}} E_{\text{break}} \right)^2 [1 - 2\ln(x)] = 0 \]

which gives for the maximum \( \ln(x) = 0.5 \) or \( a_{\text{energy}} = \frac{b_{\text{real}}}{\sqrt{e}} \approx 0.6 b_{\text{real}} \) and

\[ W'_{\text{energy}} = \frac{\pi \varepsilon_0 \varepsilon_r}{2e} \left( b_{\text{real}} E_{\text{break}} \right)^2 \]

representing an increase of about 26.4% over the energy density in a PFL maximised for voltage, at a slightly lower operating voltage of

\[ V_{\text{energy}} = \frac{b_{\text{real}} E_{\text{break}}}{2 \sqrt{e}} \approx 0.824 V_{\text{voltage}} \]

It should be noted that the total energy density of the PFL will be slightly higher than that found using the energy stored per unit length \( W' \), due to the energy stored in the fields at both ends of the line.
The specific impedance $Z_0$ of a coaxial PFL is

$$Z_0 = \frac{\ln(b/a)}{2\pi\varepsilon_0 c \sqrt{\varepsilon_r}}$$

where $c$ is the speed of light in vacuum ($c \approx 3 \cdot 10^8$ m/s). For a PFL designed for a maximum energy density $Z_{\text{energy}} = \frac{1}{4\pi\varepsilon_0 c \sqrt{\varepsilon_r}}$ (i.e., half the impedance for a PFL designed to maximise voltage). For example, for oil having $\varepsilon_r \approx 2.25$, the specific impedance of an oil-filled PFL optimised to have the highest energy density is $Z_{\text{energy}} \approx 20 \Omega$. This explains the values for the RADAN’s PFL and Blumlein PFL (both using oil) in Table 2.4. Other specific impedance values for energy density optimised PFLs are 30 $\Omega$ for a gas-filled with $\varepsilon_r=1$ and 3.46 $\Omega$ for a water filled PFL with $\varepsilon_r \approx 75$. Unfortunately, this type of design cannot be applied in our case for reasons made clear below.

C. Matching the PFL with a specific load impedance

In this case, if the load has specific impedance $Z_0$, using equations (2.41) and the specific impedance equation the inner and outer radii of such a PFL will depend on the maximum voltage applied as

$$a_{\text{impedance}}Z_0 = \frac{\sqrt{V}}{2\pi\varepsilon_0 c \sqrt{\varepsilon_r} Z_0 E_{\text{break}}}, \quad b_{\text{impedance}}Z_0 = a_{\text{impedance}} Z_0 e^{\text{impenedance} \cdot F_{\text{break}}}.$$

The results obtained for the three possible PFL designs are summarised in Table 2.4.

<table>
<thead>
<tr>
<th>Type of design</th>
<th>Inner radius</th>
<th>Maximum voltage</th>
<th>Characteristic impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Maximising voltage</td>
<td>$\frac{b}{e}$</td>
<td>$\frac{b E_{\text{break}}}{e}$</td>
<td>$Z_{\text{voltage}}$</td>
</tr>
<tr>
<td>B Maximising energy density</td>
<td>$\frac{b}{\sqrt{e}}$</td>
<td>$\frac{b E_{\text{break}}}{2\sqrt{e}}$</td>
<td>$\frac{1}{2} Z_{\text{voltage}}$</td>
</tr>
<tr>
<td>C Given impedance $Z_0$</td>
<td>$\frac{Z_0}{Z_{\text{voltage}}}$</td>
<td>$b E_{\text{break}} Z_0 e^{-Z_0 Z_{\text{voltage}}}$</td>
<td>$Z_0$</td>
</tr>
</tbody>
</table>

Table (2.4)

Main characteristics for three types of PFL design for a given outer radius $b$ and a given dielectric material having a relative permittivity $\varepsilon_r$ and electric breakdown $E_{\text{break}}$.

The results are given in terms of the characteristic impedance

$$Z_{\text{voltage}} = \frac{1}{2\pi\varepsilon_0 c \sqrt{\varepsilon_r}}.$$
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Following design C, for a purely resistive load \( R_{\text{load}} = Z_0 = 30 \, \Omega \), a gas-filled PFL will have a too low an energy density and a water-filled PFL too large an outer diameter. Choosing oil as the dielectric and a conservative value of \( E_{\text{break}} \approx 150 \, \text{kV/cm} \), when operated at a PRF of \( 500 \, \text{Hz} \), a 1 MV PFL to generate a 10 ns flat 500 kV voltage impulse on the load will have the following approximate dimensions

- inner diameter: 178 mm
- outer diameter: 376 mm
- length: 1 m

where the length is calculated using a speed of voltage signal along the PFL of \( v_{\text{oil}} \approx 2 \times 10^8 \, \text{m/s} \). The capacitance of this PFL is about 167 pF, storing about 83 J when charged to 1 MV.

There are however two drawbacks to the simple PFL solution:
- the first is the charging voltage, requiring an output of over 1 MV from the Tesla transformer
- the second is the rather low capacitance of the PFL, possibly competing with the secondary winding Tesla capacitance and jeopardising the global efficiency of the system.

Electric field distribution

Figure (2.38 (a) and (b)) shows the electric field distribution inside the pulse forming line and switch for a secondary voltage of 560 kV, suggesting that no breakdown issues will arise.

Figure 2.38 Electric field distribution for a secondary voltage of 560 kV a) Tesla transformer b) PFL and switch
**Output closing switch**

The output high-voltage spark-gap operates in a self-breakdown mode in a pressurised SF$_6$ environment. The switch is made from a pair of 40 mm diameter bead-blasted brass hemispheres.

![Spark gap switch](image1)

**Figure 2.39 Spark gap switch**

![Testing of spark gap switch](image2)

**Figure 2.40 Testing of spark gap switch for high pressure withstand**

**Testing of TPFL 2**

The experiment with a water-filled open PFL figure (2.41) was performed mainly to calibrate the V-dot sensor, using a conventional voltage divider mounted at the PFL output to measure the PFL charging voltage. The experimental data (Figure (2.43)) enabled the overall capacitance of the secondary circuit to be estimated as 729 pF, which is 2% larger than the design value provided by the electrostatic solver. The experiment also allowed calibration of the V-dot sensor, by comparing the output from the divider with the numerically integrated signal from the sensor. The sensitivity of the probe is estimated using the equation

$$v_{osc} = K \frac{dv}{dt}$$

as 98.8 ps, only -4% different from the figure obtained from a theoretical prediction during its design.
2. PULSED POWER GENERATORS

![Graph showing the measured current in the secondary circuit.](image)

**Figure 2.41** The Measured current in the secondary circuit

![Image of PFL main components.](image)

**Figure 2.42** PFL main components
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Figure 2.43 Voltage across PFL output (a) red trace: Filamentary programme result [23], black trace: experimental data from voltage divider, blue trace: theoretical calculations using equation 2 (b) detail showing only the first 2 μs red trace: Filamentary programme result, black trace: experimental data from voltage divider

Figure (2.45) shows the complete system during the final stage of testing, with the various connections to the SF$_6$ gas bottle and recovery pump and the water purifying unit all evident. The capacitor charging voltage was raised in steps of 5 kV from 20 kV, the minimum operational voltage for the trigatron, to 30 kV. At each voltage the inter-electrode distance of the PFL high-voltage spark-gap switch and its chamber pressure were conveniently adjusted for proper functioning. As already discussed, the primary circuit resistance plays an important role in defining the overall energy efficiency. If the capacitor bank ESR is regarded as constant, the experiments highlighted an important variation in the trigatron resistance: from 100 mΩ at 20 kV, when the overall efficiency is 72%, to 30 mΩ at 30 kV when the corresponding efficiency is 84% (see Figure (2.44)).

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Figure 2.44 Variation of overall system efficiency with trigatron resistance

![Graph showing variation of overall system efficiency with trigatron resistance](image)

Figure 2.45 The complete system during the final stage of testing

![Image of the complete system during testing](image)

Figure (2.46) presents results obtained with the bank charged to 30 kV, which demonstrate that the PFL was charged to 533 kV before the high-voltage switch closed the circuit and discharged the line.

Repetitive operation was demonstrated at around 1 Hz, with the trigatron automatically activated by its programmable laser-coupled trigger system.
Figure 2.46 Experimental results with PFL charged to 533 kV (a) Oscilloscope signal from the V-dot probe (b) Integrated signal compared with theory
CHAPTER THREE
ELECTRO-MAGNETIC SENSORS
3. Electro-magnetic sensors

3.1 Background of small loop sensor

When measuring the electric field produced in the far field region of an antenna in either a steady state mode or a transient (pulsed) situation, D-dot probes are normally used. When positioned too close to the antenna their response is however not adequate, i.e. the radiation is far from a plane wave, and the electric field vector has a 3D distribution. Therefore, other means of measuring the electric field must be investigated and one possible candidate is a single turn sensor. When used as a probe this is sensitive in one direction only, so that in what follows two such probes need to be positioned at a right angle to measure the near field 2D electric field distribution generated by a Valentine antenna.

A single-turn loop antenna is a conductor shaped into a closed circular or square form, with a gap that provides the output terminals. When used as a radiating element the loop has a conductor length that is usually less than about one-tenth of the radiating field wavelength [35] i.e. the number of turns times the boundary length is less than one tenth of the radiated field wavelength \((N \times \text{Boundary length} \leq \frac{\lambda}{10})\). The field radiated by this type of antenna is equivalent to that of a magnetic dipole, and it therefore has the same mathematical formulation as the field radiated by the dipole. The arrangement adopted in this thesis can however also be used as a receiver (and will be termed a sensor in what follows), because of its simplicity in analysis and construction. Common applications are as receiving antennas for portable radios, navigation using radio waves, and as probes for field strength meters [35].

In this research two small loop sensors were used to measure the field radiated from the Valentine antenna powered by TPFL1, as discussed in Chapter 2. Single turn sensors were built to respond to the transient electromagnetic waves that are radiated and to convert these into a voltage signal. In this chapter the design and calibration of the sensors is discussed and the results of measurements are presented.

3.2 Brief theory of the small loop sensor

When a small-loop sensor is used to measure a transient magnetic field \(B(t)\), the emf generated in the sensor \(\text{emf}(t)\) is proportional to the time rate of change of the magnetic flux density (i.e., \(dB(t)/dt\))

\[
\text{emf}(t) = S \frac{dB}{dt}
\]

(3.1)

where \(S\) is the effective loop area

When the sensor has \(N\) turns, the effective loop area is simply:

\[S = NA\]
3. ELECTRO-MAGNETIC SENSORS

where $A$ is the effective area of one turn.

For a sinusoidal excitation, $(B = B_0 \sin(2\pi ft))$ having a frequency $f$, equation (3.1) becomes

$$emf(t) = 2\pi f N A B_0 \cos(2\pi ft) \quad (3.2)$$

The relationship between the electric field $E$ and magnetic field $B$ at the centre of the loop is $\frac{cB}{E} = \frac{cE}{B}$, where $c$ is the speed of electromagnetic radiation in vacuum and the emf of the sensor can be expressed as the product of the electric field strength $E(t)$ and the effective length of the sensor $l_e$

$$emf(t) = l_e E(t) \quad (3.3)$$

Since $f = \frac{c}{\lambda}$, where $\lambda$ is the wavelength of the radiation to be measured, the effective length is given by

$$l_e(f) = \frac{2\pi N A}{\lambda(f)} \quad (3.4)$$

3.3 Design of small loop sensor

The sensor used to measure the electric field radiated from the Valentine antenna was made from a length of coaxial cable, with both the inner and outer conductors of copper and the insulation between them of polyethylene, as shown in Figure (3.1(a)).

![Design and construction of the small loop sensor](image-url)

(a) Micro coaxial cable with outer full copper jacket, used in manufacturing the sensor (b) Loop sensor ready to be used.

Figure 3.1 Design and construction of the small loop sensor (a) Micro coaxial cable with outer full copper jacket, used in manufacturing the sensor (b) Loop sensor ready to be used.
3. ELECTRO-MAGNETIC SENSORS

The insulation prevents any direct interaction between the currents in the internal and the outer conductors and the small gap shown in Figure (3.1(b)) represents the effective length of the small loop sensor. Two sensors were manufactured; one with its connections tangential to the active loop (sensor1) and the other with these connections perpendicular to the plane of the loop (sensor2). These will be used later for measuring the 2D electric field distribution.

![Equivalent circuit of the sensor connected to an oscilloscope](image)

Figure 3.2 Equivalent circuit of the sensor connected to an oscilloscope

Figure (3.2) shows the equivalent circuit of a small-loop sensor feeding an oscilloscope, where $L$, $R$, and $C$ are the probe parameters, $R_i$ and $C_i$ are the integrator parameters and $R_T = Z_e = 50 \, \Omega$, where $R_T$ is the matching resistor. If the transmission along the cable is lossless, the cable can be ignored in the analysis, and by using Figure (3.3) the output voltage of the sensor $v(t)$ can be obtained from the solution of the second-order differential equation:

$$LC \frac{d^2v}{dt^2} + \left( \frac{L}{R_T} + RC \right) \frac{dv}{dt} + \left( 1 + \frac{R}{R_T} \right) v(t) = \text{emf}(t) \quad (3.5)$$

![Equivalent circuit of the sensor](image)

Figure 3.3 Equivalent circuit of the sensor

If the capacitance $C$ is sufficiently small to be neglected, equation (3.5) reduces to

$$\frac{L}{R_T} \frac{dv}{dt} + \left( 1 + \frac{R}{R_T} \right) v(t) = \text{emf}(t) = S \frac{dB}{dt}$$
For sinusoidal excitation, if $2\pi f L_p << R_T + R_p$, then the output is proportional to the time rate of change of magnetic flux density $(1 + \frac{R_p}{R_L})v(t) = S \frac{dB}{dt}$.

If a DC attenuation factor $a$ is introduced as:

$$a = \frac{R_T}{R_T + R}$$

Then the output for a steady state sinusoidal excitation at a frequency $f$ is

$$v(t) = a \cdot \text{emf} = a S \frac{dB}{dt} = a N A 2\pi f B_o \cos(2\pi ft)$$

(3.6)

3.4 Calibration of small loop sensor

The sensor was calibrated in two ways, firstly by using the magnetic field generated by a Helmholtz arrangement of two magnetic coils and secondly by use of the electric field generated by a horn antenna.

3.4.1 Magnetic calibration using Helmholtz coil configuration

The Helmholtz arrangement of two coils produces in a central volume an almost uniform magnetic flux density. It consists of two identical circular coils, of equal diameter and the same number of turns, placed along a common axis through the centre of the coils. For a Helmholtz arrangement these two coils are separated by a distance equal to their common radii, and their currents flow in the same direction, as shown in Figure (3.4(a))

![Figure 3.4 Helmholtz coil construction](image)

(a) Dimensions of the Helmholtz pair used in calibration (b) Helmholtz pair ready for use in calibration
Helmholtz coils have been used for the calibration of magnetic field sensors or probes for several decades and, more recently, they have also been used in low frequency magnetic field immunity tests. This technique is under consideration as one of several methods for calibrating sensors or probes in IEEE standards project P1309 [36].

Calculation of the magnetic field generated by the Helmholtz pair is straightforward. Since the field is generated by an electric current, the Biot-Savart Law can be used in its integral formulation

$$ \vec{B} = \frac{\mu_0 I}{4\pi} \oint_C \frac{d\vec{l} \times \hat{k}_r}{R^2} $$

or better in its differential formulation

$$ d\vec{B} = \frac{\mu_0 I}{4\pi} \frac{d\vec{l} \times \vec{R}}{R^3} $$

with $R$ being the distance between the current element $dl$ and the point $P$ where the field is calculated. In what follows the magnetic field along the axis of the loop at the point $P$ will be determined.

Consider a single turn circular loop of radius $a$, which carries a current $I$ as shown in Figure (3.5),

![Figure 3.5 Schematic of a single turn loop carrying a current I](image)

Calculation of magnetic field generated by a current flowing through a circular loop $n$ element of length $d\vec{l}$ along the current path is given by

$$ d\vec{I} = a d\theta \vec{k}_\theta $$

where $\theta$ is the angle subtended at the coil by the line $R$ and $\vec{k}_z, \vec{k}_r, \vec{k}_\theta$ are unit vectors in cylindrical coordinates.
The distance $R$ from the differential element to the point $P$ in equation (3.8) is

$$ R = \sqrt{a^2 + z^2} \quad (3.10) $$

or in vector form

$$ \mathbf{R} = z\mathbf{k}_z - a\mathbf{k}_r $$

In these conditions, the vector element in the Biot-Savart equation (3.8) can be rewritten as

$$ d\mathbf{I} \times \mathbf{R} = a\ d\theta\ \mathbf{k}_z \times (z\mathbf{k}_z - a\mathbf{k}_r) = a\ z\ d\theta\ \mathbf{k}_r + a^2 d\theta \mathbf{k}_z \quad (3.11) $$

and equation (3.8) becomes

$$ d\mathbf{B} = \frac{\mu_0 I a d\theta}{4\pi} \frac{z\mathbf{k}_z + a\mathbf{k}_r}{(a^2 + z^2)^{3/2}} \quad (3.12) $$

When the integral is performed, the contribution from the radial term is cancelled, because for any element $d\mathbf{l}$ the radial component of the field produced is cancelled by that of a diametrically opposite element. The field produced along the current loop axis is therefore

$$ B_z = \frac{\mu_0 I a^2}{4\pi(a^2 + z^2)^{3/2}} \int_0^{2\pi} d\theta \quad (3.13) $$

$$ = \frac{\mu_0 a^2 I}{2(a^2 + z^2)^{3/2}} $$

For an $N$ turn coil

$$ B_z = \frac{\mu_0 N I a^2}{2(a^2 + z^2)^{3/2}} \quad (3.14) $$

For the Helmholtz coils used in this thesis, the parameters are as given below. As evident in Figure (3.4(b)) the ten turns of each (single layer) coil are parallel and have the same radius

- Number of turns ($N$) = 10
- Current flowing through the coils ($I$) = 6A
- Radius of the coils ($a$) = 25.30mm
- Spacing between the coils ($s$) = 25.30mm
- Pitch of each turn in each loop in each coil ($p$) = 0.82mm
- Permeability of vacuum $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$

When calculating the fields produced by the $N$ turns of a single layer coil, $z$ in equation (3.14) has to be replaced by

$$ z_j = a + pj $$
where \( j = 1,2,\ldots,9,10 \) is the turns number. The field produced by the Helmholtz pair can therefore be calculated from

\[
B_z^{H} = \frac{2 \mu_0 a^2 I}{2} \sum_{j=1}^{9} \frac{1}{a^2 + (z_j)^2} j^{3/2} = K I
\]

where \( K \) is a (constant) form factor. For the experimental arrangement in Figure (3.4) \( K = 3 \times 10^{-4} \text{T/A} \), which gives a predicted field at the centre of the Helmholtz pair of \( B = 1.8 \times 10^{-3} \text{T} \) for a current of 6A.

Calibration is achieved by placing the sensor at the centre of the Helmholtz pair as shown in Figure (3.6(a) & (b)). The Helmholtz pair is fed from a pulse generator, with a current monitor (Stangeness Industries model 0.51.0w) attached to an oscilloscope to monitor the current flowing through the coils.

A commercial H-dot probe from Rhode and Schwarz Co. (30 MHz to 3 GHz (RS H 50-1 part number 1147.2707.00)) as shown in Figure (3.7), was also used as a reference to cross-check the calibration.
The procedure for the sensor calibration was to position the sensor to be calibrated in the centre of the Helmholtz arrangement and to record the output voltage signal. By using equations (3.1) and (3.15), using the emf $v(t)$ signal and using the recorded current $I(t)$ flowing through the Helmholtz arrangement. The total effective loop area for the R&S H-dot probe and for the two sensors was obtained. Table (3.1) shows the total effective loop area and the diameters of the two sensors and the R&S H-dot probe.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Area ($\text{mm}^2$)</th>
<th>Effective Diameter (mm)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;S probe</td>
<td>79.3</td>
<td>10.05</td>
<td>Manufacture’s diameter 10.00mm [37]</td>
</tr>
<tr>
<td>Sensor 1</td>
<td>62.0</td>
<td>8.89</td>
<td></td>
</tr>
<tr>
<td>Sensor 2</td>
<td>94.7</td>
<td>10.98</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Results from magnetic calibration effective loop area for both the R&S H-dot probe, and the two B-dot sensors

From the R&S catalogue it is known that the effective diameter of the H-dot probe is actually 10.05 mm, enabling the error in the diameter to be evaluated as 0.5 %, which in turn corresponds to an error in the magnetic calibration of only 1 %. This gives increased confidence in the magnetic calibration technique. Figure (3.8) shows that once calibrated the time dependence of the magnetic fields obtained using equation (3.15) and the measured current $I$ and the magnetic field obtained from (3.1) integration, are clearly closely matching.
Figure 3.8 Time variation of the magnetic flux density $B(t)$ obtained experimentally by integrating equation (3.1) is shown as blue lines and is compared with the $B(t)$ calculated from equation (3.15) using the current measurement shown as red lines. Note that the two traces (blue and red) are practically indistinguishable. Using Farnell PG101 pulse generator the results of this analysis are shown for: (a) R&S probe, (b) Sensor1 and (c) Sensor 2.
3. ELECTRO-MAGNETIC SENSORS

B. Electric calibration using a Horn antenna

A second calibration based on an electric field method was performed to cross-check the magnetic calibration method, and to ensure that electric field measurement can indeed be performed with our B-dot sensor. This used an antenna, consisting of a metal waveguide shaped like a horn to emit electromagnetic waves. Such horn antennas are used to generate UHF above 300 MHz, with many types discussed in textbooks [38]. In the present calibration a Pyramidal Horn was used as shown in Figure (3.9(a)&(b)). Both the R&S H-dot probe (specifically used for electric field measurement) and the two sensors to be calibrated were placed inside the antenna as shown in Figure (3.9(c)).

Figure 3.9 (a) A Horn antenna (b) Arrangement including the Horn antenna used in the electric calibration (c) Commercial H-dot probe and one of the loop sensors located inside the Horn antenna
3. ELECTRO-MAGNETIC SENSORS

Figure 3.10 Calibration of the two sensors with reference to the R&S H-dot probe (a) Sensor1 (red trace) compared with the R&S reference probe (blue trace). (b) Sensor2 (red trace) compared with the R&S reference probe (blue trace).

A pulse generator applied a steady state sinusoidal voltage to the horn antenna which radiated an electric field with a frequency of 120 kHz. Figure (3.10) compares the $E(t)$ signals obtained from the two sensors with the reference signal from the R&S probe. It shows a 3% difference from the magnetic calibration of Sensor1 and 7% for Sensor 2. The differences are explained as arising from the accuracy with which all sensors are positioned inside the horn antenna.

3.5 Studies of electric fields produced by a Valentine antenna

In this chapter the final aim is to measure the pulsed electric fields produced from the TPFL1, with the high voltage generator connected to a Valentine antenna. As shown in [39] the antenna is capable of producing an electric field of 239 kV/cm in air when energised by a 10-stage 300 ps Marx generator at a pulse repetitive frequency of 350 Hz and a pulse forming device based on the use of a gaseous spark gap. However, in the present thesis the Valentine
antenna is immersed in water, using a cylindrical tube filled with purified water that covers the antenna, as shown in Figure (3.11). In this case the electric field produced has a lower intensity than when in air since the permittivity of water (80) is higher than that of air (1). A similar study by [40] used pulsed electromagnetic waves to apply high intensive electric fields in the treatment of cancer. The technique used to measure the electric field was based on a loop sensor located 30cm from the radiating element, which was representing by a focusing bowl antenna. The measured electric field was 3 kV/cm, when 10 kV was applied to the radiating element.

![Figure 3.11](image1.png)  ![Figure 3.12](image2.png)

Figure 3.11 (a) The Valentine antenna connected to the high voltage generator TPFL1 (b) Cylindrical tube covering the antenna, later filled with water.

In the experiments described below the two loop sensors, calibrated earlier, were located up to 30 mm from the Valentine antenna (near field measurement) as shown in Figure (3.12). One was located along the Z axis, and the second along either the X or Y axes. The three axes are indicated in Figure (3.13)

![Figure 3.12](image3.png)

Figure 3.12 Location of the two sensors 30 mm from the Valentine antenna
The 2D electric field distribution produced by the Valentine antenna when energised by TPFL1 was obtained by placing the sensor at different locations within of the antenna, as shown in Figure (3.13).

Figure 3.13 Mapping of the electric field produced by the Valentine antenna. (a) Valentine antenna connected to the TPFL1. (b) Top view of the Valentine antenna and the points at which the loop sensors are located.

The various locations of the two sensors are at the points shown in Figure (3.13); one sensor is always along the Z-direction which the position of the second sensor varies between the X-direction and Y-directions.

This method helps to clarify the distribution of the radiated pulsed electric field in the near field, and determines how strong will be the pulsed electric field to be used in the non-invasive method for destroying *E-coli* bacteria.

**A. Measurements of pulsed electric fields produced by the Valentine antenna**

Figure (3.14) shows the 400 kV high voltage generated by the TPFL1 and gives a good indication of the pulsed field that will radiate from the Valentine antenna. However, since the antenna is immersed in water medium which affects the field radiation by giving lower electric field magnitude. Later in Chapter 5, it is shown that the electric field is not sufficiently strong for use in PEF processing.
As discussed previously, the TPFL1 is connected to a Valentine antenna. In reference [39] it was proved that the radiating system can produce voltage pulses in excess of 250 kV/m. The peak-to-peak of the radiated field measured in air has been measured to be close to 450 kV/m (far field measurement) [41]. As discussed earlier the aim is to measure the electric field generated in a water sample positioned in the high-field region of the antenna in the near field after the strips (curve) surface of the antenna [41]. A modelling result using the time-domain electromagnetic software CST Microwave Studio provided by our colleagues at Pau is shown in Figure (3.15).

Figure 3.15 Modelling the Valentine antenna with a water volume placed in the high field region

Figure (3.16) shows the electric field measured by the small loop sensor at the X-axis and the Z-axis. The maximum peak of the electric field intensity from the Valentine antenna was only 25 kV/cm. This indicates that because the high permittivity of the water the electric field intensity is insufficiently high to kill the E-coli bacteria in a polyethylene container.
3. ELECTRO-MAGNETIC SENSORS

Figure 3.16 Electric field measurement at X-direction

Figure 3.17 Zoom in for the electric field measurement at X-direction
Figure 3.19 Zoom in for the electric field measurement along Z-direction
B. Electric field distribution

When the TPFL1 feeds the antenna high voltage pulses are generated in the region before the double-strip flares of the Valentine antenna at the beginning of the exponential profile. In the corresponding radiation, high frequencies are produced in the parallel section and low frequencies in the exponential section. However, some of the low frequency radiation is reflected back to the generator [42].

Figure (3.20) shows the pulsed electric field distribution of the radiation of the pulsed electric field on the double-strip flares of the Valentine antenna, when the two sensors are located along the X and Y-coordinates. Figure (3.20) shows the distribution of the field at points between -21.25 and 75 mm, and 0 and 25 mm respectively, with the Z-coordinate fixed at 30 mm.

![Mapping of the pulsed electric field at z = 30 mm](image)

As shown from the mapping of the pulsed electric field produced by the Valentine antenna, the fields are much lower than those used in the existing invasive technique ($\approx 100kV/cm$ [43]), and they therefore are unlikely to be sufficiently strong for use in the non-invasive technique.
CHAPTER FOUR

ELECTRO-OPTIC SENSOR
Chapter 4

4. Electro-optics

In general, the measurement of strong electric field pulses is important in many industrial applications, including the pulse testing of power system and electric field equipment [44], the design and reliability of components used in radar systems, and the design and operation of pulsed lasers [45]. These measurements are normally made indirectly using a spark gap or a measurement system that incorporates a high voltage divider, and the corresponding electric field is inferred from the voltage measurement using simple formulae. The direct measurement of free space pulsed electric fields, usually produced by antennas, is made using either D-dot or B-dot sensors. However, when the electric fields are not produced by antennas and the measurement is required to be performed close to metallic electrodes, the methods mentioned before are not appropriate. Electro-optic measurements are particularly attractive in such cases for use with very intense electric pulses, as no interconnecting cables are required and the light beam is totally insensitive to stray electro-magnetic fields [45]. In addition, the long fibre optic connections allow sensitive instrumentation to be located remotely and therefore reduces the shielding requirement.

The principle of electro-optic measurement are very similar to those of photoelasticity with both based on a double refraction (bi-refraction) effect. This phenomenon was discovered by David Brewster, with the double refraction effects being produced by a mechanic stress applied to an isotropic material. It was found that a plate of glass under a simple compressive stress acquired the properties of a negative uniaxial crystal and under simple tension those of a positive uniaxial crystal, with the lines of stress in each case corresponding to the optical axis in the analogous crystal. This indicates that any light passing through the plate in any direction normal to the line of stress was polarised both in and perpendicular to that line [46].

In this chapter electro-optic methods are generally described, with the main focus being on the Kerr effect (since the medium of the PEF cell is water) which is discussed in detail. The advantages of applying this method for use in non-invasive pulsed electric field (PEF) experiments are explained.

4.1 Background of waves in dielectric media

In general, the characteristics of any medium in material form are determined by the polarization (P) and magnetisation (M) densities on one hand, and the electric (E) and magnetic (H) fields on the other hand. Overall, these forms of relationship are termed constitutive [12], with the former pair of quantities describing the dielectric properties of the medium and the latter pair the magnetic properties.

Since this chapter is devoted to electro-optic measurement, the discussion concentrates on the relation between the polarisation (P) and the electric field (E). The relation between these can be considered as a system, in which E is the input and P is the output that is created by the dielectric medium.

The block diagram of Figure (4.1) illustrate the connection between P and E, which in a homogeneous and isotropic dielectric media are parallel vectors that are proportional at every position and time, so that
4. ELECTRO-OPTIC SENSOR

\[ P = \varepsilon_0 \chi E \quad (4.1) \]

where \( \chi \) is the electric susceptibility defined as a constant that indicates the polarisation degree of a dielectric material in response to an applied electric field and \( \varepsilon_0 \) is the free space permittivity.

The connection between the electric flux density \( D \) and the electric field strength \( E \) depends on the electric properties of the medium, which are characterised by the polarisation density \( P \) in the relationship

\[ D = \varepsilon_0 E + P \quad (4.2) \]

Substituting (4.1) in (4.2)

\[ D = \varepsilon E \quad (4.3) \]

where \( \varepsilon = \varepsilon_0 (1 + \chi) \) which shows that \( D \) and \( E \) are also parallel and proportional. In general, the speed of light in a medium is

\[ c = \frac{1}{\sqrt{\varepsilon \mu}} \quad (4.4) \]

The ratio of the speed of light in free space \( c_0 \) to that in the medium is defined as the refractive index \( n \), so that

\[ n = \frac{c_0}{c} = \sqrt{\frac{\varepsilon_0 \mu_0}{\varepsilon \mu}} \quad (4.5) \]

Since \( \varepsilon = \varepsilon_0 (1 + \chi) \), and for a nonmagnetic material \( \mu = \mu_0 \), equation (4.5) becomes

\[ n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} = \sqrt{1 + \chi} \quad (4.6) \]

where \( \varepsilon \) and \( \varepsilon_0 \) are the permittivities of the medium and of free space.

In the case of an anisotropic media, which is defined as a medium in which the optical properties are not the same in all directions, the refractive index will be different for light travelling through the medium in different directions. This leads to the proportionailities of equations (4.1) and (4.2) remaining constant while the coefficients \( \chi \) and \( \varepsilon \) become functions of position (say ‘r’) so that \( \chi = \chi(r) \) and \( \varepsilon = \varepsilon(r) \) and the relationship between \( E(r) \) and \( P(r) \) is as illustrated in figure (4.2)
4. ELECTRO-OPTIC SENSOR

\[ E(t) \quad \chi(t) \quad P(t) \]

Figure 4.2 A medium characterised by a position dependent susceptibility \( \chi(r) \)

In an inhomogeneous material, the position dependence of the refractive index can be expressed as [12]:

\[ n(r) = \sqrt{\frac{\varepsilon(r)}{\varepsilon_0}} = \sqrt{1 + \chi(r)} \] (4.7)

Furthermore, in anisotropic materials the index of refraction depends not only on the position but also on the direction.

4.1.1 Background of non-linear optics

Reference [47] explains linear and nonlinear interaction between two light waves of different frequency intersecting in a medium. This explanation shows that in the case of linear interaction the waves are uncoupled and propagate independently. However, in nonlinear interaction the waves are coupled, which means that each wave can modify the properties of the other, changing both its amplitude and phase. A second interaction arises between a wave with a frequency different from that of the other incident beams, and this is called frequency conversion of waves.

The mechanism of nonlinear optical interaction is characterised by a response time that governs how fast the medium can change its properties in response to the incident light. Figure (4.3) shows the effect of a light wave’s electric field \( E \) on the charge distribution within an atom. This effect is to cause a charge separation in which the positively charged nucleus is displaced in the direction of \( E \), whereas the negatively charged electron is displaced in the opposite direction. This results in an electric dipole generated by each atom.

Richard Quimby [47] showed both the origin of optical nonlinearity, and the potential energy of an electron as it is displaced from equilibrium by the electric field. Figure (4.4) explains the resulting optical nonlinearity.
Figure 4.4 (a) atom’s potential energy varies quadratically with x (b) Symmetrical material has equal polarisation magnitude for an applied field E (c) Non symmetrical material has different polarisation magnitude for an applied field E.

Figure (4.4 (a)) shows the potential energy of an electron as it is displaced from equilibrium by an applied electric field. The restoring force on the electron varies linearly with the charge displacement x and therefore the potential energy varies quadratically with x. However, when x is large the potential energy curve flattens out (Figure 4.4(a)) and the restoring force becomes smaller due to the $\frac{1}{r^2}$ dependence of the coulomb force. This leads to $\chi$ no longer being constant and therefore a non linear dependence of $P_x$ on $E_x$. This non linearity can be expressed as follows:

$$P_x = \varepsilon_0 (\chi_1 E + \chi_2 E^2 + \chi_3 E^3)$$  \hspace{1cm} (4.8)

where $\chi_1$ is the linear susceptibility and $\chi_2$ and $\chi_3$ are second and third order susceptibilities. Terms containing higher orders than $E^3$ are usually negligible.

Figure (4.4(b)) shows the characteristics of a materials with inversion symmetry (inverting lattice). In these materials the magnitude of the polarisation depends on the magnitude of the electric field but not its direction. As a result the graph $P_x$ vs $E_x$ displays symmetry with
respect to the origen and therefore \( P_x \) is an odd function of \( E_x \), i.e. \( \chi_2 = \chi_4 = ... = 0 \). At high electric fields the polarisation may not be linear as depicted in Figure (4.4(b)). If the material does not have inversion symmetry, then the polarisation depends not only on the magnitude of the electric field but also on its direction (Figure 4.4(c)).

4.1.2 Molecular orientation

According to [12] a dielectric medium is anisotropic if its optical properties depend on direction. In addition, the properties of a material are governed by its microscopic properties; the shape and orientation of the individual molecules and the organisation of their centres in space. However, optical materials have different kind of positional and orientation types of order:

- If the location of the molecules are randomly positioned in space, and oriented along random directions then the medium is isotropic such as a gas or a liquid.

- If the orientation of the molecules is random, the material is ‘polycrystalline’ because the structure takes the form of disjointed crystalline grains. Although polycrystalline material behaviour in general is anisotropic, their average behaviour is isotropic.

- If the molecules are oriented in the same direction, and are organized in space in a regular periodic pattern, as in crystals, the medium is anisotropic.

- If the orientation order of the molecules lacks complete positional order, they are anisotropic and their orientation are not totally random, for example liquid crystals.

In the absence of on electric field, thermal disturbance will cause the liquid molecules to settle into a random distribution of orientations and Figure (4.5) illustrates the random alignment and distribution in a liquid.

![Random molecule distribution in a liquid in the electric field absence](image)

Fig. 4.5 Random molecule distribution in a liquid in the electric field absence

When a strong electric field is applied, the interaction of the E field with the induced dipoles tends to orient the molecules as shown in Figure (4.6). This creates a macroscopic asymmetry in the material that changes its optical properties.
A light wave passing through this modified medium will experience a different refractive index for different orientations of its \( E \)-field vector. In general, the polarisability of the molecules is higher when \((E)\) is parallel to the long axis of the molecules. The result is a field induced ‘birefringence’, in which the refractive index depends on the direction of polarisation of the light wave. The rotation and the alignment of the molecules is illustrated in Figure (4.7). If an electric field is applied as in the figure, the electric forces tend to tilt the molecules through an angle \((\theta)\) from their original direction towards alignment with the electric field \((E)\).

When molecules have no specific orientation (Figure (4.5)), they are pointing in all directions, and no net refractive index can be observed. According to the Cambridge Polymer Group, for a sample to exhibit birefringence, three criteria must be met:

- There must be non-zero difference between two of the refractive indices \( n_\perp \) and \( n_\parallel \) of the sample or

\[
\Delta n = n_\perp - n_\parallel
\]  

(4.9)

- There must be a net orientation in the sample to yield a primary refractive index in the sample.
The optics used to view the sample must be oriented correctly (the accuracy of the alignment).

Figure (4.8) illustrates a general approach to the measurement of an electro-optic effect. Unpolarised light passing through a linear polariser is polarised into components, neither parallel nor perpendicular to the applied electrical field. The polarised light then passes through an optical cell (Kerr or Pockels), which is connected to two electrodes for the application of an external electric field. After that, the light passes through a second polariser which is oriented orthogonally to the first polariser. The amplitude of the emerging polarised light is measured as changes in the light intensity using an optical detector. The results for a specific sample are usually reported in terms of the phase difference $\phi$ between the components of the light beam.

![Diagram of electro-optic measurement](image)

**Figure 4.8 General set up for electro-optic measurement**

In general, the characteristic of the electro-optic effect is that different components of the applied electric fields are termed the **Orienting field** and the **Sensing field**. The former occurs when the light is linearly polarised and the dipoles are randomly oriented [48], and they tend to align due to interaction of the E field with the induced dipoles as shown in Figure (4.6). This applied field is the oriented field given later by $(E_0)$ as in equation (4.18).

The **Sensing field** is the electric field associated with the light beam, where the partial alignment the molecules is a result of anisotropy in the material. The effect of this on the sensing field is represented by two relative propagation velocities, and the indices of refraction $n_{||}$ and $n_{\perp}$. However, the sensing field has a frequency that produces a negligible perturbation in the orientation of the molecules.

If an intense sinusoidal laser beam of frequency $\omega$ propagates inside a material medium; the electric field of the light wave has a time dependence given by

$$E(t) = A \cos \omega t$$  \hspace{1cm} (4.10)

where A is the amplitude. This creates a time varying polarisation according to equation (4.1). Assuming that the medium is a crystal, then $\chi_2 \neq 0$ [47] and equation (4.1) becomes

$$P(t) = \varepsilon_0 \chi_1 A \cos \omega t + \varepsilon_0 \chi_2 A^2 \cos^2 \omega t + ......$$  \hspace{1cm} (4.11)

Using the identity $\cos^2 \theta = \frac{1+\cos 2\theta}{2}$ and neglecting higher order powers, equation (4.11)
becomes

\[ P(t) = P_0 + P_{\omega} \cos \omega t + P_{2\omega} \cos 2\omega t \]  \hspace{1cm} (4.12)

where \( P_0 = \varepsilon_0 \chi_2 \frac{A^2}{2} \)

\( P_{\omega} = \varepsilon_0 \chi_1 A \)

\( P_{2\omega} = \varepsilon_0 \chi_2 \frac{A^2}{2} \)

The first term \( P_0 \) corresponds to optical rectification, in which a static polarisation is produced in response to the rapidly varying electric field of the light wave.

The term \( P_{\omega} \cos \omega t \) causes the atoms to radiate light at the frequency \( \omega \), which is the result of the linear refractive index discussed previously.

The third term \( P_{2\omega} \cos 2\omega t \) is the second harmonic generated when the dipole oscillating at frequency \( 2\omega \) radiates at the frequency \( 2\omega \).

When the material medium is liquid \( \chi_3 \neq 0 \) [47], and by use of the identity

\[ \cos^3 \theta = \frac{3 \cos \theta + \cos 3\theta}{4} \],

equation (4.1) become

\[ P(t) = P_0 + P_{\omega} \cos \omega t + P_{2\omega} \cos 2\omega t + P_{3\omega} \cos 3\omega t \]  \hspace{1cm} (4.13)

where \( P_0 = 0 \)

\( P_{\omega} = \varepsilon_0 A \left[ \chi_1 + \left( \frac{3}{4} \right) \chi_3 A^2 \right] \)

\( P_{2\omega} = 0 \)

\( P_{3\omega} = \frac{1}{4} \varepsilon_0 \chi_3 A^3 \)

and since \( P_0 = P_{2\omega} = 0 \), since the material medium is liquid there is neither optical rectification nor second harmonic generation in the liquid medium.

### 4.2.1 Pockels effect

The Pockels effect appears [49] “when the refractive index modification of a material is proportional to the electric field, causing a linear electro- optic effect”, and it occurs only in crystalline materials such as lithium niobate (\( \text{LiNbO}_3 \)), potassium dideuterium phosphate (KDP), and barium borate (BBo). Figure (4.9) shows a commercial Pockels cell assembly made by Lions Ltd.
A brief analysis of the Pockels effect follows.

When an external electric field is applied to a Pockels cell, for which $\chi_2 \neq 0$, then

$$ e(t) = E_0 + A \cos \omega t \quad (4.14) $$

Introducing this result into equation (4.11) leads to

$$ P(t) = \varepsilon_0 \chi_1 (E_0 + A \cos \omega t) + \varepsilon_0 \chi_2 (E_0 + (A \cos \omega t)^2 \quad (4.15) $$

and therefore:

$$ P_\omega = \varepsilon_0 \chi_1 A + \varepsilon_0 2\chi_2 E_0 A $$

in which $\chi'_1$ is the effective susceptibility, given by

$$ \chi'_1 = \chi_1 + 2\chi_2 E_0 \quad (4.16) $$

This gives

$$ P_\omega = \varepsilon_0 \chi'_1 A $$

The effect of the electric field is thus to change the susceptibility by

$$ \Delta \chi_1 = 2\chi_2 E_0 \quad (4.17) $$

where

$$ \Delta \chi_1 = \chi'_1 - \chi_1 $$

and the resulting change in the refractive index follows by differentiating equation (4.6) as,

$$ \Delta n = \frac{1}{2\sqrt{1 + \chi_1}} \Delta \chi_1 \quad (4.18) $$

$$ n_\parallel - n_\perp = \frac{1}{n} \chi_2 E_0 \quad (4.19) $$
This gives the Pockels effect as
\[
n_{\parallel} - n_{\perp} = \frac{1}{2} n^3 r E_0
\]  
(4.20)

where \( r \) is the Pockels coefficient \( r = \left( \frac{2}{n^4} \right) \chi_2 \) [47].

### 4.2.2 Electro-Optic Kerr Effect

This effect was first observed in 1875 [50] and in general it occurs in three different ways: an electro-optic Kerr effect (DC Kerr effect), an optical Kerr effect (AC Kerr effect) and a magneto-optic Kerr effect. In this thesis only the DC Kerr effect technique is used and investigated and will be simply termed ‘Kerr effect’.

The principle of the Kerr effect is that the refractive index changes in direct proportion to the square of the electric field. In other words it is a quadratic electro-optic effect and Figure (4.10) shows a typical arrangement of a Kerr cell.

In a liquid medium \( \chi_3 \neq 0 \), and the application of an external electric field gives rise to a component of polarisation, according to equation (4.12), of
\[
P_\omega = \varepsilon_0 \chi_1' A
\]

where
\[
\chi_1' = \chi_1 + 3 \chi_3 E_0^2
\]

and the susceptibility of the electric field therefore changes by
\[
\Delta \chi_1 = 3 \chi_3 E_0^2
\]

where the corresponding change in the refractive index of the medium is
\[
\Delta n = \frac{3 \chi_3}{2n} E_0^2
\]
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which could also be written as

$$\Delta n = B\lambda E_0^2$$  \hspace{1cm} (4.21)

where B is termed the Kerr electro-optic coefficient and $\lambda$ is the wavelength of the light passing through the medium.

Because of the Kerr effect, a phase shift $\phi$ is induced between the components of the polarised light beam, parallel and perpendicular to the applied field, defined as

$$\phi = 2\pi BLE_0^2$$  \hspace{1cm} (4.22)

where $L$ is the effective path length of the light through the material stressed by the external electric field $E_0$.

The measured light intensity ($I$) is given by Malus’ law [52] which states that the intensity of the transmitted light, when the second polariser is rotated, is directly proportional to the square of the cosine of the angle between the transmission axes of the second and the first polarisers.

The electric field $E_0$ can be determined by the two components $E_0 \cos \theta$ and $E_0 \sin \theta$ shown in Figure (4.11). If an analyser (i.e., second polariser) is used, the only component that will be transmitted is $E_0 \cos \theta$, which is parallel to the transmission axis. The other component $E_0 \sin \theta$ will be absorbed by the polariser.

![Figure 4.11 Malus’ Law principle](image)

Therefore the intensity of light transmitted by the analyser is

$$I \propto (E_0 \cos^2 \theta)$$

$$I = I_0 \cos^2 \theta$$

where $I_0$ is the maximum intensity of light emerging from the polariser.

In this thesis the 1st polariser is always located at 45° with respect to the direction of the applied field and the 2nd polariser at −45°, which means that the two polarisers are orthogonal.
with an initial offset angle of $\frac{\pi}{2}$. In such conditions, the intensity of light resulting from measurement can be calculated as

$$I = I_0 \sin^2 \theta$$  \hspace{1cm} (4.23)

4.3 Measurement of the Kerr effect in liquids

Figure 4.12 Arrangement for measurement of electro-optic Kerr effect in liquids [53]

Figure (4.12) shows the general arrangement adopted in this thesis for measuring the Kerr effect in a liquid. The components required are as specified below:

**Laser:** solid state laser, of wavelength $\lambda = 658$ nm. The light power is about 10 mW

$P_{45}, P_{-45}$: The first polariser is located at $45^\circ$ to the electric field of the light and the second polariser is orthogonal to the first.

$Q$: Quarter wave plates.

**Lens1 & Lens 2:** BK7 Plano-Convex type lenses of 6mm diameter, and 7.75mm radius of the convex side.

**Water cell** Two water cells were designed for use in the present project [53], the first was of 5 mm thick plastic, with two fixed stainless-steel electrodes shaped in the Bruce profile, whereas the second cell was of 50 mm wide plastic with 20 mm wide parallel stainless-steel plate electrodes. More details of both cells are provided later. The cell electrodes are connected to a pulse voltage generator.

**O/E:** Tektronix Opto-Electronic Converter type P6701A/B.

**OSC:** Oscilloscope with an input accepting the output of the optical/electronic converter.
4.3.1 Optical Components

High performance solid state laser

Figure (4.13) shows the high performance solid state laser that was used. It has excellent noise and power stability characteristics and is a compact fully integrated design with a built in thermo electric cooler.

![High performance solid state laser](image)

The laser emits an excellent beam profile with a pure TEM 00 diffraction limited beam. It is an ideal for long distance positioning metrology, processing, and inspection and spectroscopy applications. The thermo electric cooler ensures operation over a wide temperature range (10-35°C), while minimizing fluctuation in power and virtually eliminating high frequency noise. It has a low power consumption of less than 40 W and a universal AC/DC converter giving a regulated 5V DC output from standard AC input. This model is CRDH certified at a class 111b laser, and table (4.1) presents its principle features.

<table>
<thead>
<tr>
<th>CDRH</th>
<th>111b, all models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Diameter</td>
<td>&lt;1 mm</td>
</tr>
<tr>
<td>Beam Divergence</td>
<td>&lt;1.5 mard</td>
</tr>
<tr>
<td>Noise</td>
<td>&lt; 0.5% RMS</td>
</tr>
<tr>
<td>Power Stability</td>
<td>± 3%</td>
</tr>
<tr>
<td>Mode</td>
<td>TEM00</td>
</tr>
<tr>
<td>Mode quality</td>
<td>M^2 &lt;1.1 (594 nm; &lt;1.2)</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>10° C to 35° C</td>
</tr>
<tr>
<td>Warm up time</td>
<td>15 Min.</td>
</tr>
<tr>
<td>Expected operating life time</td>
<td>10,000 hour</td>
</tr>
<tr>
<td>Laser head</td>
<td>35mmHigh × 50mmWide × 100mmLong</td>
</tr>
<tr>
<td>Power supply</td>
<td>55mmHigh × 105mmWide × 125mmLong</td>
</tr>
</tbody>
</table>

Table 4.1 Details of solid state laser [54]
Polarisers

A polariser is an optical filter which converts a beam of light of undefined or mixed polarisation into well-defined polarised light. Two linear polarisers are normally used located such that light passing through the first polariser is perpendicular to the direction of the light passing through the second polariser. Figure (4.14) shows the linear polarisers from Edmound optics that were used for the experimentation.

Figure 4.14 Linear polarisers from Edmound Optics [54]

Quarter-wave plates

In general, a quarter wave plate is an optical device that shifts the phase between two perpendicularly polarised components of light wave travelling through it, for example converting linear polarisation to circular polarisation, so that the angle of the electric field vector at a fixed point describes a circle as time progresses. Simply, it is a birefringent crystal with a carefully chosen orientation and thickness. Figure (4.15(a)) illustrates the quarter wave plate that was used during the experimentati...

Figure (4.12) shows that there are two quarter wave plates, the first placed between the first polariser and the optical cell, and the second between the optical cell and the second polariser and orthogonal (the first one is at 45°, and the second one is at –45°) to the first quarter wave plate. The using of quarter wave plate eliminates Isoclinic and Isochromatic fringes produced by the first linear polariser, (more details about Isoclinic and Isochromatic fringes are given in [46]). These quarter wave plates are usually made of Mica, which is a natural product mixed with a group of a complex aluminosilicate mineral, and having a sheet or plate structure of a different chemical compositions and physical properties. The material is cut to a thickness allowing the production of two equal electric field components of light [55]. The thickness of the quarter wave plate is such that the phase difference is ¼ wavelength.
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Figure 4.15 (a) the layout of the quarter wave plate (b) quarter-wave plate [55]

Collimators

Figure 4.16 Different types of Collimators [54]

The collimators used in this thesis are from Edmunds Optics [54]. In general, collimators have a low back reflection, and are designed to collimate or focus light exiting a fibre to a desired beam diameter or spot size. They were used in the experiment to couple light in and out of the optical devices. Figure (4.17) illustrates the operating principle of a collimator.

Figure 4.17 Operating principles of a collimator [54]

The collimated beam diameter BD and the full divergence angle DA depends on the focal length of the lens f, the core diameter a, and the fibre numerical aperture NA. The collimated beam characteristics are given by:
4. ELECTRO-OPTIC SENSOR

\[
BD = 2fNA \tag{4.24}
\]

\[
DA = \frac{a}{f} \tag{4.25}
\]

**Lenses**

The lenses used in the experimentation are of the plano convex form shown in Figure (4.18). This type of lens has a positive focal length and is ideal for focusing light.

![Figure 4.18 Basic principle of the Plano Convex lens](image)

**Lens calculation**

Since the lenses are used in two different media (air and water), three different refractive indices; the air refractive index \(n_0\), the lens refractive index \(n_1\) and the water refractive index \(n_2\) are relevant, as is evident from figure (4.19).

Index \(n = 1\) (air) \hspace{1cm} Index \(n_2 = 1.333\) (water)

![Figure 4.19 Lens calculation in two different mediums (air & water)](image)
4. ELECTRO-OPTIC SENSOR

During the present work, paraxial formulae (which are based on the behaviour of paraxial rays that are nearly parallel to the optical axis) were used in the calculation of the focal length in the two different medium (this formulae is quoted from Cvimellesgriot. The effective focal length assumes two distinct values, \( f' \) in air and \( f'' \) in water medium.

Calculation of the lens constant \( k \) is considered first as this constant appears frequently in calculating lens formulae. It is a precise function of the lens radius, thickness, air refractive index, and both the lens and the water refractive indexes, and is given by:

\[
k = \frac{n_1 - n}{r_1} + \frac{n_2 - n_1}{r_2} \times \frac{t_z (n_1 - n) \times (n_2 - n_1)}{n_1 \times r_1 \times r_2}
\]  

(4.26)

and the effective focal lengths by:

\[
f = \frac{n}{k}, \text{ and } f' = \frac{n_2}{k}
\]  

(4.27)

Lens specifications

Table (4.2) gives details of the lenses used in both the experimentation and the electro-optical sensor [54].

<table>
<thead>
<tr>
<th>Lens Type</th>
<th>Effective Focal length</th>
<th>Back Focal Length</th>
<th>Centre Thickness</th>
<th>Edge Thickness</th>
<th>Radius</th>
<th>Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>BK7</td>
<td>30 mm</td>
<td>29.14 mm</td>
<td>1.3 mm</td>
<td>1.01 mm</td>
<td>15.50 mm</td>
<td>6 mm</td>
</tr>
</tbody>
</table>

Table 4.2 Lens details

Opto-Electronic converter

The opto-electronic converter used in the experiment is a Tektronix type P6701A as shown in Figure (4.20). It is an analogue optical/electrical (O/E) converter, which convert an optical (input) signal into an electrical (output) signal. The P6701A has a DC stable circuit with low offset drift (\( \leq 1\mu W \)), which improves the performance for extinction ratio measurement and absolute optical power levels.

![Figure 4.20 Opto-electronic converter type P6701A](image)

The optical input to the converter is connected to an SMA style fibre optic connector (FC style) as shown in Figure (4.21).
The optical signal is focused on the photodiode surface by means of a rod lens [56]. Photons are absorbed at the photodiode, generating a current proportional to the optical input power. The converter is calibrated so that the current is converted to 1V/mW with an optical input wavelength of 850nm. Figure (4.22) illustrates the response of the photodiode depends on the wavelength of the input source.

![Figure 4.22 Spectral response of the O/E converter photodiode. [56]](image)

Table (4.3) shows the optical and the electrical characteristics of the P6701A converter

<table>
<thead>
<tr>
<th></th>
<th>Wavelength</th>
<th>Optical input</th>
<th>Maximum optical input for linear output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical</td>
<td>500 to 850 nm</td>
<td>Accepts fibre up to 200µm core diameter NA^2 ≤0.29</td>
<td>1mW</td>
</tr>
<tr>
<td>Conversion gain</td>
<td>Bandwidth</td>
<td>Noise equivalent power</td>
<td>Rise time</td>
</tr>
<tr>
<td>1V/mW ±8% at DC,850 nm</td>
<td>DC to 850MHz</td>
<td>≤5µW(rms)</td>
<td>≤411ps</td>
</tr>
</tbody>
</table>

Table 4.3 Optical and electrical characteristics of the O/E converter [56]
Ker Water Cells (KWCs)

In this thesis the two different designs of water cells that were used in the determination of the Kerr constant, used basically the same electro-optic arrangement, in which two immersed metallic electrodes are mounted a distance $d$ apart, with their flat surfaces parallel. The electrode geometry, together with the various metallic and plastic materials used in the construction of the KWCs influence the electric field distribution along the laser beam, which can only be fully taken into account when the field integral is calculated using a 2D or even a 3D electrostatic solver. Great care was taken to eliminate the presence of air bubbles, and demineralised water (resistivity 33 kΩcm) and ordinary tap water (resistivity between 4 kΩcm and 5 kΩcm) were both used in experiments with identical results. The two electrodes ($E1$ and $E2$ in Figure (4.23) are connected to a pulsed power generator, with the high-voltage impulses produced across them measured using high-quality North Star voltage probes type PVM 5 and PVM 6, both having a maximum pulsed voltage and frequency of 100 kV and 80 MHz [57]. PVM 6 is used to measure signals up to 5 MHz, for which the accuracy guaranteed by the manufacturer is less than 1.5%, while PVM 5 is for impulses faster than 5 MHz, with an accuracy of less than 3%. The voltage probes are attached to the input of digital oscilloscopes having a bandwidth limited to 250 MHz (for reasons explained later).

The trigger generator type TG-70 (L-3 Sciences [13]) contains a 0.1 μF capacitor which can be charged up to 70 kV and discharged into a long 50 Ω high-voltage coaxial cable through a SF₆ pressurised triatron. Because the KWC impedance is much larger than the characteristic impedance of the coaxial line, a number of high-voltage reflections are generated, which are used as a train of voltage impulses in the electro-optic experiments.

A solid state 660 nm laser mounted in a Faraday cage launches light (using lens $L1$) into a long optical fibre ($F1$), terminated by a collimator ($L2$) mounted on a XYZ mechanism (for alignment of the laser) close to a first polarizer ($P1$) that polarises the light entering the KWC. $P1$ is not present for arrangements where $F1$ is a polarisation maintaining fibre. If necessary, the light beam inside the cell is further compressed by a pair of plano-convex lenses ($L3$ and $L4$) and, after emerging from the KWC, it is analysed by a second polarizer ($P2$) before being collected by a second collimator ($L5$) attached to another XYZ mechanism that helps with the required accurate alignment of other optical components. From $L5$ the light is launched into another long optical fibre ($F2$) connected to wideband opto-electronic ($O/E$) converters type Tektronix P6701A/B, having a bandwidth of 850 MHz and an optical to electrical sensitivity of 1 mW optical input power providing to 1 V electrical output. The converters are attached to digital oscilloscopes ($OSC$) used to record the time-dependent light variation $I(t)$, placed in a remote Faraday cage and powered by a UPS. Due to the high-frequency noise generated by reflections in the optical system, the bandwidth of the
oscilloscopes has to be limited to 250 MHz, similar to that of the oscilloscopes used in the voltage measurements. To increase the optical measurement precision, in certain experiments, a quarter wave plate $Q$ was introduced between $P1$ and the KWC.

The Kerr experiments presented below had the following aims:
- to determine the water Kerr constant at STP (normal temperature and pressure) and for the characteristic wavelength to be used in the future system when a fast impulse electric field is applied, having a ns rise time and a strength of at least 350 kV/cm.
- to prove that the Kerr effect in water is unaffected by the application of a train of fast electric impulses followed by a slow decay or plateau.

*These findings* are essential for the Kerr system to be used in the future non-invasive PEF processing studies and cannot be inferred as true from the published literature. It was decided however to leave for the near future further experiments to determine the variation of the Kerr electro-optic coefficient ($B$) with temperature.

**Kerr water cell 1 (KWC 1)**

The plastic cell used in this research is shown in Figure (4.24) and was of circular cross section 254 mm in diameter with a wall thickness of 5 mm. The cell uses a pair of near Bruce profiled carefully polished stainless-steel electrodes, each having a flat area of 33 mm diameter and an outer diameter of 100 mm, mounted in an acrylic cylindrical container with an axial separation $d = 2.87 \pm 0.05$ mm. The cylindrical symmetry enabled 2D Maxwell SV software (discussed later) to be used to determine the distribution of the electric field component $E_z$ inside water. The field integral (given later in equation (4.31)) was then calculated, giving an effective light path length $l' = 55.30$ mm. This cell was used for the measurement of voltages in excess of 50kV and for measuring a long train of intense electric field impulses as shown later in Figure (4.36(a)&(b)).

![Figure 4.24 Kerr Water cell1 for Kerr effect measurement at $\geq 300$ kV/cm](image)

**Stainless-steel Electrodes**

For many years it has been recognized that *the electrodes* used in the studies of electrical discharges should provide an almost uniform field region near the axis with the shape of the electrodes leading to discharges taking place only in the uniform region of the field. The majority of the electrodes used in literature have a flat central area with curved edges. Initially the curved part was designed empirically but in (1947) Bruce published the technique to design the profile, now named after him.
Figure 4.25 Schematic of Bruce profile [58]

Figure 4.25 shows the Bruce profile used to provide uniform field from the electrodes used in the water cell. The flat part (AB) is of a diameter not less than the maximum gap length to be used. (BC) is a sine curve based on the axes (OB) and (OC), so that, \( XY = OC \sin\left(\frac{\pi}{BO} \times \frac{X}{2}\right) \) [58]. CD forms the arc of circle with centre at (O), and the electrodes that are located in the water cell are shown in Figure (4.24).

![Stainless steel electrodes manufactured following Bruce profile design](image)

**Kerr Water Cell 2 (KWC2)**

KWC2 was designed to generate smaller electric fields that provide accurate data. This cell uses a pair of 400 mm long parallel-plate stainless-steel electrodes, placed a distance \( d = 5.00 \pm 0.05 \) mm apart with the aid of polyethylene supports (Figure 4.27(a) and (b)). An electric pump, coupled to the cell through plastic tubes, removes any impurities or air bubbles produced during a discharge. As the geometry of the cell is three dimensional (Figure 4.46(a) and (b)), 3D Maxwell software was used to determine the electric field distribution. The field integral of the \( E_z \) component was calculated along the Ox axis (i.e., along the laser beam in water) as presented later.
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Figure 4.27  KWC2 (a) electrode details during assembly (b) ready for mounting on the optical bench

4.4 Modelling of the Kerr Water Cells (KWCs)

The software used to model the Kerr water cells was Maxwell SV package, 2D and 3D, and is an interactive package for analysing electric and magnetic fields in structures with uniform cross-sectional or fully rotational symmetry.

Depending on which simulator package is selected, the following field quantities can be established:

- Static electric field, forces, torques, and capacitances due to voltage distributions, permanently polarized materials, and charges.
- Static magnetic field, forces, torques, core loss, and inductances due to DC currents, static external magnetic fields, and permanent magnets. Field can be simulated in structures that contain linear and non-linear materials.
- Time-varying magnetic fields, forces, torques, and impedances due to AC currents and oscillating external magnetic fields.
- Time-varying axial electric fields, displacement currents, and conduction currents.

The software’s generalised, finite element based field solvers allow the simulation of electric and magnetic fields in any type of device, from cross-sections of motors and transformers to integrated circuit packages. The structure must be drawn and specify all relevant material characteristics, boundary conditions describing field behaviour, sources of charge, current or voltage specified, together with the quantities that are to be computed of such as forces and torques. The simulator generates field solutions and computes the requested quantities.

4.4.1 Maxwell SV 2D Control panel

The Maxwell 2D Control Panel shown in Figure (4.28) acts as a front end to all Maxwell software products. Through the Projects command, it enables the creation of projects and access to Maxwell 2D.
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Figure 4.28 Control panel of Maxwell SV 2D

Click on Projects from the control panel to open the Project Manager window

Figure 4.29 Project Manager window of Maxwell SV 2D

After selecting the type of model to be created, a Cartesian model is developed in the XY plane, where the 2D model represents the XY cross-section of a structure that extends infinitely long in the Z-direction. An axisymmetric model is created in the RZ plane, where the 2D model represents a cross-section that is revolved around an axis of symmetry.
In this research the RZ axis plane was chosen to draw the electrodes, as shown in Figure (4.30).

and these were drawn according to the following co-ordinates:

Top line co-ordinate: (0, 31.2) (16.5, 31.2)
Bottom line co-ordinate: (0, 0) (36.3, 0)
First arc co-ordinate: Origen (16.521, -43.951)
   Start point (16.5, 31.2)
   End point (36.587, 28.472)
Second arc co-ordinate: Origen (29.911, 4.38)
   Start point (36.587, 28.472)
   End point (44.04, 25)
Third arc co-ordinate: Origen (36.3, 13.7)

Start point (44.04, 25)

End point (36.3, 0)

Figure (4.31) shows the modelling of the water cell with the electrodes in position.

Figure 4.31 Model of the water cell
After the water cell is modelled, the next step is to set up the materials for the modelling system. Referring to Figure (4.32), the electrode material is stainless-steel. The background of the modelling system is air, the cell is of Plexiglas, and the water model has a relative permittivity of 80 and conductivity of $5 \times 10^{-6} \text{S/m}$. The Post Processor displays the contour, shaded, and arrow plots of the electromagnetic or electric field pattern and manipulates the corresponding field solutions. Figure (4.33) shows the electric field strength at an applied voltage of 1V.
4.4.2 Maxwell SV3D

The Maxwell 3D desktop consists of several windows, a menu bar, toolbars, and a status bar. It has a usability of opening multiple windows in Maxwell 3D to display different parts of the model. For instance, one window can remain fixed on the winding, one on the diagram, and one on the main desktop window.

![Maxwell desktop](image)

Figure 4.34 Maxwell desktop

After opening a new project in the modeller window (3D or 2D project), a solution type should be chosen first to identify the analysis and the parameter solutions that the user want, e.g. magneto-static or electrostatic analysis. For the identification of the materials, the user clicks on the object name on the left side of the modeller screen. The types of excitations available depend on the actual analysis type. As an example, table 4.4 shows the excitations available for electrostatic problems.
4. ELECTRO-OPTIC SENSOR

<table>
<thead>
<tr>
<th>Excitation</th>
<th>Type of Excitation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>The DC voltage on a surface or object. This excitation type is available for both electrostatic and DC conduction electric Solvers.</td>
</tr>
<tr>
<td>Charge</td>
<td>The total charge on a surface or object (dielectric). This excitation type is available for electrostatic solvers only.</td>
</tr>
<tr>
<td>Floating</td>
<td>Used to model conductors at unknown potentials. This excitation type is available for electrostatic solvers only.</td>
</tr>
<tr>
<td>Volume Charge Density</td>
<td>The volume charge density in an object. This excitation type is available for electrostatic solvers only.</td>
</tr>
</tbody>
</table>

Table 4.4

The meshing process in Maxwell 3D, which is optional mesh refinement settings that provide Maxwell with mesh construction guidance. This technique of mesh construction is referred to as "seeding" the mesh, which is performed using the Mesh Operations commands on the Maxwell 3D or Maxwell 2D menu. Determine the field for the drawing, again depends on the solver. For an electro-static

4.5 Experimental results and the Kerr constant calculation

As discussed earlier, the Kerr effect is produced by the interaction of an electric field with anisotropic substance that includes optical birefringence. This birefringence is a quadratic function of the electric field strength [59]

\[ n_{\parallel} - n_{\perp} = \lambda B E^2 \]  

(4.28)

In equation (4.28), \( n_{\parallel} \) and \( n_{\perp} \) are the refractive indices for the light with the electric vector respectively parallel and perpendicular to the applied polarising external field \( E \), \( \lambda \) is the light wavelength and \( B \) is the Kerr constant. The resulting phase shift \( \phi \) between the two electric field components of a linearly polarised light along a direction perpendicular to a Homogeneous field \( H \) is expressed as:

\[ \phi = \frac{n \pi}{\lambda} (n_{\parallel} - n_{\perp}) = \pi B E^2 \]  

(4.29)
where \( l \) is the light path length under the influence of the external electric field. When the electric field is non-homogeneous, the phase shift is expressed as:

\[
\phi = \pi B \int_0^l E(x)^2\,dx
\]  

(4.30)

In this equation the Kerr constant is assumed to have the same value along the light path. This may not always be true, as \( B \) is a function of both temperature and pressure (discussed later), which may both vary along the light path. When an external \textit{time dependent} and \textit{non-homogeneous} electric field is generated in a water probe, the retardation can be determined at any time \( t \) by recording the time variation of the corresponding light intensity \( I(t) \) given by the Malus Law:[52]

\[
I(t) = I_{\text{max}} \sin^2 \left( \frac{\delta(t)}{2} \right) = I_{\text{max}} \sin^2 \left( \pi B \int_0^l E(x, t)^2\,dx \right)
\]  

(4.31)

where \( I_{\text{max}} \) is the maximum value of the light intensity. Equation (4.31) is only valid when the input light launched by a laser is linearly polarised at an angle of \( \pi/4 \) with respect to the direction of the externally applied electric field and the output light is analysed using a polariser orientated perpendicular to the initial direction of polarisation.

**Calculation of Kerr effect in water cell**

When the electric field is produced between a pair of electrodes immersed in water, the application of a transient voltage \( V(t) \) from a high voltage impulse generator enables equation (4.32) to be simplified to

\[
I(t) = I_{\text{max}} \sin^2 \left( \frac{\pi B l' V^2(t)}{d^2} \right)
\]  

(4.32)

where, \( d \) is the electrode separation and \( l' \) is the effective path length, taking into account the effects of fringing fields at the plates edges. By assuming that the volume of the liquid is \textit{infinite}, analytical expressions for \( l' \) are available for particular plate geometries, such as the Rogowski profile or square ended electrodes [60]. In the case of other electrode geometries and also for taking into account the influence of nearby \textit{perturbing} objects, such as the metallic connections of the electrodes and the dielectric walls of the Kerr cell, an electrostatic solver must be used to evaluate the electric field integral \( \int_0^l E(x)^2\,dx \).

The result of modelling and integral calculation of Kerr effect using Maxwell SV 2D for Kerr water cell1 designed for this project is shown in Figure (4.35(a) and (b)).
Figure 4.35 a) Modelling of Kerr water cell1 (b) electric field strength mapping for 1 V applied and the corresponding $E_z$ distribution along the laser path used to calculate the field integral. Because of symmetry, both (a) and (b) show only the right-hand half of the arrangement.

The results presented in Figure (4.36 (a),(b)) and Figure (4.37) are for the Kerr water cell1 and the electric field. The value of the Kerr constant obtained from this was $B = 2.45 \times 10^{-14} \text{m/V}^2 \pm 7\%$, in all experiments for electric fields up to 300 kV/cm and even higher e.g. 350kV/cm.

In the procedure that was used to obtain experimental data when using KWC1, a high voltage generator applied a train of electric impulses to the KWC1 electrodes, when each peak allows a separate determination of the Kerr constant $B$ with less error as is presented later (see Figure (4.44)) and this value is then compared with all the values obtained from the other peaks to establish if $B$ changes during the application of a train of impulses. The light intensity obtained experimentally is compared with that theoretical calculation (equation (4.31)), using the voltage data $V(t)$ and the effective length $l'$. This method of comparing is preferred because the greater sensitivity highlight any small differences that exist. The alternative and less sensitive method compares the measured voltage with that calculated using equation (4.32) together with experimental light intensity data and the value obtained for $B$. 
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Figure 4.36 (a) The corresponding modulation of light intensity obtained experimentally (red) and theoretically (blue). (b) Zoom of the corresponding modulation of light intensity obtained experimentally (red) and theoretically (blue).

Figure 4.37 Time variation of the central electric field
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Figure (4.38(a) and (b)) shows the modelling of KWC2 and the integral calculation using Maxwell SV 3D for KWC2.

![Model of Kerr water cell 2](image)

Figure 4.38 Modelling of Kerr water cell 2

Figure (3.38) shows the 400 mm long parallel-plate stainless-steel electrodes, located a distance $d = 5.00 \pm 0.05$ mm apart with the aid of polyethylene supports. 3D Maxwell software was used to determine the electric field distribution. The field integral of the $E_z$ component was calculated along the Ox axis (i.e., along the laser beam) and the corresponding effective length was found as $l' = 404.11$ mm. It was also established that, as expected from the design, the field is extremely homogeneous inside the water (Figure 4.39) and the beam diameter or small errors in its positioning are therefore not important for this cell.

![Graph of electric field component](image)

Figure 4.39 Variation of the electric field component $E_z$ inside the water for 1 V applied between electrodes; the field integral was calculated using the distribution along Ox-axis

Typical results obtained with KWC2 are presented in Figure (4.40). Because the corresponding values at retardation for the same applied voltage are much larger than those produced by KWC1, KWC2 provides, at least in principle, a more accurate determination of the Kerr constant. To increase even more the optical measurement precision, a Q-plate was introduced into the optical arrangement, giving the typical result shown in Figure (4.41). The same $B$ value of $2.45 \cdot 10^{-14} \text{m/V}^2 \pm 5\%$ was obtained in all experiments for electric fields up to about 200 kV/cm. The statistical scatter for many experiments was less than $\pm 1\%$. 
Figure 4.40 (a) Time variation of the central electric field (b) Typical results of Kerr effect from KWC2 experiments. The corresponding modulation of light intensity obtained experimentally (red) and theoretically (blue); the two traces are practically indistinguishable.
Figure 4.41 Typical results from KWC2 experiments using a Q-plate
Upper figure shows the time variation of the central electric field; an arrow indicates electrical breakdown, and the lower figure shows the corresponding modulation of light intensity obtained experimentally (red) and theoretically (blue). The two traces are practically indistinguishable until the electrical breakdown indicated by an arrow

4.5.1 Factors affecting the water Kerr constant
When experiments are performed at various temperatures or under high-pressure conditions or when the externally applied electric field is very strong, the Kerr constant B changes substantially from its value at standard temperature and pressure (STP) and low electric field value. Detailed theoretical considerations of the Kerr effect in liquids are complicated and outside the scope of this thesis, but useful estimations can be made using the Born formula, valid for fluids [61]:

\[ B = \frac{n^2 + 2}{\lambda n} \left( \varepsilon_r + 2 \right)^2 N \Theta \]  

where \( n \) is the refractive index of the liquid, \( \varepsilon_r \) its static dielectric constant, \( N \) the number of molecules per unit volume and \( \Theta \) a complex function depending on the liquid temperature \( T \) and its polarizability. Based on the Born formula, a short analysis of the various factors affecting B follows.

The first term of Equation (4.33) suggests that, for optical frequencies, the following dispersion relation holds

\[ B(\lambda) \sim \frac{n(\lambda)^2 + 2}{\lambda n(\lambda)} \]  

(4.34)
and the Kerr constant therefore depends on the wavelength of the laser chosen. Without going into details, not all laser wavelengths are however practical, because of water absorption.

The predicted temperature variation is of the general form:

\[
\frac{B(T)}{B(T_{\text{ref}})} = A_0 + \frac{A_1}{T} + \frac{A_2}{T^2} + \frac{A_3}{T^3}
\]

(4.35)

where \(T_{\text{ref}}\) is a reference temperature and \(A_i\), for \(i=0\ldots3\), are constants usually determined experimentally for each liquid. Using available data [62] for water and a wavelength \(\lambda=660\text{ nm}\), the set of constants is \(T_{\text{ref}}=296\text{ K}, B(T_{\text{ref}})=3.43 \times 10^{-14}\text{ m/V}^2\), \(A_0=255.46\), \(A_1=-2.322 \times 10^5\ K\), \(A_2=7.038 \times 10^7\ K^2\), \(A_3=-7.087 \times 10^9\ K^3\) and a similar set of data is available in [63]. During PEF treatment, the food is usually heated to a temperature of \(T=318\text{ K}\), and in such cases a correction for \(B\) is required.

The pressure variation of \(B\) is not presented in the literature. However, theoretical predictions for the pressure \(P\) dependence of the dielectric constant \(\varepsilon_r=\varepsilon_r(P)\) suggest important variations at pressures above 200 Mbar [64]. Such pressures, will certainly affect the measurement, and can be generated by strong shock waves due to electrical breakdown inside microscopic air bubbles that may be present in water. In another scenario, and relevant to the present application, high-pressures can be applied in combination with the PEF technique to induce a synergetic phenomenon.

The Kerr constant \(B\) can also be influenced by the frequency \(f\) of the electric field. Fortunately, for most liquids, including water [65], the dispersion of the dielectric constant \(\varepsilon_r=\varepsilon_r(f)\) remains constant up to about 1 GHz.

Finally, \(B\) is influenced by the electric field intensity \(E\). Although no theoretical estimation exists, a strong influence is implied by equation (4.32) i.e., \(B(E)=[\varepsilon_r(E)+2]^2\). The dielectric constant \(\varepsilon_r=\varepsilon_r(E)\) is predicted to have a non-negligible variation for applied electric fields in excess of 1 MV/cm, followed at higher values by an abrupt fall at around 10 MV/cm [66]. Recent experiments have qualitatively confirmed saturation in the Kerr effect for applied electric fields in excess of 3 MV/cm [67]. Reliable published experimental results for electric fields up to 100 kV/cm show that the variation of the dielectric constant \(\Delta\varepsilon_r\) is given in this interval by [68]:

\[
\frac{\Delta\varepsilon_r}{E^2} = 10^{-13} \frac{m^2}{V^2}
\]

(4.36)

Equations (4.33) and (4.37) can be used to predict the variation in \(B\) due to an externally applied field of 100 kV/cm of only about -0.26 \%, an effect which can be neglected. By extrapolating however Equation (4.36) to an applied field in excess of 300 kV/cm, as generated during the experiments presented below, the change in \(B\) is predicted to be about -2.3 \%. This effect, depending on the measurement precision, may be observable.

4.5.2 Analysis of Kerr data for water

Equation (4.32) has been used, during recent decades, in both determining the Kerr constant \(B\) of liquid substances and in the development of extremely precise high-voltage transient sensors [45,69,70]. For the latter application, obviously requiring very precise pre-determination of \(B\), nitrobenzene is the preferred liquid medium. This choice is due mainly to the high value of \(B\) and the long (millisecond) delay in the appearance of perturbing liquid turbulence after application of external voltage. Another reason for choosing nitrobenzene is the very satisfactory agreement in the published Kerr constant data at various temperatures.
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and wavelengths. However, as already mentioned, the present application necessarily requires a system operating with water. A literature search of the Kerr constant data for water [59] and [71,72,73] proved to be, unexpectedly, extremely unreliable. The collected data is presented in both Table (4.5) and Figure (4.42(a)) shows a very large scatter. For example, at 633 nm, the ratio between the lowest and highest published values is almost two. It is worth mentioning that in only two occasions is an (optimistic) estimation of the measurement errors provided. In an effort to clear the view, it was rather arbitrarily decided to process the data using the following methodology:

- discard all data for which no detailed presentation is available for the corresponding experimental arrangement. This applies to all reference data from handbooks and journal citations
- apply a temperature correction, such that all data applies for 298 K.

The result of this processing is shown in Figure (4.42(b)) and this time, again for 633 nm, the differences are only about 20%. It is very important to note that, as presented in Figure (4.43(b)), for each a set of data corresponding to different wavelengths reported in a single reference, the data points lie precisely on the corresponding dispersion relation calculated using Equation (4.34). This means that some of the dispersion curves contain an offset which can be interpreted as indirectly proving that at least some of the reported data contains a systematic error. The next section provides an analysis of the possible systematic experimental errors in determining the Kerr constant in water, with the conclusions later used in the design and subsequent analysis of the experimental data obtained during the development of the Kerr effect system.
### Table 4.5: Kerr constant data reported in the literature

<table>
<thead>
<tr>
<th>Kerr constant $\left(10^{14} \text{ m/V}^2\right)$</th>
<th>Wavelength (nm)</th>
<th>Measurement error (%)</th>
<th>Reference</th>
<th>Type of reference and reference tables</th>
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<td>[64]</td>
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<td>[75]</td>
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<td>633</td>
<td>-</td>
<td>[63]</td>
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<td>4.13</td>
<td>436</td>
<td>-</td>
<td>[77]</td>
<td></td>
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<tr>
<td>3.21</td>
<td>546</td>
<td>-</td>
<td>[77]</td>
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<tr>
<td>3.02</td>
<td>578</td>
<td>-</td>
<td>[77]</td>
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<tr>
<td>3.62$\text{)}$</td>
<td>442</td>
<td>3</td>
<td>[78]</td>
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<tr>
<td>2.54$\text{)}$</td>
<td>633</td>
<td>3</td>
<td>[79]</td>
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<tr>
<td>3.40 to 3.60$\text{**)}$</td>
<td>589</td>
<td>-</td>
<td>[80]</td>
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<td>3.40</td>
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<tr>
<td>4.17</td>
<td>633</td>
<td>-</td>
<td>[82]</td>
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<tr>
<td>5.30</td>
<td>365</td>
<td>-</td>
<td>[48]</td>
<td></td>
</tr>
</tbody>
</table>

*) data obtained at 30°C

***) data obtained in the interval 5°C to 30°C

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Figure 4.42 Water Kerr constant a) Data from literature corresponding to Table 1 b) Data after applying the methodology described in text Curves 1, 2 and 3 were obtained using the dispersion relation of Eq. (4.34) and correspond respectively to data from [62], [65] and [78,79]. The full circle in the lower left corner is the result of the present work Error bars are shown when available

4.5.3 Sources of errors in determining the Kerr constant for water

In what follows only experiments undertaken with a Kerr cell maintained at constant temperature and atmospheric pressure are considered. If a high-voltage impulse V(t) is applied to the electrodes, the Kerr constant is found from Equation (4.32) as:

$$B = \frac{\delta(t) l^2}{2\pi l' V(t)^2}$$

(4.37)

where the retardation $\delta(t)$ at any time t is experimentally determined by recording the light intensity time variations $I(t)$. By assuming small errors, the measurement is affected by the following uncertainties:

$$\frac{\Delta B}{B} = \pm \frac{\Delta \delta(t)}{\delta(t)} \pm 2 \frac{\Delta d}{d} \pm \frac{\Delta l'}{l'} \pm 2 \frac{\Delta V(t)}{V(t)}$$

(4.38)

Each term in the right-hand side of Equation (4.35) is analysed below in detail.

i) **the errors in determining the retardation** are calculated from Equation (4.31) and after tedious calculation, the result obtained is:

$$\frac{\Delta \delta(t)}{\delta(t)} = \left[ \cos^{-1} \left( -1 \right)^n \left( 1 - \frac{2I(t)}{I_{\text{max}}} \right) \right] - \cos^{-1} \left[ \left( -1 \right)^n \left( 1 - \frac{2I(t)}{I_{\text{max}}} \right) \right]$$

$$\frac{\Delta \delta(t)}{\delta(t)} = \frac{n\pi + \cos^{-1} \left( -1 \right)^n \left( 1 - \frac{2I(t)}{I_{\text{max}}} \right)}$$

(4.39)
where \( n \) is an integer defined by \( \delta(t) = n + k \) (the fraction \( k \) takes values between 0 and 1) which, together with \( \frac{I(t)}{I_{\max}} \) and \( \frac{\Delta I(t)}{I_{\max}} \), are all directly obtained from the I(t) oscillogram (see Appendix for calculation details).

Figure (4.43) illustrates the phase shift errors (when \( Q \) is not located) for the first four electric peaks indicated are calculated using Equation (4.40) as follows:

Peak 1: \( n=2, \frac{I_1}{I_{\max}} \approx 0.933, \frac{\Delta I_1}{I_{\max}} \approx \pm 0.033 \), \( \frac{\Delta \delta}{\delta} \approx \pm 1.72\% \)

Peak 2: \( n=2, \frac{I_2}{I_{\max}} \approx 0.183, \frac{\Delta I_2}{I_{\max}} \approx \pm 0.008 \), \( \frac{\Delta \delta}{\delta} \approx \pm 0.29\% \)

Peak 3: \( I_3 \) is almost equal to \( \Delta I_3 \), and it is therefore not easy to estimate. If \( \frac{I_3}{I_{\max}}=0 \), the calculation becomes difficult and for convenience we have not considered such cases.

Peak 4: \( n=1, \frac{I_4}{I_{\max}} \approx 0.022, \frac{\Delta I_4}{I_{\max}} \approx \pm 0.013 \), \( \frac{\Delta \delta}{\delta} \approx \pm 1.31\% \)

where \( I_i \) and \( \Delta I_i \) for \( i=1..4 \), are the peak maxima and the corresponding errors.

When \( Q \) is present in the optical arrangement of Figure (4.23), Equation (4.49) takes the form:

\[
\frac{\Delta \delta(t)}{\delta(t)} = \left\{ \begin{array}{l}
\sin^{-1}\left[ (-1)^{n+1} \left( 1 - 2 \left( \frac{I(t)}{I_{\max}} \pm \frac{\Delta I(t)}{I_{\max}} \right) \right) - \sin^{-1}\left[ (-1)^{n+1} \left( 1 - 2 \left( \frac{I(t)}{I_{\max}} \right) \right) \right] \right] \\
\frac{n\pi + \sin^{-1}\left[ (-1)^{n+1} \left( 1 - 2 \left( \frac{I(t)}{I_{\max}} \right) \right) \right]}{\pi} + \sin^{-1}\left[ (-1)^{n+1} \left( 1 - 2 \left( \frac{I(t)}{I_{\max}} \right) \right) \right]
\end{array} \right\}
\]

\[ (4.40) \]

with \( \frac{\delta(t)}{\pi} = n + k - \frac{1}{2} \). For the particular case of Figure (4.51), the phase shift error for the first electric peak indicated is calculated as follows:

Peak 1: \( n=5, \frac{I_1}{I_{\max}} \approx 0.03, \frac{\Delta I_1}{I_{\max}} \approx \pm 0.007 \), \( \frac{\Delta \delta}{\delta} \approx \pm 0.23\% \)

\[ +0.23\% \quad -0.26\% \]
Figure 4.44 Expansion of part of Figure (4.41): the time of the first electric field peak is produced is clearly indicated.

ii) the errors in determining the distance between the Kerr cell electrodes are related to the practical arrangement. Without taking exceptional measures this distance, usually close to 3 mm, can only be measured with a precision of about ±50µm, resulting a total error of about ±3%.

ii) the errors in determining the effective path length are difficult to estimate for previous published work, which optimistically claims errors of about ±1% [62] or even less [78,79]. Today, by using state-of-the-art 2D and 3D electrostatic solvers, the effective path length (the electric field integral) can be calculated without any significant error for any electrode geometry and taking into account all perturbing Kerr cell elements. The electric field analysis can also be used in estimating more subtle errors, such as those introduced by the light beam diameter and by a less than perfect beam alignment in respect to the electrode surface.

iv) the errors in the measurement of the high-voltage impulse generated across the Kerr cell are related to two, very different aspects. The first of these is the voltage probe precision and previous published work has estimated this at ±1% [62] or even less [79], without providing any details of the voltage probe itself. The authors believe that unless exceptional measures are taken the error in the voltage measurement will even in the best case be somewhere between ±1.5% and ±3%, which provides an error in the Kerr constant of between ±3% and ±6%. This estimation includes errors introduced by the voltage probe precision, the oscilloscope and possibly the electromagnetic noise induced by high-voltage generators.

There is however another, and even more subtle, source of error. When a voltage probe is connected in parallel with the Kerr cell electrodes, the impulse voltage measured by the oscilloscope is given by:

$$V_{\text{oscilloscope}} = V_{\text{capacitive}} + V_{\text{resistive}} + V_{\text{inductive}}$$

The first term can be expressed as

$$V_{\text{capacitive}}(t) = \frac{q(t)}{C} = \frac{\int_{0}^{t} i(t) \, dt}{C}$$
where $q(t)$ is the charge accumulated in the water capacitor formed by the Kerr cell electrodes having a capacitance $C$

$i(t)$ is the corresponding current.

The second term of (4.37), which is

$$v_{\text{resistive}}(t) = R i(t)$$

is related to the resistance $R = \frac{\varepsilon \rho}{C}$ of the water cell, where $\varepsilon$ is the water permittivity and $\rho$ its conductivity and the resistance of the connecting conductors is neglected.

The final term is a function of the self-inductance $L$ of the electrode circuitry, including the connections with the voltage probe, as

$$v_{\text{inductive}}(t) = L \frac{di}{dt}.$$  

The effect of the inductive term on the accuracy of the voltage measurement is not mentioned in the literature on Kerr data although, judging from the available description of the arrangements, their self-inductance was probably quite large. The inductive term may not be important, but only if a very low-frequency voltage impulse is applied or if the measurement is made during the plateau of a multi-microsecond rectangular voltage pulse. However, as pointed out in [62] and [63], application of a strong electric field for a few microseconds produces water turbulence, a phenomenon which perturbs the measurements and is the principal reason why working with water is so difficult. In the present experiments, in which fast voltage impulses are applied, the technique used for the estimation of the influence of the inductive term not require any further measurement, apart from voltage, but needs the values of lump parameters $C$ and $L$, which can accurately be estimated using standard methods, and $R$ calculated from $\frac{\varepsilon \rho}{C}$.

If a voltage measurement is made using a digitizing oscilloscope, a set of $N_t$ voltage data separated by a constant time interval $\Delta t$ is obtained as $v_k$, with $k=1..N_t$. The corresponding time rate-of-change of current $\left. \frac{di}{dt} \right|_k$ followed by the current $i_k$ itself and then the charge accumulated in the Kerr cell capacitor $q_k$, can all be calculated in succession at each time-step $k$ using the algorithm as

$$\left. \frac{di}{dt} \right|_k = \frac{C v_k - \frac{1}{4} \left. \frac{di}{dt} \right|_k - i_{k-1} \frac{dt}{dt} - q_{k-1}}{L C + \frac{1}{4} + R C \frac{dt}{dt}}$$  

(4.42)

$$i_k = \frac{dt}{2} \left( \left. \frac{di}{dt} \right|_k - \left. \frac{di}{dt} \right|_{k-1} \right) + i_{k-1}$$  

(4.43)

$$q_k = \frac{dt}{2} (i_k - i_{k-1}) + q_{k-1}$$  

(4.44)
with the initial conditions being $i_0=0$ and $q_0=0$. For the last initial condition $\frac{di}{dt}$, an estimate is required, which however does not influence the results even in the case of a 100% error in the estimated value. The inductive voltage term can then simply be obtained at any time step as $L \frac{di}{dt}$. This technique was applied in the analysis of experimental data whenever it was possible. It is obvious that unless exceptional measures are taken, the total systematic error may well be in excess of ±10%, which provides a convenient explanation of the systematic difference between most of the results in Figure (4.42(b)). It also sets a practical limit to the precision expected from the use of a Kerr system operating with water.
CHAPTER FIVE

NOVEL NON-INVASIVE PULSED ELECTRIC FIELD TECHNIQUE
Chapter 5

5. Novel non-invasive Pulsed Electric Field Technique

5.1 Introduction

Thermal methods, i.e. pasteurization, are commonly used in the food industry for destroying pathogenic microorganisms and to improve the stability of the product during storage. Pasteurization is a process in which liquid food is heated to destroy bacteria at specific temperature for a length of time after which it is immediately cooled. This process is based on the use of one of the following time and temperature relationships [8]:

- High temperature- short time treatment: in this process higher heat is used for shorter times, for example milk is pasteurized at 72°C for 15 seconds.
- Low temperature- long-time treatment: in this process lower heat is used for a longer time, for example, milk is pasteurized at 65°C for 30 minutes.

However, because of the heat generated, the colour, flavour and nutrients of the food may all be affected. The alternative of a non-thermal method of processing using a pulsed electric field (PEF) is therefore of great interest to the food industry and it is at present one of the emerging processes. However, PEF as implemented at present in industrial food processing is an invasive process, in which short (i.e. microsecond) high voltage pulses are applied via a pair of electrodes to the food in a treatment chamber, thus producing high electric fields and currents. In general, the interactions of these pulses with biological cells may be classified as either

1) **Electroporation**, in which the pulse frequency matches the RC characteristic time of the membrane. These pulses charge the cell membrane with a voltage to a threshold value (≈ 1V) that can cause a breakdown in the cell membrane and pore formation (more details are given later).

2) **Intracellular manipulation**, in which intense electric pulses with durations ranging from hundreds of ns to sub nanoseconds are used to destroy the nucleus [8].

Normally, PEF is applied to samples heated to about 50°C (in some tests up to 60°C) but the temperature is always maintained under that used in pasteurization. Heating is required for the efficiency of the PEF process and is at a level related to the mechanical stress of the membrane [83].

Nowadays, consumers require high quality, fresh and safe foods. The PEF method is in principle able to deactivate pathogenic microorganisms without any significant loss of the organoleptic and nutritional properties of the food. Moreover, this treatment method is more effective than thermal methods in destroying bacteria, such as listeria innocua, e-coli and salmonella typhimurium. The first results in the use of pulsed electric field (PEF) research applied to food processing appeared some fifty years ago [9,83], but more recently the use of this technique for industrial liquid (or ‘pumpable’) food sterilization has been widely investigated. Noteworthy results have been reported by Old Dominion University,
5. NOVEL NON-INVASIVE PULSED ELECTRIC FIELD TECHNIQUE

Washington State University and Ohio State University in the USA, Kumamoto University in Japan, the Technical University, Berlin in Germany, the Technical University of Delft in the Netherlands and the Efremov Institute in Russia.

In this chapter the present PEF method is investigated in more detail including a general background on E-coli bacteria and their equivalent electrical circuit, the influence of the temperature on the bacteria, and the results of using PEF. The presently used industrial technique is outlined, together with a description of the novel non-invasive technique proposed in this thesis. Proof of principle experiments is explained and their results investigated, finally, a comparison is provided between the non-invasive technique and other competing techniques.

5.1.1 Pulsed Electric Field Technique

The classification of PEF interaction is qualitatively based on a comparison of the pulse duration with the charging time constant of a cell membrane. The pulse duration and electric field intensity are two key parameters that could potentially be manipulated to achieve a tailored deactivation of cells for the specific requirements of intended applications. If the pulse duration is longer than the membrane charging time such phenomenon as membrane breakdown, and pore formation are expected. If the pulse duration is shorter than the membrane charging time, intracellular effects are expected, for example nanosecond pulses with high intensity and a fast rise time can cause effects, such as increased membrane permeabilization, and nanometre sized pore formation [84].

At the molecular level, for ‘long’ pulses the membrane is the primary component that interacts with the applied PEF, and it may be represented in electrical terms as a capacitance in parallel with a resistance. When the applied pulse duration is much longer (at a lower frequency case) than the charging time constant of the membrane, the resistance of the membrane insulates the cytoplasm from the external electric field and free charges build up on both sides of the membrane. However, if the applied pulsed duration is much shorter than the charging time constant (at a high frequency case) it might bring about a short circuiting effect of the membrane capacitance, which would allow the electrical field to penetrate into the cell.

**Cell membrane**

This is a biological membrane that separates the interior of a cell from the outside environment, and basically protects the cell from outside forces. It is selectively permeable to ions and organic molecules, and controls what enters and exits the cell to maintain an internal balance. It is associated with a variety of cellular processes such as ion conductivity and cell signalling, and its structure consist of:

1) lipid bilayer which is a two layers of phospholipids
2) proteins embedded in the membrane.
Figure (5.1) shows the cell membrane and its structure.

![Cell membrane and its structure](image)

When there is no stress on the cell membrane, it acts as a barrier to protect the cell. However, when a PEF is applied the membrane is stressed by a compressive force, which creates electrical stress and strain.

**Membrane Pore**

This is a protein that helps to establish and control the voltage across the plasma membrane of the cell. It regulates the flow of ions across the membrane of the cell. Figure (5.2(a) & (b)) shows the membrane pore formation.
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Figure 5.2 Schematic diagram of the membrane pore formation (a) lipids pores. (b) proteins pores.

Since the cell membrane contains a lipid bilayer, it is like oil and is insoluble in water. The lipid molecule contains a polar head region and a non-polar tail region. The polar head region has several electrically charged sites so, under any external electrical stress induced by electric fields, electro-pores are formed. Li Yang and Huey Huang have shown that it is the proportion of other molecules in the membrane that will determine whether the pore is open or closed [85]. Their model suggested that the molecules that initiate membrane breakage will be lipids and proteins. Figure (5.2 (a) and (b)) show the membrane pore formation with the lipids and the proteins. The formation of these can be explained based on pore energy, which is the change of free energy resulting from the formation of a cylindrical pore, with a radius in the lipid bilayer at different pore radii as Figure (5.2 (a)) shows. These pores have a wall of hydrocarbon lipid tails that are termed hydrophobic pores and a wall of reoriented lipid molecules with polar heads termed hydrophilic. Figure (5.1(b)) shows the hydrophilic head and hydrophobic tail. In a hydrophobic pore, when the radius and energy are zero, the membrane will be in an undisturbed state. When the radius is increased by a small value, the formation of the hydrophobic pores is energetically more positive, which is assumed to be the initial stage of electroporation. When the radius of hydrophobic pores exceeds a critical value varying between 0.3 and 0.5 nm, the pore energies of both hydrophobic and hydrophilic pores become equal. In hydrophilic pores, the energy is lower than that of hydrophobic pores, which causes a reorientation of the membrane pores toward a lower energy configuration. [8] explains the formation of hydrophobic and hydrophilic pores depending on pore radii and energies. The formation of hydrophilic pores with an effective radius of 0.6 to 1.0 nm causes reversible electrical breakdown or an increase in membrane conductance and permeability to ions.
Electroporation

Naturally, a cell uses low electro-chemical potentials across the membrane to open channels for the exchange of various substances, such as calcium ions, with the external environment as Figure (5.3) shows. A much stronger externally applied electric field may open the membrane channel so much that it literally breaks the membrane. This involves the fundamental behaviour of cell and artificial bilayer membranes, and is increasingly attracting consideration for applications in biology, biotechnology and medicine. In general, electroporation phenomenon can be said to be a significant increase in the electrical conductivity and permeability of the cell membranes caused by an externally applied electric field.

![Cell membrane; (upper) before and (lower) after electroporation](image)

The non-thermal killing of microorganisms by strong electric field pulses has been reported in recent years, and the accumulation of experimental insight has increased rapidly. This has created great interest in modelling lipid systems, as it allows the study of the molecular mechanism of electroporation. Under the influence of a strong electric field the cell molecules show a dramatic increase in both permeability and conductivity.[9]

Electroporation experiments have been carried out on three types of systems [86]:
- cell suspensions
- individual cells
- planer bilayer lipid membranes

The data obtained shows one common feature of great importance, which is that the membrane plays a role in amplifying the applied electric field; a typical example is provided by the potential distribution in the region surrounding a spherical cell with a non-conducting membrane in an external electric field $E_e$.

To describe the mechanism of electroporation with the application of a pulsed electric field, an equivalent circuit model of the cells is usually adopted [9].
Voltage Build up Across Cell Membrane

In general, a slow electric field impulse affects only the outer membrane and not the intracellular membrane, since the outer membrane shields the interior from the influence of the electric field. If however, the pulse duration becomes very short, and the cut off frequency of its Fourier spectrum become very high, the electric field can penetrate the outer membrane and affect the intracellular membrane. This will modify its permeability, but without causing permanent damage to the outer cell membrane [87,88]. Therefore, for each electrical impulse, depending on its Fourier content, various parts of the cell can be affected, depending on their characteristic charging time.

The electroporation processing of a cell is divided into the four stages illustrated in Figure (5.4) which are:

1- Water surrounds the outside of the cell membrane, and cytoplasm stays inside the cell.
2- When a pulsed electric fields is applied to the cell, permeable pores are created in the membrane through which water molecules will flow into the cell.
3- If the pulsed electric field is sufficiently strong and applied for a sufficient time the cell membrane breaks and this enables the surrounding water to enter the cell.
4- Eventually the cell membrane may be ruptured. The inner cytoplasm (which is a part of the cell between the cell membrane and the nuclear envelope), and is the jelly-like substance in a cell that contains the cytosol, organelles, and inclusions, will flow to the outside of the dying cell, as shown in Figure (5.5)

The breakdown is reversible if the pores are small in relation to the total membrane surface. If the size and the number of pores become large in relation to the total membrane surface the breakdown in this case is irreversible which is associated with mechanical destruction of the cell membrane.
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5.1.2 *Escherichia coli* bacteria

*Escherichia coli* is a Gram-negative bacteria (Gram negative is related to the Gram method of differentiating bacteria species into two large groups Gram–positive and Gram-negative [89]) which possess several characteristics uncommon in most other bacteria, and is an indicator of contamination in food products. This microorganism is found on plants, in soil and water, in the intestinal tract of animals, in animal products, and in prepared foods handled by people. *E-coli* cells are also recovered from improperly sanitized working surfaces in processing plants [89]. Figure (5.6) shows the *E-coli* bacteria, which is known to be an important food borne pathogen, that has been implicated in several occurrences of food poisoning involving fluid foods, such as juices, and dairy products.

![E. coli bacteria](image)

Figure 5.6 *E-coli* bacteria. (a) *E-coli* showing the length and parts [90] (b) Microscopic photo of *E-coli* [91]

Studies of the inactivation of different strains (pathogenic and non-pathogenic) of *E-coli* suspended in a variety of media under different treatment conditions in different treatment chambers and electric fields have been reported by various researchers. Each of these has confirmed the effectiveness of PEF treatment. Ref. [2] summaries the treatment conditions and the inactivation results which were achieved in several studies of PEF.

Hulsheger and Niemann [92] demonstrated experimentally that, after 10 pulses at 20 kV/cm, a 3.5 log reduction was achieved when *E-coli* cells were suspended in Na$_2$S$_2$O$_3$, and NaH$_2$PO$_4$/Na$_2$HPO$_4$. Other researches have shown that the presence of organic acids has an effect on microbial inactivation levels when combined with PEF treatment. An investigation of the effects of benzoic and sorbic acids is described in [93] at 1000 ppm with the pH, ionic strength of medium, number of pulses, and the results showed a higher degree of inactivation (up to 1 log) with ionic media.
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5.1.3 Factors affecting the growth of E-coli

There are several factors affecting the growth of E-coli. As mentioned earlier, various researchers have studied PEF treatment using E-coli in different suspension media, and have found that the levels of both pH and temperature play a role in the growth of E-coli. Ref [8], represents investigations of the effect of the pH and temperature on E-coli, at pH levels of 2, 5, 7.4, 9 and 11 and temperatures of 4°C, 22°C, 37°C, 50°C, 70°C. These experiments established that acids and bases both apparently create a negative impact on the cell growth, such as the intracellular stability. Also, they showed that at cold temperature the cell metabolism begins to slow down and the growth is limited. However, at higher temperatures the cell parts began to fall apart and the growth stops completely. Vega-Mergado [94] observed that at 55°C, when the E-coli was suspended in pea soup a high log reduction was obtained, and at 32°C the reduction of the E-coli became ≈1 log. This suggests that higher temperatures cause a higher cell membrane fluidity, which makes it easier for the organic acids to transfer into the cells and the cells are satiated by high stress. Some researchers reported that E-coli is unable to grow properly at 45°C.

Another factor is the resistivity, which is an important characteristic of any treatment media in which microorganisms are suspended. Schoenbach [83], used tap water with a resistivity of $\rho = 1.9\, \text{k}\Omega\, \text{cm}$ and nutrient broth with $\rho = 0.1\, \text{k}\Omega\, \text{cm}$, and showed that the higher the resistivity of a medium, the higher is the electric field required to achieve the same population reduction, and with a pulse width of 60ns, 100 kV/cm is required for a 1 log reduction in water, and 70 kV/cm for nutrient.

5.1.4 E-coli equivalent circuit

Figure (5.6) shows the cell membrane, which contains the channels that are controlled by the applied voltage, and allows ions to flow through the membrane as a leakage current. To study the effect of pulsed electric field on a cell, it is necessary to model the cell. For example, a spherical cell immersed in a conducting medium, presents a region consisting of cell exterior, membrane, and cytoplasm. These are all characterised by their resistivity and permittivity values.

Figure (5.7(a)) shows a lumped element model [83] for the interaction between the cell membrane and nucleus and an externally applied electric field. In figure (5.7(a)) $C_s$ and $R_s$ represent the capacitance and resistance of the suspension medium, and $C_m, R_{m1}, R_{m2}$ represent the capacitance of the outer membrane and the resistance of the outer membrane and of the cytoplasm of the cell, $C_n$ and $R_n$ represent the capacitance and resistance of the nucleus. During application of a pulsed electric field the various components become charged. When the voltage achieves a value of approximately 1 V the component is stressed over the limit from which it can recover. Figure (5.7(b)) shows the electrical network of the cell membrane.
Figure 5.7 (a) Electrical equivalent circuit of the cell [83] (b) the electrical network [94]

In Figure (5.7(b)) the current carried through the membrane results from either charging of the membrane capacitor or movement of ions through the three circuit resistors in parallel with the capacitor. This ionic current is divided into components carried by sodium and potassium ions \( I_{Na}, I_{K} \), and a small leakage current \( I_{I} \) made up of chloride and other ions. A driving force, caused by the movement of the molecules determines each component of the ionic current. This force is measured as an electrical potential difference and a permeability conductance. Each component of the ionic current is equal to the conductance multiplied by the difference between the membrane potential \( E \) and the equilibrium potential for each ion as

\[
I_{Na} = G_{Na}(E - E_{Na}) \\
I_{K} = G_{K}(E - E_{K}) \\
I_{I} = G_{I}(E - E_{I})
\]

When an electrical field is applied to a cell in a conducting medium such as water, the electrical charges that build up along the cell membrane cause a change in voltage across the membrane. For low electric fields the induced voltage opens channels in the cell membrane, which leads to changes in the ionic concentrations that are close to the cell membrane and causes stress for a short duration. This does not cause damages to the cell, since the electric field is low. When the electric field is increased however the membrane permeability increases to such a level that either the cell needs a long time (seconds to hours) to recover or to cell death. The magnitude of a critical voltage \( V_{c} \) across the membrane depends on the type and the size of the cell and on the pulse duration [87]. Some researchers suggest that the requirement of transmembrane voltage is 100 mV or less [83]. The amplitude of the applied pulsed electric field requires charging the membrane to a critical voltage \( (V_{c}) \) is given by [9] as
5. NOVEL NON-INVASIVE PULSED ELECTRIC FIELD TECHNIQUE

\[ E_c = \frac{V_c}{\xi} \cdot \frac{r}{[1 - e^{(-\tau/\tau_c)}]} \]  \hspace{1cm} (5.1)

where \( r \) is the radius of the cell and \( \xi \) is a factor that depends on the shape of the cell e.g. \( \xi = 1.5 \) for spherical cells. Ref. [9] shows that in general the factor is given as

\[ \xi = \frac{l}{(l - \frac{d}{3})} \]  \hspace{1cm} (5.2)

where \( l \) is the length of the \( E\)-\( coli \) cell and \( d \) is its diameter.

As a simple example, the critical electric field for the breakdown of bacteria having dimensions of approximately 1 \( \mu \)m and a critical voltage of 1 V across the cell membrane; is 10 kV/cm for pulses of tens of microsecond to millisecond duration. However, organisms other than bacteria have eukaryotic cells with dimensions in the range of 10-40 \( \mu \)m, making them weaker to electric fields than bacteria.

The survivability \( s \) of surviving microorganisms has a linear decrease with the pulse duration and an exponential decrease with the field amplitude. This survivability is given by an empirical law [9] as

\[ s = \frac{\tau}{\tau_0} \left( \frac{E - E_c}{E_0} \right) \]  \hspace{1cm} (5.3)

where \( \tau \) is the pulse duration

\( E \) is the strength of the applied field

\( E_c \) is the critical field

\( \tau_0, E_0 \) are constants that depend on the type of the cell suspension.

The required electrical energy density \( W \) can be written as

\[ W = \frac{\tau}{\rho} \cdot \frac{E^2}{2} \]  \hspace{1cm} (5.4)

where \( \rho \) is the sample resistivity.

In more detail, during pulsed electric field processing the voltage builds up across a cell and charges accumulate across the membrane, causing its potential to increase. According to [83,88,95] the charging time of an \( E\)-\( coli \) cell membrane can be calculated using the spherical cell model as:
5. NOVEL NON-INVASIVE PULSED ELECTRIC FIELD TECHNIQUE

\[ \tau_c = \left( \frac{1+2V}{1-V} + \frac{R_2}{R_1} \right) C_m D \]  

(5.5)

where, \( C_m \) is the capacitance of the membrane per unit area

\( R_1 \) is the resistivity of the suspending medium

\( R_2 \) is the resistivity of the cytoplasm

\( V \) is the volume concentration of the spheres

\( D \) is the diameter of the cell

An approximate value for \( C_m \) is

\[ C_m = \frac{\varepsilon_0 \varepsilon_r}{d} \]

Where \( d =5\text{nm} \) is the uniform thickness of the cell membrane and \( \varepsilon_0 \varepsilon_r = 4.4\times10^{-11} \text{ F/m} \) is the permittivity of the membrane forming material. Using these values \( C_m \) was found as \( 1\mu\text{F/cm}^2 \) [95, 96]. The value of \( V \) of 0.8 for a face centred cubic orientation because it is a realistic orientation for nonconductive cells in suspension. The values of \( D \) of 1.4 \( \mu\text{m} \) and of \( 100 \Omega\text{cm} \) have previously been used for \( E\text{-coli} \). However, due to larger reported variations in the value of \( \rho_2 \) of between 100 and 500 \( \Omega\text{cm} \) [83, 96, 97] both the lower and upper limits were used in calculating \( \tau_c \) with the result found to lie between 52 and 81 ns.

5.2 Comparison between the invasive method and the non invasive method

To help in understanding the differences, Figures (5.19(a)) and (b) later) show the schematic arrangement for sterilizing water for both invasive and non-invasive PEF techniques. In the first scenario, a pulsed power generator applies a high-voltage impulse across two metallic electrodes immersed inside the water sample; a current is generated through the liquid along with an electric field and Joule energy is deposited during the discharge of the generator. In the second scenario a remote source (e.g., an antenna) produces an electric field inside the water sample, with no electronic or ionic current being present. In both cases the temperature of the liquid is very important, with higher temperatures increasing the effectiveness of the PEF treatment by inducing a structural fatigue of the cell membranes and thus making them more susceptible to electrical breakdown. This synergy is used in practice with the liquid usually being preheated to around \( T=313 \text{ K} \) (40 °C) prior to being PEF processed.

In what follows, the most important drawbacks related to industrial PEF systems applied invasively to liquid (pumpable) food are outlined.
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I. Invasive PEF technology: the main drawbacks

A. Joule (thermic) effect and energy consumption
As already indicated, all PEF systems presently in use are invasive, with large currents of between a few hundreds amperes and even more than one kiloampere flowing through the liquid during processing. The deposited Joule energy causes the local temperature of the liquid to rise substantially and obviously implies a very large energy consumption. In some cases external cooling is required to avoid the liquid reaching pasteurization temperatures, further increasing the overall energy consumption.

B. Electrode effects
The inter-electrode current inherent in invasive PEF technology may generate unwanted and significant side effects. For example, hydrolysis may introduce metal particles from the metallic electrodes into the food or produce toxic chemicals such as hydrogen peroxide (which ironically, helps in killing micro-organisms!).

The distance between a pair of electrodes in a processing cell should be as short as possible to minimize the applied voltage and therefore the energy consumption. However, this presents an obstacle to any ‘chunks’ present in the liquid food being treated.

A number of important issues also relate directly to the electrodes, such as the need for regular cleaning due to the formation of surface deposits, replacement because of corrosion every 100 hours or so and, most importantly, because of accidental electrical breakdown.

C. Electric field direction
The available literature indicates that there is an orientation effect and that to produce a given level of decontamination for food contaminated with rod-shaped bacteria by a field applied radially requires pulses having a fivefold increase in the intensity of a field applied axially. Fluid turbulence is therefore generated in industrial PEF systems to ensure that the bacteria are attacked at various angles as they pass through the treatment cells, where the only direction of the applied electric field is across the two electrodes.

II. Non-invasive PEF technology: main advantages, the challenge and the need for a proof-of-principle experiment

A. Energy considerations and the challenge
If no electrical breakdown is present, no ionic and electronic currents are produced through the treated samples during non-invasive PEF treatment, apart from the unavoidable generation of very small displacement currents, and no temperature rise is therefore expected, even following the application of a very large number of electrical pulses. This implies a very important reduction in the energy consumption making the non-invasive method, at least in principle, extremely energy efficient. It is obvious that to avoid an electrical breakdown in water, the applied electric field pulse has to be fast. According to [86] the shorter the pulse duration $\tau$, the more intense is the required electric field, since $E = A \tau^{-\frac{1}{2}}$, where $A$ is a constant. From a superficial view point this is not encouraging but, because the electrical energy density required for lysing is given by equation (5.4), the energy density $W$ actually decreases for shorter pulses i.e., $W \approx \tau^{-\frac{1}{4}}$. For a given pulse duration, the overall energy efficiency of non-invasive PEF processing applied to a given food sample therefore depends only on the ability of the pulsed power system to generate sufficiently intense electric fields. However, the remote generation of intense electric fields inside food samples having a
relative permittivity around 60 is not easy and presents the major challenge to applying this novel technology. Once this obstacle is overcome, the possibility of generating 2-dimensional fields will remove the need to create artificial turbulence and will help in simplifying the system design and increasing the processing efficiency.

B. More advantages
When using non-invasive technology the problems mentioned earlier related to the metallic electrodes are all eliminated since, at least in principle, no part of the equipment is in contact with the food being processed. As a consequence, much more generous volumes can be processed and the method is certainly not limited to liquid food. This may turn out to be actually the most important advantage of the non-invasive method! When successfully applied in practice, the non-invasive method will allow pre-packed food (both liquid and solid) to be processed in a special room on supermarket premises, thereby increasing the shelf life and reducing the (accepted) traditional losses. The reduction in wasted food would certainly provide a very significant economy. Another very important application of the non-invasive PEF method could be to speed up the ageing process of bottled wine. The number of areas of further possible applications is very large, both including outer space exploration and the defense industry.

C. The need for proof-of-principle experiments
A comprehensive survey of the available PEF literature shows that practically all authors agree that the electric field plays the major role in the observed reduction in the number of microbes during processing of liquid samples. However, a number of issues related to the electric current localized thermal effects raised the very justified question: what is the contribution to sterilization brought about by the large electric currents generated during an invasive PEF processing? In [87] it is suggested that: ‘…the viability of E. coli is mainly determined by the electric field, rather than by the current density in the suspension’ (the underline does not appear in the original), but others [98] suggest the opposite: ‘…it is believed that electroporation is not the only killing mechanism associated with pulsed electric field sterilization….The current through the orange juice is believed to be a strong contributing factor for these results’. A definite answer to this question is of extreme importance for the future of the non-invasive PEF technique. The considerable technical effort required to develop the novel technology to an industrial level is not justifiable without undoubtedly demonstrating that effective PEF processing can be achieved using only electric fields, in the complete absence of ionic or electronic currents. The present work is dedicated to obtaining an answer to this issue.
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5.3 PEF Invasive Treatment Chamber

5.3.1 Background

Different geometries of treatment chambers have been designed, and these may be categorized depending on the direction of the electric field and the liquid food flow. The main categories of chamber are:

- **batchwise**
- **continuous mode**

Static chambers as shown in Figure (5.8) are typically used for batchwise operations, and coaxial chambers as shown in Figure (5.9)) for continuous operations, which are both more economic and more efficient for large scale operation as in the food industry. Both systems are used in laboratories for research purpose.

![Figure 5.8 Static chamber for batchwise operation](image)

![Figure 5.9 Continuous chambers for continuous operation](image)

There are four major aspects to be considered in the design of a treatment chamber:

1. Uniform distribution of the electric field.
2. Electrode shape optimisation.
3. Mechanical construction and materials
4. Geometry and dimensions.
The first two of these play a major role in the design of the treatment chamber. As the distribution of the electric field is uniform in the treatment region, maximum microbial inactivation is caused. The design of the electrodes should minimise local field enhancements, since these increase the probability of dielectric breakdown inside the chamber. Ref [77] suggests a method of optimising the electrode configuration, which optimises the initial contour for the electric field inside the chamber. The final two aspects influence the chamber construction. The material selected to construct a treatment chamber needs to be cleanable in situ (no need to remove the electrodes) or to employ an autoclaving process, (a high pressure sterilisation by steam that cleans the electrodes of any bacteria). Features for cooling the electrodes should be included to prevent a temperature rise above a target level, typically of 50°C  to 60°C. Some researchers recommend the use of electrochemically inert materials such as gold, platinum and carbon to construct the electrodes.

### 5.3.2 Non-invasive treatment chamber

As discussed in chapter 1, all PEF systems presently used in the food industry are invasive, and produce currents of between 500 A and 1 kA [99] between a pair of electrodes. At present there is no absolute proof that the current passing through the treated liquid does not play a role in the food process, in addition to the applied electric field.

The current passing through the treated liquid certainly deposits Joule energy that causes a rise in the temperature of the liquid towards the pasteurisation level. It is important to note that the inter- electrode current may also cause unwanted side effects such as hydrolysis, which may introduce metal particles from the electrodes into the liquid food.

In this thesis two treatment chambers were used with the non-invasive technique. The first of these is shown in Figure (5.10). The samples of *E.coli* bacteria were contained in polyethylene vials, as illustrated in Figure (5.11).

The second, PEF cell was connected to a water container as shown in Figure (5.12), this is 200 mm by 200 mm by 200 mm, with two glass windows and with HV and ground electrodes in place. A PEF cell which contains the *E.coli* bacteria is connected to the HV and ground electrodes in the water container; as shown in Figure (5.13(a)) and behaves as a capacitor. Figure (5.13(b)) shows Maxwell 3D modelling of the cell which contains thin 0.05 mm aluminium electrodes; each in contact with a ceramic material of 17.6 mm by 11.7 mm and a diameter of 35 mm with the gap between the HV and the ground ceramic being 3 mm. This PEF cell has a capacitance of 2200 pF and the components are kept in position by a plastic tube. It is connected to the electrodes of the water container as shown in Figure (5.14). More details are given later.
Figure 5.10 First treatment chamber used for non-invasive PEF processing

Figure 5.11 Polyethylene vials used to contain the *E-coli* bacteria

Figure 5.12 Water container used within the PEF cell (treatment chamber)
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Figure 5.13 PEF cell construction

(a) (b)

Figure 5.14 PEF cell connected to the pulsed power generator using cylindrical metallic electrodes and positioned inside a water container, with the laser beam passing through the cell

5.4 Non-invasive PEF system

Figure (5.15) shows the PEF system used in this thesis for the process of destroying *E.coli* bacteria. The high voltage electrode of the water container is connected to the high voltage generator TG70 by a coaxial cable type RG-218/U as discussed earlier. A commercial high voltage sensor, North Star model PVM-6, is also connected to the high voltage electrode and is used to measure the voltage signal as a reference, with the output of the sensor connected to oscilloscope 1 as illustrated in Figure (5.15). A polyethylene cap covers the water container which has input and output tubes connected to the pump and a radiator respectively. The water is heated to 40°C, in a cyclic process. The pump takes heated water from the radiator and passes it to the treatment chamber, so that the environment of the *E.coli* is also at 40°C. A laser beam passes through the water container to measure the effect of PEF using the electro-optic Kerr effect.
5.5 Modelling of the PEF cell and PEF system

The PEF cell and treatment chamber was modelled with the integral of the electric field inside the cell calculated using Maxwell 3D software, and the complete PEF system modelled using LT-Spice package.

5.5.1 Treatment chamber and PEF cell modelling

Maxwell 3D software was used to model both the water container and the PEF cell, so as to determine the electric field produced in the cell using the field calculator of the software, which helps to calculate the electric field achieved in the PEF cell. Figure (5.16) shows the treatment chamber model connected to the cell and the electrodes (HV, and ground) and a laser beam passing through the treatment chamber via two glass windows and the PEF cell.
The PEF system shown in Figure (5.17 (a)) contains two ceramic cylinders, each with a capacitance $C_p$ of 2 nF and with two metallic face painted and having a connecting electrode attached to them. These electrodes (metallic face painted) are coupled to the two bar electrodes of the water container; one to the high voltage generator cable and the other to ground. The distance between the two ceramic discs (as discussed previously) is 3 mm.

![Diagram of PEF system](image)

**Figure 5.17** (a) Maxwell 3D model for the PEF cell (b) Electric field strength using Maxwell 3D

By using the field calculator in Maxwell 3D software, the integral of the electric field in the PEF cell was calculated and Figure (5.18) shows that for 1V applied to the cell an electric field of 285kV/cm was obtained.

![Electric field distribution](image)

**Figure 5.18** Electric field distribution inside the cell provided by Maxwell software for 1 V applied on the cell and the water heated to 40°C (a) variation of the electric field component $E_x$ along the Oy axis i.e., along the laser path (b) variation of the electric field component $E_x$ along a line parallel to Oy and at 0.1 mm distance from the ceramic cylinder. The model coordinates are shown in Figure (5.16).

The electric field variation along the laser beam allows calculation of the effective length $l$ as 22.95 mm. The light modulation generated by the Kerr effect can be predicted using the effective length and hence the total voltage applied by the generator. Figure (5.19 (a) (b) & (c)) shows the PEF cell model used in the experiment of proof of principle.
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Figure 5.19 PEF techniques for sterilizing water, having relative permittivity $\varepsilon_w$, conductivity $\sigma$ and temperature $T$. a) Invasive technique; a pair of metallic electrodes are positioned inside water. b) Non-invasive technique; a remote source, such as a pulsed power generator feeds an impulse antenna. c) Non-invasive proof-of-principle arrangement.

Figure (5.20) shows the equivalent circuit for the non-invasive arrangement (PEF cell)

Figure 5.20 Circuit diagram for the PEF cell

From Figure (5.19) the total capacitance $C_T$ is

$$\frac{1}{C_T} = \frac{1}{C_w} + \frac{2}{C_c} \quad (5.6)$$

or

$$C_T = \frac{C_c C_w}{2 C_w + C_c} \quad (5.7)$$

where $C_c$ is the ceramic capacitance, and $C_w$ is the water capacitance

Since $\varepsilon_0 = 8.854 \times 10^{-12}$ and the permittivity of the ceramic at 40°C is 3200, the total capacitance calculated by Maxell software is $C_T = 206 \, pF$, of which the water capacitance is $C_w = 249.6 \, pF$

The total voltage $V$ applied to the PEF cell is given by
where $V_c$ is the voltage across the ceramic capacitor, and $V_w$ that across the water capacitor.

Since the charge $Q$ is equal on the three capacitors

$$Q = C_T V = C_w V_w$$

and the voltage applied to the water is

$$V_w = \frac{C_T}{C_w} V$$

(5.9)

In which $\frac{C_T}{C_w}$ is the percentage of the voltage dropped in the water

$$\frac{C_T}{C_w} = \frac{C_c}{2C_w + C_c} = 82.5\%$$

and the energy in the PEF cell for an output voltage $V_o = 70 \times 10^3 V$ is

$$W = \frac{C_T V_o}{2} = 0.505J$$

and that in the water is

$$W_w = \frac{C_w (PV \times V_o)^2}{2} = 0.416J$$

The volume of water with a diameter $D_w = 43.6 \times 10^{-3} mm$ and a height of $3 \times 10^{-3} mm$ as is

$$Vol = \frac{\pi D_w^2}{4} \times H_w \times 10^6 = 4.479 cc$$

The energy density is $0.093 J/cm^3$. 

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Fahd A. Banakhr
5.5.2 PEF system modelling using LT-Spice

LT-Spice software [15] was used to model the PEF system, and to estimates the current in the PEF cell, and it offers the complete range of Spice functionalities. LT-Spice IV has two basic models of driving the simulator:

1- Use of the program as a general purpose schematic capture program with an integrated simulator.
2- Feed the simulator with a handcrafted net-listed or a foreign net-list generated with a different schematic capture tool.

LT-Spice is intended to be used as a general purpose schematic capture program with an integral spice simulator. The design process involves iterating the circuit until the desired circuit behaviour is achieved in the simulation.

Figure (5.21) shows the LTSpice model for the whole PEF system (circuit diagram), and Figure (5.22) provides a comparison between the measured and modelled values of the voltage pulse.

![LTSpice model of the electrical system used in proof-of-principle non-invasive PEF experiments](image)

The TG-70 generator basically consists of a capacitor discharged through three long coaxial cables. The cell is connected at the end of one cable, in parallel with a crowbar switch, while the other two cables are simply terminated with resistors.
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Figure 5.22 Voltage impulse applied on the non-invasive PEF cell for the TG-70 capacitor charged to 35 kV a) without crowbar switch (LTSpice simulation) b) with crowbar switch: LTSpice simulation compared with a typical experimental result c) displacement current corresponding to (b)

5.6 Experimental procedure

As discussed previously the PEF cell contains the E-coli bacteria and is connected to the water container (Figure (5.15)), before the high voltage is applied to the system.

The procedure adopted for the experiment is:

- Three PEF cells taken to Flavometrix company, where a microbiologist fills them with E-coli bacteria.
- The filled cells are returned to the pulsed power laboratory at Loughborough University and are connected in turn to the water container (Figure (5.16)).
- The temperature of the water in the treatment chamber and the PEF cell is set to 40°C compared with the heater (water tank Figure (5.15)).
- The high voltage sensor is connected to the high voltage generator cable.
- The high voltage generator is charged to 35-40 kV.
- For the first PEF cell, 100 pulses (100 ns duration) were applied, with a 1.5 minutes pause between each pulse to give the liquid inside the cell time to settle down, and two and half hours being required to complete the first experiment. For the second cell, 50 pulses were also applied with a 1.5 minutes pause between them. For the third PEF cell the charging voltage was reduced to 27 kV, and of100 pulses were applied with 1.5 minutes between them. This experiment was repeated eight times as table (5.1) shows

<table>
<thead>
<tr>
<th>Day</th>
<th>Month</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>19th</td>
<td>December</td>
<td>2011</td>
</tr>
<tr>
<td>8th</td>
<td>February</td>
<td>2012</td>
</tr>
<tr>
<td>15th</td>
<td>February</td>
<td>2012</td>
</tr>
<tr>
<td>22nd</td>
<td>February</td>
<td>2012</td>
</tr>
<tr>
<td>29th</td>
<td>February</td>
<td>2012</td>
</tr>
<tr>
<td>7th</td>
<td>March</td>
<td>2012</td>
</tr>
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<td>14th</td>
<td>March</td>
<td>2012</td>
</tr>
<tr>
<td>21st</td>
<td>March</td>
<td>2012</td>
</tr>
</tbody>
</table>

Table 5.1 Experimental dates agreed with Flavometrix

- At the end of each experiment, the PEF cells were put in an ice-filled container and returned to Flavometrix for the counting procedure (discussed later). Flavometrix send a report (see Appendix) showing the counting results and how effective the experiment a method is in destroying *E.coli* bacteria.

### 5.6.1 Counting bacteria technique

There are several methods of counting bacteria, which are helpful in the quantification of bacteria in molecular biology, where the bacteria are formed in groups (colonies). A bacterial colony is formed within the culture media that had been injected with bacterial cells. This colony allows cells to reproduce and to form bacterial colonies within or on the surface of the medium. If the colonies are sufficiently large, they are usually visible to the eye, which allows to the number of colonies formed to be easily determined. [100, 101]

There are two widely used methods for determining bacterial numbers; the standard (plate count) method and spectrophotometric. In this thesis the results reported for counting *E.coli* bacteria from Flavometrix were based on the standard method.

The standard method is achieved by diluting a sample onto a grid line plate (usually used for the biological counting experiments) as Figure (5.24(a)) shows, this dilution is performed by counting a known volume of a sample with a known volume of a sterile saline or phosphate buffer. Figure (5.23) shows the procedure for counting the bacteria.
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The plates with 30-300 colonies per standard sized plate are counted, with this number chosen because it is sufficiently high to have statistical accuracy, and low enough to avoid nutrient competition among the developing colonies. After the bacteria colony is plated and ready for the count, the plate is taken to the colony counter instrument as Figure (5.24(b)) shows.

![Grid plate showing the colony counting technique](image1)

(a) Grid plate showing the colony counting technique [103]

(b) Colony counter instrument [104]

Figure 5.24 (a) Grid plate showing the colony counting technique [103] (b) Colony counter instrument [104]

5.7 Non-invasive PEF method results

The results shown in this sub-section were provided by Flavomitrix. They are based on having three PEF cells (discussed earlier) with four controls. One control stayed at Falvometrix at room temperature, while the other three were taken to Loughborough University. Each PEF cell connected to the water container as a control was immersed in the water tank at 40°C.

5.7.1 TPFL2 results

Figure (5.10) and Figure (5.11) show the technique used with the first non-invasive PEF method. The *E.coli* bacteria samples were prepared by Falvometrix in maximum recovery diluent and placed into the polyethylene tubes and the samples analysed as:

- S1 sample 1 PEF processed
- S2 sample 2 PEF processed
- S3 sample 3 PEF processed
- C1 control with sample 1, which is placed in the heater
- C2 control with sample 2
- C3 control with sample 3
- C4 (SB) Sutton Bonington control that remained in Falvometrix, and was left at room temperature.

Table (5.2) shows the results of using TPLF2. The table shows a slight reduction in growth compared to the SB control sample. According to the report (see Appendix) the PEF using TPLF2 has any significant effect on the level of the bacteria. However, there is evidence that it does very slightly slow growth.

<table>
<thead>
<tr>
<th>Counts carried out on receipt from Loughborough</th>
<th>Average</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unused</td>
<td>6.822</td>
<td>0.064</td>
</tr>
<tr>
<td>S1</td>
<td>6.814</td>
<td>0.108</td>
</tr>
<tr>
<td>S2</td>
<td>6.712</td>
<td>0.013</td>
</tr>
<tr>
<td>C1</td>
<td>6.806</td>
<td>0.02</td>
</tr>
<tr>
<td>C2</td>
<td>6.948</td>
<td>0.021</td>
</tr>
<tr>
<td>C3</td>
<td>6.967</td>
<td>0.013</td>
</tr>
<tr>
<td>On ice at SB</td>
<td>6.839</td>
<td>0.061</td>
</tr>
<tr>
<td>Ambient sample at SB</td>
<td>7.238</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5.2 non-invasive PEF method using TPFL2 results

The polyethylene tubes containing the *E.coli* bacteria have much lower permittivity (2.23) than that of the water (80) causing the electric field to be higher and concentrated in the tube. Figure (5.25 (a) & (b)) shows results obtained using the Maxwell model when the applied voltage is 1 V.

![Maxwell model of the TPFL2](image)

(a)

(b)

Figure 5.25 Maxwell model of the TPFL2. (a) electric field distribution inside TPFL2. (b) electric field distribution on the polyethylene tube and inside it.

The results of non-invasive PEF using TPFL2 indicates non-useful result so, that another non-invasive method was developed.
5. NOVEL NON-INVASIVE PULSED ELECTRIC FIELD TECHNIQUE

5.7.2 PEF cell results

Table (5.3) and (5.4) shows the results reported by Flavometrix using PEF cell for non-invasive method (see Appendix for the reports)

<table>
<thead>
<tr>
<th>Counts carried out on receipt from Loughborough</th>
<th>Log cfu/ml</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor-like vessel</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Control Loughborough in Water bath</td>
<td>6.15</td>
<td>1.422</td>
</tr>
<tr>
<td>Control 1 SB at room temp</td>
<td>5.203</td>
<td>0.041</td>
</tr>
<tr>
<td>Control 2 SB at room temp</td>
<td>5.769</td>
<td>1.363</td>
</tr>
<tr>
<td>Control 3 SB at room temp</td>
<td>5.742</td>
<td>1.528</td>
</tr>
<tr>
<td>Control SB at 40 deg</td>
<td>6.35</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Table 5.3 PEF cell result obtained on 19-12-2011

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count (log cfu/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Loughborough 1</td>
<td>6.55</td>
</tr>
<tr>
<td>Control Loughborough 2</td>
<td>6.69</td>
</tr>
<tr>
<td>Control Loughborough3</td>
<td>6.61</td>
</tr>
<tr>
<td>Control at SB</td>
<td>8.62</td>
</tr>
<tr>
<td>Capacitor 1</td>
<td>3.39</td>
</tr>
<tr>
<td>Capacitor 2</td>
<td>1.27</td>
</tr>
<tr>
<td>Capacitor 3</td>
<td>3.54</td>
</tr>
</tbody>
</table>

Table 5.4 PEF cell result obtained on 21-03-2012

These results show great progress in the design of the structure of the non-invasive PEF method. As discussed earlier the PEF cell uses ceramic material with a permittivity higher (3000) than that of the water (80), which causes the electric field to be higher in the water or the medium of the *E-coli* bacteria. From both tables (5.3) and (5.4), 6 and 5 log reduction respectively are evident, and indicate that the PEF cell gives a useful and positive result, comparing with other literature results.
Figure (5.26) shows the Kerr effect response for one applied electric field impulse with a strength up to about 200 kV/cm. This result proves that just electric field is used to destroy the *E coli* bacteria, without passing a current into the PEF cell because if a current passes through the PEF cell, the response of the Kerr effect would be zero.

![Kerr effect response graph](image)

**Figure 5.26** Kerr results obtained during the experiment of the proof-of-principle non-invasive PEF cell. (a) central electric field inferred from voltage measurement. (b) Kerr signal obtained during the experiment.

Figure (5.27) shows the main results: the variation of the log reduction function of the applied central peak electric field. Basically, a reduction between 4 log and 6 log was obtained for fields between 130 kV/cm and 200 kV/cm. Also presented are the results reported in [90] obtained with an invasive PEF technique by applying 70 electric impulses with strength up to 110 kV/cm and 130 ns duration at a water temperature maintained close to 50 ºC. Qualitatively, the comparison between the two sets of data suggests the non-invasive PEF method is producing similar effects to the invasive PEF technique but using less energy. The major difference is that while during the invasive PEF the current flowing through the sample was 860 A (40 J/cm³) [99], in the present non-invasive tests the displacement current was...
less than 0.15 A i.e., 5700 times smaller! It is obvious that the Joule effect in the non-invasive PEF tests can be totally neglected. The electric field energy density stored inside the non-invasive cell in each shot was less than 0.093 $J/cm^3$, a very low figure.

Figure 5.27 Comparison between the non-invasive PEF processing and the Invasive PEF processing. Red dots show the log reduction using invasive PEF processing at 50°C [99]. Brown squares show the results of non-invasive PEF processing at 40°C for applying 100 shots. Blue triangles show the results of non-invasive PEF processing at 40°C for applying 50 shots.
CHAPTER SIX

CONCLUSION AND WAY AHEAD
Chapter 6

Conclusion and the way ahead

6.1 Major achievement

The research programme described in this thesis was focused on the application of ultra-fast, high intensity pulsed electric fields (PEF) in a novel and non-invasive method of processing liquid food, that is potentially suitable for use on an industrial scale. Because of the nature of the experimentation, an accurate and special purpose opto-electronic sensor based on the Kerr effect needed to be developed to measure the intense pulsed electric fields in water, and a compact PEF cell had to be designed and manufactured to enable the application of the pulsed fields to water samples containing *E-coli* bacteria.

PEF is a mature technology used in the industrial processing of liquid food, e.g. juices, that requires metal electrodes in direct contact with the food (Figure (5.7) chapter 5), and therefore it is an invasive technique. The current flowing through the invasive treatment chamber is high, between 500 A and 1000 A, which typically causes a high temperature rise from 50°C to 70°C in the food being processed and the significant energy losses resulting in flavour modifications. In the non-invasive method discussed only a very small displacement current flow through the cell, so that the temperature rise is very low and certainly will allow the flavour to be fully preserved.

Two high voltage generators are discussed and used as a vital part of the experimentation, both being based on Tesla transformers combined with various pulse forming lines. The radiating element used with one generator is a Valentine antenna, covered by a cylindrical tube filled with deionised water, and in the other generator the PFL was filled with deionised water and located between the Tesla transformer output and a spark gap. In the first of the two systems, the bacteria samples can be located next to the Valentine antenna and in the second they were located within the PFL itself.

A third generator used in this thesis is a commercial high voltage generator containing a 0.1 μF capacitor which can be charged up to 70 kV and discharged into three, parallel-connected, 50Ω/5 ns high-voltage coaxial cables through a SF₆ pressurized trigatron was connected directly to the novel non-invasive cell that contained the *E-coli* bacteria. This novel arrangement was required since the pulsed electric fields generated by the two high voltage generators were too low for applications.

The PEF measurement is done using an electro-optic measurement technique. This technique does not require interconnecting cables and the laser beam is totally insensitive to stray electro-magnetic fields. The Kerr effect technique was chosen for use in the present research, since the medium of the *E-coli* is water, where the molecules are initially randomly positioned in space and later once the field is applied they become oriented along the field direction. Two Kerr water cells were manufactured. The first had Bruce shaped stainless steel electrodes and was used to produce a long train of intense electric field pulses. The second cell had parallel plates 40 mm long, which provides smaller electric fields but more accurate
6. CONCLUSION AND WAY AHEAD

data. These two cells helped to determine the Kerr water constant, which has unreliable values reported in the literature. The Kerr constant was determined as \(2.45 \times 10^{-14} \text{ m}^2/\text{V}^2 \pm 5\%\) and is believed to be accurate for the experiment conditions, the factors affecting its determination were:

1) The retardation
2) The effective path length
3) The high voltage impulse generated across the Kerr cell
4) The effect of the inductive term on the accuracy of the voltage measurement
5) The application of a strong electric field for a few microseconds produces water turbulences.

The pulsed electric field interaction with the bacteria based on a comparison of the pulse duration with the charging time constant of a cell membrane is reported. The pulse duration and electric field intensity seems to be the key parameters in damaging the bacteria. Two non-invasive arrangements were investigated in the research programme. One of these used the TPFL2 generator, with the E-coli bacteria sample contained in polyethylene vials. The result showed a slight reduction in the growth of the bacteria, compared with a control sample. The polyethylene vials have a permittivity 2.230 which caused the electric field to be high and concentrated in the vial wall rather than in the water containing the microbes.

A proof of principle non-invasive arrangement required the design and development of a treatment chamber to contain the E-coli bacteria. For this, two ceramic cylinders each with a capacitance of 2 nF, were connected to metallic electrodes, separated 3 mm. This volume was filled by water containing E-coli. A simple circuit analysis demonstrated that 82% of the total voltage produced by the generator across the PEF cell is applied to the medium.

PEF cell results show between 5 and 6 log reduction, which indicates a positive and considerable progress in the design of the structure of the non-invasive method. Moreover, the PEF were monitored using electro-optic Kerr effect, where as previous researches all using invasive PEF, have not mentioned an accurate electric field measurement. This shows the capability of measuring the PEF in the advanced design of the cell. Non-invasive experiments were performed to answer important issues. The major findings can be resumed as follows:

- Undoubtedly, the non-invasive PEF technique can produce a very significant reduction in the initial concentration of E-coli bacteria; the effects were achieved in the presence of only a very limited displacement current.

- Qualitatively the results suggest that, when similar electric field impulses are applied, the non-invasive PEF produces effects comparable to the standard invasive PEF, using less energy

- The results show that, only up to 100 shots are required to obtain a significant log reduction. In each shot an electric field between 150kV/cm and 200 kV/cm has to be generated in the water, with a corresponding low electric field energy density of about 0.1 J/cm³
6. CONCLUSION AND WAY AHEAD

- When non-invasive PEF experiments are performed, monitoring of the electric field by Kerr-effect is essential.

To sum up, the non-invasive PEF technique were studied. Two non-invasive arrangements were examined. One of these used the TPFL2 generator, with the E-coli bacteria sample contained in polyethylene vials. The result showed a slight reduction in the growth of the bacteria, compared with a control sample. The other non-invasive arrangement (PEF cell) has two ceramic cylinders each with a capacitance of 2 nF, were connected to metallic electrodes, separated 3 mm. This volume was filled by water containing E-coli. The results show between 5 and 6 log reduction, which indicates a positive and considerable progress in the design of the structure of the non-invasive method. The PEF were measured using electro-optic Kerr effect since the Kerr water constant in this research was found $2.45 \times 10^{-14} \text{m/V}^2 \pm 5\%$. This shows the capability of measuring the PEF in the advanced design of the cell. Non-invasive experiments were performed to answer important issues.

6.2 The way ahead

Based on the findings reported it is possible to think about the design of a future non-invasive PEF system for the industrial processing of pre-packed food. The food, solid or liquid, will be immersed in water maintained at a convenient temperature (possibly less than 40 °C) while a remote pulsed power generator produces a series of very intense electric fields impulses. As modern repetitive pulsed power generators can easily operate at a PRF of say 100 Hz (although kHz operation is also possible) the processing will take only about one second. Although a large number of issues still remain to be answered, the present work clearly opens the door for the novel technology.

6.3 Worldwide recognition

Publications


2) B M Novac, I R Smith, F Banakhr, L Pecastaing, R Ruscassie, A de Ferron and P Pignolet. ‘Experimental investigation of the Kerr effect in water under intense and fast transient electric field’ IEEE International Power Modulator and High Voltage Conference, 2010, Atlanta, USA.

6. CONCLUSION AND WAY AHEAD


6) B M Novac, **F Banakhr**, I R Smith, L Pecastaing, R Ruscassie, A de Ferron and P Pignolet. ‘Kerr effect systems for the measurement of intense transient electric fields in water’ accepted for publication in the IEEE Transaction on Plasma Science.


8) B M Novac, **F Banakhr**, I R Smith, L Pecastaing, R Ruscassie, A de Ferron and P Pignolet ‘Novel non-invasive pulsed electric field: proof of principle experiments’, will be submitted and published in the IEEE Transaction on Plasma Science soon.

**Awards**

1) 2011 Sir Robert Martin Faculty (Engineering) Prize (Loughborough University).

2) 2012 High Voltage Association Student Excellence Award (IEEE International Power Modulator and High Voltage Conference) San Diego, USA, 2012.

**Letter from**

Diversified Technologies, Inc. company

Looks for collaboration possibilities between Diversified Technologies and pulsed power group in Loughborough University.
Project title: Investigating the use of electric fields to kill bacteria

Client: Loughborough University

Report number: RFM213V1

Signatures and dates

Report author: Dr J Davidson, R & D Manager 7th July 2011

Distribution: Flavometrix

Loughborough University
1. Introduction
A new food processing method has been developed at Loughborough University based upon electric fields which may potentially significantly reduce a product's microbial population without a detrimental effect on the food flavour/texture. Loughborough University would like to test the effectiveness of this new processing method using microbiological testing. A meeting of all parties involved agreed to test the equipment using *E. Coli* bacteria in liquid media, housed in plastic vials. The number of bacteria with and without processing would be compared. Previous work had showed no effect of the electric field; however, in this experiment the electric field used was significantly stronger.

2. Materials and Methods
The E.Coli samples were prepared in Maximum Recovery Diluent (MRD) and placed into sterile plastic tubes (provided by Loughborough University). The samples analyzed were as follows:

From Loughborough University:
1. S1 – Sample 1 PEF processed
2. S2 – Sample 2 PEF processed
3. C1 – Control with S1 (No electric field just heat)
4. C2 – Control with S1 (No electric field just heat)
5. C3 – Control with S2 (No electric field just heat)
6. Unused and left on ice at all times

Sutton Bonington (SB) controls
1. Left on ice
2. Left at room temperature

Upon receipt of the processed samples the bacteria were plated out in order to facilitate the counting. A portion of each sample was transferred into test tubes and incubated overnight with shaking at 37 °C. Following this a second plate count was performed. This was done to see if perhaps the electric field stunts the growth of bacteria (if it did not manage to kill them).

Results and Discussion
A one log reduction in cell count would indicate that the electrical field had an effect on the bacteria. A visual inspection of the test tubes showed that they were all turbid, indicating that there was growth in all samples. Table 1 shows the counts carried out after plating out on BHI media. Initial counts performed on receipt of samples showed no significant differences but the count carried out after a further growth of 12 hours showed that samples S1, S2 and C1 showed a slight reduction in growth when compared to other samples. As expected, the sample left at room temperature had higher counts.
Table 1: Viable colony count CFU/ml $\log_{10}$ of E coli on BHI media. Samples were labelled as provided by University of Loughborough

<table>
<thead>
<tr>
<th>Counts carried out on receipt from Loughborough</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Unused</td>
<td>6.822</td>
</tr>
<tr>
<td>S1</td>
<td>6.814</td>
</tr>
<tr>
<td>S2</td>
<td>6.712</td>
</tr>
<tr>
<td>C1</td>
<td>6.806</td>
</tr>
<tr>
<td>C2</td>
<td>6.948</td>
</tr>
<tr>
<td>C3</td>
<td>6.967</td>
</tr>
<tr>
<td>On ice at SB</td>
<td>6.839</td>
</tr>
<tr>
<td>Ambient sample at SB</td>
<td>7.238</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Counts carried out after further growth for 12 hr</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>Std Dev</td>
</tr>
<tr>
<td>Unused</td>
<td>8.321</td>
</tr>
<tr>
<td>S1</td>
<td>7.841</td>
</tr>
<tr>
<td>S2</td>
<td>7.737</td>
</tr>
<tr>
<td>C1</td>
<td>8.053</td>
</tr>
<tr>
<td>C2</td>
<td>8.954</td>
</tr>
<tr>
<td>C3</td>
<td>8.973</td>
</tr>
<tr>
<td>On ice at SB</td>
<td>8.987</td>
</tr>
<tr>
<td>Ambient sample at SB</td>
<td>9.221</td>
</tr>
</tbody>
</table>

To summarise the electric field has no effect on the level of bacteria. However, there is evidence that it does very slightly slow growth.
CONFIDENTIAL

Project title: Investigating the use of electric fields to kill bacteria

Client: Loughborough University

Report number: RFM228V1

Signatures and dates

Report author: Dr J Davidson, R & D Manager 19th Dec 2011

Distribution: Flavometrix

Loughborough University
Introduction

This study was carried out to determine if an electrical field is bactericidal. Significant modifications have been made on the new technology since the last testing.

Materials and Methods

Since it was requested that the bacteria should be suspended in ultra-pure grade A water, the methods of British Society for Antimicrobial Chemotherapy (BSAC) was adopted with some modification for the preparation of bacterial suspension (BSAC Methods for Antimicrobial Susceptibility Testing Version 10.2 May 2011). Cultures were prepared and washed with ultra pure water to remove traces of media. The cultures were adjusted to optical density (OD) 0.2 at 500nm which is four times the recommended OD. This is because it was very likely that the test would not be carried out 15 min after inoculation as required and to compensate for cells that would be lysed in the ordinary water which also had no nutrient supplement. Adjustment was carried out with a spectrophotometer.

Triplicates of final bacteria suspension were given to University of Loughborough for application of the electrical field. Three capacitor-like containers were filled with the E.coli suspension. Three other containers were also filled with the bacterial suspension as a control, whilst another three sets were left at room temperature (approx 21 deg) at Sutton Bonington (SB). About 50mls of the pure water used for suspension was also provided. One extra vial was left at 37 deg to encourage growth of the bacteria. Samples were serial diluted and plated out immediately on receipt from University of Loughborough on nutrient media and incubated overnight at 37°C; following which, colonies that emerged were counted. However, only one sample was treated with electrical field at Loughborough.

Results and Discussion

The results show that the electrical field is efficient in killing the bacteria used. There were 5 to 6 log reductions of the bacteria count. In fact, no growth was observed on the plates from cultures subjected to the electrical field (Table 1) indicating that the treatment is bactericidal and may be used for sterilization purposes.
### Table 1 Count of E. Coli (Log cfu/ml) in various containers kept at different temperatures

<table>
<thead>
<tr>
<th>Counts carried out on receipt from Loughborough</th>
<th>Log cfu/ml</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor-like vessel</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Control Loughborough in Water bath</td>
<td>6.150</td>
<td>1.422</td>
</tr>
<tr>
<td>Control 1 SB at room temp</td>
<td>5.203</td>
<td>0.041</td>
</tr>
<tr>
<td>Control 2 SB at room temp</td>
<td>5.769</td>
<td>1.363</td>
</tr>
<tr>
<td>Control 3 SB at room temp</td>
<td>5.742</td>
<td>1.528</td>
</tr>
<tr>
<td>Control SB at 37 deg</td>
<td>6.350</td>
<td>1.350</td>
</tr>
</tbody>
</table>

To summarise the electric field had a significant effect on the level of bacteria. All bacteria were destroyed.
**Effect of Electrical Field on E. coli Mar 21 2012**

**Introduction**

This study was carried out to determine if an electrical field is bactericidal.

**Materials and Methods**

Tests were carried out as before using ultra-pure water instead of growth media. Duplicates of final bacteria suspension were given to University of Loughborough for application of the electrical field. Three samples and controls were submitted for analysis.

**Results and Discussion**

Results show that there was growth in all samples. Overall there were 5 log reductions for capacitor 2 and 3 log reductions for capacitor 1 and 3.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count (log cfu/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Loughborough 1</td>
<td>6.55</td>
</tr>
<tr>
<td>Control Loughborough 2</td>
<td>6.69</td>
</tr>
<tr>
<td>Control Loughborough 3</td>
<td>6.61</td>
</tr>
<tr>
<td>Control at Sh</td>
<td>8.62</td>
</tr>
<tr>
<td>Capacitor 1</td>
<td>3.39</td>
</tr>
<tr>
<td>Capacitor 2</td>
<td>1.27</td>
</tr>
<tr>
<td>Capacitor 3</td>
<td>3.54</td>
</tr>
</tbody>
</table>
Additional Information

<table>
<thead>
<tr>
<th>Sample</th>
<th>count1</th>
<th>count2</th>
<th>count3</th>
<th>volume</th>
<th>dilution</th>
<th>Final Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Loughborough1</td>
<td>15</td>
<td>17</td>
<td>21</td>
<td>0.000076</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Control Loughborough2</td>
<td>19</td>
<td>20</td>
<td>24</td>
<td>0.000133</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Control Loughborough3</td>
<td>26</td>
<td>18</td>
<td>1.1</td>
<td>0.000065</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

Raw data file is provided as requested. Decimals of log figures reported earlier may vary mainly due to approximations. The volume and dilution is shown as above. Place the cursor on the count you are interested in and the volume and dilution will show on the formula bar. Volume of bacteria (20µl) was constant but dilutions vary because counts were performed on countable dilutions in the dilution series prepared. Also note that SDev shown on the raw data from 22 Feb were not included in the final reports from that date because after meeting of 20th Feb, samples were treated as one independent test; hence no SDev was included in reports.
REFERENCES
REFERENCES

CHAPTER ONE


CHAPTER TWO


REFERENCES


REFERENCES


CHAPTER THREE


[40] Yasushi Minamitani, Takaya Ueno,” Intensity of Electric Field Radiating from High-power Pulsed Electromagnetic Wave Generator for Use in Biological Applications”, IEEE Transactions on Dielectrics and Electrical Insulation Vol. 17, No. 6; December 2010.


CHAPTER FOUR


REFERENCES


[58] http://home.earthlink.net/~jimlux/hv/bruce.htm


[60] M. Born, Ann. Physik, 360, pp. 177-240, 1918


[63] E. Banachowicz and I. Danielewicz-Ferchmin, Static permittivity of water in electric fields higher than 108V/m and pressures varying from 0.1 to 600 MPa


REFERENCES


CHAPTER FIVE


[90] University of California Museum of Paleontology


REFERENCES


[99] Renuka Narsetti, Randy Curry “Microbial Inactivation in water using Pulsed Electric Field and Magnetic Pulse Compressor Technology” IEEE 0093-3813, 2006

[100] David Hussong, Russell Madsen “Analysis of Environmental Microbiology Data from Clean room Samples”, Pharmaceutical Technology, 2004


