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NOVEL PLASMA SOURCES FOR THE
PLASMA OPENING SWITCH

by

Paul Stevenson MEng(Hons) DIS MIEE

A doctoral thesis
submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University

October 2002

LOUGHBOROUGH UNIVERSITY
Department of Electronic and Electrical Engineering

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SYNOPSIS

The plasma opening switch (POS) is used in pulsed power systems where a fast opening and very high current switch is required. Plasma is injected into the switch, which carries a large conduction current before it opens in a process that lasts for a few nanoseconds and transfers the current to a parallel-connected load. The conduction and opening times of the switch are dependent on the plasma parameters such as distribution, speed, temperature and species, which are all determined by the plasma source. This thesis begins with a description of the POS, with its conduction and opening mechanisms and the techniques of plasma generation all being considered, before it concentrates on the simple and inexpensive carbon gun.

Plasma is normally produced by a pulsed discharge that evolves plasma from the evaporation and ionisation of a carbon based insulator. The first prototype carbon gun discussed in the thesis uses a classical coaxial arrangement that successfully produces dense, fast and hot plasma, although this is only capable of filling a small region with plasma. A number of plasma diagnostic techniques are described, before details are provided of the electrical probes that were used to characterise the plasma. In a large POS a well-distributed plasma is obtained by combining a large number of guns in a complex and large system. This restricts the compactness of the POS resulting in a problem for any future commercial applications. A succession of developments to the prototype gun has led to a novel ring-shaped version that produces a much improved distribution of plasma, without the need for additional guns. In this, a pulsed discharge is initiated at a single point and the self-generated magnetic field forces the discharge to spread and to travel around the gun, whilst continuously ejecting plasma into the POS. The ideas and theories that explain how a discharge can be forced to move are described, together with details of the prototype designs. Results are given to confirm the operation of the gun, using high speed photography and electrical probes.
I would like to acknowledge the advice and assistance that I received from my colleagues within the Department of Electronic and Electrical Engineering at Loughborough University, in particular Keith Gregory, Ivor Smith and Robert Cliffe whose assistance and guidance made it possible to complete this thesis and the papers published. Finally, thanks to George, Pete and Jerry for assistance with the construction of the equipment needed for this research and to Rishi, Bucur, Peter and Rod for their assistance, advice and cooperation.

This research has been funded by the Engineering and Physical Science Research Council (EPSRC) who gave me the opportunity to achieve a PhD and, through the equipment pool at the Rutherford Laboratories, loaned a fast oscilloscope and two high-speed cameras that produced the results needed to confirm the success of my plasma sources.

Also an acknowledgement should be given to the Institute of Electrical Engineers and the Royal Academy of Engineers who together funded my expenses for the IEEE Pulsed Power Plasma Science 2001 Conference in Las Vegas and also a visit to the Pulsed Power and Plasma Science Laboratory at Texas Tech University.

Finally, thanks to the support from my family and friends throughout the years of my undergraduate and postgraduate studies that gave me the strength and determination to succeed. Especially I am eternally grateful to my girlfriend Ruth for her endless support and patience throughout this research and especially during the writing of this thesis.
SYMBOLS

\(a\) Acceleration \((\text{ms}^{-2})\)
\(a_t\) Width of flashboard sheets \((\text{m})\)
\(A\) Atomic number
\(A\) Probe area \((\text{m}^2)\)
\(A_1, A_2\) Area of probe 1 (2) \((\text{m}^2)\)
\(A_p\) Apparent probe area exposed to flowing plasma \((\text{m}^2)\)
\(A_{\text{turn}}\) Area of single turn (chapter 6) \((\text{m}^2)\)
\(B\) Magnetic flux density \((\text{T})\)
\(c\) Velocity of light \((3 \times 10^8 \text{ ms}^{-1})\)
\(c_t\) Separation of flashboard sheets \((\text{m})\)
\(C\) Capacitance \((\text{F})\)
\(C_v\) Specific heat capacity \((\text{JK}^{-1}\text{kg}^{-1})\)
\(D\) Gap width \((\text{m})\)
\(e\) Electron charge \((1.602 \times 10^{-19} \text{ C})\)
\(E\) Electric field strength \((\text{V m}^{-1})\)
\(E\) Mean energy of a particle \((\text{J})\)
\(E_1, E_2\) First (\(t^p\)) ionisation energy \((\text{J})\)
\(f\) Frequency \((\text{Hz})\)
\(f(v)\) Velocity distribution function
\(F\) Force \((\text{N})\)
\(F_i\) Fraction of particles ionised
\(F_s\) Ionisation factor
\(F_{\text{total}}\) Total force on the line current \((\text{N})\)
\(F_x\) Force per unit length applied to line current \((\text{N m}^{-1})\)
\(h\) Planck’s constant \((6.63 \times 10^{-34} \text{ Js})\)
\(H\) Magnetic field strength \((\text{Am}^{-1})\)
\(i_{1+}, i_{2+}\) Ion current due to probe 1 (2) \((\text{A})\)
\(i_{1-}, i_{2-}\) Electron current due to probe 1 (2) \((\text{A})\)
\(I\) Current \((\text{A})\)
\(I_{\text{BIP}}\) Bipolar current limit \((\text{A})\)
\(I_{\text{cl}}\) Magnetic insulation critical current level \((\text{A})\)
\(I_{\text{el}}\) Enhanced erosion critical current level \((\text{A})\)
\(I_e, I_i\) Electron (ion) current \((\text{A})\)
\(I_{\text{es}}, I_{\text{is}}\) Electron (ion) saturation current \((\text{A})\)
\(I_G\) Generator current \((\text{A})\)
\(I_L\) Load current \((\text{A})\)
\(I_S\) Switch current \((\text{A})\)
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<td>$m_a$</td>
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<td>$N$</td>
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<td>Radius</td>
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<td>Half of ring separation</td>
<td>m</td>
</tr>
<tr>
<td>S</td>
<td>Sheath area</td>
<td>m²</td>
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<tr>
<td>t</td>
<td>Time</td>
<td>s</td>
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<td>t_c (t_e, t_o)</td>
<td>Conduction (erosion, enhanced erosion) duration</td>
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<td>t_load</td>
<td>Time when the plasma reaches the load end of the POS</td>
<td>s</td>
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<td>T (T_e, T_i)</td>
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<td>K, [eV]</td>
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<td>K</td>
</tr>
<tr>
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<tr>
<td>U</td>
<td>Velocity of plasma mass</td>
<td>m/s²</td>
</tr>
<tr>
<td>U_0</td>
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<td>m/s</td>
</tr>
<tr>
<td>U_loss</td>
<td>Velocity lost due to friction</td>
<td>m/s²</td>
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<td>v</td>
<td>Velocity</td>
<td>m/s</td>
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<tr>
<td>v</td>
<td>Mean speed of a particle</td>
<td>m/s²</td>
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<tr>
<td>v_{ms}</td>
<td>RMS particle speed</td>
<td>m/s</td>
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<tr>
<td>v_D</td>
<td>Drift (or flow) velocity</td>
<td>m/s², [cm µs⁻¹]</td>
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<td>v_e (v_i)</td>
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<td>Voltage</td>
<td>V</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>m³</td>
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<td>V_a</td>
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<td>V_gap</td>
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<td>V</td>
</tr>
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<td>V_G</td>
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<td>V</td>
</tr>
<tr>
<td>V_H</td>
<td>Hall voltage</td>
<td>V</td>
</tr>
<tr>
<td>V_S</td>
<td>Space potential</td>
<td>V</td>
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<tr>
<td>W</td>
<td>Energy</td>
<td>J, [eV]</td>
</tr>
<tr>
<td>W_L (W_{en})</td>
<td>Energy delivered to a (matched) load</td>
<td>J</td>
</tr>
<tr>
<td>W_{th}</td>
<td>Thermal energy</td>
<td>J</td>
</tr>
<tr>
<td>X</td>
<td>Position of centre of plasma mass</td>
<td>m</td>
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<tr>
<td>X_l</td>
<td>Exposed length of inner electrode</td>
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<tr>
<td>X_{max}</td>
<td>Maximum displacement before leaving gun</td>
<td>m</td>
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<tr>
<td>Z</td>
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<td></td>
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<tr>
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<td>α</td>
<td>Bipolar ratio</td>
<td></td>
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<tr>
<td>α</td>
<td>Exponential current damping factor</td>
<td></td>
</tr>
<tr>
<td>γ (γ_p)</td>
<td>(Peak) electron relativistic factor</td>
<td></td>
</tr>
<tr>
<td>ε</td>
<td>Electromotive force induced on coil</td>
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</tr>
<tr>
<td>ε_0</td>
<td>Permittivity of free space</td>
<td>(8.85 × 10⁻¹² C²Vm⁻¹)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>δ</td>
<td>Skin depth</td>
<td>(m)</td>
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<tr>
<td>ζ</td>
<td>Fraction of current in moving sheet</td>
<td></td>
</tr>
<tr>
<td>θ₁</td>
<td>Angle between point and start of current filament</td>
<td>(rad)</td>
</tr>
<tr>
<td>θ₂</td>
<td>Angle between point and end of current filament</td>
<td>(rad)</td>
</tr>
<tr>
<td>κ</td>
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<td>μ₀</td>
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<td>(4π × 10⁻⁷ Hm⁻¹)</td>
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<tr>
<td>ρ</td>
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<td>σ</td>
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<td>Electrical path length for L₁ (L₂) and Z₁ (Z₂)</td>
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1 INTRODUCTION

Inductive energy storage has long been a more attractive alternative for pulsed power than conventional capacitive storage, because its greater energy density brings about systems that are more compact and of higher power. A large current from a generator (such as a capacitor) charges a storage inductor before a switch opens and transfers the current to a parallel load. The energy stored in the inductor (and the generator) is transferred to the load, with a current waveform whose rising edge is faster than that obtainable from the generator alone. The function of the switch is thus to firstly conduct current as a closed switch with a low impedance, and then to rapidly block this current by changing to a high impedance and withstanding the inevitable high voltage that will ensue.

A lack of good opening switches, particularly those that are compact and capable of repetitive firing, has long inhibited the progress of inductive storage systems. One switch that is however widely used in research applications is the plasma opening switch (POS), which is capable of blocking a very high current in a few nanoseconds. Plasma is previously injected into the switch to carry the large conduction current and, through processes of magnetic pressure and erosion, a gap forms in the plasma that blocks the current. Chapter 2 of the thesis describes the POS, its conduction and opening mechanisms, and outlines a number of models that can predict the switch performance and plasma behaviour. The duration of both the conduction and opening phases are dependent on the plasma parameters that in turn are controlled by the selection and design of the plasma source, the limitations of which greatly inhibit commercial exploitation. It is hoped that the novel plasma source developed in this thesis will contribute towards future more compact POS designs. The prototype POS described at the end of Chapter 2 is the platform for the experiments described in this thesis.

The history of plasma, its applications and existence in nature, space, fusion and technology are described in Chapter 3, together with the physics of plasma behaviour and the various techniques available to generate plasma for pulsed and continuous applications. Flashboards, carbon guns, gas guns and techniques that use the
interaction of a laser beam with a solid are the traditional methods outlined in Chapter 4 that are used to produce sufficient plasma to conduct the large current in the POS during the conduction phase. Chapter 5 describes the various types of carbon plasma gun used in experiments worldwide, together with a number of models that begin to predict the expansion of carbon plasmas. A prototype carbon gun and pulser system is described, that uses a conventional coaxial arrangement with a pulsed surface discharge of a carbon-based insulator. This discharge vaporises and ionises insulator molecules to form a plasma beam that is ejected outwards through conical holes in a copper plate.

Plasma diagnostic techniques are described in Chapter 6 to measure the plasma behaviour on both macroscopic and microscopic scales, by the detection of the magnetic fields generated by the moving plasma and its electrical properties. A technique is developed that uses electrical probes to characterise plasma using the theory of ion collection and sheath formation. Results are given that confirm the operation of the prototype gun by measuring the temperature, density and speed of the plasma. Finally a technique is described that captures a 3D image of the plasma beam using a novel and simple optical technique.

In a large POS, evenly distributed plasma is obtained by combining up to 36 such guns in a complex and large arrangement that inevitably restricts the overall compactness of the system. To overcome this a novel ring-shaped carbon gun is described in Chapter 7 that produces an improved distribution of plasma from a single gun. A pulsed discharge initiated at a single point between two rings spreads and moves along the rings as a result of the interaction between the magnetic field generated by the current in the rings and the moving charge in the arc discharge, whilst continuously ejecting plasma into the POS. Theories advanced to explain how this discharge moves are confirmed by results from high speed photography and electrical probes.

The current distribution near the discharge is expected to limit the effectiveness of the discharge motion, with components of the current either propelling the discharge into the POS region or opposing the discharge rotation. In Chapter 8, a MatLab computer program is described that simulates the current distribution between an equipotential
surface and a single point in a conducting block, by taking into consideration the effects of mutual inductance, self inductance and resistance. Results confirm the predicted current distribution and suggest that by reducing the ring width an optimised ring gun can be developed. Finally an optimised ring gun is described and tested in Chapter 9, and produces results that confirm the faster rotation of a discharge through a full turn of the rings, with plasma ejected into the POS region at a sufficient density and distribution to operate a POS.
2 PLASMA OPENING SWITCH

2.1 Opening Switches

The term opening switches refers to a family of devices that are capable of conducting current for a time by acting as a closing switch, and then opening to prevent the flow of current [1]. The switch achieves current interruption by transferring the conducted current to a parallel load circuit, and it must subsequently be able to withstand the voltage generated by the current flowing through the load. When there is no alternative parallel circuit, it must be capable of absorbing all the energy stored in the circuit inductance and of withstanding the open-circuit voltage of the current source. This kind of switch is used to provide fault current protection in systems such as HVDC transmission, to sharpen the current pulse from a capacitive discharge and to transfer the inductive energy stored in a circuit to a load. Applications for opening switches appear in defence, nuclear fusion and industry within pulsed particle accelerators, lasers, impulse radiation sources, intense microwave sources, high power radar and induction heating systems.

Opening switches are normally divided into two basic types, direct-interruption and current-zero [1] depending on whether the voltage used to transfer the current from out of the switch is produced internally or externally.

2.1.1 Direct-Interruption Opening Switches

In the direct-interruption switch the transfer voltage is developed by an internal process that increases the switch impedance from zero to a value that is much greater than the load impedance. This transfer time must be fast in order to reduce losses within the switch that decrease the final current supplied to the load. Examples of this type of switch include fuse wires, dense plasma focus devices, superconducting switches, lasers and the plasma opening switch (POS).

2.1.2 Current-Zero Opening Switches

This second method uses an external voltage source that drives the switch current to zero and allows the switch to open. A fast recovery is required from such a switch,
because it is often used in AC systems where current zeros occur twice in each cycle. They are also used in DC systems where an auxiliary circuit is used to temporarily force a current zero. Examples of such switches include solid-state thyristors, vacuum switches, hydrogen thyratrons and liquid metal plasma valves.

2.2 Brief Description of the POS

The POS [1-3] is often used in pulse conditioning, inductive energy storage systems and pulse power compression, as it provides the fastest known method of transferring currents of up to several mega-amperes to a load. It is normally used in a circuit where the rise time of a generator current needs to be sharpened before it is supplied to a load. The typical POS has the coaxial electrode arrangement seen in Fig. 2.1, with the generator at one end and the load at the other.

![Simple POS arrangement](image)

*Figure 2.1. Simple POS arrangement*

The generator can be a charged capacitor bank or any other appropriate source of current, whilst the loads at present are normally low-impedance (short-circuit) links across the electrodes. Prior to the conduction of current through the switch, a source injects plasma through a mesh in the anode towards the cathode, filling the vacuum region between the load and the generator. This plasma source will typically be
carbon plasma guns (cable guns), flashboards, gas guns and devices that use the energy from a laser beam to ionise a solid [4]. The generator is fired after a brief time interval during which the plasma reaches the necessary concentration and distribution. POS operation is conveniently divided into three modes of operation, when conducting (Fig. 2.2(a)), opening (Fig. 2.2(b)) and finally when fully open (Fig. 2.2(b)) [1]. During the conduction phase the plasma is in parallel with the load, short-circuiting this branch and taking all the current from the generator.

Ideally, the plasma should conduct the generator pulse for the duration required for the current to build to a high level, whilst charging a vacuum storage inductor between the generator and the switch plasma, and also short-circuiting the load. Above a critical current level a rapidly expanding gap between the switch plasma and cathode, transfers the current from the plasma to the load (Fig. 2.2(b)) in a process that gives a load current rise time that is significantly shorter (about 10 times faster) than would be obtained with the generator alone. Once the switch is fully open all the current from the generator and the storage inductor flows through the load, as illustrated in Fig. 2.2(c).
In the majority of cases the generator applies a negative voltage to the inner electrode, making this the cathode and the outer electrode the anode, as seen in Fig. 2.1. This is either because the intended load, such as an electron beam or inverse diode, needs this arrangement or because attempts at a positive polarity POS have resulted in slower opening times [3]. It has been indicated that the slow opening is due to the weaker cathode electric field, when it is the larger electrode, or because the plasma is injected from the outside such that it opposes the conduction current. It is now almost universal practice to use the negative polarity arrangement, with the plasma injected through the anode towards the central cathode.

2.3 Applications

2.3.1 Inductive Energy Storage

Inductive energy storage systems are widely used in high power TW nanosecond generators [5], neutron burst production [6] and pulsed power compression using a water dielectric pulse line [7-8].

![Figure 2.3. Inductive energy storage system](image)

In the typical system [1,9] shown in Fig. 2.3, a generator discharges a high-current \( I_G \) through a storage inductor \( L_1 \) (storing magnetic energy) and through plasma in the closed POS switch. When this current reaches its peak the POS (or any fast opening switch) rapidly opens, becoming high impedance and transferring the current to the load. If the load inductance \( L_2 \) is very small in comparison to the storage inductance \( L_1 \), the output pulse duration becomes \( L_1/R_L \) and the peak voltage about \( I_2R_L \). The low impedance generator can be treated as a short-circuit after the switch is opened, so that the charging current is transferred and the voltage is multiplied by the ratio of the conduction time to the output pulse duration. Unfortunately the output pulse rise-time and voltage are both restricted by the opening time of the switch and
its voltage hold-off capability. A single opening switch will normally manage only about a 10-fold voltage increase.

2.3.2 Pulse Sharpening Application

This application is a form of inductive energy storage, in which the inductor $L_1$ in Fig. 2.3 is the stray inductance of the connection between a capacitor and the opening switch [1]. The load is bypassed by a closed opening-switch during the initial part of the capacitor discharge, and then at the peak current the switch opens to force a rapid transfer of the current to the load, as shown in Fig. 2.4. The output pulse is made sharper than can be obtained by using the capacitive discharge alone.

![Figure 2.4. Pulse-sharpening waveform](image)

2.4 POS Conduction Mechanisms

The conduction phase lasts for the period during which the switch isolates the load from the system by behaving as a short-circuit. All the current from the generator is conducted through the switch plasma between the anode and cathode whilst charging the storage inductor. The mobility of the lighter electrons in comparison to the heavier carbon ions means that conduction is primarily by electrons emitted from the cathode. The electron motion is influenced both by the strong electric and magnetic fields present in the plasma and by collisions between particles. Accurate prediction of the effect of interaction between particles such as electrons and ions is a complicated process that is gradually being solved by particle simulations (see section 2.7). At present the opening process is described by a number of conduction models that are termed bipolar, magnetic pressure and snowplough conduction [1-2,10-14].
2.4.1 Bipolar Conduction Model

In this section a bipolar conduction model of the POS is described, based on the electrostatic behaviour of electrons and positive ions by Weber et al [2,10]. During the conduction phase a cathode sheath grows between the plasma and the cathode, restricting the flow of current. The cathode becomes a space-charge-limited electron emitter, whilst the plasma acts as a space-charge-limited ion emitter. Ions from the plasma drift towards the cathode with a drift velocity $v_D$. Electrons from the cathode cross the small space-charge cathode sheath. The emitted electron current density is about two orders of magnitude larger than the ion current density and is related to it by the bipolar ratio $\alpha$

$$\alpha = \frac{J_e}{J_i} = \sqrt{\frac{m_i}{Zm_e}} \approx 105 \text{ for } C^{2+}$$

(2.1)

where $J_i$ and $J_e$ are the ion and electron current densities, $m_i$ and $m_e$ are the ion and electron masses and $Z$ is the ion charge state. The ion current density is determined from their drift velocity $v_D$ by

$$J_i \leq n_e e v_D$$

(2.2)

where $n_i$ is the ion density and $e$ is the charge on an electron. Using the bipolar ratio $\alpha$ in equation (2.2) and assuming overall neutrality is maintained this limits the electron current density to the bipolar current density limit $J_{BP}$, given by

$$J_{BP} \approx J_e = n_e e v_D \sqrt{\frac{m_i}{Zm_e}} \gg J_i$$

(2.3)

where $n_e$ is the electron density. Bipolar conduction is illustrated in Fig. 2.5 where the switch current $I_S$ equals the generator current $I_G$ and the load current $I_L$ is zero.

* the cathode sheath is a region of positive space charge (see section 3.2.3)
The cathode current is uniformly distributed over the cylindrical plasma length $l$, to give a bipolar current limit $I_{BP}$ of

$$I_{BP} = 2\pi r_c I_{BP} = n_i Z e v_D (2\pi r_c l) \sqrt{\frac{m_i}{Z m_e}}$$

(2.4)

where $r_c$ is the cathode radius. During the conduction phase the sheath expands along the length of the plasma, as seen in Fig. 2.5, until conduction ceases when it extends along the entire plasma length.

2.4.2 Magnetic Pressure Model

The imbalance of current between the load and generator side of the plasma region results in a strong azimuthal magnetic field $B_\phi$ on the generator side [10]. This interacts with the switch current $I_5$ to cause a magnetic pressure $B_\phi^2/(2\mu_0)$, where $\mu_0$ is the permeability of free space ($4\pi \times 10^{-7}$ Hm$^{-1}$), which sweeps the plasma axially towards the load, as seen in Fig. 2.6.
Integration of the magnetic force at the centre of the plasma mass, which is a thin cylinder of inner radius $r_c$ and initial plasma length $l_0$, gives its displacement $\Delta z$ as [10]

$$\Delta z = \frac{\mu_0 Ze}{8\pi^2 r_c^2 l_0 m_e n_e} \int \int I_3^2 dt^2$$  (2.5)

This displacement of plasma results in an axial current that causes radial motion of the plasma, as described in section 2.5.2, which can eventually open the switch at a current level far below the bipolar conduction current limit $I_{BP}$ in equation (2.4).

### 2.4.3 Snowplough Model

A further development to the magnetic pressure model is the following one-dimensional snowplough model for the conduction phase by Rix et al [11]. This uses the following assumptions:

1) the plasma develops a current-carrying channel whose width is much less than the plasma length $l$;

2) the plasma pressure is negligible;

3) the channel is roughly perpendicular to the direction of power propagation.
The snowplough movement of the plasma is represented by

$$\frac{d}{dt}(m_u \frac{dz}{dt}) = \frac{B_0^2}{8\pi}$$

(2.6)

where \(m_u\) is the mass per unit area of the plasma being displaced. Assuming this is constant, integrating equation (2.6) over a cross-section of the coaxial geometry gives

$$m_u \pi(r_a^2 - r_c^2) \left[ \frac{d^2}{dt^2} \left( \frac{z^2}{2} \right) \right] = \frac{1}{160} \int_0^2 \ln \left( \frac{r_a}{r_c} \right)$$

(2.7)

where \(r_a\) is the anode radius. Assuming the snowplough action begins at zero displacement (\(z = 0\)) and that the mass density \(m_u\) at this time is zero, then

$$\frac{600\pi(r_a^2 - r_c^2)}{\ln \left( \frac{r_a}{r_c} \right)} m_u I_s^2 = 12 \int_0^{t_{load}} \int_0^t \frac{r_a^2}{r_c^2} (\text{t}) \text{dt}$$

(2.8)

where \(t_{load}\) is defined as the time at which the snowplough arrives at the load end of the POS. Assuming the switch current to increase linearly with time \((I_S = I_S t)\), gives

$$I_S(t_{load}) = I_S \sqrt{m_u \left( \frac{600\pi(r_a^2 - r_c^2)}{\ln \left( \frac{r_a}{r_c} \right)} \right)^{\frac{1}{2}}}$$

(2.9)

showing that, to maintain the right-hand side constant, the onset of switch opening is dependent on the total charge through the switch. This is in contrast to the bipolar model, where the conduction phase ends when the generator current exceeds a current threshold.

2.4.4 Summary of the Conduction Mechanisms

The bipolar model is the simplest to understand and can be applied to a POS that conducts for a short duration (< 1μs), because the displacement of plasma towards the
load due to magnetic forces is insignificant. In a longer conduction POS this displacement becomes important, so that both the magnetic pressure and snowplough models need to be considered.

2.5 POS Opening Mechanisms

The switch opens when its impedance rises from zero to a high value, blocking the flow of current and transferring it to a downstream load. A common feature of all the models proposed is that the switch opens because a gap forms between the switch plasma and the cathode. The dynamics of the switch are governed by the rate of growth of the gap and it is this process that so often leads to disagreement between the various models.

It is assumed in all the models that the POS is fully open when the magnetic field in the gap is sufficiently strong to deflect all the electrons towards the load end, as illustrated in Fig. 2.7, preventing any from traversing the gap to conduct current between the electrodes [10]. In this state the switch is described as magnetically insulated.

![Diagram showing the opening of a plasma switch](image)

**Figure 2.7. Magnetic insulation gap near the cathode**

This state occurs when the gap width $D$ is equal to the electron gyroradius, which leads to the critical current $I_{cl}$ [10]

$$I_{cl} = \frac{2\pi m_e c}{e \mu_0} \sqrt{\gamma^2 - 1} \frac{r_c}{D} \approx 8500 \sqrt{\gamma^2 - 1} \frac{r_c}{D}$$

(2.10)
where $c$ is the velocity of light in vacuum and the electron relativistic factor $\gamma$ is related to the gap voltage $V_{\text{gap}}$ by

$$\gamma = 1 + \frac{eV_{\text{gap}}}{m_ec^2} \quad (2.11)$$

The processes behind the growth of this gap are explained by extending the erosion, magnetic pressure and snowplough models as shown below.

### 2.5.1 Erosion Model (PEOS)

The opening stages of the erosion model [2,10] are described as erosion, enhanced erosion and magnetic insulation. The conduction phase explained in section 2.4.1 ends when the generator current reaches the bipolar threshold current limit $I_{BP}$ of equation (2.4) and the sheath extends along the entire length of the plasma. The erosion phase in Fig. 2.8 begins when the ion current $I_i$ exceeds $I_{BP}$, at which time the gap grows because ions are collected at the cathode faster than they can be replaced by the plasma.

![Figure 2.8. Erosion phase](image)

The gap grows at a rate determined by the diminishing ion density in the gap as [2]

$$\frac{dD}{dt} = \frac{I_i - ad_{BP}}{n_e Ze(2\pi c l)} \quad (2.12)$$
where $\alpha$ is the bipolar ratio from equation (2.1). After a while the electrons start to deflect towards the load end, although they are still able to conduct current between the two electrodes. This is the start of the enhanced erosion phase, illustrated in Fig. 2.9, which begins when the generator current $I_G$ reaches a second critical current level $I_{C2}$, given by [2]

$$I_{C2} = 8500 \kappa \sqrt{y^2 - 1} \frac{L_e}{D}$$

(2.13)

where $\kappa$ is a numerical factor that accounts for space-charge effects.

![Figure 2.9. Enhanced erosion phase.](image)

The rate of gap growth now increases dramatically, with magnetic insulation being achieved when the generator current $I_G$ exceeds the critical current $I_{C1}$, as shown in Fig. 2.7. The small fraction of the generator current that remains in the switch is due to the small ion current.

### 2.5.2 Magnetic Pressure Model

Magnetic pressure from the generator end forces the plasma towards the load end during the conduction process, as discussed in section 2.4.2. An axial current $J_z$ arises as a result of this movement of charge towards the load, and interacts with the azimuthal magnetic field $B_\phi$ to produce a radial $J \times B$ force [10,11]. This force opens a gap on the generator side of the plasma where the field is strong, as illustrated in Fig. 2.10. The effect diminishes towards the opposite side of the plasma where the
magnetic field is zero, until the current begins to be transferred to the load at which
time the magnetic field opens a gap along the entire length.

![Figure 2.10. Opening mechanism due to magnetic pressure](image)

The gap-opening rate [10] is described by

\[
\frac{d}{dt} \left( m_u \frac{dD}{dt} \right) = J_z B_{\phi}
\]  

(2.14)

or in the snowplough effect [11] by

\[
m_u \frac{d}{dt} D \frac{dD}{dt} = \beta \frac{B_{\phi}^2}{8\pi}
\]  

(2.15)

where the scale factor \( \beta \) accounts for the material and the magnetic back pressure of
the plasma.

2.5.3 Summary of the Opening Mechanisms

As mentioned previously, magnetic pressure is the opening mechanism used to
describe the plasma behaviour in the long-conduction POS, where the plasma is being
swept along during the conduction phase. However the opening phase of this process
is too slow to explain the fast opening action that has been observed in experiments.
The prevailing idea is that once a gap forms the opening mechanism becomes
predominantly enhanced erosion, with the overall mechanism being a combination of
both magnetic pressure and erosion.
2.6 Theoretical Model of the POS

The Naval Research Laboratories (NRL), in Washington, developed the following model [13] for the POS based on the erosion technique, which has become the standard that other models and designs have adopted. It can be used to predict the switch voltage, current and impedance as a function of input waveforms, geometry and switch parameters. Scaling relationships linking the POS dimensions to the duration of each phase have been developed to assist in the design of a switch. Initially, expressions for the relevant time scales, peak load power and the energy transfer efficiency are derived from a simple lumped circuit analysis. Following this a simple transmission line model is used to analyse the transit time effects. Together these provide a number of rules that need to be applied to POS design.

2.6.1 Lumped Circuit Analysis

The simple lumped circuit in Fig. 2.11 represents a typical circuit for pulse power compression and power multiplication.

![Figure 2.11. Lumped circuit analysis](image)

The inductances $L_1$ and $L_2$ represent the inductance of the vacuum storage region and the section of the coaxial arrangement between the plasma and the load. The following analysis assumes that $L_1$ is initially current charged to $I_0$ by the generator and that for efficient charging $L_1$ is chosen so that $L_1/R_G \approx \tau_p$ where $\tau_p$ is the generator pulse duration and $R_G$ is the generator resistance. Assuming the switch impedance $R_S$ rises instantaneously from zero to a large value when opening, that the generator voltage is negligible after opening has begun, and that the initial load current $I_L$ is zero, enables the system to be represented by the equations
\[ 0 = R_G I_G + L_1 \frac{dI_G}{dt} + R_S (I_G - I_L) \]  
\[ 0 = R_L I_L + L_2 \frac{dI_L}{dt} + R_S (I_L - I_G) \]  (2.16)

The approximations \( R_S \gg R_L, R_S \gg R_G \) and \( L_1 \gg L_2 \), which when taken to the limit give the following solutions for equation (2.17)

\[ \tau_+ = \frac{L_2}{R_S} \]  
\[ \tau_- = \frac{L_1}{R_G + R_L} \]  (2.17)

The smaller of these roots \( \tau_+ \) is equivalent to the switching time \( \tau_S \), whilst the other \( \tau_- \) scales with the output pulse width. Hence, for a fast rise time the inductance \( L_2 \) must be small and the switch impedance \( R_S \) large. In addition, the output pulse width can be seen to be dependent on the storage inductance \( L_1 \) and the load and generator impedances. The result of equations (2.17), together with the initial conditions \( I_G(0) = I_0 \) and \( I_L(0) = 0 \), can be used in equations (2.16) to give

\[ I_G(t) \approx \frac{L_1 I_0}{(L_1 + L_2)} \left[ e^{-\frac{L}{\tau_+}} + \frac{L_2}{L_1} e^{-\frac{L}{\tau_+}} \right] \]

\[ I_L(t) \approx \frac{L_1 I_0}{(L_1 + L_2)} \left[ e^{-\frac{L}{\tau_+}} - e^{-\frac{L}{\tau_-}} \right] \]  (2.18)

\[ I_S(t) \approx I_G - I_L \approx I_0 e^{-\frac{L}{\tau_+}} \]

The power delivered to the load, \( P_L = I_L^2 R_L \) has a peak of

\[ \dot{P}_L \approx \frac{R_L L_1^2 I_0^2}{(L_1 + L_2)^2} \left\{ 1 - \frac{2}{\chi} [\ln(\chi) + 1] \right\} \]  
where \( \chi = \frac{R_S L_1}{L_2 (R_G + R_L)} \gg 1 \)  (2.19)

The power multiplication factor is determined from the ratio of the peak power delivered to the load against that delivered to a matched load, where \( R_L = R_G, L_1 = L_2 = 0 \) and \( R_S \to \infty \). Applying a square wave voltage pulse of magnitude \( V_0 \) and duration \( \tau_p \) to a matched load will deliver a peak power of \( \dot{P}_m = V_0^2 / 4 R_G \). If the same
voltage pulse is applied prior to the switch being opened, the initial generator current \( I_0 \) is

\[
I_0 = \frac{V_0}{R_G} \left[ 1 - e^{-\frac{R_G\tau_p}{L_1}} \right]
\]  

(2.20)

giving the peak power delivered to a matched load as

\[
\hat{P}_m = \frac{1}{4} L_2^2 R_G \left( 1 - e^{-\frac{R_G\tau_p}{L_1}} \right)^2
\]  

(2.21)

and a power multiplication factor of

\[
\frac{\hat{P}_L}{\hat{P}_m} \approx \frac{4 R_L}{R_G} \left( \frac{L_1^2}{(L_1 + L_2)^2} \right) \left[ 1 - e^{-\frac{R_G\tau_p}{L_1}} \right]^2 \left\{ 1 - \frac{2}{\chi} [\ln(\chi) + 1] \right\}
\]  

(2.22)

It can be seen from this equation that for high power multiplication the load resistance \( R_L \) should be large in comparison to the generator resistance \( R_G \).

The energy delivered to the load \( W_L \) is derived by integration of the load power as

\[
W_L = \int_0^\infty \frac{1}{2} I_0^2 R_L \, dt = \frac{L_1^2 V_0^2 R_L}{2 R_G^2 (R_G + R_L)(L_1 + L_2)^2} \left[ 1 - e^{-\frac{R_G\tau_p}{L_1}} \right]^2
\]  

(2.23)

which can be compared to the energy delivered to a matched load, \( W_m = V_0^2 \tau_p / 4 R_G \) to give the energy efficiency as

\[
\frac{W_L}{W_m} = \left( \frac{R_L}{R_G + R_L} \right) \left( \frac{L_1}{L_1 + L_2} \right)^2 \left\{ \frac{2 I_1}{\tau_p R_G} \left[ 1 - e^{-\frac{R_G\tau_p}{L_1}} \right]^2 \right\}
\]  

(2.24)
Three sources of energy loss are apparent in the terms of equation (2.24), with the first being the energy absorbed by the generator after the switch opens which is minimised when $R_L \gg R_G$. The energy lost due to switch heating is described by the middle term and is minimised by making $L_2 \ll L_1$. Finally the last term is the energy reflected back into the generator during charging of the storage inductor, which is found to be minimised when $(R_G \tau_p)/L_1 = 1.25$.

### 2.6.2 Transmission Line Analysis

Although the lumped circuit model takes into account the effect of finite opening times, it ignores the transit time effects that are important when defining the system performance. In a transmission line model the inductors $L_1$ and $L_2$ are replaced by equivalent impedances $Z_1$ and $Z_2$ and electrical path lengths $\tau_1 = L_1/Z_1$ and $\tau_2 = L_2/Z_2$. When the switch is closed and the storage inductor is initially charged to $V_0$, forward and backward moving voltage waves of $\pm V_0Z_l/2$ are superimposed on the line. If the switch is opened instantaneously these waves are reflected at each end of the line, thus reducing the power transferred to the load.

In order to prevent reflections at the load end the line must be terminated by a matched load resistance $R_L = Z_2$. When $R_L = Z_2 = Z_l$, all the energy stored prior to the switch opening is delivered to the load resistance during a period $2\tau_1$ at the maximum power level. This implies that the system should be designed with $R_L = L_2/\tau_2 = L_1/\tau_1$.

### 2.6.3 POS Scaling Relations

The POS model described in section 2.5.1 will now be extended to derive a series of scaling relationships [13] for the duration of each phase. A Mathcad spreadsheet, given in Appendix A, uses these relationships to design a prototype POS. Firstly the open-circuit voltage waveform in Fig. 2.12 is used as the generator voltage $V_G$, with a rise time $\tau_r$ and pulse width $\tau_p$. 

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Assuming that the switch impedance is zero during the conduction and erosion phases enables the circuit to be described by

\[ V_G = R_G I_G + L_1 \frac{dI_G}{dt} \]  \hspace{1cm} (2.25)

which also assumes that the switch plasma is stationary during the conduction phase as a result of minimal effect from the magnetic field. Using the initial condition \( I_C(0) = 0 \) enables equation (2.25) to be solved to give

\[
I_G = \frac{V_0}{R_G} \tau_0 \left[ \frac{t}{\tau_0} - 1 \right] \left(1 - e^{-\frac{t}{\tau_0}}\right) \quad 0 \leq t \leq \tau_r
\]

\[
I_G = \frac{V_0}{R_G} \left\{ 1 + \frac{\tau_0}{\tau_r} \left[ \frac{\tau_r}{e^{\frac{\tau_r}{\tau_0}}} - e^{-\frac{t}{\tau_0}} \right] \right\} \quad t \geq \tau_r
\]

where \( \tau_0 = L_1/R_G \). Using these equations and the bipolar current limit \( I_{BP} \) of equation (2.4), allows the conduction time \( t_c \) to be derived, to a first order of accuracy, as

\[
t_c \approx \frac{\tau_r}{2} + \frac{2m_e n_e \nu_D \tau_0 R_G}{\sqrt{m_e V_0}} \sqrt{\frac{m_e Z}{m_e}}
\]

(2.27)

The conduction time is thus dependent on the plasma density, which provides limited control over the duration of the charging current by varying the performance of the plasma source.
After $t_c$ the erosion phase begins, with the gap width $D$ increasing from zero. Using equations (2.4), (2.12) and (2.27) gives the rate of gap expansion to a first order as

$$D(t) = \frac{\nu D (t-t_c)^2}{(2t_c - r_0)} \quad t > t_c$$

(2.28)

During this phase the opening rate is typically $10^7 \text{ cm s}^{-1}$, which is too slow to explain the fast switching action observed in the POS. The switch resistance $R_S$ and its voltage $V_S$ remain low during this period, with the latter being described by [13]

$$V_S(t) = 1 \times 10^3 \left( \frac{V_0 D^2(t)}{I_c R_G} \right)^{\frac{2}{3}} \left[ 1 + \frac{r_0 - r_c}{\tau_r} \right]^{-\frac{1}{3}}$$

(2.29)

The erosion phase ends when the switch current exceeds the critical current given by equation (2.13). Using this critical current, the gap width $D$ and the switch voltage $V_S$ gives the duration of the erosion phase $t_e$, again to a first order, as

$$t_e = \frac{3.75 \times 10^4 \tau_0 r_c R_G}{V_0 \sqrt{\nu D (t_c - \frac{1}{2} \tau_r)}}$$

(2.30)

This slow opening process fails to explain the fast switching action that is a result of the enhanced erosion phase $t_n$, given by [13] as

$$t_n = 1.1 \times 10^{-8} n_i \sqrt{A F(\gamma_p)} \left( \frac{r_c}{\ell_L} \right)^3$$

(2.31)

where $A$ is the atomic number, $F(\gamma_p) = \frac{1}{3} (\gamma_p + 1)^{\frac{3}{2}} - \frac{1}{2} 2^{\frac{3}{2}} (\gamma_p + 1)^{\frac{1}{2}} + 2^{\frac{3}{2}}$ and $\gamma_p$ is the peak electron relativistic factor during the enhanced erosion phase.

Axial $\mathbf{J} \times \mathbf{B}$ forces on the plasma must be taken into consideration when designing the POS structure to prevent the plasma reaching the load end before the switch opens, and the system must therefore conform to the design limitation of
Plasma Opening Switch

\[
\tau_c \frac{I_L}{L} < \frac{2 \times 10^{-4} I \sqrt{D} (r_a^2 - r_c^2)}{r_e v_D r_0 \ln \left( \frac{r_a}{r_e} \right)}
\]  

(2.32)

In the small POS described in section 2.8 (developed using the Mathcad spreadsheet in Appendix A) plasma is ejected from the POS before the current reaches the critical level required for opening to occur. A method to initiate the opening mechanism at a much lower critical current level was considered, in which the cathode shape is modified to force the plasma outwards. Further investigation is however still needed in this area before the compact POS can be fully realised.

2.7 Simulation of the POS Behaviour

Many mechanisms contribute towards the POS behaviour, such as the magnetohydrodynamic (MHD) displacement, electron-magnetohydrodynamic (EMH) penetration of magnetic fields and electrostatic gap formation [14]. In a long-conduction POS the conduction mechanism is predominantly MHD, which results in a current channel in the plasma with displacement and distortion of the plasma towards the load end in a snowplough effect. However, whilst an MHD code can simulate the conduction phase, a particle-in-cell (PIC) code is preferred to simulate the opening process that is predominantly erosion. The following sections described some of the simulation methods that are available.

2.7.1 Simple Electrostatic and Electromagnetic Models

An electrostatic model of plasma considers charged particles being moved due to both internal and external fields [15,16]. The electric fields are calculated from Maxwell’s equations, firstly by assuming that the position of all the particles and their velocities are known. The forces on the particles are determined from the fields and then, using the equations of motion, are moved during a small time step to a new position where the field and the velocity are recalculated. This process is repeated many times using numerical methods. However this type of program is not a true simulation of plasma behaviour, because it fails to consider the effects of electromagnetic waves.

The added complications of the \( \mathbf{J} \times \mathbf{B} \) forces from Maxwell’s equations are normally applied, but the overall computational requirement is often too much for all but very
powerful computers. The problem can however be overcome by reducing the number of particles by many orders of magnitudes below that in the real plasma, or by overlaying a mathematical mesh that has a charge and current density at each of the mesh points. Unfortunately these simple models ignore the oscillations, fluctuations, inconsistencies and collisions that together form realistic plasma.

2.7.2 MHD Simulations

MHD simulations of the POS by programs such as the two-fluid code ANTHEM [17,18] model the affect of $J \times B$ forces during conduction, which narrow the plasma channel as illustrated in Fig. 2.13.

These figures confirm the theory of section 2.4.2, that during conduction a current channel develops on the generator side and is swept towards the load by magnetic forces. At the end of the conduction phase a saddle forms in the channel, where it is possible that the opening process begins.

2.7.3 Particle-in-Cell (PIC)

MHD simulations are suitable for demonstrating the conduction phase and the distortion of the plasma channel, but the final stages of conduction and the opening
process are best modelled using PIC codes [16,19-20] because the dominant process is electrostatic. The simulated plasma at the start of this method needs to represent the density saddle (see section 2.7.2) generated during the conduction phase. The lower boundary of the simulation is on the cathode side of the saddle, where there exists a space charge limited source of electrons termed the "effective cathode", and the upper boundary is a small layer of immobilised ions near the anode surface. Results indicate the current flows in a wedge-like pattern moving axially near the effective cathode. As expected, ions are removed from near the effective cathode to leave a gap that expands towards the load until magnetic insulation is achieved.

2.8 Experimental POS Design

Extensive research is being undertaken throughout the world to model accurately the plasma behaviour inside the POS and to develop from this a fuller understanding of the switch operation. However it was decided early in the programme that a mainly experimental approach would be more appropriate. The present research thus began by the construction of an experimental POS in an attempt to achieve the compact POS that is the objective of this research.

Designed using the NRL erosion model of Appendix A, as shown in Figs. 2.14 and 2.15, the POS uses a concept first introduced in the plasma focus opening switch [21,22] where the outer electrode (anode) is a cage design, comprising a number of aluminium rods screwed into an anode plate. The inner electrode (cathode) is a hollow aluminium cylinder clamped into an insulated polypropylene base located in the anode plate. A threaded rod through this cylinder enables pressure to be applied between small plates at the top and bottom of the cylinder. Immediately below the switch is the inductance storage region, designed as a hollow structure in which the length and radius of the space can be varied to provide tuning of the inductance. The switch dimensions are based on a model that required estimates of the generator impedance, the rise-time and the process by which the switch opens, and the plasma parameters. For this reason a composite design was chosen, to enable modifications to be made after initial experimentation had been performed.
The model indicated that, with the present design, plasma would be ejected from the load end of the coaxial electrodes before the opening process begins. This distance travelled by the plasma during conduction is a limiting factor on the present size of the POS, which needs to be overcome before the compact POS is realised. A number of proposals have been considered that could modify the cathode so as to initiate the opening process below the critical current level at which this will naturally occur. One idea was to promote the creation of the sheath needed for opening to begin by physically obstructing the flow of the plasma. After this the enhanced erosion phase would start and the switch would rapidly open in the normal manner. It was intended that the experimental POS would be used as a platform for experiments with different electrode sizes and shapes to gain results that could be used in the future to confirm the models being developed elsewhere.

A source needs to inject plasma through the anode rods towards the cathode, to fill the base of the switch with sufficient plasma to conduct the large switch current. As the research developed it became clear that the present plasma sources limit the compactness of the POS and that before the objective could be achieved a new plasma source is needed. This topic rapidly grew and soon developed into the objective of this thesis.
Figure 2.14. Cross-sectional POS structure.

Figure 2.15. Top view of POS.
3 THE GENERATION AND PHYSICS OF PLASMA

3.1 The Plasma

Solid, liquid and gas are the three normal states of matter that are found on earth. However, plasma is often referred to as the fourth state of matter and indeed it constitutes more than 99% of the universe. A gas consists of numerous neutral particles comprising atoms that are constructed from negatively charged electrons orbiting a nucleus, which is a collection of neutrons and protons. The electrostatic forces between the nucleus and the surrounding electrons hold the atom together. Ionisation occurs when sufficient energy is supplied to the atom to overcome this attractive force, so breaking the internal bonds and freeing electrons. Initially this process creates a weakly charged gas that, when sufficiently ionised so that its electrical characteristics predominate over the normal characteristics of a gas, is described as plasma.

3.1.1 History of Plasma – the Beginning and the Future

It is not over dramatic to say that plasma is the most important state of matter in the universe, because of its abundance and its dominance in the big bang that supposedly created the universe. Hot plasma from the explosion cooled immediately after this event, forming the atoms and molecules that gave the normal states of matter. In space plasma still exists in abundance, emanating from the fusion reaction in the sun and others stars. In 1879 Sir William Crooke identified the existence of a fourth state of matter but it was not until 1929 that Dr. Irving Langmuir first described an ionised gas as plasma [23]. Today the use of plasma has expanded into many areas of science and technology, such as IC manufacturing, and it is a part of frequently used daily items such as light bulbs and plasma screens. In nature the effect of plasma is seen during thunderstorms, when strong electric fields ionise channels of air that form the conductive paths to earth known as lightning. The importance of plasma will grow even more in the future as more research is undertaken into fusion and new methods of propulsion for space exploration.
3.1.2 Applications and Existence

The conductivity, the effects of both magnetic and electric fields, and the efficiency it offers when used as a source of radiation, all make plasma an attractive medium for various applications and natural events [23,24]. These can be divided into a number of groups, as discussed in the following sections.

3.1.2.1 Space Plasmas and Natural Occurrences

Although of minor importance for the present research the occurrence of natural forms of plasma are also worth mentioning:

1) Ionospheres and magnetospheres of planets
2) Interstellar and intergalactic medium, astrophysical jets
3) Solar and stellar winds, and atmospheres
4) Corona and aurorae
5) Space and astrophysical plasmas
6) Shocks, flux ropes and coronal mass ejections
7) Lightning and ball lightning

3.1.2.2 Fusion Plasmas

Nuclear fusion [25] is the energy-producing process that takes place continuously in the sun and all other stars. In the core of the sun, at temperatures of 10-15 million degrees Celsius, hydrogen is converted into helium, providing enough energy in the form of heat and light to sustain life on earth. On earth different fusion reactions are being explored as a future energy source for electrical generation, with the easiest reaction occurring between the nuclei of the two heavy isotopes of hydrogen - deuterium (D) and tritium (T). The fuel is heated to over 100 million degrees Celsius, at which point its state changes to plasma. Electrons are stripped away from the atom leaving behind only the nuclei required for the fusion process.

3.1.2.3 Technology

The diversity of levels of ionisation, temperature, pressure and density, and whether they are single or multi species, makes plasmas appear in numerous commercial and technological applications. The following is a small list of some of those where plasmas are already employed:
The Generation and Physics of Plasma

1) Surface processing: etching, thin film deposition, welding, cutting, hardening, fabric treatment and cleaning
2) Volume processing: flue gasses electron scrubbing, waste treatment, metal recovery, chemical and toxic waste treatment
3) Chemical synthesis: ceramic powders, diamond film synthesis, electron beam driven fuel and paint injectors
4) Lasers: ablation plasmas, laser and plasma wave undulation for femtosecond pulses of x-rays and gamma rays
5) Displays: field-emitter arrays and plasma displays
6) Radiation processing: water purification and plant growth
7) Isotope separation
8) Energy converters: MHD generators and thermionic energy converters
9) Switches: electric and pulsed power
10) Medicine: sterilization and meat pasteurisation
11) Propulsion
12) Beam sources
13) Material analysis

In addition, many devices are based around plasma, including:

1) Plasma opening switches
2) Vacuum electronics
3) Plasma displays and light sources
4) Plasma armature railguns
5) High power switch tubes (thyatrons, ignitrons and klystrons)
6) Plasma focus and pinch plasmas for x-ray and beams
7) Compact x-ray, gas and free electron lasers
8) Pulsed power systems
9) Electron cyclotron resonance reactors
10) Photon accelerators and plasma lenses for particles accelerators
11) Incinerators and flames
3.2 Plasma Physics

This section describes some of the plasma physics taken from Brown [26] that involve important plasma properties such as density and temperature. The density of plasma is normally described by the plasma electron density $n_e$, the plasma ion density $n_i$, or the neutral particle density $n_n$. Particle density is normally expressed in units of cm$^{-3}$ except in equations where it is in m$^{-3}$.

3.2.1 Percentage Ionisation

The percentage ionisation is derived from the ratio of the ion density $n_i$ to the combined ion and neutral particle densities by

$$\text{percentage ionisation} = \frac{n_i}{n_i + n_n} \times 100\% \quad (3.1)$$

When the percentage ionisation exceeds 10% the plasma is classified as highly ionised, with the typical characteristics of plasma dominating over the material properties. At lower levels of ionisation the interaction of the charged and neutral particles must be considered.

3.2.2 Distribution Functions

Plasma particles are continually in motion, either under the influence of an external field or due to a natural diffusion process. They have a kinetic energy of motion that allows them to be represented by a velocity distribution function $f(v)$, that in the absence of any external forces and assuming a Maxwellian distribution is given by

$$f(v) = n \left( \frac{m}{2\pi kT} \right)^{\frac{3}{2}} e^{-\frac{mv^2}{2kT}} \quad (3.2)$$

where $m$ is the particle mass, $n$ is the particle density, $k$ is Boltzmann's constant (1.38x10$^{-23}$ JK$^{-1}$) and $T$ is the plasma temperature (in Kelvin). Plasma temperatures are usually referred to in electron volts (1 eV = 11600 K).
The mean energy of a particle $\bar{E}$ is

$$\bar{E} = \frac{1}{2} kT$$

(3.3)

which in an isotropic plasma is divided equally between the three possible degrees of freedom.

The mean speed of a particle $\bar{v}$ in plasma is given by

$$\bar{v} = \frac{8kT}{\sqrt{\pi m}}$$

(3.4)

and its equivalent rms particle speed $v_{rms}$ is,

$$v_{rms} = \sqrt{\frac{3kT}{m}}$$

(3.5)

### 3.2.3 Plasma Sheath and Electric Field Shielding

A plasma (or cathode) sheath forms around an electrode that is biased with a negative potential. Ions are attracted towards the cathode surface, forming a region of positive space charge that eventually prevents further ions from reaching the cathode. This region is termed the sheath, and electrons or ions must have sufficient energy to cross it before conduction can take place. In fact only ions either in the sheath or on its edges (transition region) are drawn towards the cathode, outside it the ions are shielded from the electric field and remain unaffected by the presence of the cathode. It is this effect that limits the bipolar conduction in section 2.4.1. Almost all the voltage drop occurs across this sheath with the potential distribution as illustrated in Fig. 3.1.
3.2.3.1 The Debye Length

The distance over which the sheath shields the electric field is commonly known as the Debye length $\lambda_D$, and is given by

$$\lambda_D = \frac{\varepsilon_0 kT}{\sqrt{e^2 n_e}}$$

(3.6)

where $\varepsilon_0$ is the permittivity of free space ($8.85 \times 10^{-12} \text{ CV}^{-1}\text{m}^{-1}$).

3.2.4 Plasma Frequency

A change from plasma neutrality brought about by some outside influence is restored by an internal force that gives rise to oscillations at the electron plasma frequency $\omega_{pe}$, generally termed the plasma frequency, where

$$\omega_{pe}^2 = \frac{e^2 n_e}{\varepsilon_0 m_e}$$

(3.7)

whilst the ions oscillate at the ion plasma frequency $\omega_{pi}$

$$\omega_{pi}^2 = \frac{Z^2 e^2 n_i}{\varepsilon_0 m_i}$$

(3.8)
3.2.5 Magnetic Field Effects

A particle in a plasma with a charge $q$ and a velocity $v$ perpendicular to a magnetic flux density $B$ experiences a force $F$ that is perpendicular to both the velocity and the magnetic field given by

\[ F = Bqv \]  \hspace{1cm} (3.9)

3.2.5.1 Cyclotron Radius

The force of equation (3.9) moves the particles through a circular orbit that has a radius called the cyclotron or gyro radius $r_p$ given by

\[ r_p = \frac{mv}{qB} \]  \hspace{1cm} (3.10)

3.2.5.2 Cyclotron Radial Frequency

The frequency at which cyclotron motion occurs is called the ion or electron cyclotron radial frequency $\omega_p$ given by

\[ \omega_p = \frac{eB}{m} \]  \hspace{1cm} (3.11)

3.2.6 Particle Flow

Plasma particles flow like any normal gas, but because they are charged a macroscopic current can arise. In plasma, unlike a metal, it is not just electrons that give rise to current flow as the ions are also free to move. The resultant current density $J$ is given by

\[ J = J_i - J_e = n_e v_e(v_i - v_e) \]  \hspace{1cm} (3.12)

where the drift velocities of the electrons and ions are $v_e$ and $v_i$ and it is assumed that the positive ions are singularly charged such that the ion and electron concentrations are equal.
3.3 Plasma Generation

Plasma is generated in the gaseous state, when inelastic collisions occur between atoms or molecules and electrons (electron impact ionisation) or photons (photon ionisation) with sufficient energy to eject electrons from the neutral atom, leaving behind a positive ion in a process called ionisation. There are several methods that can supply this energy, such as heating, compression, radiation by electric or magnetic fields, and bombardment by high-energy particles, as illustrated in Fig. 3.2 [27]. In the case of a solid, energy must first be supplied to vaporise and form the gas that is needed.

![Diagram of Plasma Generation](image)

Figure 3.2. Plasma generation

Thermal energy is normally obtained from flames by the exothermic chemical reactions of molecules involved in the process. Compressing a gas has the capability of heating it, whilst also increasing the probability of collisions by bringing the particles closer together. Another way of enhancing the probability is to inject beams of energetic particles into the gas, forcing them to collide with the gas particles and transferring kinetic energy to them. Neutral particles are often used for this purpose in
fusion applications, because they are unperturbed by the electric and magnetic fields that hold the plasma in position. Electric and magnetic fields can however be used to heat and accelerate electrons that then collide with gas particles, transferring their kinetic energy to them. In the following sections a number of plasma sources are described that use these principles of energy transfer.

3.3.1 Discharge Plasma Sources

One of the more commonly used methods of generating and even maintaining low temperature plasma is by applying an electric field to a neutral gas. Any gas, even the vapour emitted from the surface of a material, contains a number of free electrons and ions as a result of natural interactions with light rays and background radiation. These free charge carriers are accelerated by the electric field to velocities that are sufficient to create new charged particles when they collide with neutral gas particles. Secondary electrons and ions arising from this process lead to further collisions, resulting in an avalanche affect that produces dense and sustainable plasma. The electric field can be dc, ac, pulsed, rf, microwave or a dielectric barrier discharge.

The Bohr model of an atom (see Fig. 3.3) describes a single electron of mass $m_e$ and charge $-e$ orbiting a positive nucleus with charge $+Ze$.

![Bohr model of the atom](image)

Figure 3.3. Bohr model of the atom

The electrostatic force between the positive nucleus and a negative electron opposes the effect of the centripetal acceleration holding the atom together, such that

$$\frac{m_e v^2}{r} = \frac{Ze^2}{4\pi \varepsilon_0 r^2}$$

(3.13)
It is this force that must be overcome if the electron is to be freed from the atom. Except for the simplest of atoms, the hydrogen atom, electrons are actually found in different orbits around the nucleus, with each having different energy levels. If an electron is to move between two such levels, energy must be either supplied to the atom or emitted in the form of light or heat, as shown in Fig 3.4.

\[
\begin{align*}
\text{Energy} & \quad E = hf \\
n=1 & \quad n=2 \quad n=3 \quad n=4 \quad n=5 \quad n=\infty
\end{align*}
\]

**Figure 3.4.** Energy levels in an atom

In order to ionise an atom, the impacting electron or photon needs to have adequate energy to promote the orbiting electron from the outermost energy level to infinity. This would be the first ionisation energy \( E_1 \), given by

\[
E_1 = e\phi_1 \tag{3.14}
\]

where \( \phi_1 \) is the first ionisation potential. The second ionisation energy removes the next electron that is normally in the adjacent orbit closer to the nucleus, and consequently needs more energy for it to be released from the atom, and so on.

### 3.3.1.1 DC Discharges

Non-thermal plasma is created inside a closed vessel by application of a dc discharge across the gas between two internal electrodes. Depending on the applied voltage and the current a variety of plasmas can be produced, from a range of discharges such as a Townsend or dark self-sustained discharge through to an arc formation \([27,28]\), as seen in Fig 3.5.
A common example of such a discharge is the streetlight, where a normal glow discharge in a gas emits a bright light. A positive ion is accelerated by the electric field to the cathode, where it evolves secondary electrons that are subsequently accelerated to very high energies. Upon colliding with the atoms and molecules in the gas these transfer some of their energy by processes such as excitation, dissociation and ionisation whilst the remaining energy is emitted as light.

### 3.3.1.2 Pulsed Discharges

Pulsed discharges are used in plasma generation because of a number of advantages that they offer over the dc discharge:

1) the source can be operated at a higher power for the short duration,
2) controllability is provided by varying the duty cycle,
3) a reduction in effects such as thin film deposition from variations in the neutral gas composition between the plasma boundary and centre.

One such plasma source is the plasma focus, shown in Fig. 3.6, which consists of two coaxial electrodes separated by a hat-shaped insulator at one end whilst the other is open-ended. An electromagnetic valve releases gas into the space between the
The Generation and Physics of Plasma

electrodes and the electric field generated by the energy stored in a capacitor causes electrical breakdown in the gas.

![Plasma focus during run down (a) and pinching (b)](image)

Figure 3.6. Plasma focus during run down (a) and pinching (b)

An umbrella-like region of plasma is driven along the electrodes by an azimuthal magnetic field towards the open end, where the plasma pinches inwards with a decreasing inner radius and a subsequent concentration of the magnetic field, giving the high power density (TW cm⁻²) associated with the plasma focus. Applications for this plasma source range from pulsed neutron sources for analysis of the volatile components in coal to soft x-ray radiation in lithography and microscopy.

3.3.1.3 Microwave Discharges

Discharges excited and sustained by high frequency electromagnetic fields are of interest for plasma production in both technical and industrial applications. Many use microwave discharges at a frequency of 2.45 GHz and a wavelength of 0.12 m that is comparable to the dimensions of the container. They give rise to only very small electron and ion oscillations, making collisions between the ions and either the container walls or the cathode unlikely, so that energy is only absorbed into the gas as a result of collisions between the electrons and neutral particles. The efficiency of this process is dependent on the frequency of the collisions, which in turn depends on the gas pressure and composition. Electromagnetic waves with frequencies below the
electron plasma frequency (see section 3.2.4) will be reflected, but penetration will still occur up to the skin depth that is normally a few centimetres.

3.3.1.4 Radio Frequency (RF) Discharges

Radio frequency discharges are usually in the 1 – 100 MHz frequency range and their wavelengths are large in comparison to the dimensions of the plasma chamber. At low frequencies the field accelerates the ions to the cathode surface, thereby emitting secondary electrons that enhance the ionisation process. As the frequency increases, the ions and electrons begin to fail to reach the cathode, so that the process becomes limited to collisions between the electrons and neutral particles.

Energy is transferred to the plasma by either capacitive ‘E’ or inductive ‘H’ coupling. The first of these uses two parallel electrodes separated by a few centimetres, either in direct contact with the plasma or insulated by the container walls that together produce an rf electric field across the plasma region. In the second method a magnetic field is generated inside the plasma by current flowing in a coil or wire positioned either inside or outside the plasma.

3.3.1.5 Dielectric Barrier Discharges

The dielectric or silent barrier discharge is a special type of ac or rf discharge that operates at a pressure of between 0.1 and 10 bar. Siemens used this type of discharge in 1857 for the generation of ozone from air, and even today it is still used for the ozone treatment of water. A discharge is generated between two electrodes that have a gas-filled dielectric barrier between them at a voltage between 1 and 100 kV and a frequency between 50 Hz and 1 MHz. A large number of streamers, whose current is limited by the dielectric properties, deposit charge onto the dielectric surface, and remains there to compensate for the externally applied electric field. The lifetime of the streamers is very short (1 – 10 ns), with resulting electron densities of $10^{14} - 10^{15}$ cm$^{-3}$ and electron energies of 1 – 10 eV. Other applications for this type of discharge include methanol production, thin film deposition, remediation of exhaust gases, plasma displays and pumping CO$_2$ lasers.
3.3.2 Beam Plasma Sources

Plasma can be generated by the interaction of a beam of electrons or photons with either a gaseous or solid material, as discussed below.

3.3.2.1 Electron Beam Ion Source (EBIS)

The EBIS [26] produces multiple charged ions through a process of multiple electron impacts, where each impact causes a single electron to be removed from the atom or ion. The process involves the production of an electron beam that collides with a gas to create single charged ions, which are then contained by an electric potential ion trap for a sufficiently long time for multiple collisions and ionisations to occur. This is a complex and expensive device, whose applications are limited to investigative studies of electron impact ionisation, spectroscopy and the nuclear properties of highly charged ions.

3.3.2.2 Beam Ion Source (BIS)

The EBIS generates multiple charged ions by electron impact ionisation only and the beam itself does not actively interact with the plasma. In the BIS the main ionisation process is a beam-plasma discharge [26], in which microwave radiation and electron cyclotron resonance heat the plasma electrons to a temperature sufficient for ionisation. The microwaves are generated within the plasma by its interaction with the electron beam, producing an effective plasma source in which the microwave generation and ionisation by the heated plasma electrons occur in the same place.

3.3.2.3 Laser Beam Ions Source

The interaction of a high-powered laser beam focused to a small point on a solid surface gives power densities that exceed $10^8 \text{ Wcm}^{-2}$ [26]. The light penetrates the surface, where the electron density is low, until it is fully absorbed at the point where the electron plasma frequency equals the laser frequency. Light absorption at this point rapidly heats the solid, creating a vapour that is ionised by photon and hot electron collisions to produce dense hot plasma that expands outwards. A very dense plasma plume explosively ablates the material, as the plasma expands along the easiest direction, which is usually perpendicular to the surface. As the plasma expands the electron density reduces, until eventually it reaches a level where the
laser again penetrates and further heating occurs. The plasma character depends on the type of material and the laser power density. Lasers commonly used are the Nd:YAG and CO₂ with respective wavelengths of 1.06 and 10.6 μm, with the latter being the most useful for plasma heating. Improvements in laser technology and costs are making this plasma source more attractive, with its potential as a single ion source in a cyclotron, for ion implantation and it can also be easily used for the POS.

3.3.3 PIG Ion Source

The PIG ion source gained its name from the Penning or Philips Ion Gauge. Electrons emitted by cathodes located at the ends of a tubular anode structure, are accelerated into the hollow anode as a beam, where they become trapped axially by an electric field and radially by a magnetic field. This beam also ionises a gas supplied to the tubular structure forming dense plasma from which the ion beam is extracted through slits in the anode walls.

3.3.4 Electron Cyclotron Resonance (ECR) Ion Source

The ECR is used in the production of highly charged ion beams for accelerators and nuclear physics experiments. Several impacts with energetic electrons are made possible, by momentarily confining the plasma in a magnetic field producing high charged ions. Optimisation of this ionisation process is accomplished using ECR heating, where an electromagnetic field at the cyclotron frequency of the electrons in the magnetic field is radiated into the plasma. At this frequency energy is efficiently transferred from the wave to the electrons in the plasma.

3.3.5 Other Plasma Sources

There are many other plasma sources that are used for specific applications, such as in MHD thrusters and ion engines for space propulsion, neutron production in fusion experiments and in the radiation of x-rays, microwaves etc. This chapter has provided only a small selection of the available sources but this is sufficient to show their potential. In the next chapter the plasma sources used in POS experiments are discussed in more detail.
4 PLASMA SOURCES FOR THE POS

It has been shown both experimentally [29] and theoretically that the plasma source for a POS needs to fill the region between the two coaxial electrodes with plasma at a sufficient density, velocity, mass, charge and spatial distribution to provide a short-circuit during the conduction phase (equation (2.27)), and to achieve the large bipolar threshold current (equation (2.4)) needed before opening can begin. Additionally, the erosion and enhanced erosion phases (equations (2.30) and (2.31)) of the opening process are also dependent on the plasma parameters. The plasma source is thus a key component of any POS that needs optimising to achieve maximum switch performance. A number of different sources that have been used throughout the world are discussed below [4].

Flashboards and carbon plasma guns were the plasma sources used in early POS research, where a simple, inexpensive and yet effective source was needed. In a small POS the carbon gun is the normal choice, however as the POS size increases a large number are needed. The alternative source was the flashboard that, with its large surface area, could fill a large POS. In recent years the introduction of lasers and the development of new gas breakdown techniques has led to a new generation of sources, which produce clean, hotter and denser plasmas. Unfortunately, these sources are often both expensive and complex, and they have the dangers inherent in the use of these technologies.

4.1 Flashboards

Fig. 4.1 shows two typical flashboards used at Loughborough* that were produced by etching a PCB board to remove the majority of copper from the high voltage side and leave behind a number of chains. Fig. 4.1(a) is a double-sided PCB with the reverse side left untouched to provide a current return path. Three such flashboards were arranged around the outside of a POS with a mutual separation of 120°, to inject plasma through grids in the anode towards the cathode.

* Research by H R Stewardson, Research Associate at Loughborough University
In essence this type of flashboard comprises a number of parallel-connected spark gap chains located on an insulator surface [4,30-34]. A thin layer of graphite is coated on the surface of each of the gaps using either a pencil, as for Fig. 4.1(b), or a graphite based varnish. In use, normally either a spark gap or a nail switch closes, to discharge the energy stored in a capacitor bank and to apply a high voltage pulse across the flashboard surface. Electrons loosely attached to the molecules on the surface of the dielectric initially create a small current across the board. Resistive heating and surface ablation remove and vaporise dielectric molecules, to create a vapour with free electrons that are accelerated by the electric field to speeds associated with a high kinetic energy. These collide with the dielectric atoms and molecules, transferring their kinetic energy and causing ionisation to occur. The ionised vapour enhances the discharge current, until a surface flashover occurs that produces the dense plasma that is needed.

The discharge current $I$ that flows in opposite directions on the two sides of the flashboard produces a strong linear magnetic field $B$ close to the surface of the board [30], as illustrated in Fig. 4.2. This interacts with the moving charged particles on the surface of the flashboard to produce a $\mathbf{J} \times \mathbf{B}$ force that propels plasma away from the surface. It is then normally directed through grids in the anode towards the cathode to fill the POS switch region. The main advantage of the flashboard is that the large
surface area is capable of filling a large POS with dense plasma, although the heat from the flashover eventually damages the boards by breaking the copper chains away from the surface.

4.1.1 Characterisation Using Spectroscopy

Spectroscopy is a method whereby light emitted from a flashboard is broken down into its individual frequency components and is analysed to determine the type of ions and atoms that are present and their relative densities. The plasma produced by a flashboard is assumed to be predominantly carbon, emanating from the graphite coated on the surface, which is confirmed by monitoring emissions in both the visible and ultraviolet regions. These have been compared experimentally [31] to the intensity ratios of known carbon emission lines, with very low levels of C (carbon atoms) and C$^{3+}$ ions being detected, although the plasma is predominantly C$^+$ and C$^{2+}$
carbon ions. The velocity of the plasma away from the surface is typically $10 - 11 \, \text{cm} \, \mu \text{s}^{-1}$ and that across the surface is $1.7 \, \text{cm} \, \mu \text{s}^{-1}$. Although the flashboard chains are copper no detectable traces of this appear, even at a sensitivity 1000 times higher than that used to detect the carbon ions. An important observation is that the distribution and velocity of plasma across the surface is initially greater at the positive electrode end.

The intensity of light emitted indicates an electron density of $(1.5 \pm 0.5) \times 10^{13} \, \text{cm}^{-3}$ and a temperature of $3.5 \pm 0.5 \, \text{eV}$. Models and experiments have together shown that the plasma composition is approximately 60% $\text{C}^+$ and 40% $\text{C}_2^+$.

### 4.1.2 Optimisation of Flashboards and Driving Capacitor

The flashboards used at Sandia National Laboratories [32] comprise a double-sided stripline on a Kapton substrate, with gaps etched on the high voltage side and coated with Aerodag carbon paint. Experiments there have confirmed a number of advantages and disadvantages of flashboards.

**Advantages:**

1) the energy stored in the capacitor discharges through a series of gaps thereby increasing the energy efficiency,

2) the strip line is very thin, enabling the source to be fitted into a small space.

**Disadvantages:**

1) the large surface area gives a high inductance that leads to a greater voltage stress across the surface. A significant problem is voltage punch-through and arcing between the board and nearby conductors,

2) performance variations occur depending on the dielectric surface preparation, Aerodag thickness, gap width and flashboard position relative to nearby conductors,

3) poor turn-on for some of the chains at low voltage,

4) variations in plasma density and velocity across the flashboard.
Photography using an open-shutter camera has shown that at low voltage all the chains do not initially flashover unless a conditioning shot is performed at high voltage. After this the flashboard can be operated at a low voltage, with all the chains turning on, although a variation in the intensity of light emitted from the different chains is observed. Decreasing the gap resistance by applying three or more layers of Aerodag gives the most uniform light output.

A number of modifications were made to the original design to improve the turn-on reliability, such as adding carbon resistors in series with each chain, decreasing the number of chains to achieve a higher current in each chain and increasing the size of the driver capacitor. The resistors were added to maintain a residual voltage on the remaining chains after the first had flashed over, since the first to turn-on normally takes all the current, collapses the voltage and prevents the others from turning on. All the chains then lit uniformly, but the variation in the density of plasma ejected between the top and bottom of the flashboard increased. Reducing the number of chains improved the turn-on uniformity, but decreased the plasma velocity and reduced the output at the positive end of the board. Finally an increase in capacitance (from 0.1 to 0.6 \(\mu\)F) removed the variation in plasma output from end to end, increased the plasma velocity from 10 to 20 cm \(\mu\)s\(^{-1}\) and turned all the chains on uniformly.

4.1.3 Flashboard Plasma Speed

Maxwell Laboratories [33] demonstrated that the distribution of plasma from a typical flashboard reaches a peak for only a small fraction of a microsecond, which makes the optimal triggering of the POS very difficult. The normal flashboard design, with the current return sheet on the reverse side of the board, produces plasma with a fast flow velocity of between 15 and 20 cm \(\mu\)s\(^{-1}\). The modified design, described below, gives a flow velocity between 3 and 5 cm \(\mu\)s\(^{-1}\), thus greatly extending the duration of the optimum triggering window.

4.1.3.1 Slow Plasma Flashboard

Although this has the same arrangement of chains and gaps as the previous flashboards, the current return path is now positioned at the front of the plasma side, as shown in Fig. 4.3(a). In the normal arrangement of Fig. 4.3(b) the return path is
behind the plasma side, thereby contributing to the $\mathbf{J} \times \mathbf{B}$ force that accelerates the plasma. In the modified design the return path produces a magnetic field that attempts to confine the plasma to a region near the flashboard.

![Diagram of plasma flashback arrangements](image)

**Figure 4.3.** Slow (a) and fast (b) plasma flashback arrangements

The magnetic field generated by the discharge current in the wires prevents the plasma from expanding freely outwards until the current in the wires is zero, and also reduces the speed at which the plasma is ejected.

### 4.1.3.2 Medium Speed Plasma Flashboard

An alternative approach [31] to prolonging the optimum triggering time is to design the return path in such a way that the magnetic field has an insignificant effect on the plasma. In the design illustrated in Fig. 4.4, the return path is parallel to the chains, so that the magnetic field it produces at the plasma surface is negligible.

The 100 nH inductors serve to decouple the six chains and so improve the uniformity of the initial breakdown, with the velocity of the first peak of plasma being measured as 10 cm $\mu$s$^{-1}$.  

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4.2 Carbon Guns

The carbon gun is a coaxial design in which the inner electrode (cathode) and either the outer electrode (anode) or a cable sheath are separated by a carbon-based insulator [4,34-37]. A high-voltage pulse produces a flashover between a sharp point of the cathode and the edge of the anode across the surface of the insulation. In the initial stage of this, the loosely attached electrons on the insulator surface conduct a small current. Resistive heating from the current vaporises the insulator molecules, to produce a region of dense vapour close to the surface. A strong electric field ionises the vapour, to produce a medium for the large discharge current that is observed experimentally. Plasma ejected from the surface by thermal expansion is accelerated by interaction of the strong magnetic field with the moving charged particles. Plasma flow velocities up to 10 cm µs\(^{-1}\) were achieved, with electron densities between \(10^{12}\) and \(10^{17}\) cm\(^{-3}\) and electron temperatures of 10 to 15 eV. Various types of carbon guns used in POS experiments are discussed in Chapter 5, together with a number of theoretical models.

4.2.1 Comparison of the Flashboard and Carbon Gun POSs

Two interferometry techniques were used to compare the performance of a POS, called Hawk, at the NRL when using either flashboards or carbon guns [37]. The first
technique used a He-Ne laser (633nm) and an acousto-optic modulator for heterodyne phase detection. The second used a differential detection scheme coupled with a sophisticated vibration isolation system. Plasma produced by the carbon gun was shown to have a slower velocity (up to 3 cm $\mu$s$^{-1}$) than that produced by the flashboard (up to 30 cm $\mu$s$^{-1}$), allowing a correspondingly longer time delay between the plasma guns being fired and the POS driven. The flashboard dielectric is a polyamide (C$_{22}$H$_{10}$N$_2$O$_5$), and the plasma ejected consists of C$^+$ (24.4 eV) and C$_2^{2+}$ (47.9 eV) ions. On the other hand, the substrate for the carbon gun is often PTFE (C$_2$F$_4$), and the plasma produced is a combination of C$^+$ and unwanted fluorine ions F$^-$ (35.0 eV). Observations showed that the carbon ions initially produced by the carbon guns are further ionised during the conduction phase of the POS to C$_2^{2+}$ ions.

4.3 Gas Guns

A strong electric field applied to a gas accelerates free electrons and ions that are present in any gas to speeds that are sufficient to ionise the neutral particles when they collide. The gas used in these guns is typically argon, neon, hydrogen or air. Two forms of this gun are considered below, the first being a coaxial gas puff gun [38] and the second using the inverse punch effect [39].

4.3.1 Coaxial Gas Puff Gun

The coaxial gas puff gun is a fast acting electromagnetic valve that vents gas into a tubular structure comprising a plasma generation chamber and a graphite coaxial electrode, as shown in Fig. 4.5. The opening time of the valve ranges from 20 to 800 $\mu$s, during which it injects nitrogen at a pressure between $5 \times 10^{-4}$ and 0.5 Pa. Two sparks gaps, located 180° apart near the gas inlet, produce high energy sparks to ionise the gas.
The plasma is accelerated along the coaxial arrangement by $\mathbf{J} \times \mathbf{B}$ forces produced by interaction between the radial plasma currents and the azimuthal magnetic field generated by the electrode currents. As the plasma nears the end, a more complicated process takes over that also includes shock propagation and particle collisions to produce high velocity plasma. The current flowing through the plasma further heats it and causes a shock wave to propagate down the gun. This deposits energy into a thin layer of gas immediately in front of the flowing plasma, ionising the gas to produce more hot plasma.

The pulser circuit for this plasma gun contains four parallel-connected capacitors totalling 150 $\mu$F and charged to 4 kV. The current discharged into the coaxial electrodes through a low inductance switch reaches a peak of 23 kA, with a quarter cycle time of 70 $\mu$s. The fast valve action is triggered by the critically damped discharge of two further capacitors into a solenoid. Plasma diagnostics gave a flow velocity of 3.9 cm $\mu$s$^{-1}$, electron temperatures between 10 and 20 eV and a plasma density between $5 \times 10^{13}$ and $7 \times 10^{14}$ cm$^{-3}$, depending on the gun voltage.

### 4.3.2 Inverse Pinch

The inverse-pinch plasma source [39] used for the Hawk POS at the NRL is the inverse of the conventional gas puff z-pinich and produces a radially expanding plasma ring. The device is mounted inside the central conductor (cathode) of the POS.
coaxial electrode arrangement. A pulsed electromagnetic valve fills the gun with a gas such as argon, neon, hydrogen or air and after a time delay of about 350–700 μs, a closing switch discharges current into it from a 20 kV, 7.4 μF capacitor bank. This ionises the gas, producing a discrete ring of plasma that expands radially outwards, with no plasma in its wake, and passes through semi-transparent windows in the cathode walls.

4.4 Laser Plasma Guns

Sources based on a flashover, such as in carbon guns and flashboards, typically have poor repeatability of the plasma properties, since the insulator materials are gradually eroded and the extreme heat damages the electrodes and insulation. The plasma itself is often impure and "dirty", containing material from the gun electrodes and insulation. However the use of a CO$_2$, Nd: YAG or ruby laser overcomes these problems and still produces the highly dense plasma that is required.

An intense laser beam focused upon the surface of a solid produces a power density exceeding $10^8$ W cm$^{-2}$ [40]. This penetrates the material surface where the electron density is low, but it is absorbed before the electron plasma frequency (see section 3.2.4) becomes equal to the laser frequency. The energy absorbed rapidly vaporises the insulator material and, together with photon collisions, ionises the vapour. Thermal pressure explodes a very dense plasma plume that is normally perpendicular to the surface. As the plasma expands outwards its electron density decreases, to allow further light penetration that heats and ionises the plasma even more.

Akiyama et al [40,41] used a Q-switched Nd:YAG laser with a pulse width of 7 ns and a maximum repetition rate of 10 pps to produce plasma. A 4 mm thick, 4 cm diameter, carbon plate was irradiated by a 400 mJ pulse of light at an incident angle of 45°, producing a typical flow velocity of 5 cm μs$^{-1}$ and a plasma density of $3 \times 10^{14}$ cm$^{-3}$. An advantage of this technique is its ability to repetitively fire a POS at up to 10 times per second, although the shortest opening times and highest repeatability are achieved at below $3\frac{1}{3}$ times per second. The lifetime of a fixed target is typically 1500 shots before a hole is burnt in the carbon plate. Rotating the
target and using mirrors to move the beam between shots to distribute the ablation over a wider area increases the lifetime to several hundreds of thousands of shots.

Ruby lasers and CO$_2$ laser [42] have both been used in POS experiments, with the target material again being a carbon plate. The CO$_2$ laser produces a higher energy 5 J laser pulse with a peak power of 5 5 MW, a wavelength of 10.6 µm and a pulse width of 1 µs. The higher energy in this beam ionises the material to produce mainly C$_2^+$ carbon ions with a velocity of 6.5 cm µs$^{-1}$. The normal choice is the CO$_2$ or Nd:YAG laser because the longer wavelength heats the plasma more.

The advantages of using a laser-produced plasma source are:

1) high plasma density, ionisation and flow velocity
2) multiple firings
3) directional plasma stream
4) versatility since any solid material is a potential plasma source
5) long lifetime
6) good repeatability

Unfortunately the additional complications, cost and extra safety precautions needed for a laser make it unattractive for a research laboratory. Since the present research needed a simple and inexpensive solution, the carbon gun is investigated in more depth throughout the remainder of this thesis.
5 CARBON PLASMA GUNS

5.1 General Description

Carbon guns are used in the research laboratory because they are an inexpensive and reliable source of plasma for both POSs and other plasma switches. The carbon gun has a central electrode surrounded by a carbon based tubular insulator, such as PVC or PTFE, and finally by an outer electrode or sheath. A high voltage pulse applied between the two electrodes results in a flashover discharge across the insulator surface that vaporises the molecules close to the surface. Free electrons in the vapour and on the surface are accelerated to high speeds by the strong electric field between the electrodes, before they collide with neutral particles. Energy transferred during these inelastic collisions ejects the outer orbiting electron from the atoms, leaving behind positive ions and freeing secondary electrons in a process that is termed ionisation. Multiple ionisations produce plasma that is propelled away from the surface of the insulator by thermal pressure, and accelerated to high speeds by the interaction between the moving charged particle and the magnetic fields close to the gun.

The plasma mainly consists of single and double charged carbon ions, leading to the name carbon plasma gun that indicates the type of plasma produced. The term cable gun describes such a type of gun that uses a flashover across the insulation at one end of a section of coaxial cable. This is the simplest and cheapest form of carbon plasma gun, but unfortunately it produces a multi-species plasma contaminated by both chlorine and fluorine from the insulation. Alternative guns have been tested that use a more complicated arrangement, including coating of the flashover surface with graphite based paint. The solution proposed in this chapter and tested in Chapter 6 is a new type of gun, in which the cable insulation is exchanged for a replaceable hydrocarbon sleeve.

Information regarding the behaviour of plasma after being ejected from the carbon gun is imprecise, with only a small number of mathematical models being available to describe the plasma formation and its propulsion. A model for the expansion of
plasma from a flashboard using the magnetic field produced by the currents flowing across the surfaces of the board is therefore included, as the basis for the prototype carbon gun model given at the end of the chapter.

5.2 The Mendel Gun

One of the earliest carbon plasma guns was a complex design by Mendel [34], which was aimed at increasing the efficiency by using a conical coil for the outer conductor (anode), as seen in Fig. 5.1. Electrical energy from a capacitor is translated into magnetic energy stored in the gun inductance, which is initially small to allow the current to rise rapidly, and then ultimately large to store the greatest amount of energy. The inductance grows as the plasma expands outwards so that the length of coil in contact with the plasma increases.

![Diagram of the Mendel gun](image)

**Figure 5.1. Mendel gun**

The hard insulator between the outer and inner conductors of this gun is coated with a graphite-based paint. Broadband microwave emissions during the first half-cycle of the high voltage pulse indicated three surface flashovers of the graphite-coated insulator. High-speed framing photography showed the plasma accelerated by the magnetic field to be moving towards the end of the gun.

The gun needs two or three conditioning shots after each coating before the output reaches a reasonable level, but eventually the graphite paint becomes completely vaporised and the insulator is eroded. Erratic operation ensues, with subsequently
high levels of impurities in the plasma. Frequent recoating is necessary if this situation is to be avoided.

The pulser in Fig. 5.2 uses a sealed and pressurised spark gap SG to discharge the stored capacitor energy into the gun(s). A single 0.6 μF capacitor C and spark gap can supply three parallel guns, and incorporating additional capacitors can extend the system even further.

![Pulser circuit diagram](image)

**Figure 5.2. Mendel gun pulser circuit**

Any remaining energy on the capacitors after the experiment is discharged back through the charging resistors into the dump. A link called the “short”, as shown in Fig. 5.2, is then used to prevent voltage recovery inside the capacitor and the subsequent risk of electric shock. Discharging through this short may however result in damage to the components and circuitry.

A plasma detector that used a system of biased grids to remove electrons from the plasma and accelerate ions into a collector detected plasma 160 cm from the gun. The time of arrival of the peak collector current showed the majority of plasma to be travelling at 10 cm μs⁻¹. Spectroscopy then confirmed that the plasma consisted of 40% of both C⁺ and C²⁺ ions, with the remainder being a combination of C³⁺, C⁴⁺, H⁺
and F⁻ ions. Using the charge state and velocity of the plasma, a prediction of the electron temperature at between 10 and 15 eV was obtained. The plasma density at 30 cm from the gun was measured as $9 \times 10^{13} \text{ cm}^{-3}$.

5.3 Cable Guns

The benefits of the conical coil in the Mendel gun were found to be relatively small and an alternative simpler design was soon developed. This design also removed the need for the continual applications of graphite paint, by constructing the gun from the end of a section of coaxial cable.

5.3.1 Hawk Generator Cable Guns

The experiments at the NRL used between 12 and 36 cable guns to produce the high-density plasma ($\sim 10^{17} \text{ cm}^{-3}$) needed for a long-conduction POS [35]. They were constructed from sections of semi-rigid coaxial cable, with an inverted cone drilled into the end, as shown in Fig. 5.3. Energy stored in a capacitor is discharged across the Teflon ($\text{C}_2\text{F}_4$) insulation between the inner conductor and the sheath.

Plasma from the flashover expands outwards from the indented surface and is accelerated into the POS by magnetic fields self-generated by the current in the gun. A number of guns were arranged azimuthally in a ring, to distribute evenly the dense plasma that is produced. Although the result is a simple and cheap plasma gun, directional control is virtually impossible and, as the cable insulation erodes, the plasma contaminates with both fluorine and chlorine ions.

Figure 5.3. Cable gun used in Hawk experiments
5.3.2 ASO-X Generator Cable Guns

The cable guns in the ASO-X generator [4], illustrated in Fig. 5.4, are a development of the simpler guns used in the Hawk experiments that provide directional control of the plasma flow. The guns are terminated inside the POS anode, and comprise a copper wire central electrode 2.9 mm in diameter, passing through the centre of a polyethylene insulator with an outer diameter of 9.7 mm. A copper sheath is electrically connected to the POS anode, which in turn is connected to both the ground and the brass nozzle, and surrounds the insulation. The nozzle is drilled with a 3 mm conical hole to spread the plasma beam outwards and is mounted on the POS anode flush to the cable end. Eight guns were arranged with 45° separations to produce plasma of sufficient density.

![Figure 5.4. ASO-X cable gun](image)

The ASO-X circuit of Fig. 5.5 supplies two guns from a single 0.7 μF capacitor charged to 20-30 kV through a 5 kΩ charging resistor, with the gun side at ground potential. When the single triggered spark gap is fired, the high voltage side is forced to ground, supplying the centre electrode of the gun with a negative voltage pulse. The maximum amplitude of the current through the gun, as measured using a Rogowski coil, is 8 kA with a 1.6 μs quarter period.
The high electric field across the insulation surface between the copper wire and the grounded nozzle initiates a small discharge current. This vaporises and ionises the insulation, eventually producing a flashover that gives dense plasma that is ejected through the nozzle into the POS.

5.3.3 Modified Nozzle for the ASO-X

The ASO-X generator carbon gun was modified [43] with a new nozzle shape that could vary the direction of plasma injection. The brass nozzle was now shaped with a slanting hole at 30° to the normal, as shown in Fig. 5.6, and plasma could be injected upstream, downstream or azimuthally, as shown in Fig. 5.7.

Figure 5.5. ASO-X circuit schematic

Figure 5.6. Modified nozzle
The main conclusion from experiments on the ASO-X was that significant improvement in the POS voltage and impedance can be achieved by injecting plasma downstream towards the load end for a short-conduction POS and radially for a long-conduction POS. Injecting the plasma azimuthally is a compromise that gives a reasonable opening time in both cases.

Azimuthal injection is used to spin the plasma and to fill a wider area in an attempt to enhance the switch performance. An alternative arrangement that produces the same effect is to angle alternate guns so that they point clockwise and anticlockwise.

### 5.4 Model of a Carbon Plasma Gun

A 0-dimensional model of a single plasma gun by Rodriguez and Elizondo [44] is described in this section, having the arrangement of a coaxial carbon gun that is similar to the experimental prototype in section 5.6. The basis of their model is the conservation of energy and momentum, with microscopic analysis of the plasma behaviour avoided by considering it to be a moving mass of charge. The following sections describe the parameters and the basic set of equations used in the model, whose geometry is illustrated in Fig. 5.8.
5.4.1 Mass

The rate of change of plasma mass $M$ is assumed to be proportional to the current $I$, and given by

$$M = kI$$  

(5.1)

where $k$ is a constant of proportionality called the mass rate constant. Experimental data [45] estimated it to be $0.4 \times 10^{-6}$ kg C$^{-1}$ for copper and $2.0 \times 10^{-6}$ kg C$^{-1}$ for graphite, so that a 440 nF capacitor charged to 30 kV would erode about 26 $\mu$g of C or nearly $10^{18}$ electron-ion pairs.

5.4.2 Fraction Ionised

Plasma consists of only a fraction $F_i$ of the total particles being ionised, with the remainder being neutral particles, such that [44]

$$F_i = e^{-\phi_i / kT_n}$$  

(5.2)

where $\phi_i$ is the ionisation potential (see section 3.3.1) and $T_n$ is the initial temperature of the new material calculated later in section 5.4.5.
5.4.3 Velocity

The conservation of momentum is used to determine the acceleration of the plasma mass $M$ whose velocity is $U$

$$ MU + M\dot{U} = \left[ \frac{k}{m_i} \right] T x X M + \frac{\mu_0}{2\pi} \ln \left( \frac{r_o}{r_i} \right) I^2 - F_{ic} \left[ \frac{m_i}{e} \right] \frac{IU}{M} $$

(5.3)

where the ionisation factor $F_{ic}$, assuming bipolar conduction, is

$$ F_{ic} \geq \sqrt{\frac{m_e}{m_i}} \approx 0.7\% \text{ for } C $$

(5.4)

The first term on the left hand side of equation (5.3) is the net force acting on the plasma mass. The second term is mass loading to take into account the change in plasma mass from section 5.4.1. The three terms on the right hand side are respectively the hydrodynamic, magnetic and drag forces, assuming that the volume and length of the plasma are located at the centre of mass position $X$. The magnetic force is derived from the integral of $\mathbf{J} \times \mathbf{B}$ between the two electrodes, where the magnetic flux density $B$ at a radius $r$ between the two electrodes is

$$ B = \frac{\mu_0 I}{2\pi r} $$

(5.5)

The drag force in equation (5.3) results from friction between the plasma and the gun walls. Other contributions such as that between the plasma particles are assumed to be negligible, since almost all the plasma is moving in the same direction and collisions are infrequent.

5.4.4 Energy

The conservation of energy $W$ in this model is described mathematically by

$$ -W = F_{ic} \left[ \frac{m_i}{e} \right] I^2 U^2 + \frac{\mu_0}{2\pi} \ln \left( \frac{r_o}{r_i} \right) I^2 U + M \left( F_i - \frac{e \phi_i}{m_i} + C_V T_S \right) $$

(5.6)

where $C_V$ is the specific heat capacity and $T_S$ is the sublimation temperature.
The first term on the right hand side is the friction loss, the second is the work done by the magnetic propulsion and the third is the energy lost by the rate of mass increase. The energy used to ionise the new material is the most significant contribution to this final term.

5.4.5 Temperature

The plasma temperature is determined from the rate of change of thermal energy $W_{th}$ given by

$$W_{th} = \frac{3}{2} \left( \frac{k}{m_r} \right) T_S M + \left( \frac{m_i}{e} \right) HIU^2 - \left( \frac{k}{m_r} \right) TM \frac{U}{X} - (A\sigma_S)T^4$$  \hspace{1cm} (5.7)

where the first term is mass loading assuming that new ions are added at the sublimation temperature, the second is the wall friction loss and the third accounts for cooling as the plasma expands towards the end of the gun. The final term is the radiated heat from a black body whose area $A$ is $(\pi(r_2^2 - r_1^2))$, with the Stefan-Boltzmann constant $\sigma_S$ being $5.67 \times 10^{-8}$ Wm$^{-2}$K$^{-4}$. Solving equation (5.7) gives the temperature in terms of the thermal energy $W_{th}$ as

$$T = \frac{2}{3} \left( \frac{m_i}{e} \right) \frac{W_{th}}{M}$$  \hspace{1cm} (5.8)

Only the friction term in equation (5.6) heats the plasma to produce the thermal energy for equation (5.7), giving the initial temperature $T_n$ of new material as

$$T_n = \frac{2}{3} \frac{F_{nc}}{k} \frac{m_i^2}{e} \frac{U^2}{K}$$  \hspace{1cm} (5.9)

5.4.6 Initial Plasma Velocity

If the thermal energy evolved by the friction loss is used to create new plasma, the friction and mass loading terms on the right hand side of equation (5.6) can be equated, giving an initial plasma velocity $U_0$ of
Equation (5.10) gives a smaller speed (typically 1.3 cm μs⁻¹) than that measured, which is due to the acceleration produced by the neglected interaction between the magnetic field and the moving charged particles.

This model has provided some extremely useful information on the processes involved in the carbon plasma gun. It has shown the exchange of energy between that stored in the capacitor, to the mechanical and thermal energy losses in the gun and the kinetic energy transferred to the ejected plasma.

5.5 Model for Flashboard Plasma Expansion

The process by which plasma is accelerated away from the flashboard surface is similar to that occurring in the carbon gun. The simple model [30] of the flashboard plasma expansion described below assumes the plasma to be a conducting sheet, accelerated by \( \mathbf{J} \times \mathbf{B} \) forces acting at the centre of mass. The geometry is assumed to be planar, enabling these forces to be written as magnetic pressure differences.

5.5.1 Magnetic Field Calculations

The magnetic field produced by the flashboard is generated from a fixed sheet of current at the back of the flashboard and a moving sheet of current that is the expanding plasma. The magnetic field has components in the \( x \) and \( y \) directions of

\[
B_x = \frac{2I}{c_f a_f} \left[ \tan^{-1}\left( \frac{a_f + 2x}{2y} \right) + \tan^{-1}\left( \frac{a_f - 2x}{2y} \right) \right]
\]

\[
B_y = \frac{I}{c_f a_f} \ln \left[ \frac{(x - \frac{1}{2} a_f)^2 + y^2}{(x + \frac{1}{2} a_f)^2 + y^2} \right]
\]

(5.11)

where \( c_f \) and \( a_f \) are the separation and width of the sheets, \( x \) is the distance across the sheets and \( y \) is the distance away from the flashboard. Taking a line along the plane of symmetry of the current sheets (\( x = 0 \)) gives a magnetic field that simplifies to
as illustrated in Fig. 5.9. Note that when $y$ approaches zero the component $B_x$ approaches $\frac{2\pi I}{c_f a_f}$, which is identified as $B_0$ in Fig. 5.9.

\[
B_x = \frac{4I}{c_f a_f} \tan^{-1} \left( \frac{a_f}{2y} \right)
\]

(5.12)

The magnetic field outside the sheets has a non-zero value that is a maximum close to the sheets and decreases as the distance from the sheets increases. Hence, any plasma ejected from the moving sheet will pass initially through a region of strong magnetic field, during which it is rapidly accelerated to full speed.

5.5.2 The Plasma Model

The plasma sheet is divided into a massive and immobile sheet directly in front of the flashboard and a moving sheet. It is this second sheet that is the plasma expanding
outwards and whose mass is to be measured. The current is divided between the two sheets, with the fraction in the moving sheet represented by $\zeta$.

The equation of motion for the expanding plasma sheet at its centre of mass is

$$\left( \frac{M}{V} \right) \frac{dv}{dt} = \frac{\partial}{\partial x} \left( \frac{B^2}{8\pi} \right)$$  \hspace{1cm} (5.13)

where the plasma of mass $M$ occupies a volume $V$. The magnetic flux density $B$ is determined from equations (5.11) and (5.12), with the current multiplied by the factor $\zeta$. Importantly, the maximum velocity is reached rapidly after the initial current flow, and following this the velocity remains almost constant. The results obtained from this model are summarised as:

1) the terminal velocity of the plasma expansion is proportional to the current flowing through the plasma, and reaches a maximum of $70 \text{ cm } \mu\text{s}^{-1}$ when all the current is flowing through the moving plasma,

2) the plasma accelerates when close to the moving sheet, reaching a terminal velocity after the first $0.1 \mu\text{s}$ when $\zeta = 0.15$,

3) the duration of the acceleration is dependent on the fraction of the current flowing in the moving plasma. The maximum time for this period is $0.6 \mu\text{s}$ when $\zeta$ approaches unity.

5.6 Prototype Gun

A simple and inexpensive plasma source was required in the early stages of the present research, to investigate the principles of plasma generation using pulsed discharges and to develop the plasma diagnostic techniques described in Chapter 6.

5.6.1 Concept

A coaxial carbon gun, similar to the cable and Mendel guns described in sections 5.2 and 5.3, is the first prototype plasma gun described in this research. Conventionally the cable gun is used as the plasma source for small POSs, although the design inevitably involves erosion of the cable insulation. This is often a material such as
PTFE or PVC, so that the plasma is contaminated by a significant amount of both fluorine and chlorine. The concept of the new design is to replace the cable insulation by a hydrocarbon sleeve, so the plasma produced now consists of only carbon and hydrogen ions. Since the hydrogen ion is a single proton, it will rapidly recombine with an electron to produce hydrogen gas. The gun will thus produce almost pure carbon plasma.

5.6.2 Construction and Operation

The prototype carbon gun shown in Fig. 5.10 uses the hydrocarbon sleeve (shown in the photograph) to maintain electrical isolation between the inner electrode (cathode) and the outer electrode (anode). The cathode is a 2 mm diameter copper rod soldered to the inner conductor of a section of URM67 50 Ω cable. This passes through the centre of the insulator sleeve, ending 4 mm from the front surface, as shown in Fig. 5.11.

![Coaxial carbon plasma gun](image)

**Figure 5.10.** Coaxial carbon plasma gun.

The aluminium gun case is electrically connected to the cable sheath by a brass cable gland screwed into the aluminium case, which also grips the PVC outer cable insulation to increase the mechanical strength. The earthed case and the copper plate in Fig. 5.10 together act as the anode. The hydrocarbon sleeve extends over the cable...
insulation by approximately 30 mm, to prevent unwanted electrical breakdown between the two electrodes.

![Coaxial Carbon Plasma Gun Cross Section](image)

Figure 5.11. Coaxial carbon plasma gun cross section.

A high voltage pulse, from the pulser of section 5.6.3, causes a surface flashover across the inner surface of the sleeve between the end of the cathode rod and the copper anode plate. The heat from the discharge vaporises molecules close to the surface, which are then ionised by the strong electric field. Plasma expands outwards through a conical shaped exit hole that provides limited control of the plasma beam shape and direction. The strong magnetic field produced by the gun current close to the gun accelerates the ions to the measured speed (see section 6.4.5). A high vacuum (about $10^{-4}$ mbar) is necessary to allow the plasma to flow.

5.6.3 Experimental Arrangement

The prototype experiments were performed using the system described in Fig. 5.12. The controls and safety interlocks needed to perform the experiments successfully and in a safe environment are described in Appendix B. A vacuum in the region of $10^{-7}$ mbar is achieved by a two-stage vacuum system that incorporates a rotary vacuum pump and a diffusion pump as described in Appendix C.
Figure 5.12. System diagram
The pulser circuit of Fig. 5.13 applies a high voltage pulse (up to 20 kV) to the coaxial carbon gun, with the anode referenced at ground potential and the cathode supplied with a negative voltage. The dump and charge unit described in Appendix B comprises resistors, contactors S1 and S2, and the charging unit.

![Figure 5.13. Pulser circuit and dump/charger unit.](image)

The 1 µF 40 kV Maxwell capacitor shown in Fig. 5.14 is charged to a voltage \( V \), through the double-pole isolator contacts S1 and the 18 kΩ charging resistance. Once the required voltage is reached the isolator contacts are opened to isolate the circuit from the charger. The 200 kΩ aqueous CuSO₄ resistor, shown in Fig. 5.15, maintains a high impedance path to the laboratory ground to reference the system to a fixed voltage.

![Figure 5.14. 1 µF Capacitor with feedback voltage resistor divider.](image)
In early experiments the stored energy was dissipated through a closing switch termed the “nail switch”, in which the strip lines leading to the capacitor and gun are separated by several layers of Mylar. A weight released by the activation of a 12 V solenoid, drives a nail through the upper strip line and the Mylar layers, until electrical breakdown between the nail point and the lower strip line closes the switch. In the experiments described in section 6.4.2, the noise induced on the plasma probe signals by the nail switch closure was found to be excessively high, so to reduce this to acceptable levels the switch was replaced by the mechanically triggered spark gap SG in Figs. 5.16 and 5.17. Energising the 12 V solenoid releases the trigger electrode (a 10 mm round-ended brass bar embedded in a PVC disc), which falls between guide slots to land between the gap electrodes. Electrical breakdown occurs between the electrodes, thus closing the switch and discharging the stored energy from the capacitor into the gun before physical contact is made. The spark gap electrodes are made from brass, rather than aluminium or copper, because of the lower level of erosion and ablation caused by spark damage. A high voltage pulse is transmitted down the 120 mm wide copper strip line SL to the terminals on the vacuum chamber. The positive side of the transmission line is connected to the laboratory earth via the
vacuum chamber, forcing the other side to a high negative voltage. A short length of URM67 50 Ω cable feeds this pulse from the vacuum side of the terminal to the gun.

![Image](image.png)

**Figure 5.16.** Mechanically triggered spark gap.

![Diagram](diagram.png)

**Figure 5.17.** Spark gap closure.

The gun current discharged from the capacitor is recorded using the magnetic pickup probe P, shown in Figs. 5.13 and 5.18, which is located in a tunnel T of the strip line SL. An oscilloscope records the voltage induced in the coil by the magnetic field.
generated by the gun current. This signal, which is proportional to the rate of change of the gun current, is numerically integrated and scaled on a computer to give the original current waveform, as described in Appendix E.

![Image of carbon plasma gun]

**Figure 5.18.** Magnetic pickup probe.

### 5.7 Mechanical Strength

The first experiments highlighted a number of problems with the mechanical and dielectric strength of the materials. The high temperatures developed inside the gun degrade the hydrocarbon sleeves, making them hard and brittle (almost glass-like), with the deep cracks seen in Fig. 5.10 gradually developing on the flashover surface. Plasma is still produced, but the amount is reduced until eventually the insulator fractures and the arc erodes the aluminium on the inside of the gun case, as seen in Fig. 5.19. The material used throughout the majority of the experiments was polypropylene, which lasted for 20 – 30 shots before any serious reduction in performance. This was sufficient for the preliminary experimentation and the availability of this material made it an attractive choice. High-density polyethylene (HDPE) proved to be slightly more durable and lasted for over 30 shots.
The connection between the inner conductor of the cable and the cathode rod introduced problems. Originally this was a small soldered connection but this was unable to conduct a high current without the excessive heat produced damaging the joint. This caused occasional miss-fires and flashovers inside the gun, damaging the aluminium case, coaxial cable and sleeves. A solution was found by using a small brass ferrule to enclose and strengthen the connection, although only after a number of experiments had been performed to remove unwanted corona and tracking from inside the gun.

5.8 Model of the Prototype Gun

The first section of this model enables the processes involved in ionisation of the polypropylene chain to be studied. An estimate for the energy needed to ionise one unit of the chain is obtained from the ionisation energies of the atoms and the energy in the covalent bonds of the polymer structure. This is compared to the energy provided from the capacitor, to estimate the quantity of material eroded in each shot. The model described in section 5.4 gives an approximation of the temperature and the velocity of the new plasma before it leaves the gun. A comparison is made with the temperature measured during the experiments described in section 6.4.5, to predict the velocity of the plasma immediately after leaving the gun opening. This value is then entered into a MatLab model that, in a similar manner to the simple plasma model of section 2.7.1, determines the magnetic field generated by the gun current, calculates the resulting force on a moving particle, velocity and its position after a small time period. This sequence is repeated numerous times, to give details of the changes in both velocity and position.
5.8.1 Polypropylene Properties and Structure

Polymers are structurally arranged by joining single units to form long chains in a process called polymerisation. One of the simplest of polymers is polyethylene, which is a chain of carbon atoms with hydrogen atoms attached to each carbon atom. During polymerisation the double bond between the carbon atoms in the ethylene unit is broken, and the electrons that make the bond are used to link with other carbon atoms, as illustrated in Fig. 5.20. This forms the long chain that is characteristic of a polymer and is given the prefix poly-.

![Ethylene structure and polymerisation.](image)

Branching takes place when hydrogen atoms are replaced with a string of polyethylene to produce low density polyethylene (LDPE). When no branching is present the polymer is described as high density polyethylene (HDPE), which is much stronger but costs more to manufacture.

Propylene is similar to ethylene except that a methyl group (-CH₃) replaces one of the hydrogen atoms attached to each carbon atom. The polymerisation process now produces a string of carbon atoms that have a methyl group attached to alternate carbon atoms, as illustrated in Fig. 5.21.

![Propylene structure and polymerisation.](image)
The majority of sleeves used in the carbon plasma gun were polypropylene, whose structure is given in Fig. 5.21. Ionisation of polypropylene firstly requires energy to break the covalent bonds between the propylene units to reverse the polymerisation process. If negative energy represents the energy supplied to the system then the total energy \( E \) required for this process is given by [46]

\[
E(CH_2 = CH_2) = 699 \text{kJmol}^{-1} = 7.27 \text{eV} \\
E(CH_3 - CH_3) = 369 \text{kJmol}^{-1} = 3.84 \text{eV} \\
E = E(CH_2 = CH_2) - E(CH_3 - CH_3) - 2 \times \frac{1}{2} E(CH_3 - CH_3) = -0.41 \text{eV}
\]  

(5.14)

The remaining covalent bond energies needed to split the polymer into the individual atoms and the total energy to be supplied are given by [46]

\[
E(CH_2 = CH_2) = 699 \text{kJmol}^{-1} = 7.27 \text{eV} \\
E(CH - H) = 448 \text{kJmol}^{-1} = 4.67 \text{eV} \\
E(C - H) = 335 \text{kJmol}^{-1} = 3.49 \text{eV} \\
E(C_2H_5 - H) = 435 \text{kJmol}^{-1} = 4.53 \text{eV} \\
E(C - CH_3) = 368 \text{kJmol}^{-1} = 3.83 \text{eV} \\
E(CH_2 - H) = 439 \text{kJmol}^{-1} = 4.57 \text{eV} \\
E(CH - H) = 448 \text{kJmol}^{-1} = 4.67 \text{eV} \\
E(C - H) = 335 \text{kJmol}^{-1} = 3.49 \text{eV} \\
\text{Total } E = -36.51 \text{eV}
\]  

(5.15)

Ionisation of a molecule of polypropylene gives three carbon ions and six hydrogen ions. If the carbon ions are ionised to double positive carbon ions \( C^{2+} \), the energy needed for ionisation is [46]

\[
\phi_i(H) = 13.60 \text{eV} \\
\phi_i(C) = 11.26 \text{eV} \\
\phi_i(C^+) = 24.38 \text{eV} \\
\text{Total } \phi_i(3C6H) = 188.52 \text{eV}
\]  

(5.16)

However, the strong attraction that a hydrogen ion (proton) has on any surrounding electrons will quickly recombine the atoms and form the strong hydrogen molecule, releasing \( 3 \times 4.49 \text{ eV} \) bond energy and decreasing the ionisation energy to 106.92 eV.
The total energy needed to vaporise and ionise a single unit of polypropylene is 230.3 eV (or \(3.68 \times 10^{-17}\) J).

5.8.2 Mass Constant

Experiments with a short-circuit replacing the gun gave a current waveform that indicated only 5.6% of the stored energy is transferred into the gun, with the remainder being dissipated in the resistance of the strip lines, the spark gap and the connections. The total energy stored in the capacitor is 128 J, so the energy available to produce the plasma is about 17.8 J. The maximum number of molecules \(N\) that could be ionised by this energy is

\[
N = \frac{\text{Available Energy}}{\text{Energy Required to Ionise One Unit of Polypropylene}} = \frac{17.8}{3.68 \times 10^{-17}} = 4.84 \times 10^{17} \quad (5.17)
\]

assuming that the plasma is totally ionised. The mass of a single unit of polypropylene is \(6.97 \times 10^{-26}\) kg, so the total mass of polypropylene eroded by the discharge is \(33.7 \times 10^{-9}\) kg (33.7 \(\mu\)g). The mass rate constant in equation (5.1) assuming it to be the mass increase per charge stored in the capacitor, is

\[
K = \frac{33.7 \times 10^{-9}}{1 \times 10^{-6} \times 17000} = 1.98 \times 10^{-6} \text{ kg C}^{-1} \quad (5.18)
\]

when the capacitor is charged to 17 kV. The rate of mass increase is therefore

\[
M = KI = 1.98I \times 10^{-6} \text{ kg s}^{-1} \quad (5.19)
\]

where the current \(I\) measured experimentally fits the equations below

\[
I = 15430 \ 4 \sin(\omega t) e^{-\alpha t} \quad (5.20)
\]

with a damping factor \(\alpha\) of 129829 and a frequency of \(1003 \times 10^6\) radians\(^{-1}\).
5.8.3 Initial Plasma Velocity

The initial flow velocity of the plasma before it leaves the gun is given by equation (5.10) as 6.7 cm $\mu$s$^{-1}$. On the other hand, the thermal energy acquired by the plasma using the electron temperature of 276,000 K measured in the experiments described in section 6.4.5 is given by

$$W_{th} = \frac{3}{2} kT \times \frac{M}{m_i} = 9.6 \text{ J}$$ (5.21)

The initial plasma temperature is taken as the sublimation temperature $T_s$ (473 K), giving an initial thermal energy of 0.016 J. The difference between the initial and final thermal energies is a result of the heat generated from the friction between the plasma and the gun walls, as explained in section 5.4.5. This friction reduces the kinetic energy and the plasma velocity by

$$\Delta W_{th} = \frac{1}{2} M U_{loss}^2 \Rightarrow U_{loss} = 2.4 \text{ cm } \mu\text{s}^{-1}$$ (5.22)

which gives an initial plasma velocity of approximately 4.3 cm $\mu$s$^{-1}$. This is lower than the measured velocity, because the effect of the acceleration due to magnetic forces on the ions and electrons has been neglected. The magnetic model in the following section uses this initial velocity and accounts for the effect of the magnetic field on the motion of a particle away from the gun.

5.8.4 Magnetic Field Model

A simulation to determine the behaviour of the carbon ions after leaving the gun was performed using a MatLab procedure that considers the motion of an ion during small time steps, using the assumption that over a short period the acceleration remains constant. The program calculates the magnetic field at a specific point, determines the force on a carbon ion at this point, and returns the new velocity and position at the end of the period. The flow diagram in Fig. 5.22 describes the program procedures and sub-routines given in Appendix D.
Initially the global constants are fixed and the variables initialised to a starting value of zero. The first stage of the program calculates the variables over very small time steps, during the initial 0.1 µs when the acceleration is large and changing.
continuously. After this time the velocity is constant and the step is increased to 10 ns to decrease the computation time. At the start of the loop the current \( I \) is calculated at a time \( t_I \), using equation (5.20) that matches experimental data. For each loop of the main routine the position, acceleration, velocity and force are recorded for later analysis.

5.8.4.1 Magnetic Field

The sub routine “Magnetic m” calculates the magnetic flux density \( B_z \) given the position coordinates \((x,y)\) and the current \( I \). The symmetrical nature of the carbon gun makes it acceptable to consider a 2-dimensional current path. A filamentary approach allows the magnetic field to be calculated from the contributions of the upper and lower filamentary currents in Fig. 5.23.

The assumptions made in this model are:

1) the current on the cathode surface can be replaced by a line current on its axis that produces the same external magnetic field, which is zero within the conductor and along its axis,

2) the current in the gun case is assumed to flow along the inside edge, distributed evenly within a layer described by the skin depth and represented by a line current at the mid point of this layer,

3) the current in the cathode is twice that in the anode segments,
4) markings on the copper plate indicate that the plasma flows along the tapered edge of the hole and bends along the outside of the plate. The current is assumed to reach a point in the middle of the hole, to divide into two sections that flow in opposite directions along the outside of the copper plate.

Using these assumptions the line currents are mapped on to a Cartesian grid with the origin at the intersection of the two branches, as shown in Fig. 5.24.

![Cartesian coordinates for the line currents](image)

where the skin depth $\delta$, with the resistivity $\rho$ of aluminium of $2.7 \times 10^8 \ \Omega \ m^{-1}$ and a running frequency $f$ of 160.77 kHz to match the experimental system in section 5.6, is

$$\delta = \sqrt{\frac{\rho}{\pi \mu_0 f}} = 0.21 \ mm$$

The component of the magnetic field at the point P in Fig. 5.25, due to the current $\frac{1}{2}I$ in the upper segment, has a positive (out of the paper) magnetic flux density given by the equation for the magnetic flux density due to a finite length wire, as

$$B = \frac{\mu_0 I}{8\pi r} (\sin \theta_2 - \sin \theta_1)$$
where the angles are defined by

\[
\sin \theta_1 = \frac{-(L + x)}{\sqrt{(L + x)^2 + \left(r_o + \frac{1}{2} \delta - y\right)^2}}
\]

\[
\sin \theta_2 = \frac{-x}{\sqrt{x^2 + \left(r_o + \frac{1}{2} \delta - y\right)^2}}
\]  

(5.25)

Using the same techniques, the components of the flux densities due to the remaining current segments are derived and combined to provide the magnetic field around the gun. The program calculates the magnetic field at positions projecting from the front of the gun, to give the plot in Fig. 5.26, confirming that the magnetic field close to the gun surface is extremely intense. A similar result would be obtained for the cylindrical structure of the coaxial carbon gun.

**Figure 5.25.** Dimensions for the upper segment.

**Figure 5.26.** Magnetic field near the gun exit hole.
5.8.4.2 Applied Force and Acceleration

The Lorentz force on a positively charged particle $q$, moving in the direction of the positive x-axis with a velocity $v_y$ in a magnetic flux density $B_z$, is

$$ F_x = B_z q v_y $$ (5.26)

From the assumption that a single carbon ion initially at the centre of the hole bends towards the copper plate along a median path, as indicated in Fig. 5.27, the initial plasma velocity from section 5.8.3 has components in the x and y directions given by

$$ v_y = 4.3 \times \sin 30 = 2.1 \text{ cm/μs} $$
$$ v_x = 4.3 \times \cos 30 = 3.7 \text{ cm/μs} $$ (5.27)

![Ion Path Diagram](Figure 5.27. Carbon ion path on exiting through hole.)

The carbon ion travelling along the copper plate with a velocity $v_y$ in the magnetic field $B_z$ experiences a force given by equation (5.26). The acceleration $a_x$ of the ion from the surface is

$$ a_x = \frac{F}{m_i} $$ (5.28)

The acceleration of a carbon ion with respect to time is shown in Fig. 5.28 for the first nanosecond. After this the acceleration is approximately zero.
5.8.4.3 Displacement and Velocity

In the sub-routine "Motion.m" the displacement and velocity at the end of the time step are determined from the equations of motion, as

\[ v = u + a\Delta t \]
\[ s = ut + \frac{1}{2} a\Delta t^2 \]  

where \( \Delta t \) is the duration of the step. The sub-routine is given an initial velocity, position, acceleration and the time step and returns a 2 × 2 matrix with the new velocity and position of the ion.

A graph of the expected velocity versus displacement is shown in Fig. 5.29.
The graph is limited to 0.1 mm along the x-axis from the surface of the gun because after this the carbon ion is at its maximum velocity of about 8.2 cm µs⁻¹ (comparable to the measured velocity in section 6.4.5). The model has confirmed that ions are accelerated by the magnetic field which is self-generated by the current in the gun and that this occurs in the first nanosecond when the ion is close to the gun.
6 PLASMA DIAGNOSTIC

6.1 Macroscopic Measurements

A number of techniques are available to either observe or measure the large-scale properties of plasma [47]. These include the total current, the average electrical and thermal conductivities, the total momentum, and the size, intensity and motion of the luminous region. In the following sections a number of the more significant techniques are discussed.

6.1.1 Current Measurements

Flowing plasmas are currents that generate large and rapidly changing magnetic fields [47-48]. A magnetic pickup loop or coil located in this magnetic field will have an electromotive force $\varepsilon(t)$ induced in it, as given by the product of the rate of change in magnetic flux $\phi$ and the number of turns $N$, such that

$$\varepsilon(t) = N \frac{d\phi}{dt}$$

(6.1)

The magnetic pickup coil is modelled by an internal inductance $L$ and the emf voltage source in an RC integrator, as in the circuit of Fig. 6.1.

![Figure 6.1. Schematic of RC integrator circuit](image-url)
where the corresponding equation is

\[ N \frac{d\phi}{dt} = L \frac{di}{dt} + iR + \frac{1}{C} \int_0^t i \, dt \]  

(6.2)

By assuming that \( R >> L \omega \) and \( t << RC \), the output voltage \( V(t) \) is

\[ V(t) = \frac{1}{C} \int_0^t i \, dt = \frac{1}{RC} \int_0^t N \frac{d\phi}{dt} \, dt = \frac{KN}{RC} \]  

(6.3)

where the constant \( K \) accounts for variations in the geometry and position of the coil. This method unfortunately produces only a small signal voltage that is susceptible to noise, although it can of course be amplified. Recent improvements in computer processor speeds have however made numerical integration the preferred method.

The Rogowski coil of Fig. 6.2 is a multiturn solenoid, shaped as a torus, which encircles the current to be measured and overcomes the need for the constant \( K \).
The output voltage is now related to the current by

$$\sigma(t) = \mu_0 A_{\text{turn}} \frac{dI}{dt}$$  \hspace{1cm} (6.4)

which after integration by either an RC network or numerically gives the original current waveform.

### 6.1.2 Electrical Conductivity

Electrical conductivity is often measured as a means of determining the electron temperature of the plasma. In the absence of a magnetic field, the conductivity $\sigma$ and electron temperature $T$ are related by [49]

$$\sigma = 0.015 \frac{T^2}{Z \ln \Lambda} \quad \text{where} \quad \Lambda = \frac{12\pi \left( \frac{\varepsilon_0 k T}{e^2} \right)^{\frac{3}{2}}}{n_e}$$  \hspace{1cm} (6.5)

Initially, the total plasma resistance is calculated from the ratio of the potential difference across the plasma to the current flowing through it, and an average value for the conductivity can be obtained if the dimensions of the plasma are known. Unfortunately, pulsed plasmas are continually changing shape and moving so fast that their exact dimensions are impossible to determine.

### 6.1.3 Photography

The two standard methods of photographing the luminosity radiated by plasma or electrical discharges are snapshot and framing photography, and streak photography [47].

#### 6.1.3.1 Snapshot and Framing Photography

Conventional photography is useful in the study of steady-state or slowly varying discharges, although when the movement is very fast the technique needs to be extended by using mechanical high-speed shutters and by rapidly moving the photographic image between frames, using techniques such as fast rotating mirrors and prisms, or electric fields. The older Hadland cameras (one of which captured the
first image in Chapter 7) use numerous electric fields generated by plate electrodes, to angle the image onto different portions of a Polaroid film. More recent cameras, such as the Hadland 468, use an optical beam splitter to project eight images onto eight intensified CCD images sensors*. High-speed digital electronics control the exposure time and image sequence of each image recorded by the sensors. The images are digitised and stored in memory to be later downloaded to a computer through an optical fibre link.

Interpretation of luminosity results is complicated by the high intensities of light that can be radiated by regions of fairly weak plasma density that have a high degree of ionisation. Additionally, the spectral emission from certain ionisation processes may be outside the sensitivity range of the film or sensors.

6.1.3.2 Streak Photography

Streak photography records a long narrow section of the image formed on the film by a narrow slit in the optical system. This image is moved at high speeds in a direction perpendicular to its longest dimension, to produce a sequence of smeared images. Each successive image corresponds to an interval in time, with the result that the photograph displays the time variation of the luminosity.

6.2 Magnetic Measurements

6.2.1 Magnetic Probes

The simplest magnetic probe [47-48], shown in Fig. 6 3, consists of a small coil of light gauge wire placed near the closed tip of an insulating jacket, so that it is unaffected by the heat and charge of the plasma. A three-dimensional map of the magnetic field is usually obtained by rotating the probe on a pivot.

The output voltage from the coil is proportional to the area-turns product, and

\[ V(t) = NA_{\text{turn}} \frac{dB}{dt} \]

(6 6)

* Extracted from Hadland 468 manual whilst on loan from EPSRC
which is either RC or numerically integrated to give the magnetic flux density. A high signal level is preferred to reduce the effect of noise and this is obtained by having a large number of turns, with a small area $A_{\text{turn}}$ used to reduce any disturbance to the plasma. However, the inductance (and thus the number of turns) is limited by the required frequency response of the coil.

![Diagram of Magnetic Probe](image)

**Figure 6.3.** Magnetic probe

### 6.2.2 Hall Probes

Magnetic coils depend on the rate of change of the magnetic field, so that in a steady state field they become totally ineffective. In this situation the Hall effect is an attractive alternative [48].
Although the effect is really a plasma phenomena, Hall devices normally use a thin slab of semiconducting material placed in the magnetic flux density $B$ to be measured. The electrons, being the majority charge carrier, drift towards face $R$ as a result of the interaction between the magnetic field and the moving charge in the current $I$ flowing from face $P$ to face $Q$. This displacement of charge produces a potential difference, called the Hall voltage $V_H$, that is perpendicular to the field and the current (i.e. between face $R$ and face $S$), and is given by

$$V_H = \frac{R_H}{d} IB$$

(6.7)

where $R_H$ is the Hall coefficient and $d$ is the semiconductor thickness across which the magnetic field is directed. The probe has a greater sensitivity than magnetic coils, but the need for a cable to supply the current $I$ results in complications from extra noise and additional vacuum-air connectors. Finally, the hot plasma often destroys the expensive Hall probe, so that in a number of situations magnetic coils are still preferred.

### 6.2.3 Magneto Resistance Probes

The effect of a magnetic field on the resistance of a semiconductor can also be used for magnetic measurements. Unfortunately the non-linearity of its response means the effect has hardly been investigated for plasma measurements.
6.3 Electrical Measurements

Electrical probes are very useful in measuring various plasma parameters, such as electron temperature, carrier concentration and velocity. Two different techniques employing either a single or double electrode arrangement are described below. Also described is a method of measuring the current in flowing plasma by a device called the Faraday cup.

6.3.1 Single (Electrode) Probe

In the single probe arrangement originated by Langmuir [50], the area of a reference electrode is large in comparison to that of the probe. In most cases the reference electrode forms an integral part of the plasma circuit, i.e. the anode or cathode of the plasma gun or the POS. The high temperature of plasma will damage most materials, so that the probes are often manufactured from metals such as stainless steel, platinum, molybdenum, nickel and tungsten using insulating materials such as ceramic and glass. Examples of single probes are shown in Fig. 6.5 [47,51-52].

A voltage $V_a$ applied between the probe and the reference electrode drives current through the plasma, and when it is varied the typical characteristic [47,53] of Fig. 6.6 relating the probe current $I$ to the applied voltage $V_a$ is obtained.
6.3.1.1 Floating Potential and Ion Saturation Current

The floating potential $V_f$ occurs when the net current is zero, requiring the rate of charge arriving at the probe due to both electrons and ions to be equal. Although the overall electron and ion charge densities are equal, the mean velocity of the electrons $v_e$ (equation (3.4)) exceeds that of the ions $v_i$ by the factor $\sqrt{m_i/m_e}$, so that initially more electrons arrive at the probe and a negative charge accumulates on its surface. This repels further electrons and attracts ions, forming a sheath of positive charge around the probe that grows until an equilibrium state is achieved between the two types of carrier current. At this point there is no resultant current flowing through the probe and it is said to be at the floating potential $V_f$.

In region AB the probe potential is negative with respect to $V_f$, repelling almost all the electrons and ensuring that the probe absorbs all the ions entering the sheath. The probe current is then termed the ion saturation current $I_{S}$, and is given by

$$I_{S} = J_{S} = J_{i} A$$ (6.8)
where \( S \) and \( A \) are the surface areas of the sheath and probe respectively. For a random Maxwellian distribution this current is \([47,53]\)

\[
I_S = \frac{1}{4} n_e \bar{v}_e A = \frac{1}{4} n_e \sqrt{\frac{8kT}{\pi m_e}} A \tag{6.9}
\]

where the \( \frac{1}{4} \) factor compensates for both the three dimensions of freedom included in the average thermal velocity and the flow of charge both into and out of the sheath. If the flow (or drift) velocity \( v_D \) of the plasma ejected from a gun is used in equation (6.9) this factor is removed, because virtually all the charge then flows in a single direction. In this case the ion saturation current \( I_S \) is given by

\[
I_S = n e v_D A_p \quad n_e = n \quad n_e \approx n \tag{6.10}
\]

where \( A_p \) is the apparent surface area of the probe that is exposed to the approaching plasma.

### 6.3.1.2 Transition Region

The transition region BC in the characteristic of Fig. 6.6 occurs when the probe potential is positive with respect to the floating potential. Initially only high-energy electrons are able to overcome the sheath to become absorbed by the probe. However, as the potential is increased more electrons cross the sheath and the number of ions entering is reduced, so that the ion sheath diminishes. Since the electrons throughout this region are in a random Maxwellian distribution, the curve is exponential and follows the Boltzmann distribution law \([47,53]\)

\[
\frac{e^{(v_S - v_a) / kT}}{n_e} = n_e \tag{6.11}
\]

The probe current, using the relationship in equation (6.9), is given by

\[
I = J_e A = \frac{1}{4} n_e \bar{v}_e A = \frac{1}{4} n e \bar{v}_e A e^{(v_S - v_a) / kT} \tag{6.12}
\]
6.3.1.3 Electron Saturation Current

The transition region ends at the space potential $V_s$, which occurs when the probe is at the same potential as the surrounding plasma and charged particles migrate to the probe only because of their thermal velocities. Biasing the probe with a voltage positive with respect to $V_s$ accelerates electrons towards the probe and repels the ions. An excess of negative charge builds up on the surface, until it becomes equal to the positive charge on the probe, when the thin sheath of negative charge that is formed shields the plasma outside this region from the applied electric field. Electrons reach the probe by means of their thermal velocities alone, with the charge absorbed being dependent on the surface area of the sheath and remaining relatively constant to give the flat characteristic of region CD at the level of the electron saturation current $I_{es}$. This current is determined from equation (6.12) when $V_s = V_a$, giving

$$I_{es} = \frac{1}{4} n e \bar{v}_e A$$

(6.13)

Substituting the electron saturation current in equation (6.12) gives the probe current in the transition region as

$$I = I_{es} e^{\frac{e(V_s - V_a)}{kT}}$$

(6.14)

and if the logarithm of $I$ is plotted against the applied voltage $V_a$ the resulting line characteristic in region BC of Fig. 6.7 is described by

$$\ln I = \ln I_{es} + \frac{e}{kT} (V_s - V_a)$$

(6.15)

where the gradient $e/kT$ gives a measure of the electron temperature.
The electron saturation current $I_{es}$ at the break point C from the straight line can be substituted into equation (6.13) to give a measure of the plasma density. This needs the velocity of the plasma to be known, and although this can be calculated from the average thermal velocity in equation (3.4), the result is not accurate in magnetically driven flowing plasma. Alternatively, the plasma drift velocity $v_D$ (or flow velocity), measured experimentally (see section 6.4.5) can be used in

$$I_{es} = nev_D A_p \quad (6.16)$$

which is similar to equation (6.10).

### 6.3.2 Double (Electrode) Probe

In most cases an electrode in contact with the plasma can be used as a reference electrode for the single probe system. However, in some cases the floating double probe system [47,53-55] of Fig 6.8 is used, where two electrodes are biased with respect to each other and insulated from ground.
The two electrodes are immersed in the plasma with a voltage $V_a$ applied between them, which is defined as being positive when current flows in the plasma from electrode 1 to 2, such that $V_a = V_1 - V_2$. Both are negative biased with respect to the plasma space potential $V_s$, giving the potential distribution of Fig. 6.9, so that the electrons are repelled from both, leaving ions as the majority charge carrier. This limits the net current in the plasma to the smaller ion saturation current, reducing the disturbance to the plasma and giving the typical double probe characteristic of Fig. 6.10.
When the applied voltage is zero, both electrodes are at the floating potential $V_f$ and no net current flows between them. If $V_a$ is slightly positive, more electrons will flow to electrode 1 than to electrode 2. As the applied voltage is increased electrode 2 becomes increasingly negative, until in region CD all the electrons are repelled and only the ion saturation current $i_{2+}$ due to electrode 2 remains. If a negative applied voltage is used the situation is reversed, with electrode 1 becoming increasingly negative and the current limited by the ion saturation current $i_{1-}$ of electrode 1.

The electron currents $i_{1-}$ and $i_{2-}$ due to probes 1 and 2 in the transition region are given by the Maxwellian distribution as [53]

$$i_{1-} = A_1 J_r e^{\frac{eV_a}{kT}}$$
$$i_{2-} = A_2 J_r e^{\frac{eV_f}{kT}}$$

where $J_r$ is the random electron current density due to their thermal velocities. The probe current $I$ is equal to the net current from the contributions of the electron and ion currents for both electrodes, or

$$I = i_{1-} - i_{1+} = i_{2+} - i_{2-}$$

Figure 6.10. Typical double probe V-I characteristic
and substituting the electron currents from equations (6.17) gives [53]

$$\frac{n_1 + I}{n_2} - I = \frac{A_1}{A_2} e^\frac{(V_1 - V_2)}{kT} - \frac{A_1}{A_2} e^\frac{V_2}{kT}$$

(6.19)

The logarithmic plot of the ratio on the left side of this equation against the applied voltage $V_a$ gives a straight line in the transition region, with a gradient of $e/kT$. If the electrode areas are identical ($A_1 = A_2$) and $n_1 = n_2 = n_s$, the probe current $I$ is given by [53]

$$I = \frac{n_s \left( e^\frac{V_a}{kT} - 1 \right)}{1 + e^\frac{V_a}{2kT}} = n_s \tanh \left( \frac{e^\frac{V_a}{2kT}}{kT} \right)$$

(6.20)

The ion saturation current is obtained from the shape of the probe characteristic and equation (6.10) can be used to determine the plasma density. Examples of typical double probes arrangements are shown in Fig. 6.11 [47,55]
6.3.3 Faraday Cups

Faraday cups can be used to measure the total current in a focused beam, using a cup opening that is larger than the beam diameter, or the average current density at a point within the beam, using an opening smaller than the beam. In its simplest form [56], a Faraday cup is constructed from a stainless steel stud with a hole partly drilled through its centre, as shown in Fig. 6.12.

![Faraday cup diagram]

**Figure 6.12. Simple Faraday cup arrangement**

The measured current density $J$ of electrons and ions entering the hole from the plasma beam is

$$J = \frac{I}{\pi r^2}$$  \hspace{1cm} (6.21)

where $I$ is the current collected by the cup and the aperture area is $\pi r^2$. When the plasma hits the bottom and sides of the cup, secondary electron emission occurs that decreases the accuracy of the measurement. If a positive bias voltage $V_a$ is applied to the cup, all the electrons with an energy of less than $eV_a$ are retained to reduce the secondary emissions. Vertical baffles at the base of the cup, in the form of a spiral of electron absorbing structure coated with graphite [57], as shown in Fig. 6.13, also reduce the secondary emissions.
6.4 Experimental Probe Arrangement

A series of plasma diagnostic experiments were undertaken to develop a technique for measuring the plasma density, temperature and flow velocity. The following sections describe the details of the probes, biasing circuit and current measurement technique and the experiments performed on the prototype coaxial carbon gun of section 5.6.

6.4.1 Biasing Circuit

The electrical probes are biased by the circuit of Fig 6.14 [58], using a battery pack with taps at 12 V increments to charge five parallel capacitors through the charging resistors $R_1$ and $R_2$. The discharge resistor $R_3$ ensures that all the stored energy is safely dissipated before handling. The five capacitors are parallel connected between two 100 mm wide copper strip lines to reduce their overall inductance, as shown in Fig. 6.15. The pickup coil $P$ located inside a tunnel $T$ in the strip line $SL$ measures the probe current. The probes are connected via the vacuum-air interface to the vacuum chamber by a length of URM76 coaxial cable.
The voltages induced in the pickup coils are proportional to the rate of change in the current through the copper strip lines, as described in Appendix E. Because the currents being measured are small compared to the gun current discharge, the output signals pick up considerable noise from the surrounding equipment and circuits. Numerous experiments were performed before this noise was reduced to an acceptable level, and in the following section a number of these are described.

6.4.2 Noise Reduction

The types of noise induced onto the sensitive plasma signals are either high frequency, through inductive and capacitive coupling, or low frequency from poor
Plasma Diagnostic

earth paths and loops. Fig. 6.16 shows examples of the early results that highlighted the problems to be overcome before a useful signal could be achieved.

The underlying signals are clearly overridden by noise induced from sparking in the pulser circuit. It was observed that the high current vacuum-air interface showed signs of sparking and surface tracking along both the cable and connector on the vacuum side. Constructing three new connectors, with an increased contact area and a higher mechanical pressure, largely overcame the problem.

Experimental results also indicated that the nail switch closure (section 5.6 3) emitted considerable radiated and conducted noise as the nail punctures through each of the Mylar layers, causing a series of rapid sparks. The spark gap (section 5.6 3) was introduced primarily because of its reduced turn-on noise, and it has the advantage of being easier to assemble. A reduced amount of electrical noise was still present in the signals, as shown in Fig. 6.17(a), but this could now be removed by digital and analogue filtering. MatLab Digital Fast Fourier Transform (DFFT) routines split the signal into its individual frequencies and by removing those that are undesirable the inverse DFFT routine produced the much cleaner signal shown in Fig. 6.17(b).
The numerical integration process that reproduces the original current waveform from the $\frac{di}{dt}$ magnetic pickup coil signal is also a successful method of filtering the high frequency noise, and it is used in section 6.4.3 onwards. When the system was expanded to an array of plasma probes, the low frequency noise or ramping became a more significant problem. Over a series of experiments it became apparent that it was related to the exact position of the oscilloscope and pickup probes, indicating that it was largely due to different levels of capacitance between the probes, oscilloscope, power circuit and the laboratory floor. The presence of the electric field emitted by the large current pulse charges these capacitances to different voltages and the current that flows along the available paths (including the probe circuit) to achieve charge equilibrium gives rise to false readings.

Fig. 6.18(a) shows the considerable high frequency noise and smaller underlying ramping from an unshielded pickup coil held at a distance from the oscilloscope. Although the low frequency ramping is relatively small, it is greatly enhanced by the numerical integration process. In Fig. 6.18(b) the noise is minimised by taping the pickup coil to the top of the oscilloscope, so that they have the same capacitance to earth and are charged to the same voltage. The same effect can also be achieved by reducing the capacitive coupling between the magnetic pickup coils and the high current circuit. As shown in Fig. 6.19 an incomplete shield surrounds the coil, and this allows penetration of magnetic flux whilst preventing the detection of external electric fields.
A coaxial cable connects the pickup probes either at a distance from (a) or taped to (b) the oscilloscope.

Second copper sheath connected to turn and covered in heathshrink

Ground connection (close to tunnel)

Second sheath also encloses the signal cable. Over a series of experiments the best results were obtained when this sheath was connected to the oscilloscope case and the
coil shield, giving the result in Fig. 6.20(a). Connecting this sheath to the laboratory earth results in an enhancement of the ramping effect, as shown in Fig. 6.20(b), which is expected since the process inevitably increases the cable capacitance to earth.

![Graph](image-url)

*Figure 6.20. Outer sheath connected to the oscilloscope (a) and the laboratory earth (b)*

The previous results indicate that enclosing all the plasma pickup coils, oscilloscopes, battery mains supplies and probe biasing circuits in an enclosed metal environment, such as a Faraday cage, will give the best results. The arrangement adopted used the Faraday cage in Fig. 6.21 and produced the acceptable result shown in Fig. 6.22.
Unfortunately, the ramping and high frequency noise reappeared when the pickup coils were used to detect the current from the plasma probes. A dummy cable [59] parallel to the active plasma probe cable has successfully removed such noise in experiments elsewhere. But this inevitably involves additional equipment and
vacuum connectors. Instead, it is preferable to shield the coaxial cables leading from the Faraday cage to the vacuum chamber using copper tubing clamped to the cabinet and insulated from the vacuum chamber to prevent earth loops. This gave the plasma probe signal, shown in Fig. 6.23, which had an acceptable level of noise that was removed by the numerical integration process to give the clean signals of Fig. 6.25.

![Figure 6.23. Final result after shielding all the equipment and cables.](image)

6.4.3 Double Probes

![Figure 6.24. Prototype double probe.](image)

The prototype double probe of Fig. 6.24 was either connected to, or isolated (floating) from, the laboratory earth and supplied with a negative bias voltage by the circuit of Fig. 6.14. The plasma waveforms shown in Fig. 6.25 confirm the double probe theory
in section 6.3.2, which stated that the maximum current conducted through the floating probe is limited to the smaller ion saturation current.

![Graph of Gun Current vs Plasma Probe Current](a)

![Graph of Gun Current vs Plasma Probe Current](b)

**Figure 6.25.** Floating (a) and grounded (b) cylindrical double probes biased at -84V.

The coaxial double probe in Fig. 6.26 when used with the outer conductor earthed and the inner conductor biased at -84 V, gave the plasma waveform of Fig. 6.27. The two-stage rising edge and small current reversal present in the previous waveforms are both greatly enhanced in the coaxial probe. The current reversal may be due to either ringing in the bias circuit or a positive plasma potential charging the bias capacitors. Spectroscopy observations elsewhere have indicated that the uneven rise is due to the arrival at different times of carbon ions, C\(^+\) and C\(^{2+}\).
A floating coaxial probe swept with an applied voltage of ±120 V in steps of 12 V gave the V-I characteristic in Fig. 6.28, which is similar to that predicted for the typical floating double probe.
The ion saturation currents due to the two electrodes are described by the straight-line equations

\[
\begin{align*}
    i_{1+} &= -7.9 + 0.06I \\
    i_{2+} &= 8.1 + 0.05I
\end{align*}
\]  

(6.22)

which can be substituted into equation (6.19) to give an equation for the probe current in the transition region. The logarithm of the ratio \( \Psi = (i_{1+} + I) / (i_{2+} - I) \) gives the characteristic in Fig. 6.29, which according to theory should be a straight line with a gradient of \( e/kT \) in the transition region. This technique fails to follow the theoretical predictions and gives only an approximate estimate for the electron temperature as 129,000 K (11 eV).

![Figure 6.29. Logarithmic probe characteristic.](image)

6.4.4 Faraday Cup

An experiment using a Faraday cup gave the signal in Fig. 6.30, which shows it to be sensitive to the fast electrons that arrive before the heavier ions, giving the negative pulse at the beginning of the waveform. This cup was biased with a negative voltage meant to repel the electrons from being collected, but it appears that the more energetic ones overcome this. Although an interesting result, this signal is difficult to use and can only measure the current density of the moving plasma.
6.4.5 Three Probe Array

An experiment performed on the prototype carbon plasma gun aimed to investigate its plasma parameters using three coaxial probes positioned along the axis at 30, 70 and 110 mm from the anode plate. An example of the probe current waveforms for each probe and the gun current \( G \) is shown in Fig. 6.31.

The probe signals are mutually coupled through the outer conductor of the coaxial cable at the BNC-BNC vacuum-air connector, linking all their outer electrodes with a low impedance path. The effect of this coupling was limited by maintaining a stable potential at the vacuum connector using the laboratory earth. The resulting
characteristics in Figs. 6.32 and 6.33 resemble that of a single probe system (see section 6.3.1), where the large reference electrode comprises the vacuum chamber, gun case and outer probe electrodes.

The logarithm of the probe current plotted against the applied voltage in Fig. 6.33 gives a straight line in the transition region (equation (6.15)) of gradient $e/kT$, giving a high electron temperature of 23.8 eV. The plasma flow velocity $v_0$ calculated from data obtained at 30, 50, 70, 90, 110 and 150 mm from the gun anode plate is shown in Fig. 6.34 and gives an approximate value of 8.5 cm $\mu$s$^{-1}$.
The electron saturation current \( I_{es} \) where the break in the straight line occurs in Fig. 6.33 is 40.4 A. Using \( I_{es} \) and \( v_b \) in equation (6.16) gives a consistent electron concentration \( n_e \) of approximately \( 1.4 \times 10^{14} \) cm\(^{-3}\) over the distance studied.

### 6.5 Optical Experiment

In the absence of expensive high-speed photographic equipment, a simple and inexpensive solution was used to capture an image of the plasma beam ejected from the prototype carbon gun. Glass plates (90×90×4 mm) were positioned vertically across the path of the beam to collect the carbon deposited by the moving plasma over a series of ten shots, as illustrated by Fig. 6.35. A 300 dpi flatbed scanner captured an image of the deposit on the plasma as a TIFF (Tagged-Image File Format) picture, such as shown in Fig. 6.36. This was converted to an 8-bit greyscale image, cut to the required frame size and reduced to a resolution of 100 dpi, in an effort to reduce the computation time.
6.5.1 MatLab Computation

The MatLab program in Appendix F was written to accept a series of such images and produce Fig. 6.37, a 3D contour plot that represents the shape of the plasma beam. Each contour represents an area that holds the stated percentage of the total greyness on the closest plate.
Initially, the program creates the figure area and axis, prepares the colours for the contour lines and holds the figure to superimpose the contours on to the same plot. The following code translates the greyscale TIFF image into a 2D matrix, whose component values represent the 8-bit grey scale and whose position in the matrix corresponds to a position on the plate.

```matlab
A = imread('c:\my documents\research\plates\30mm cut 1.tif');
```

The matrix is inverted to ensure that the values 1 and 256 represent the colours white and black respectively. An allowance is incorporated for the greyness of the glass, by subtracting the numerical value of the lightest part of the image from each matrix component. This process is repeated for each image, using memory allocations identified alphabetically i.e. A ... E. The matrices are scanned to determine the highest value (darkest colour) in each case and the results stored in memory allocations “Amax” onwards.

Contour levels are defined as a percentage of the total grey scale on the first plate (closest to the gun and identified by A). The first line in the following code sums the
columns of the matrix A to give a single row matrix which is again summed to give a single value that is the “total” of all the components in matrix A.

\[
\text{sums} = \text{sum}(A); \\
\text{total} = \text{sum}(\text{sums});
\]

The percentage levels for the contours are fixed using an array called “Percentage” and multiplied by the “total” above, to give the required contour levels.

\[
\text{Percentage} = [0.04, 0.08, 0.16, 0.32, 0.64, 0.96]; \\
\text{ContourLevels} = \text{Percentage} \times \text{total};
\]

The components of the matrix are summed, starting with those at the maximum value for that matrix (A_{max} etc.) and progressing down from this until the summation equals or exceeds the first contour level, at which point this value is stored in a matrix Z. The function “contourc” takes the image matrix (A ... E) and the contour matrix Z to produce a matrix of the coordinates (CA ... CE) for the contours.

\[
\text{CA} = \text{contourc}(A,Z);
\]

Unnecessary information is removed from this matrix and the contour is plotted onto the figure opened at the beginning of the program. Its colour is determined from the identity in the array “level” which is set at the program initiation

\[
\text{plot3}(Z,Y,X,\text{colour}(\text{Level}));
\]

This process is repeated for the remaining contours and then for each image matrix until a 3D plot of the plasma beam is produced that can be rotated and modified to include lines that represent the outer edges of the plates, as seen in Fig. 6.37.

**6.6 Summary**

The plasma diagnostic technique designed and tested in this chapter has measured a plasma density of \(1.4 \times 10^{14}\) cm\(^{-3}\) for the prototype carbon plasma gun. Comparison with published results of between \(10^{12}\) and \(10^{17}\) cm\(^{-3}\) indicates the technique has been successful. Its accuracy depends mainly on the accuracy of the magnetic pickup coil calibration, which can be predicted as only 10% because of the precision of the
component values used in the probe bias circuits and it may be even lower if errors are introduced by the graphical analysis of the probe characteristics. A fully successful calibration could only be achieved by comparison with a tested system, but the technique can give an adequate confirmation of gun performance to within an order of magnitude. The prototype gun is predicted to produce plasma with an electron temperature of 24 eV, which although high is still comparable to published results. The plasma flow velocity of 8.5 cm \( \mu \text{s}^{-1} \) is typically that expected from a carbon plasma gun.

The optical method of section 6.5 highlights the disadvantage of this design, in that only a small cone of plasma is produced as a result of the coaxial geometry. For a reasonably sized switch, up to 24 guns have been used to produce sufficiently dense, well-distributed plasma. The space occupied by this arrangement would exceed that available in the vacuum vessel used in the present experiment and serious limit the practicality of this switch in any future commercial application. The new technique discussed in Chapter 7 can produce sufficient plasma for a POS from a single carbon gun, whilst maintaining the simplicity of the present design.
7 RING CARBON PLASMA GUN

Conventional carbon guns produce a plasma cone that is only capable of filling a small POS, with up to 36 being required to provide plasma of sufficient density and with a spatial distribution that will ensure correct operation of a large POS. The guns, coaxial cables and vacuum interface that are required will clearly then necessitate an extremely large vacuum chamber. In contrast to this, any future commercial application of the POS will need a compact design. The ring carbon plasma gun described below overcomes the problem of size, whilst still producing an even distribution of plasma.

The idea for the ring gun originated from a discussion concerning the mechanism involved in the propulsion of the railgun projectile and also the processes that are present in the rotary arc gap switch.

7.1 The Railgun

The railgun [60] accelerates a metal projectile between two parallel conducting rails, as a result of interaction between current flowing in this and the magnetic field generated by the same current in the rails, as demonstrated in Fig. 7.1. The railgun is supplied with a large fast-rising current pulse that flows on the surface of the projectile. This normally heats and vaporises metal from the surface, to produce a plasma armature region on the generator side of the projectile that is eventually the predominant medium for the final discharge current. A current \( I \) flows in the rails, generating a strong magnetic flux density \( B \) between them, which interacts with the moving charged particles in the plasma armature to produce a force \( F \). This force propels the projectile along the rails and launches it from the gun, with published speeds of approximately 500 ms\(^{-1}\) [60-61].
7.1.1 Current Distribution in the Railgun

The rails of Fig. 7.1 can be divided into three regions, with the different current flow patterns [62] indicated in Fig. 7.2 all affecting the magnetic field in the gap between the rails. In region A the current penetrates the rails and the current density is approximately uniform throughout.

In region B, the effect of the high frequency forces the current to flow in the skin depth near the surface of the rails and to be concentrated at the edges, such that no magnetic field is produced inside them. Current flow near the armature is influenced...
by its presence, so that the current in region C begins with the distribution of region B but converges to flow along the surface of the armature. This effect becomes more noticeable as the armature size decreases.

7.2 Rotary Arc Gap (RAG) Switch

The RAG switch [63] overcomes the limited life-time of point-to-point spark gaps as a result of electrode erosion, by increasing the surface area of the electrodes. The switch comprises two ring electrodes separated by an air gap, with each having a split and an adjacent terminal, as shown in Fig. 7.3. A plasma jet injected between the two electrodes discharges current from a capacitor through the switch into the load, as indicated by the arrows of Fig. 7.3. This jet (or arc) is propelled between the rings by a force produced by interaction between the self-generated magnetic flux density $B$ and the current $I$ in the arc, resulting in minimal arc erosion at any single point and prolonging the lifetime of the switch. If the magnetic field is sufficiently strong, arc movement occurs across the electrode splits, completing the full turn.

The large magnetic forces and the potential for shock-wave damage were the main early concerns, and severe damage was indeed sustained in the first stainless steel prototype [63]. More recently, an alloy of tungsten (30%) and copper (70%), which is fairly resistant to arc erosion, has successfully operated at atmospheric pressure for a wide voltage range (3 to 11 kV) and conducted currents in excess of 400 kA.
7.3 Concept

The principles discussed for the railgun and the rotary arc spark gap make it apparent that a discharge initiated at a single point between two conducting rings can be propelled around a circular path. If this discharge is the surface flashover of an insulator, then the resulting vaporisation and ionisation of the insulator molecules can be used to eject plasma into the switch region of the POS, throughout 360° as the discharge travels.

A high voltage pulse at the ring terminals in Fig. 7.4 will result in electrical breakdown at a single point nearby. Current flowing in the rings near this point will generate a strong magnetic field in the gap, that will interact with the moving charged particles in the arc to produce a strong $\mathbf{J} \times \mathbf{B}$ force. This force will attempt to propel the discharge through a complete turn, thereby injecting plasma into the POS from all angles and creating a more even distribution than can be obtained by a single conventional carbon gun.

Figure 7.4. Concept of a ring carbon gun and the POS.
7.4 Theory

Operation of the proposed ring gun can be explained by assuming that the current flows along single lines azimuthally perpendicular to the arc current at the discharge point, as shown in the linear approximation of Fig. 7.5.

Assuming this ideal case, and using the Biot-Savart law, the peak magnetic flux density on the arc between M and N is given by

$$
\vec{B}_z = \frac{\mu_0 \vec{I}}{4\pi} \left[ \frac{\ell}{(s + \frac{1}{2}\delta - y)^2 + (s + \frac{1}{2}\delta + y)^2} + \frac{\ell}{(s + \frac{1}{2}\delta - y)^2 + (s + \frac{1}{2}\delta + y)^2} \right]
$$

(7.1)

where $\ell$ is the length along the current path from the terminals to the discharge point, $2s$ is the separation of the rings and $\delta$ is the skin depth of aluminium. The variation of magnetic flux density between the rings for various values of $\ell$ is given in Fig. 7.6 for the prototype gun of section 7.5.
As $\ell$ tends towards infinity the flux density approaches

$$\tilde{B}_Z = \frac{\mu_0 I}{4\pi} \left[ \frac{1}{(s + \frac{1}{2} \delta - y)} + \frac{1}{(s + \frac{1}{2} \delta + y)} \right]$$

(7.2)

and the curves in Fig. 7.6 approximate to this situation once the distance between the source and the discharge point exceeds a few millimetres. This indicates that acceleration of the plasma results from the magnetic field generated by current flowing within a few millimetres of the discharge point, confirming that using only a short section of the rings to model the magnetic field is a realistic approach. If this section is sufficiently short, any curvature in the section can be neglected, confirming that the linear approximation in Fig. 7.5 is acceptable.

The corresponding tangential force on the arc as a result of the magnetic field is

$$\tilde{F}_X = \tilde{b}(y) I = \frac{4\mu_0 I^2}{4\pi} \left[ \frac{\ell}{(s + \frac{1}{2} \delta - y)\sqrt{\ell^2 + (s + \frac{1}{2} \delta - y)^2}} + \frac{\ell}{(s + \frac{1}{2} \delta + y)\sqrt{\ell^2 + (s + \frac{1}{2} \delta + y)^2}} \right]$$

(7.3)
where \( \hat{F}_x \) is the peak force per unit length and is a maximum when close to the rings. Integrating over the whole length of the line current gives the maximum tangential driving force experienced by the arc as

\[
\hat{F}_{total} = \int_{-s}^{+s} \hat{F}_x dy = 206.366 \text{ N} \tag{74}
\]

although in practice friction between the particles and gun walls, collisions and interactions between the particles will all oppose the force.

Realistically, the current distribution produced will be similar to that of the rail gun, with current flowing across the adjacent faces of the rings and penetrating by a depth that is limited by the skin effect, as illustrated by region M in Fig. 7.7.

![Figure 7.7. Actual current distribution](image)

In region N, the current bends towards the discharge point from all available directions, with the components of the resulting magnetic field interacting with the arc to produce a force having both tangential and radial components. Although a tangential component will drive the discharge region clockwise, the remainder will oppose this action or eject the discharge into the POS. This current distribution is discussed in more depth in Chapter 8.
7.5 Prototype

7.5.1 Structure

Two equally sized aluminium electrode rings are separated by a high density polyethylene (HDPE 500) ring as illustrated in Fig. 7.8. The ring has an internal diameter 4 mm greater than the electrode diameter, producing a small channel that concentrates the discharge region and focuses the ejected plasma. The HDPE ring also extends outwards from the edges of the electrodes by 20 mm to prevent unwanted electrical breakdown.

Figure 7.8. Prototype aluminium ring carbon gun.

The dimensions given in Fig. 7.9 are designed to fit into the existing POS of section 2.8.
The rings are sandwiched by four Tufnol clamps, as shown in Fig. 7.10, equally spaced around the rings to apply the even pressure that is needed to overcome the large repulsive magnetic forces resulting from the currents in the two parallel electrodes. Each clamp is fastened to the POS anode plate, with pressure applied to the top ring by a steel bolt. The curved surface on the inside of the clamp gives extra strength at a point that would otherwise have been weak. The lower ring is located and fixed horizontally by pressure exerted through small Tufnol blocks from bolts located in the clamps.
7.5.2 Discharge Mechanism

A physical connection between the POS anode and the laboratory ground at the vacuum-air connection for the strip line maintains the lower ring at ground potential. The upper ring is biased with a high negative voltage pulse from the circuit of section 7.5.3, which initiates a discharge at a steel nail (seen in Fig. 7.11) embedded in the anode ring close to the terminals and protruding into the HDPE insulation. Electrons emitted from the insulation surface are attracted towards the positively charged point, leaving behind them a positive space charge that enhances the electric field strength in the gap, as shown in Fig. 7.12(a). This charge attracts electrons in the cathode towards the surface near the nail, creating a region of dense charge where streamers begin to travel towards the nail, resulting finally in a complete electrical breakdown. If the nail was located in the cathode ring, as illustrated in Fig. 7.12(b), positive charge would be attracted towards the nail and electrons correspondingly absorbed into the anode. Although the electric field is again enhanced, the charge in the ionisation region would be reduced and a greater breakdown voltage would be required [64].
Figure 7.11. Nail embedded in the anode ring and supply feed.

Figure 7.12. Effect of nail location on the ionisation region. (a) in anode (b) in cathode.

The breakdown occurs in the form of a surface flashover that vaporises and ionises the insulation, forming plasma in the same manner as in the conventional carbon gun. Thermal pressure propels the plasma away from the initial discharge point in all available directions. The high magnetic field between the rings interacts with the moving charged particles to create a force that propels the flashover clockwise around the gun and also into the POS switch region.
The main concern with this design was that a large current passing through a small area would erode and vaporise the surface of the electrodes [65], which is normally overcome by having a large surface area as in the rotary arc spark gap [63]. However, it was found that the only damage sustained in the prototype ring gun over a large number of experiments (>100) was the pitting along the electrode edges visible in Fig 7.11, with no noticeable deterioration in its performance. The nail only conducts the initially small current, with the discharge spreading over a large surface area before the current increases.

7.5.3 Pulser Circuit

A number of experiments were performed using the original circuit, but it was soon found that a larger magnitude and longer duration current pulse was needed to propel the discharge further round the rings. The circuit in Fig 7.13 is an enhancement of that described in section 5.6.3, with a larger capacitor, a modified spark gap SG and wider strip lines.

The 27.8 μF capacitor is charged to approximately 15 kV through the charge and dump system of Appendix B and discharged into the gun by closure of the mechanically triggered spark gap SG (see Fig. 7.14). The existing gap electrodes (from section 5.6.3) were replaced by hollow copper cylindrical electrodes, which have a larger surface area to distribute the heat more effectively and thus prolong the lifetime of the switch. Although erosion still occurs, as seen in Fig. 7.14, the electrodes can easily be replaced.
Two parallel 120 mm wide copper strip lines SL1 conduct the large discharge current from the capacitor bank to the spark gap and then to the vacuum chamber, as shown in Fig. 7.15. Initially URM67 coaxial cable conveyed the pulse inside the chamber to bolts on the electrodes. However, the large energy and high current resulted in arcing and heating at the small connectors that eventually broke, with damage sustained by the rings as seen in Fig. 7.16. This problem was overcome by using two 30 mm wide copper strip lines SL2, insulated by two layers of heat shrink tubing, which transmit the voltage pulse to wide copper blocks on the gun electrodes.
7.5.4 Electrical Probes

The plasma characteristics are determined using double electrical probes that comprise two cylindrical stainless steel electrodes of identical dimensions and surface area, as shown in Fig. 7.17. The probe protrudes through a PVC base with an exposed length of 4 mm, giving an apparent surface area of 8 mm². A section of URM76 coaxial cable connects the probes to the vacuum-air connectors and onto the biasing circuit. One of the probe electrodes is connected to the cable sheath that is earthed at the vacuum interface, whilst the other is biased over a range of voltages by the circuit.
of section 6.4.1. Plasma passing between the two electrodes conducts a level of current depending on the applied voltage and the plasma properties.

7.6 Experiments

A number of experiments were performed on the prototype gun to confirm its operation and the process by which the discharge region travels, and finally to characterise the plasma that is formed. Results were obtained using the electrical probes to measure the density, flow velocity and temperature of the plasma. Confirmation of the motion of the discharge region was obtained using electrical probes, with high-speed photography giving its speed and duration.

7.6.1 Electric Probe Results

7.6.1.1 Discharge Travel

Unfortunately, using a set of probes distributed throughout the POS region of the gun failed to provide any conclusive evidence of the mechanism by which the discharge travels. Instead the probes detected plasma ejected from all points on the gun. A daisywheel or merry-go-round device was therefore introduced to identify where the plasma originated. This consisted of a number of PVC walls glued to a circular base, which split the region into the twelve equally sized and totally separate segments seen in Fig. 7.18. This ensures that any plasma sensed by a probe is emitted only from the adjacent section of the gun.
In the first series of experiments, three probes were used to detect plasma ejected into segments a to d, using the original pulser circuit of section 5.6.3 (with the 1 μF capacitor). Results confirmed the presence of plasma near the nail and showed the initial movement of the discharge region to be either travelling, or spreading, in the clockwise direction. A pulse of plasma was also detected in segment a, immediately anticlockwise of the nail, indicating that the discharge was also travelling in the opposite direction and towards the current source.

Since the energy stored in the 1 μF capacitor was clearly too small to propel the discharge region any further than segment d, the pulser circuit was enhanced to that shown in Fig. 7.13. Six probes located in segments 1 to 6 now provided conclusive
evidence that the discharge travels, with the six probe current waveforms being given in Fig. 7.19. The discharge clearly initiates in region 1 and travels clockwise through regions 2 and 3. Slightly later a fraction of the discharge travels anticlockwise, passing through segments 6 and then 5. Plasma was detected at the furthest point away from the nail in region 4, although from the evidence available it is impossible to state from which direction it had originated.

![Figure 7.19. Plasma probe signals in segments 1-6 and gun current G.](image)

Initially, the thermal expansion spreads the discharge in all directions. Once beyond the electrode terminals, the direction in which the current flows will produce a magnetic field that interacts with the current in the arc to propel the discharge anticlockwise through regions 6 and 5. The shorter distance, and therefore the lower impedance offered to this current flow, means that the discharge will exist in the strongest field and be rapidly accelerated in the anticlockwise direction. This is reflected in the shorter time delay of the discharge travelling from region 6 to 5 than that travelling from region 2 to 3.

In an effort to prevent the unwanted anti-clockwise motion a split was introduced in both rings as shown in Fig. 7.20. This was located immediately anti-clockwise of the terminals, in an attempt to block any current flow that produces the magnetic field needed to propel the discharge anti-clockwise.
The results in Fig. 7.21 confirm that the discharge was successfully rotated in a clockwise direction, passing through segments 1-5 and almost completing a full turn. A small pulse of plasma in segment 6 indicates that thermal expansion is unavoidably propelling a fraction of the discharge anticlockwise, but that the splits in the rings prevent it from travelling any further. After a number of experiments it was concluded that the only method to remove totally the anticlockwise pulse would be to introduce a wall between segments 1 and 6, but this would also prevent the desirable multiple clockwise rotation.

The speed of the discharge can be determined from Fig. 7.22, which shows the arrival time of the plasma wave fronts at each of the probes and the distance travelled to
reach the segment where the probe is located. The gradient of the straight line gives the discharge speed as $1.6 \pm 0.1$ cm $\mu$s$^{-1}$.

![Graph showing discharge speed from the plasma probe results.](image)

**Figure 7.22.** Discharge speed from the plasma probe results.

To confirm that the rotation of the discharge is a direct consequence of the magnetic field produced by the ring currents, a number of experiments were performed using different ring arrangements to alter the shape of the magnetic field. In the first of these the top ring was reversed, so that the current reached the discharge point from opposite directions. This reduced the magnetic field at the centre of the arc, leading to the primary propulsion mechanism being thermal expansion. The results obtained from this experiment are shown in Fig. 7.23.

It can be seen from Fig. 7.23 that the nail appeared to have no affect on the initial breakdown, with the breakdown initiating in segment 4 and spreading in both clockwise and anticlockwise directions. This does not however conclusively identify the magnetic force as the driving mechanism, because the split was only some 2 mm wide and it would have quickly become filled with plasma and short-circuited. To overcome this the experiment was repeated with a larger 30 mm split, giving the results in Fig. 7.24.
It is clear from Fig. 7.24 that removing the magnetic field reduces the discharge propulsion, confirming the theory that the discharge is propelled by the interaction between the magnetic field generated by the current in the rings and the moving charge in the arc.

Analysis of the discharge mechanism using the ring gun is complicated by the fact that the discharge can approach a point from both directions. In an attempt to investigate this further, a simple linear gun was produced with an array of probes located in separate sections immediately above the gun, as shown in Fig. 7.25. It was hoped to detect the movement of the discharge by achieving electrical breakdown at a
single point, but this proved to be impossible as the electrode corners gave rise to corona that affected the initial breakdown.

**Figure 7.25.** Linear gun experiments.

### 7.6.1.2 Plasma Characterisation

The plasma characterisation determines the temperature, flow velocity and density using the technique described in sections 6.3.1 and 6.4.5. Three electrical probes with $120^\circ$ separations were located inside the switch region, at a distance of 60 mm from the inner edge of the aluminium rings. The probe characteristics were determined by sweeping the probe bias voltages in steps of 12 V over the range of $\pm 120$ V, producing in each experiment the plasma probe and gun current waveforms shown typically in Fig. 7.26.

**Figure 7.26.** Plasma probe and gun current waveforms at $+120$V bias.

A probe characteristic in the form of the logarithm of the peak probe current plotted against the probe bias voltage is shown in Fig. 7.27 for each probe. The characteristic
is described in the transition region by equation (6.15), and from this the gradients of the transition regions, corresponding to $e/kT$, give electron temperatures of 28108, 39620 and 68286 K at the 0°, 120° and 240° positions respectively. These convert to the electron temperature of $3.9 \pm 1.7$ eV that is comparable to published temperatures for cable guns elsewhere (see section 4.2), although it is significantly lower than is obtained with the conventional carbon gun.

![Figure 7.27. Logarithmic probe characteristic at the 0, 120 and 240° positions.](image)

The plasma flow velocity $v_0$ of $3.9 \pm 0.3$ cm $\mu$s$^{-1}$ was obtained in a further experiment in which three probes were aligned along the axis of an insulated channel, starting at the inner circumference of the rings and ending at the centre. On the other hand, using the electron temperature in equation (3.5) gave a thermal velocity of $1.0$ cm $\mu$s$^{-1}$. This difference is attributed to interaction between the magnetic field produced by the current flowing in the rings and the moving charged particles in the arc discharge.

The break points in Fig. 7.27 are located at the electron saturation currents $I_\text{es}$ at an overall value of $6.1 \pm 0.6$ A. Probe theory enables this current, the probe area of 8 mm$^2$ and the plasma flow velocity $v_0$ to be used in equation (6.16) to predict the electron plasma density in the POS switch region as $(1.2 \pm 0.1) \times 10^{14}$ cm$^{-3}$. 

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7.6.2 High Speed Photography

The electric probe experiments failed to establish conclusively the process by which the discharge region moves, specifically whether it spreads or remains as an arc. It was hoped to obtain more reliable evidence by using a high-speed camera (a Hadland Photonics 700\textsuperscript{*}) that was capable of taking between 8 and 16 pictures at rates of up to 10 million frames per second (fps) on Polaroid film. A typical result from a number of experiments performed to photograph the discharge (with the 1 \(\mu\)F pulser circuit) at a frame rate of \(5 \times 10^5\) fps is given in Fig. 7.28.

![Figure 7.28. Discharge motion.](image)

The discharge emanates from a single point in frame 1 (top right) and travels clockwise from this point, with the bright spots along the route suggesting that the discharge is a number of arcs at different places, rather than a single moving arc. Fig. 7.28 shows that the majority of action occurs in the period between the first two frames, so further experiments were planned to investigate this period in more depth. Unfortunately, problems developed within the camera that, even after constructing a timer and driver circuit, prevented further photography.

Fortunately, the newer Hadland Imacon 468\textsuperscript{*} (seen in Fig. 7.29) that is capable of taking eight photographs at rates of between 1000 and 100 million fps became available. Eight intensified CCDs (18 mm plate image intensifiers coupled to high resolution CCD image sensors) record the images from an optical beam splitter that takes a single optical input and divides the light into eight separate paths. Electronics in the camera control the exposure time of the individual intensifiers, by switching

\textsuperscript{*} Loaned from the EPSRC equipment pool.
the voltages applied to the plates at very high speeds using a 100 MHz crystal oscillator. The images are digitised and stored in memory within the camera, for later transfer to a remote PC through an optical fibre link. The PC also performs remote control of the camera functions, including the exposure, aperture and frame rate. One of the advantages of this camera is that each frame can be individually set at 10 ns resolution, to give total control of the image sequence.

Figure 7.29. Hadland Imacon 468.

The sequence of photographs in Fig. 7.30 was taken over a series of experiments at $10^6$ fps and 1 $\mu$s exposure time, with the number below each frame representing the time delay (in microseconds) from the initial rise of the gun current. The discharge is clearly initiated at a single point corresponding to the position of the nail and spreads anticlockwise, confirming the predicted operation. Secondary breakdown near the terminals (at 3 $\mu$s) is thought to be due to discharge from the ring edges, as a result of thermal expansion filling the gap between the electrodes with plasma. At 14 $\mu$s a new discharge starts on either side of the splits in the rings where the electric field in the gap is enhanced by the corners.
Figure 7.30(a). Direct horizontal images.
To measure the speed that the discharge rotates, a rectangular mirrored acrylic sheet was held in position above the rings by a PVC frame. This directed the image from the top of the rings, outwards through the viewing window of the vacuum chamber, and into the camera, as shown in Fig. 7.31.

Figure 7.32. Image reflected from the top of the rings.
This technique produced the sequence of images in Fig. 7.32, using the same camera settings so that the frame numbers correspond to those in the previous experiment.

Figure 7.33(a). Images of top view.
The Hadland software enabled the angle between the leading edge of the discharge and its initial point in Frame 0 to be measured for each of the first eight images, before the region became too blurred for accurate measurements. Fig. 7.33 shows the circumferential distance travelled around the inner circumference of the gun plotted against the time passed. This gives an initial speed of the discharge rotation as 1.5 cm μs⁻¹, comparable to the 1.6 cm μs⁻¹ obtained from the electric probe results in Figs. 7.21 and 7.22, increasing to 5.9 cm μs⁻¹ after 4 μs.
In an effort to prove the mechanism by which the discharge is forced to travel around the ring, experiments were performed with different ring arrangements. In the first of these the nail was moved to a location directly opposite the splits, in an attempt to prove that the discharge rotates due to the magnetic field and not just because the discharge fails to bridge the gap formed by the splits. As expected the sequence of images in Fig. 7.34 shows that the discharge only moves in the clockwise direction.

Figure 7.36(a). Images with nail opposite the splits.
In a further experiment the upper ring was reversed, which should have removed the effect of the magnetic field and left thermal expansion as the only possible mechanism for the discharge motion. However, as seen in Fig. 7.35 the effect of the current reversal was to propel the discharge region in the anti-clockwise direction, whereas thermal expansion should have acted in both directions. Unfortunately, it is impossible to align exactly the two rings and to apply an even pressure between them at all points, which could easily be the reason that the discharge travelled in a single direction. The discharge rotation has however slowed, indicating that the discharge propulsion mechanism is absent and proving that this is normally the magnetic field generated by the ring currents.
Figure 7.38(a). Images with upper ring inverted.
7.7 Summary

The results obtained in this section have proved that the ring carbon gun is able to produce plasma with a density of $1.2 \times 10^{14}$ cm$^{-3}$, a temperature of 3.9 eV and a flow velocity of 3.9 cm $\mu$s$^{-1}$, all of which are comparable to results published elsewhere that have been sufficient to operate a POS. The mechanism for the discharge travel, which propels it around the rings at 1.6 cm $\mu$s$^{-1}$, has been explained theoretically, and confirmed by experimentation as due to interaction between the current in the rings and the moving charge in the arc. The predicted current distribution in the rings from the rail gun theory indicates that the design is perhaps limiting the magnetic force available to propel the discharge region. In the following chapter a program is described that clarifies this by simulating the current distribution in a conducting sheet and this leads to a proposal for a modified ring gun design.
8  CURRENT DISTRIBUTION

The considerations of the previous chapter indicated that the current in the ring gun does not assume the ideal distribution to generate the optimum magnetic field to propel the discharge region. Instead it is distributed across the faces of the rings adjacent to the insulation and penetrates into the conductor. A deeper understanding of this distribution is therefore needed before the ring gun can be optimised to increase the rotational speed of the discharge and hopefully to propel it further.

Various published techniques are available that can predict the current distribution, although most are very complex and require significant computer power. Commercial software is available for both 2D and 3D simulations but it is very expensive if it is required to model a system with a large number of nodes. The program described in section 8.2 onwards makes the assumption that the current reaches the discharge point by a number of paths from all available directions and then, calculates the current in each path by taking into consideration their individual resistance and self inductance and the mutual inductance between paths.

8.1  Background

The current distribution under electrostatic conditions in Fig. 8.1 obtained using Quickfield* demonstration software confirmed that the current flowing through a sheet of conductor between two points P and Q will take numerous paths, with a proportion of the current to be found at all points in the conductor. Unfortunately, this software fails to explain the effect of a high frequency pulse, however it does start to indicate that the current flowing to the discharge point may be as predicted in Chapter 7.

* www.quickfield.com/free.htm
A method developed to model forces which arise when a shaped charge jet passes through electric armour [66] gave a current distribution between two single points in a conducting sheet as illustrated in Fig. 8.2. The method used Maxwell’s equations and a set of boundary conditions in some very complex mathematics to give the simplified result for the surface current density $J_S$ at a point $(x, y)$ and a time $t$ as

$$J_S(x, y, t) = \frac{I(t)}{2\pi^2} \left[ \frac{x - X}{y^2 + (x - X)^2} \frac{x + X}{y^2 + (x + X)^2} \right] + \left[ \frac{y}{y^2 + (x - X)^2} \frac{y}{y^2 + (x + X)^2} \right]$$

(8.1)

where $(\pm X, 0)$ describes the position of the two points between which the current flows and $i, j$ are unit vectors in the directions of the x and y axes.

It is reasonable to assume that the current in the ring gun will approach the discharge point in the same manner as the current in the positive quarter of the above diagram. In this case a significant proportion of the current is approaching from a direction that
will produce magnetic forces to either propel the discharge into the switch region of the POS or oppose the clockwise discharge motion.

### 8.1.1 Tubes and Slices

The term “tubes and slices” (TAS) [67] describes a method used to predict the overall impedance of a block of conducting material, and from this the total current and voltage associated with the conductor. It has been used successfully to solve electrostatic, magnetostatic and steady-state current problems with relative accuracy. Firstly the conductor is regarded as a number of parallel connected subdivisions, called tubes, as seen in Fig. 8.3(a) where the internal boundaries are very thin insulating sleeves and each tube has an individual resistance and self inductance together with a capacitance to the other tubes.

![Figure 8.3. Tubes (a) and slices (b)](image)

Secondly the block of current is divided into series conducting elements, called equipotential slices, as seen in Fig. 8.3(b) where the internal boundaries are now very thin sheets of infinite conductivity, with each slice given its own parameters as before.

Finally, the combination of the series-connected and parallel-connected elements gives an upper and lower boundary for the overall impedance of the conductor. In the simple example shown in Fig. 8.3, subdividing the conductor has achieved very little, because the shape of the tubes and slices is the same as the original block. However, for a more complicated quadrilateral such as in Fig. 8.4 the subdividing produces much simpler shapes than that of the original conductor.
Although Fig. 8.4 resembles the expected shape of the current flow, the element boundaries are too curved at present to allow an accurate calculation of the overall impedance. However, as the number of elements increases their boundaries begin to approach a straight line, so that the shape of the elements resemble rectangular blocks whose parameters can be easily calculated with relatively high accuracy.

If curved surfaces are needed to achieve an accurate representation of the expected current flow, then a number of construction lines are used to divide the conductor into smaller blocks, as shown in Fig. 8.5(a).

The tubes and slices are then overlaid so that at least one of their sides are parallel to the construction lines, and they are bent to match the anticipated current flow, as seen in Fig. 8.5(b). The upper and lower bounds of the overall impedance are determined from the parallel combination of the series-connected tube elements and the series combination of parallel-connected slice elements.
Unfortunately, this technique fails in a pulsed or AC system, because it assumes that the current is distributed evenly across the conductor. In practice, the mutual inductance between elements will force the current to concentrate at the conductor edges.

8.1.2 Finite Difference Method

The finite-difference (FD) method [67] is applicable to any system where the required value, such as the potential distribution across the conductor, can be described by a system of differential equations. It predicts the values at the intersections of a mesh of lines that are parallel to the two coordinate axes, by considering all the neighbouring points. For example, Laplace’s voltage equation can be solved using the typical five-point scheme shown in Fig. 8.6.

![Figure 8.6. 5 point finite-difference method.](image)

The voltage at the point \((i, j)\) is determined by taking the average of the surrounding four points as given by

\[
V_{i,j} = \frac{1}{4} \left( V_{i-1,j} + V_{i+1,j} + V_{i,j-1} + V_{i,j+1} \right) \quad (8.2)
\]

where the components of equation (8.2) are given in Fig. 8.6.
8.1.3 Finite Element Method

The finite element (FE) method [67] overcomes the problems associated with irregular boundaries in the FD method, as it can solve systems with complicated element shapes. The potential distribution across each element is now described by

\[ V = a + bx + cy + dx + ey + fxy + f_{xy} + ... \]  

(8.3)

where there are as many terms as there are points in the element. The whole system can be represented as a large matrix equation and solved numerically to give the constants \( a, b, c \) etc. for each element.

8.1.4 Equivalent Network Simulation Approach

Electromagnetic fields and other current dependent equations can be solved using the finite element method, but where there are moving conducting parts, such as with the railgun, the equivalent network simulation approach [68] is more appropriate. In the same manner as the TAS method, the conductor is sub-divided into elements, each with its own resistance and self inductance, and a mutual inductance to the surrounding elements. The effect of the capacitance between the adjacent elements is negligible in comparison to that of the resistance and inductances. The equivalent network approach overcomes the problems associated with the TAS method for AC or pulsed systems by each of the filaments having its own current.

When the method was used to simulate the current distribution in a railgun [68], the rails and armature were divided into the three zones shown in Fig. 8.7. In region 1 the solid conductor is replaced by a number of parallel filaments, assuming that the current only flows along the rail and that it is uniformly distributed throughout each element.
In region 2 the current is affected by the presence of the armature, and thus has components both along and perpendicular to the rails. The conductor is split into small rectangular blocks connected both in series and in parallel, such that current can flow in all directions. Each filament in the rails is represented by an equivalent impedance, as shown in Fig. 8.8. In the moving armature, region 3, the current is again restricted to travelling along long parallel elements, but the equivalent electrical circuit now has a resistance and a voltage drop at its boundary with the rail.

Figure 8.7. Segmentation for network simulation approach

Figure 8.8. Equivalent electrical circuit.
The overall circuit can be represented mathematically as a matrix equation that can be solved numerically to give the current in each branch. From this a plot of the resultant current magnitude and direction at each junction can be obtained.

8.2 Program Description

Early trials with a program written in MatLab to predict the current distribution between an equipotential surface and a single point, where the anticipated result is as shown in Fig. 8.9, resulted in singularity errors when the current paths converged to a single point. A novel technique, termed the tubes and wedges (TAW) system, was written to overcome this, by adapting aspects from the TAS system and the equivalent network approach.

![Expected current paths](image)

Figure 8.9. Expected current paths.

The TAW program takes the conducting block and splits it into an even number of wedges that meet at the lower left corner and whose equipotential boundaries are as seen in Fig. 8.10. Each wedge is divided into triangular and quadrilateral segments, emanating from the discharge point and bending towards the equipotential surface, so that the shape of the predicted current distribution starts to appear. As more wedges and segments are introduced, so the accuracy of the distribution increases.
As the shape of the segments make the calculation of the resistance and inductance difficult, the current flow is represented by tubes down the centre of each segment, as shown in Fig. 8.11, so that the magnetic field produced by the tube is similar to that produced by the current when distributed throughout the whole segment.

An impedance consisting of resistance, self inductance and mutual inductance then replaces each of the tube filaments, as shown in Fig. 8.12. Finally, the current in each tube is calculated using the series connected filament impedances, and the given voltage across the conductor.
8.3 Structure

The program, given in Appendix G, is divided between the main function in `current_distribution.m` and four other sub-functions called `mutual_inductance.m`, `self_inductance.m`, `resistance.m` and `distance.m`. The main function firstly defines the variables and constants used throughout the program, then creates and draws the current paths onto a new figure, calls the sub-functions to calculate the impedance components and finally calculates the current in each path by solving the linear solution of a matrix system for the tube currents. The percentages of the total current in each tube are outputted to the command window.

In the following sections the major parts of the program are described with the aid of flow diagrams.

8.3.1 Dimensions and Constants

The conductor is assumed to be a rectangular block whose width, perpendicular to the direction of the current flow at the equipotential surface, is given by “A” and whose length is “B”. The total thickness of the conductor through which the current flow will penetrate is identified by the variable “skin_depth”. All units of length in the program are in centimetres, as required by the equations for the self and mutual inductances calculations.
The discharge point is located on an edge of the conducting sheet with coordinates identified by "x_discharge" and "y_discharge". Around this point a small semi-circular region is constructed where the current paths are evenly distributed, as explained in the next section.

The remaining constants define the electrical properties, such as the source voltage, current and frequency.

8.3.2 Tubes and Wedges

The flow diagrams in Fig. 8.15 describe the first stage of the main program, in which the size and position of the tubes and wedges are determined. Firstly the conductor is divided into an even number of wedges, ensuring that the boundary between the two middle wedges intersects the opposite corners of the block, as shown in Fig. 8.13, so that its angle with respect to the horizontal is given by \( \tan^{-1}(A/B) \). Dividing the upper and lower segments into the required number of wedges, gives the angles "\( \Delta_{\text{upper}} \)" and "\( \Delta_{\text{lower}} \)" , which are then used to calculate the boundary angles and gradients.

![Figure 8.13. Construction of wedges](image)

The program now determines the starting points and initial gradients for all the tubes. To avoid singularity errors a semicircular region of radius "\( r \)" is defined around the discharge point as shown in Fig. 8.14, where the current tubes that enter this region are assumed to continue unaffected towards the discharge point. This region is divided into the required number of segments, with tubes starting from the region.
boundary and projecting outwards along a line that passes through the discharge point. The width of the tubes is determined from the distance between the two points where the segment and semicircle boundaries meet.

The start of each tube is the point whose coordinates are \( X_{\text{Discharge}} - r \cos \theta, Y_{\text{Discharge}} + r \sin \theta \), where \( \theta \) is the angle of the centre line through the segment with respect to the horizontal. The width of the tubes is calculated trigonometrically as \( 2r \sin(\frac{\phi}{2}) \), and remains constant throughout the entire conductor. The tubes first project outwards to meet the first wedge boundary, where they are bent towards the equipotential surface by an angle determined from a fraction of the total needed to meet the equipotential surface at right angles. After initial simulations a factor was introduced to turn the current paths by a greater angle when intersecting with the
wedge boundaries near the discharge point. Finally a small loop in Fig. 8.15(b) tests the coordinates of each tube to remove any that extend beyond the conductor edges.

**Figure 8.15(a). Main Program**

**Figure 8.15(b). Main Program**
Current Distribution

2

Open figure window

Set axes

Draw lines between tube coordinates

Set electrical and frequency constants

Resistance Procedure (output Filament_R)

Self Inductance Procedure (output Filament_I)

Complete Filament Impedance Matrix

Complete Connection Matrix

Produce Tube Impedance Matrix

Solve Linear System of Equations

Output Tube Current Percentages

End

Figure 8.15(c). Main program
In Fig. 8.15(c) a new figure window is opened whose axis lengths are set to the physical dimensions of the conductor, and each tube line is then drawn onto the figure. The impedances and subsequently current distribution are calculated in the remainder of the main program, as is described in section 8.3.6, by use of the functions explained in the following sections.

8.3.3 Mutual Inductance Calculations

The sub-function `mutual_inductance_m` receives from the main program the coordinates for a pair of filaments. In Fig. 8.16(a) the geometry of the filament pair is tested and a sub-function called to perform the required calculation. Firstly it tests the gradients of the two filaments to determine if the filaments are parallel and whether they are on the same axis. In the latter case the mutual inductance of two filaments aligned along the same axis is zero, otherwise the sub-function `parallel` described in section 8.3.3.1 is called to calculate the mutual inductance. Secondly, if the gradients are found to be unequal the program compares the distance between the intersection point of the axes and the filament ends, against the length of the filaments. This decides the location of the axes intersection and calls either the sub-function `Converge_to_a_Point` in section 8.3.3.2 or `Converge_Extended` in section 8.3.3.3.
Figure 8.16(a). Mutual-inductance – main.
Determine length and angle of filaments

Determine intersection of lines from 1a to 2b and 2a to 1b

Do they intersect?

No

Error message

Yes

Determine intersection of lines from 1a to 1b and 2a to 2b

Do they intersect?

No

Yes

Determine length and gradient of diagonals

Determine length and gradient of diagonals

Determine angle of the diagonal

Calculate the variables for inductance calculation

Calculate the mutual inductance (m) for the filament pair

Return m

Figure 8.16(b). Mutual-inductance – parallel
Current Distribution

Figure 8.16(c). Mutual-inductance - Converge_To_Point

Figure 8.16(d). Mutual-inductance - Converge_Extended
Set intersection bit in array xy to 1

Is filament 1 vertical?

No

Gradient of filament 1 is infinity

Determine gradient of filament 1

Is filament 2 vertical?

No

Gradient of filament 2 is at infinity

Determine gradient of filament 2

Are gradients equal?

Determines intersection coordinates (x, y)

Is the intersection point on the filaments?

Reset intersection bit in array xy to 0

Store intersection (x, y) in the intersection array xy

Return intersection array

Figure 8.16(e). Mutual-inductance – intersection
8.3.3.1 Parallel Filaments

The first stage of the parallel function described in Fig. 8.16(b) tests the geometry of the filaments to determine the location of the diagonals that link the filament ends, by checking that they intersect. The small sub-routine Intersection in Fig. 8.16(e) is called to calculate firstly the filament line equations and then the axes intersection. A value is returned from the routine that states whether or not the intersection point lies on the two filaments. Simple trigonometry from Fig. 8.17 gives the overlap $\delta$ (-ve when overlapping) of the filaments and their separation $d$ from the diagonals.

\[
\delta = -\text{diag\_length} \times \cos(\theta) \\
d = |\text{diag\_length} \times \sin(\theta)| \\
\alpha = m + n + \delta \\
\beta = n + \delta \\
\gamma = m + \delta
\]

Figure 8.17. Filaments in parallel.

The mutual inductance is calculated using the variables in Fig. 8.17 from [69]

\[
L_m = 0.001 \times \left[ \frac{\alpha \sinh^{-1} \left( \frac{\alpha}{d} \right) - \beta \sinh^{-1} \left( \frac{\beta}{d} \right) - \gamma \sinh^{-1} \left( \frac{\gamma}{d} \right) + \delta \sinh^{-1} \left( \frac{\delta}{d} \right)}{\sqrt{\alpha^2 + d^2} + \sqrt{\beta^2 + d^2} + \sqrt{\gamma^2 + d^2} - \sqrt{\delta^2 + d^2}} \right] \quad (8.4)
\]

8.3.3.2 Connected Filaments

The flow diagram in Fig. 8.16(c) calculates the mutual inductance of a pair of connecting filaments. Firstly the routine determines the separation $R$ of the unconnected filament ends as shown in Fig. 8.18.
\[ \cos \epsilon = \frac{m^2 + n^2 - R^2}{2mn} \]

\[ L_m = 0.002 \cos \epsilon \left[ \frac{n \tanh^{-1} \frac{m}{n + R} + m \tanh^{-1} \frac{n}{m + R}}{n + R} \right] \text{ (\textmu H)} \] (8.5)

8.3.3.3 Unconnected, Converging Filaments

The flow diagram in Fig. 8.16(d) is the procedure used in the sub-routine \textit{Converge Extended} to calculate the mutual inductance of a pair of unconnected filaments in the same plane. The geometry is tested to determine the location of the convergence point of the filament axes and which ends of the filaments are close to this point. The variables \( R_1, R_2, R_3, R_4, u \) and \( v \) are then calculated accordingly as shown in Fig. 8.19.

\[ \alpha^2 = R_4^2 + R_2^2 - R_1^2 \]
\[ 2 \cos \epsilon = \frac{\alpha^2}{mn} \]
The mutual inductance for this case is given by [69]

\[
I_m = 0.002 \cos \theta \left[ \left( \mu + n \right) \tanh^{-1} \frac{m}{R_3 + R_2} + \left( \nu + m \right) \tanh^{-1} \frac{n}{R_3 + R_4} \right]
\]

\[
-I \tanh^{-1} \frac{m}{R_3 + R_4} - \nu \tanh^{-1} \frac{n}{R_2 + R_3}
\]

(8.6)

In some cases the convergence point lies on one of the filaments, which introduces a problem when determining the above variables. The solution is to split this filament into two separate filaments and to combine the mutual inductances.

### 8.3.4 Self Inductance Calculations

The self-inductance calculations are made by the sub-function `self_inductance` described by Fig. 8.21 that uses the rectangular geometry in Fig. 8.20.

![Figure 8.20. Rectangular tube geometry](image)

The self-inductance \( L_s \) is given by [69]

\[
L_s = 0.002 I x \left[ \ln \left( \frac{2I}{B + C} \right) - \frac{1}{2} \right]
\]

(8.7)
8.3.5 Resistance Calculations

The resistance of a segment with the geometry of Fig. 8.20 is given by

\[ R = \frac{\rho l}{BC} \]  

(8.8)

where \( \rho \) is in units of ohms cm. This equation is used in sub-function \textit{resistance} in Fig. 8.22 to create an array of resistance values for all the tube filaments.
8.3.6 Current and Impedance Calculations

In Fig. 8.15(c) the main program receives two arrays containing the self inductance and resistance values for each of the tube filaments in Fig. 8.12. The potential difference $V_f$ across each filament in the steady-state system is described by

$$V_f = R_f I_f + j \omega (M_{f,1} I_{1} + M_{f,2} I_{2} + \ldots + M_{f,f-1} I_{f-1} + L_f I_f + M_{f,f+1} I_{f+1} + \ldots + M_{f,n} I_{n}) \quad (8.9)$$
where \( n \) is the total number of filaments in the system, \( R_f \) and \( L_f \) are the filaments resistance and self inductance respectively and \( M_{fi} \) is the mutual inductance between the filaments \( f \) and \( i \), which gives a voltage due to the current \( I_i \) in the filament \( i \). In matrix form this can be more clearly represented as

\[
\begin{bmatrix}
V_1 \\
\vdots \\
V_n
\end{bmatrix} =
\begin{bmatrix}
R_1 + j\omega L_1 & j\omega M_{12} & \cdots & j\omega M_{1n} \\
\vdots & \ddots & \vdots & \vdots \\
0 & \cdots & R_n + j\omega L_n
\end{bmatrix}
\begin{bmatrix}
I_1 \\
\vdots \\
I_n
\end{bmatrix}
\]

(8.10)

A transformation matrix (or connection matrix) \([C]\) consisting of 1’s and 0’s, such as that given in equation (8.11), is used to produce the mesh equivalence of equation (8.10).

\[
[C] =
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
0 & 1 & 0 \\
0 & 0 & 1 \\
0 & 1 & 0 \\
0 & 1 & 0 \\
0 & 1 & 0 \\
0 & 1 & 0 \\
0 & 1 & 0
\end{bmatrix}
\]

(8.11)

for a system with 3 tubes and 4 wedges.

The potential difference \( V \) between the equipotential surface and the discharge point is applied across the entire length of each tube and is related to the current in the tube by

\[
\begin{bmatrix}
V \\
\vdots \\
V_n
\end{bmatrix} =
\begin{bmatrix}
R_1 + j\omega L_1 & j\omega M_{12} & \cdots & j\omega M_{1n} \\
\vdots & \ddots & \vdots & \vdots \\
0 & \cdots & R_n + j\omega L_n
\end{bmatrix}
\begin{bmatrix}
I_1 \\
\vdots \\
I_n
\end{bmatrix}
\]

(8.12)

where \( t \) is the number of tubes in the system. By solving this linear system of equations the current in each tube can be calculated. Fig. 8.15(c) shows the routine
used in Matlab to complete the impedance and connection matrix, and then solve the system of linear equations. The magnitudes of the resulting complex tube currents are then translated into a percentage of the overall system current and simply given as text in the command window.

### 8.3.7 Distance Calculations

The flow diagram in Fig. 8.23 is a small sub-routine *distance* used throughout the program to calculate the distance between two points using Pythagoras' Theorem.

![Flow diagram for distance calculations](image)

**Figure 8.23. Distance sub-routine**

### 8.4 Results

The results obtained from this program confirm that when current flows between two points it distributes across the width of the conductor and will approach the discharge point from all the available directions, as expected from the published information in Chapter 7. For example, if the conductor is 3 cm wide, such as in the prototype gun of Chapter 7, the current distribution is predicted to be as shown in Fig. 8.24(a). It has been proven in Chapters 5 and 7 from the results obtained both experimentally and theoretically for the conventional carbon plasma gun and the prototype ring gun, that only the current flowing within a few millimetres of the discharge point produces a magnetic field that has any influence on the plasma.
In considering a semicircular region of 3 mm radius around the discharge point, which has the current distribution shown in Fig. 8.25(a), it can be shown that approximately only 11.2% of the total current acts to propel the discharge around the rings, whilst the majority either propels plasma into the POS region or opposes the clockwise rotation.

Figure 8.24. Current distribution in a 3 cm (a) and 0.1 cm (b) wide conductor.

In order to optimise the present design the current ideally needs to approach the discharge point along the lower left hand edge of the conductor block, so that all the current contributes to the magnetic field to drive the discharge region clockwise both faster and further. This situation is beginning to be achieved in Fig. 8.24(b) when the conductor width is reduced to 0.1 cm, thereby restricting the available current paths to those that will enter the region of influence from the preferred direction as seen in Fig. 8.25(b), and so increase the component of current that contributes to the magnetic field needed to propel the discharge clockwise. Only the components that are approaching from the opposite direction, and they do so for only a short distance, will have any detrimental affect to the required magnetic field.
Current Distribution

![Current Distribution Diagrams](image)

**Figure 8.25.** Current distribution close to the discharge point for the 3 cm (a) and 0.1 cm (b) wide conductors.

### 8.5 Summary

In summary, the simulation results have confirmed that the current approaches the discharge point from all the available directions and that with a wide conductor only a small fraction of the magnetic field generated by the current actually propels the discharge region around the rings. As expected, the current is stronger towards the outside edges of the conductor where the mutual inductance is smaller. This is in contrast to the electrostatic solution (Fig. 8.1) where the current is evenly distributed across the width of the conductor. It has been shown that the current can be forced to approach the discharge point from the required direction by reducing the width of the conductor. This idea is used in the final ring gun that is described in the next chapter and has proved to give a faster discharge rotation than in the prototype ring gun.
9 OPTIMISED RING GUN DESIGN

9.1 Structure

The wide conduction rings in the prototype gun of Chapter 7 have been shown to produce a current distribution near the discharge point that limits its performance. Only a small fraction of the total current flowing through the gun propels the discharge region, whilst the remainder either opposes this effect or ejects plasma into the switch region. The idea realised in the simulations of Chapter 8 was that narrowing the conductor width focuses the current, so that an increased component of this will propel the discharge region. In the design shown in Fig. 9.1, two 250 μm thick copper strips are aligned with their edges adjacent and separated by the HDPE insulating ring. Nylon screws fix the copper strips to the inside of the PVC shaping rings, of Figs. 9.1(b) and 9.2, and the strips are clamped by further nylon screws where they enter through splits in the PVC rings. The copper strips are prevented from forming a complete ring by a gap that discourages any unwanted anticlockwise discharge motion.

The dimensions of the rings and the location of the fixings are given in Fig. 9.2.
In the optimised ring gun the current distribution approaches the ideal case of section 7.4 by flowing along the adjacent edges of the copper strips (see Fig. 9.3), although skin effect will allow limited penetration across the face of the copper strips.
9.2 Experiments and Modifications

9.2.1 Initial Discharge

Ideally, the discharge is initiated at the point at which the strips first enter the rings, where both the lowest impedance path and the first opportunity for breakdown occur. However, the sequence of images in Fig. 9.4 obtained during one of the first experiments with the optimised gun shows that the initial discharge in fact occurred approximately $90^\circ$ clockwise from the point where the strips enter (top of the images).
In a simple modification that overcame this problem, the notch made by the nail in the previous design (see Fig. 7.11) was enhanced to produce a weak point for surface breakdown and during assembly ensuring that this point was immediately adjacent to where the strips enter the gun.

9.2.2 Strength

Once the modifications had been made, the arrangement produced the required initial discharge and the most successful result so far. The discharge rotated through a full 360°, as is confirmed by the images in Fig. 9.5.

Figure 9.5(a). Images from the first prototype with nylon screws attaching the copper rings.
Unfortunately, after this sequence of experiments, the interaction between the magnetic field and the current in the strips had caused them to distort as seen in Fig. 9.6. They had also been severely heat damaged at the point where they bent through 90° and entered the rings (Fig. 9.6(b)). The damage sustained could have been the cause of the poor sequences of images at 7 and 8 μs, which were in fact taken over consecutive experiments.
A stronger method of clamping the strips to the PVC rings is to use ceramic rather than nylon screws, which are both stronger and have a higher heat capability, but are extremely expensive. Simply using steel screws resulted in unwanted corona and inevitably produced random discharges around the gun. In an attempt to overcome this two additional PVC clamping rings as seen in Fig. 9.7 were introduced, and the holes in the copper strips enlarged to allow the steel screws to pass through whilst restricting any electrical contact. The clamping rings were slightly narrower than the copper strips to leave a small (2 mm) strip of exposed copper. The sequence of images in Fig. 9.8 shows the results obtained with this design.
Corona from the steel screws still clearly initiated discharges at multiple positions around the rings and during the experiment the strips separated vertically, as indicated in Fig. 9.9, due to the repulsive magnetic forces produced by the currents.

It was realised that the copper strips needed to be clamped in both the vertical and horizontal directions without making any electrical contact to the strips. Twelve L-shaped clamps were therefore arranged around the inside edge of each shaping ring as seen in Fig. 9.10, with nylon screws at the beginning and end of the strips and at several other locations to fix the rings in place, whilst the clamps were tightened.
The images in Fig. 9.11 show a rotating discharge initiating at the correct point and rotating clockwise, but failing to complete a full turn. Plasma appears to be collecting at the front edges of the clamps, blocking the free rotation of the discharge. However, the copper rings sustained only minimal heat damage at the point where the strips enter, together with a slight separation of the strips, proving in principle that this method could produce a design capable of functioning satisfactorily for a larger number of shots.

![Figure 9.11. L-shaped clamps.](image)

**Figure 9.12.** Results after the introduction of L-shaped clamps.

### 9.2.3 Final Structure

The final gun arrangement adopted has two Tufnol rings, with an L-shaped cross-section providing an even clamping pressure around the entire inner circumference of
the existing PVC shaping rings, as shown in Fig. 9.12. The copper strips are clamped between the shaping and Tufnol rings, leaving the thin strip of exposed copper seen in Fig. 9.12(c). After several shots the strips were damaged at the point where they enter the rings (see Fig. 9.13), which required additional strengthening with a double layer of copper.

![Tufnol Rings](image)

**Figure 9.13.** Copper strips clamped between the Tufnol and PVC rings.

![Damage to Copper Rings](image)

**Figure 9.14.** Damage to copper rings after several shots.

### 9.3 Results

#### 9.3.1 Electrical Results

The plasma temperature and density were determined using three electrical probes located in the switch region at 30 mm from the copper strips and separated by 120°. An applied voltage biased the probes in steps of 12 V over the range ±120 V, using the circuit of Fig. 6.14. Plasma passing between the probe electrodes conducts a current that depends on the applied voltage, the probe dimensions and the required...
plasma parameters. A plot of the logarithm of the peak current against the applied voltage for each probe is given in Fig. 9.14.

![Figure 9.15. Logarithmic plasma characteristic.](image)

The transition regions in Fig. 9.14, described by equation (6.15), have gradients that translate to electron temperatures of 8.3 eV at 0° and 120°, and 4.5 eV at 240°. The characteristic breaks away from the straight line of the transition region at the electron saturation currents $I_{eS}$ of 9.0 A at 0° and 240°, and 14.9 A at 120°.

The plasma waveforms of Fig. 9.15 were obtained from six probes aligned along the central axis of an insulated channel. These gave the measure of the position of the plasma front against the time elapsed, seen in Fig. 9.16, that represents a plasma flow velocity $v_D$ of $3.5 \pm 0.3$ cm $\mu$s$^{-1}$. 

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Figure 9.16. Plasma probe waveforms from the plasma flow velocity experiment.

Figure 9.17. Results from the plasma flow velocity experiment.

The electron plasma density $n_e$, derived from equation (6.16) using the plasma flow velocity $v_D$, the probe area $A$ (8 mm$^2$) and the electron saturation currents $I_{es}$, gives values of $(2.0 \pm 0.2) \times 10^{14}$ cm$^{-3}$ at $0^\circ$ and $240^\circ$, and $(3.3 \pm 0.4) \times 10^{14}$ cm$^{-3}$ at $120^\circ$.

The daisywheel arrangement (see section 7.6.1.1) detected the rotating discharge as it passed through the different segments of the gun. The sequence of plasma pulses in Fig. 9.17 confirms the full rotation of the discharge, although a small plasma pulse is still clearly rotating in the opposite direction in segment 6.
The plot of the distance travelled by the discharge to reach the segment against the time lapsed as shown in Fig. 9.18 gives the discharge speed as $5.3 \pm 1.3 \text{ cm } \mu\text{s}^{-1}$.

\[\text{Figure 9.19. Discharge travel speed.}\]

9.3.2 High Speed Photography

The two sequences of images of the discharge in Figs. 9.19 and 9.20 were obtained directly and indirectly, using a mirror to reflect the image from the top of the gun into the camera, at 500,000 fps (1 \text{ \mu s} \text{ exposure}). The first sequence shows the initial discharge occurring at two places simultaneously, an intermittent event that was probably caused by inaccuracies in the ring alignment.
Figure 9.20. Direct images of the discharge in the final prototype design.
Figure 9.21. Indirect images of the discharge in the final prototype design.

The images in Fig. 9.20 confirm that the discharge completes a full turn in between 16 and 18 μs and from Fig. 9.21 its speed can be estimated as $3.6 \pm 0.5$ cm μs$^{-1}$. The
Tufnol rings appear to have decreased the discharge speed from that obtained with the original arrangement (Fig. 9.5), but the small amount of damage now sustained does not affect the overall gun performance.

In the final experiment, a small Mylar cone reflected the image of the inside of the rings vertically onto the mirror and into the camera, through the viewing window of the vacuum chamber. The images in Fig. 9.22 show the discharge travelling around the ring from a horizontal perspective, with two bright streaks ahead of the main discharge that could be corona emitting from the ring edges.

Figure 9.22. Discharge rotation speed from the images.

Figure 9.23(a). Images reflected from the inside of the ring gun by a cone.
9.4 Summary

The results obtained in this section have confirmed that the discharge does indeed travel at a greater speed when the conductor widths are reduced. Electrical probe and photographic evidence both show that the discharge in this optimised gun reached speeds of over 3.6 cm $\mu s^{-1}$, twice as fast as in the original ring gun. The plasma produced had similar properties to that evolved by the original ring gun, with a density of $2.4 \times 10^{14}$ cm$^{-3}$, a temperature of 7 eV and a flow velocity of 3.5 cm $\mu s^{-1}$. A succession of experiments at the start resulted in distortion and heat damage to the copper strips that reduced the life-time of the plasma source and caused incorrect locations for the initial discharges. Numerous modifications had to be implemented to improve the strength of the structure and to ensure correct operation, which resulted in the present design.
The aim of this research was to produce a compact plasma source for use in future industrial applications of the POS and other such plasma switches that are required to operate with minimal maintenance. The carbon gun was chosen as the starting point for this research, because of its low cost and simplicity. Alternative plasma sources were considered, such as those involving the application of a laser or using a gas discharge, but these are too complex and expensive for the research laboratory. Initially a prototype conventional carbon gun was developed, with a hydrocarbon sleeve insulating the inner and outer electrodes of a coaxial arrangement. Surface flashover of the insulation vaporised and ionised its molecules, producing a plasma beam that was ejected outwards through a shaped hole in a copper plate. Unlike a traditional cable gun that erodes the cable insulation, with inevitable contamination of the plasma by fluorine and chlorine ions, this new design produced plasma comprising only hydrogen and carbon ions.

The original coaxial gun operated successfully without interference for over 30 shots, whilst consistently producing plasma at a density of $1.4 \times 10^{14}$ cm$^{-3}$, an electron temperature of 23.8 eV and with a plasma flow velocity of 8.5 cm $\mu$s$^{-1}$. These figures are comparable with, and in some cases better than, results published elsewhere. Unfortunately, the fast plasma flow velocity makes it difficult to achieve optimum triggering of the POS at the maximum density and distribution. A 3D image, captured using the glass plate technique, showed a small plasma beam that confirmed the need for a large number of guns to fill a POS with sufficient plasma. The space occupied by the guns, cable and vacuum connections would occupy a large vacuum chamber, making it difficult to realise a future commercial application for the switch.

The solution is the ring carbon plasma gun that takes ideas from the previous carbon gun, the railgun and the rotary arc gap switch to develop a single plasma source capable of ejecting plasma into the POS from all directions. A prototype ring gun was developed using two aluminium ring electrodes insulated by a high-density polyethylene ring. The resulting surface flashover of the insulation rotated around the gun at a speed of 1.5 cm $\mu$s$^{-1}$, whilst ejecting plasma into the switch region at an
electron temperature of 3.9 eV, a plasma flow velocity of 3.9 cm \(\mu\)s\(^{-1}\) and a plasma density of \(1.2 \times 10^{14}\) cm\(^{-3}\). High speed photography and results obtained using electrical probes confirmed that the discharge rotates as a result of interaction between the magnetic field generated by the current in the rings and moving charge in the arc discharge. The distribution of current in the rings was predicted near the discharge point to approach from all available directions, thereby reducing the maximum attainable speed of the rotating discharge and resulting in the plasma reaching the centre of the POS region before the discharge completed a full turn. This will make it difficult to achieve the even plasma distribution that is needed for successful POS operation.

A program was developed to simulate the distribution of current in a rectangular conducting block, by taking into account the effects of the mutual inductance, self inductance and resistance of tubes of current flowing from an equipotential surface to a single discharge point at an edge. Confirmation was obtained that only a small proportion of the current (~6%) approached the discharge point from the direction required to propel the discharge clockwise, whilst the remainder either opposed this rotation or propelled the plasma into the POS. The program confirmed that a reduction in the width of the rings from that found in the original ring gun will concentrate the current, so that it approaches from the direction required to propel the discharge region clockwise.

Using this information an optimised ring gun was designed, with thin copper strips formed into the shape of two rings and separated by a high-density polyethylene ring. During the initial testing of this novel design, one series of images obtained confirmed a discharge that during the duration of a single frame (1 \(\mu\)s) ejected plasma from all directions into the POS region. This design should produce the even plasma distribution that is recognised as being necessary for successful POS operation. Unfortunately, the copper strips were distorted by the strong magnetic forces and the nylon screws that clamped these were severely damaged by the extreme heat produced. To overcome this problem, Tufnol rings were introduced to further clamp the copper strips, allowing the ring gun to be operated for at least ten shots without any significant reduction in performance. Experimental analysis proved that the
discharge region rotated at 3.6 cm $\mu$s$^{-1}$, whilst ejecting plasma into the POS with an electron temperature of 7 eV, a flow velocity of 3.5 cm $\mu$s$^{-1}$ and a density of $2.4 \times 10^{14}$ cm$^{-3}$. The optimised design had accomplished a discharge speed at over twice that of the original ring gun, but still less than is required to complete a full turn before the initial plasma reaches the centre of the POS region.

Unfortunately, it appears the Tufnol rings that were used to strengthen the optimised design affected the performance of the ring gun as a plasma source, by reducing the discharge size and its maximum rotation speed. It is thought that friction between the moving particles and the Tufnol surface was opposing the magnetic driving force. An idea was proposed to use ceramic screws instead of the original nylons crews to hold the copper strips in position, but these were deemed to be too expensive. A successful design may be realised that allows free rotation of the discharge by using ceramic screws and replacing the copper strip with a stronger metal, such as brass or an alloy of tungsten and copper. The PVC rings that maintain the shape of the copper strips could be replaced with tougher materials such as high-density ceramics, and reduced in size so that the gun becomes suitable for implementation in a compact POS. A defect with the present design is the means by which the copper strips are bent through right angles when terminating to the strips lines and entering into the rings. The strong magnetic and electric fields present in this region distorted the copper strips, through the forces produced between the current in the two rings and by heat damage resulting from corona discharges. It is possible to modify the design to enhance the life-time of the gun, by reducing the angle through which the copper strips are bent. Finally a future research program needs to investigate the effect on the rotation of the discharge when the physical dimensions of the gun are reduced, and so gather the information required to develop a compact version of this plasma source. Once this had been accomplished the plasma source can be implemented in a POS and the realisation of a compact switch becomes much closer.

In summary the gun has been proved to produce plasma of suitable density, temperature and distribution to operate a POS, however to fully recognise its success the plasma source needs to be developed further and tested in an operating POS. This thesis has contributed to knowledge by investigating and developing an alternative
plasma source for the POS, which has the potential to be scaled down to fit inside a compact switch for future applications. Theoretical and experimental studies undertaken during this research have developed techniques to investigate the behaviour of charged particles in plasmas and arc discharges, predict the distribution of a high-frequency current in a conductor and have increased our understanding of the carbon plasma gun.
11 PUBLICATIONS

The following is a list of the journal and conference papers that have been published or have been submitted for publication.

Journals


Conferences


Four-stage Marx generator using thyristors

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A small-scale capacitor discharge pulse generator using thyristors in a Marx configuration is described. The four-stage generator is actively triggered in a sequential manner. The application considered is in the firing circuit of a larger switch where the generator is shown to be capable of producing pulses ranging to 230 A in less than 1.5 μs from an equivalent open-circuit voltage of 2.3 kV. © 1998 American Institute of Physics [S0034-6748(98)00211-1]

Thyristors are natural single-shot switches. They have excellent pulse current capabilities and are simple to trigger. Their only drawback is a relatively low-voltage capability. However, successful high-voltage switches have been constructed using easily available devices arranged in series stacks.

Single-shot series arrangements can be triggered in two ways simultaneously or sequentially. Simultaneous triggering requires separate external firing circuits for each device. Such stacks are not naturally well behaved, with the turn-on process tending to be uneven and somewhat random in nature. Switch operation can be improved with careful device selection, or by differential timing of individual trigger signals, but these approaches make construction unduly cumbersome. In comparison, sequential triggering is simpler, and produces a turn-on process that is naturally even and well controlled.

The first single-shot series stack used at Loughborough was in the firing circuits of the ignitron switches in a 24 kJ capacitor discharge power supply. For this application, a sequential arrangement of four 2N6399 devices was used in a circuit due to Campbell and Kasper. Operating at 2.2 kV this circuit proved capable of producing pulses rising to 250 A in 1 μs.

When producing high-voltage pulses by capacitor discharge conventionally, it is necessary to use a capacitor capable of operating at the nominal pulse voltage, and to provide a suitable charging supply of the same magnitude. Cascaded rectifiers or voltage multipliers are often used for this application because of their simplicity. It seems particularly reasonable, when using voltage-multiplying rectifiers in a power supply for a pulse generator that uses a series-stack switch, to wonder why the voltage multiplication and switching cannot be combined. It was to attempt this combination that Marx circuits were first considered, with the parallel-charge/series-discharge technique allowing the charging voltage to be significantly lower than the required output voltage. Other semiconductor Marx arrangements have been produced using either avalanche conduction or simultaneous triggering, to date none have been found which use sequential triggering.

The four-stage arrangement of Fig. 1 was designed for the ignitron firing application. The main capacitors C1 to C4 are charged via resistors R1 to R4 and diodes D1 to D4. The first stage gate capacitor C5 is charged via R1 and R5 to a fraction of the main stage voltage specified by R5 and R6, the voltage depending on the voltage capability of C5 and/or the light-activated thyristor LASCR. The first thyristor SCR1 is triggered from C5 via LASCR and R7. The remaining thyristors SCR2 to SCR4 are triggered sequentially via R8 to R10, respectively. There are two other resistors, R11 controls the LASCR turn-on characteristics and R12 limits the main output current.

The circuit differs from the classic Marx generator in that its triggering mechanism is entirely active and does not rely on breakdown conduction. However, it is essential for device survival that the natural tendency of such circuits to produce stage overvoltages is controlled. This control is provided by the diodes D2 to D4, with the additional diode D1 completing the charging circuit and providing the secondary function of a flywheel path for the main output. The gate configuration is similar to that used for the slave firing of thyristors in parallel, and produces a simple triggering mechanism. For example, when SCR1 begins to conduct SCR2 is triggered via R8 using energy from the first stage main capacitor C1.

The operation of the circuit is demonstrated at a charging voltage of 600 V and firing into the ignitron of an EEV BK488 ignitron. The voltage across R12, the 5 Ω main output resistor, shown in Fig. 2 indicates that the current reaches 230 A in 1.34 μs, a pulse which is easily capable of triggering the ignitron.

The output pulse consists of a sequence of current steps produced as each stage fires. These steps are not easily seen...
in Fig 2 but are immediately apparent when firing into a resistive load. When SCR1 is fired, C1 is connected to the load via D2, D3, and D4. In this state, the only additional voltage on the upper thyristors is the forward drop of the relevant diode. When SCR2 fires D2 is rapidly reverse biased and turns off, C1 and C2 are now connected in series and to the load via D3 and D4. The voltages on SCR3 and SCR4 are limited respectively to the forward drops of D3 and D4, although the voltages are larger because the current is larger. When SCR3 fires D3 turns off leaving only D4 to carry the load current supplied now by C1, C2, and C3 in series. The sequence is completed when SCR4 fires when all four capacitors are in series and all of the diodes are off.

It is evident from the thyristor voltages of Fig 3 that no significant overvoltage occurs on any of the devices, and the expanded timebase of this figure allows the well-ordered firing sequence to be seen clearly. In addition, the action of the diodes during the triggering sequence is evident.

The output pulse of Fig 2 is well within the fusing rating of the International Rectifier 16TTS thyristor but clearly exceeds the nominal 150 A/μs d/dt limit. This result confirms other experimental findings, which show manufacturer’s d/dt ratings to be very conservative. It is known that d/dt capability is affected by the level of gate drive, and experience suggests that thyristors, when triggered in the way described here, can survive significantly more than their nominal maximum d/dt.

The diodes should have the same voltage and current rating as the thyristors, and should be as fast as possible. The standard rectifier diodes used in the prototype produced large transient reverse currents at turn-off, and fast soft recovery diodes such as International Rectifier 10ETF or 20ETF may improve the stack response.

There is usually little penalty in having several separate main capacitors—as is required for a Marx circuit—rather than one, since the main capacitor for small pulse generators would often be assembled from several separate capacitors anyway. In the original sequential arrangement, 10 × 0.1 μF, 1500 V polystyrene capacitors were used in series/parallel to produce a 0.25 μF, 3 kV assembly. In Fig 1, 4 × 1 μF 850 V capacitors are used, equivalent to 0.25 μF at 3.4 kV. However, it is possible that the larger inductance of the 1 μF capacitors when compared to the multiparallel arrangement of 0.1 μF capacitors, adversely affects the speed of operation.

Although the circuit described has only four stages its performance suggests that pulse generators of many more stages may be possible. In addition, fully active triggering allows the circuit to operate successfully over a wide voltage range. The arrangement of Fig 1 will operate at charging voltages between 100 and 600 V, however, the performance does deteriorate at low voltages and the gate resistors may need to be changed for optimum performance.

A novel carbon gun for use with plasma opening switches

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Abstract

The carbon gun is probably the most common plasma source used in plasma opening switches. Nevertheless, it either produces a contaminated plasma, as the flashover surface erodes, or requires regular treatment with graphite paint. The novel form of the plasma gun described in this paper overcomes the disadvantages of existing designs and produces a cleaner plasma. Experimental results illustrate the performance of a prototype system.

1. Introduction

A plasma opening switch (POS) is often used in pulse conditioning circuits, as it provides the fastest known method of transferring currents of up to several mega-amperes to a load circuit in a few nanoseconds. Current increases through the plasma until reaching a threshold level, at which the switch begins to open and the magnetic energy stored in the POS is transferred to the load. In addition to the ion species and the electron temperature, the main parameters that determine the threshold current are the initial plasma density and its distribution.

The plasma sources presently available [1] are flashboards, gas puff guns, laser guns, inverted z-pinch guns and carbon guns. The carbon gun [1–4], is simple and inexpensive to build. The plasma ensues from a surface flashover across the PTFE insulation located between the electrodes formed by the sheath and central conductor at one end of a coaxial cable. A dense and high-energy plasma results from the heating and ionization of the insulator molecules, although the process inevitably erodes the cable and contaminates the plasma by the presence of unwanted components such as fluorine ions. An alternative approach inhibits the onset of erosion and the consequent contamination by the frequent recoating of the flashover surface with graphite paint [5].

This paper describes a novel design of carbon plasma gun that overcomes the disadvantages of the conventional gun and reduces plasma contaminated by the use of replaceable hydrocarbon sleeves. The performance of a prototype is examined in the paper, with the aid of experimental results provided by electrical probes.

2. Pulsed power system

The fast-pulse high-current power supply needed to drive an experimental plasma gun is shown in figure 1, and comprises a charging system, capacitor, spark gap and measurement system.

2.1 Capacitor and charging system

The 1 µF capacitor in figure 1 is charged to a maximum of 20 kV through the 18 kΩ charging resistor, after which the capacitor is isolated from the charger and mains ground by means of the double-pole mains contactor S1. After firing the gun, the contactor S2 closes and any energy remaining in the capacitor is dissipated in the 400 Ω dump resistor.

2.2 Mechanically triggered spark gap

When the mechanically triggered spark gap SG is activated, the energy stored in the capacitor is discharged into the plasma gun electrodes. Figure 2 shows the mechanical details of the spark gap, which has operated successfully at circuit voltages between 5 and 30 kV. Triggering is initiated by energizing the 12 V solenoid to withdraw the plunger holding the polyvinyl chloride (PVC) disc. The trigger electrode is a 10 mm round-ended brass bar embedded in the disc, which falls along guide slots until contact is made with the gap electrodes.

Electrical breakdown occurs in the reducing gap as the trigger electrode falls, and discharge of the capacitor is complete before a metal-to-metal contact is made with the gap electrodes. All three electrodes are made from brass, rather than aluminium or copper, because of the lower erosion caused by spark damage.
2.3 Gun current measurement

The discharge current from the capacitor is measured by means of a magnetic pickup probe P located within a tunnel T in the strip line SL between the capacitor and the plasma gun. The voltage e induced in the coil is given by

\[ e = NA \frac{dB}{dt} \]  

where \( N \) is the number of turns in the coil, \( A \) its cross sectional area and \( B \) is the magnetic flux density inside the coil. A current \( I \) in the strip line produces a flux density inside the tunnel given approximately by

\[ B \approx \frac{\mu_0 I}{w} \]  

where \( w \) is the width of the strip line. Combining equations (1) and (2), and integrating, gives the relationship between the current and the induced coil voltage as

\[ I \approx \frac{w}{\mu_0 NA} \int e \, dt \]  

Although a resistance-capacitance (RC) circuit can integrate the output voltage obtained from the coil, the resulting small signal that represents the strip line current will be vulnerable to noise. This problem is easily overcome, however, by performing the integration numerically on a computer using the trapezoidal rule, with compensation included for zero offset errors and filtering for the removal of high-frequency noise.

A number of practical precautions are employed to minimize any capacitative pickup between the coil and the strip line and to attenuate the high-frequency noise. First, the tunnel side of the strip line is grounded, with a shield electrically connected to this on the high-voltage side to minimize capacitive pickup. The coaxial cable that conveys the signal to the recording oscilloscope is shielded with a second inner sheath isolated from the signal conductors and connected to the oscilloscope case. An incomplete copper tube is connected to this sheath to shield the coil.

A further integration of the current waveform gives the quantity of charge transferred to the circuit, which can be compared to the initial charge stored in the capacitor to give a scaling factor for (3). The accuracy of this method is limited to 10% by the manufacturers tolerance on the capacitance value and the effect of ageing processes.

3. Carbon plasma gun

Conventionally, the production of plasma in the carbon gun involves either contamination by fluorine ions, or the frequent recoating of the hard insulator with graphite paint. Without recoating the flashover will erode the surface after only a few shots, with the consequent contamination of the plasma.

The requirement of regular maintenance and the problem of contamination are both much reduced in the new gun design shown in figure 3, in which the source of ions is the hydrocarbon sleeve. In some cases the high temperatures developed inside the gun can degenerate the sleeve, making it hard and brittle, with deep cracks gradually developing on the flashover surface. A plasma is still produced following this, but the amount obtained is reduced. A number of different materials have been investigated and polythene has been found to be the most durable. The molecular bonding and ionization
energy of the material will affect the density and electron temperature of the plasma formed. A tough material with stronger bond and ionization energies will need to be supplied with more energy to produce the same amount of plasma.

The cathode in figure 3 is a 2 mm diameter copper rod, soldered to the inner conductor of a URM67 50 Ω cable. The aluminium gun case is electrically connected to the sheath using a cable gland and to the copper anode plate on the front surface of the gun, as shown in figure 4. The cathode is indented by 4 mm from the face of the insulator, providing a surface between the electrodes for the flashover. The hole in the copper anode plate can be used to provide limited control of the shape and direction of the plasma beam [2]. A high vacuum (about 10⁻⁴ mbar) is necessary to allow the plasma to flow.

4. Plasma diagnostics

Although optical techniques [1], Faraday cups [6] and electrical probes have all been used for plasma diagnostics in the POS, the first of these is costly and difficult to use while the second does not provide all the data that is required for the present investigation. It was decided, therefore, to adopt the final possibility, using the single-probe system [7]. This is appropriate when the reference electrode is large in comparison to the single probe. This will certainly be the case with the new gun design, in which the vacuum chamber and gun electrodes are electrically connected to the probe. The corresponding formulae from which the gun performance can be calculated are presented in the appendix.

4.1. Probe and probe circuit details

A single-probe system was produced from the end of a length of URM76 50 Ω cable. The central conductor of the cable is exposed for 4 mm to give a cathode area of 12.5 mm² and the sheath is exposed to form the anode. Details of the probe biasing circuit are given in figure 5. An applied voltage $V_a$ appears across the probe when the capacitor $C$ is charged from the 12 V batteries via the charging resistors $R_1$ and $R_2$. The current that is discharged between the probe electrodes as the plasma passes across the probe is measured by a pickup coil located in a 100 mm wide tunnel in the strip line connecting the capacitor to the probe. Extreme care is needed in screening the coil and its connections to the monitoring equipment from the high-frequency noise and capacitive pickup. Electrostatic screening is required between the coil and the high-voltage side of the strip line.

Three probes can be connected through the vacuum chamber walls by means of a triple BNC–BNC feedthrough. The anodes are connected and grounded at this point to reference the probe voltage to a fixed potential.
5. Results

Operation of the prototype gun was investigated using three probes positioned along the gun axis at 30, 70 and 110 mm from the anode plate (figure 3). The probe current waveforms at these positions and the gun current $G$ are shown in figure 6, illustrating the type of results obtained from the pickup probes with an applied voltage $V_a$ of 1015 V.

The results given in figures 7 and 8 show, respectively, the peak probe current and the logarithm of this current against the applied voltage $V_a$. The results given in figure 8 can be analysed using equations (5) and (6) given in the appendix. The gradient of the straight line before the break $P$ describes a relatively high electron temperature $T$ of 23.8 eV compared to the results given elsewhere [3, 5] that have produced temperatures of about 10–25 eV. The plasma flow velocity $v$ measured using data such as that given in figure 6 from probes positioned at 30, 50, 70, 90, 110 and 150 mm from the gun anode plate gives a constant value of $8.5$ cm $\mu$s$^{-1}$. Simulations of the plasma behaviour under the influence of a magnetic field, determined from a two-dimensional (2D) line current model with an initial thermal plasma velocity of $1.3$ cm $\mu$s$^{-1}$, indicating a plasma velocity in the range of 9 to 10 cm $\mu$s$^{-1}$.

6. Conclusions

Both the carbon gun and the pulsed power system described in this paper have performed consistently for more than one year. The new plasma source design is easy to use and clean, and the polythene sleeve can be used for more than 30 firings without any noticeable reduction in performance. A plasma is present at sufficient concentrations for POS operation at distances of 150 mm from the gun.

Acknowledgments

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Appendix

Figure A1 shows the relationship between the peak probe current and the applied bias voltage in a typical single probe [7-9]. A space potential $V_a$ occurs when the probe is biased at the plasma potential with the majority of the current measured between the probes being due to electrons, as a result of their greater mobility. Increasing the applied voltage above $B$ attracts the electrons towards the probe and repels the ions, with the current limited by electron saturation. Applying a large negative voltage with respect to $V_a$ in the characteristic below $A$ repels all the electrons, limiting the conduction to ions, which saturate at a smaller current than with electron saturation. The transition region, between points $A$ and $B$, occurs when the applied voltage increasingly repels the electrons but the flow velocity corresponds well with results of between 6 and 10 cm $\mu$s$^{-1}$ reported elsewhere [1-3].

The saturation electron current $I_{gs}$ where the break in the straight line occurs is $40.4$ A. Using $I_{gs}$ and $v$ in equation (6) gives an electron concentration $n_e$ of approximately $1.4 \times 10^{14}$ cm$^{-3}$ consistently over the distance studied. Published results of between $10^{12}$ and $10^{17}$ cm$^{-3}$ [1-3] confirm the diagnostic method.

![Figure A1. Typical probe characteristic](image-url)
high-energy electrons are able to overcome this potential
If a Maxwellian distribution [9] of the electron energies is
assumed, the probe current \( I \) in the transition region is given as

\[
I = I_{s5} \exp \left( \frac{e(V_a - V_s)}{kT} \right) \tag{4}
\]

\[
\ln I = \ln I_{s5} + \frac{e}{kT}(V_a - V_s) \tag{5}
\]

where \( T \) is the electron temperature, \( k \) is the Boltzmann constant and \( I_{s5} \) is the saturation electron current when the
applied voltage \( V_a \) is at the space potential \( V_s \).

In the typical graph of equation (5), which is given in
figure A2, the current at the break between the regions A and
B provides a measure of the electron saturation current \( I_{s5} \), the
gradient, \( \frac{e}{kT} \), of the line in region B provides the electron
temperature. For some probe shapes the break may not be
clearly defined, in which case it is taken as the point at which
the logarithmic curve bends away from the straight line.

Ion collection theory [8] gives an approximation for the
saturation electron current in equation (6), from which the
electron concentration \( n_e \) can be determined

\[
I_{s5} \approx n_e e v A \tag{6}
\]

where \( A \) is the surface area of the probe and \( v \) is the plasma flow
velocity. The plasma flow velocity can be easily calculated
from the time intervals of the plasma reaching each probe in
an experiment where a number of probes are aligned on the
axis of the gun.

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PLASMA SOURCES FOR PLASMA OPENING SWITCHES

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Abstract Plasma opening switches are used for pulse conditionung in high performance inductive energy systems, since they are capable of switching large-current short-duration pulses with a faster closing time than any existing alternative. Although the carbon gun provides an inexpensive and easy to build plasma source that is commonly used in research laboratories to provide the plasma required by the switch, it unfortunately requires frequent maintenance or else it produces plasma contaminated by impurities such as fluorine ions. By using replaceable hydrocarbon sleeves, the alternative design proposed in this paper overcomes both of these disadvantages. The performance of a prototype gun is described, with the aid of experimental results from electrical probes and optical plates.

1 Introduction

A Plasma Opening Switch (POS) is used in energy storage systems when it is necessary to transfer a large current to a load in a few nanoseconds. The plasma source is an essential component of a POS, and dense well-distributed and highly-ionised plasma is needed to ensure that optimum working conditions are achieved. Flashboards, carbon guns, gas guns and laser-based methods have all been used to provide the plasma. The carbon gun uses electrical breakdown between coaxial electrodes and across the surface of an insulator to produce the plasma. Unfortunately, the insulation contains impurities such as fluorine ions that effect the POS performance. The use of a replaceable hydrocarbon insulator produces cleaner plasma whilst maintaining the simplicity and durability of the cable gun. Measurements of the density, temperature and velocity in a prototype gun are obtained using electrical probes. A glass plate method to capture a representation of the plasma beam shape is introduced.

2 Plasma opening switches

In a typical POS, plasma is injected through the anode into the region between the electrodes, see Fig 1, and the current to be transferred to the load is then passed through the plasma.

Figure 1. Plasma opening switch
The plasma travels along the POS, whilst conducting the current as a short circuit and storing magnetic energy downstream of the plasma. It then becomes an open circuit in a few nanoseconds, developing a high voltage across the inductive load connected between the electrodes. This transfers the current from the plasma to the load, but with a very much reduced rise time. The opening and closing mechanisms can be described in terms of either hydrodynamic or emission processes [1], with plasma density, velocity, distribution and gun surface area all being significant parameters.

3 Plasma sources

When the plasma source is a solid, the surface is initially vaporised either by the heat from a surface discharge or by the absorption of light energy. Free electrons in the neutral gas are accelerated to high velocities by an electric field, before colliding with atoms to eject additional electrons, leaving positive ions behind. These electrons promote further ionisation, giving rise to an avalanche effect that results in dense plasma. Alternatively, photons can be directed into the gas to ionise the atoms. Hydrodynamic and electrodynamic forces accelerate the electrons and ions to supersonic speeds in the switch region.

The following sections describe the various plasma sources that may be used in a POS, with emphasis given to the parameters that are important to the efficient operation.

Carbon guns: In these, a high voltage causes a flashover on the surface of the insulation between two coaxial electrodes. Molecules near the surface are vaporised by the heat from the flashover, whilst free electrons are accelerated by the electric field to speeds sufficient to ionise the molecules. Early guns used a hard insulator that needed frequent recoating with graphite paint, to prevent surface erosion and subsequent contamination of the plasma [3]. A conical coil attached to the anode was used to improve the energy efficiency of the gun and to attempt to direct the plasma beam. Cable guns [4] use one end of a coaxial cable, with the flashover occurring between the central conductor and the sheath. Thermal expansion and $\mathbf{J} \times \mathbf{B}$ forces propel the plasma to velocities up to $10 \text{ cm s}^{-1}$. Dense plasmas of between $10^{12}$ and $10^{13} \text{ cm}^{-3}$ have been reported. Unfortunately, a large number of guns (12-24) is often necessary to produce dense plasma throughout the POS.

Flashboards: A double-sided printed circuit board is etched to produce a series of multi-gap strip lines on one side [5], with graphite paint covering the gaps and a parallel and solid copper sheet on the other side providing the current return path. A flashover vaporises and ionises the graphite paint, producing plasma that is propelled away by $\mathbf{J} \times \mathbf{B}$ forces. The main advantage of the flashboard is the large surface area that is able to fill a large volume with dense plasma. Velocities up to $30 \text{ cm s}^{-1}$ have been measured, with a reduced velocity achievable by removing the parallel current return path [7].

Gas guns: A POS may use a high velocity plasma jet from gases such as $\text{H}_2$, $\text{Ne}$ or $\text{Ar}$ from a coaxial plasma gun or a pinch gun. In the coaxial plasma gun [8], an electromagnetic valve ejects a gas puff into a region between two coaxial electrodes. Electric fields from spark gaps accelerate free electrons in the gas to the velocities required for ionisation, with the subsequent plasma accelerated along the electrodes.
by a $\mathbf{J} \times \mathbf{B}$ force until propelled out of the gun. Pinch guns [9] also use an electrical breakdown in a gas to produce plasma that expands radially into the POS. Flow velocities of about 4 cm $\mu$s$^{-1}$ and densities between $10^{13}$ and $10^{14}$ cm$^{-3}$ have been achieved.

**Laser-produced plasma:** CO$_2$, Nd: YAG and ruby lasers [10,11] have all been used to produce highly pure plasma, that has an ion species dependent on the target material. An intense light beam penetrates the material surface, until being fully absorbed at the point where the electron plasma frequency equals the laser frequency [12]. Rapid heating vaporises the material, with intense ionisation resulting from photon collisions. Thermal expansion explodes a very dense plasma plume along the direction perpendicular to the surface. Plasma parameters depend on the power density and the pulse rate of the laser with flow velocities and densities of 5 cm $\mu$s$^{-1}$ and $3 \times 10^{14}$ cm$^{-3}$ having been recorded. Rotation of the beam ensures that new target material is used each time the switch operates, to ensure repeatability over thousands of shots.

4 Experimental carbon gun

The cable gun is a common source of dense plasma in research laboratories, since it is inexpensive and easy to build. However, flashover of the cable insulation contaminates the plasma with fluorine and chlorine ions that effect the characteristics of the POS and contaminate the vacuum system. The novel design shown in Fig 2 overcomes these problems, by exchanging the cable insulation with a replaceable hydrocarbon sleeve.

![Figure 2. Carbon plasma gun](image)

A cathode positioned inside the hydrocarbon sleeve is indented by 4 mm from the outer surface and the anode plate. A mechanically triggered spark gap discharges the energy from a 1 $\mu$F/20 kV capacitor into the gun, producing a surface flashover on the inside edge of the insulation. Thermal expansion propels the plasma through a hole in the anode plate, and magnetic forces close to the gun accelerate the plasma to the high flow velocities measured.

Electrical probes were used to characterise the plasma produced by a prototype carbon gun [13]. A consistent plasma density of $1.4 \times 10^{14}$ cm$^{-3}$ and an electron temperature of about 23.8 eV were measured using probes positioned on the gun axis at distances between 30 and 150 mm from the gun surface. Measurements of the time delay between the plasma front reaching adjacent probes indicated a constant flow velocity of 8.5 cm $\mu$s$^{-1}$.
An 8-bit greyscale image of the deposit was built up over ten shots on glass plates aligned vertically at positions along the gun axis. This was analysed to provide a 3D plot of the beam shape, with contours indicating the regions holding 4, 8, 16, 32, 64 and 96% of the total deposit being shown in Fig 3.

Figure 3. Plasma beam distribution

5 Conclusion

The carbon gun described in the paper has proved to be a simple and reliable plasma source throughout an extensive experimental investigation. The glass plate technique provides a successful and inexpensive visual indication of the beam shape.

References

A RING CARBON PLASMA GUN FOR THE PLASMA OPENING SWITCH

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Abstract

The carbon plasma gun is commonly used as a source of dense plasma for plasma opening switches. The plasma is produced by the surface flashover of an insulator, although an even distribution is difficult to achieve when overall space restrictions limit the number of guns that can be employed. This paper describes a novel ring gun that, in addition to overcoming this problem, also enhances the switch performance by producing a surface flashover of the insulation that travels along a circular path. A study is presented of an experimental gun, using measured data provided by electrical probes and optical techniques. Supporting theoretical explanations are given.

I. INTRODUCTION

The plasma opening switch (POS) is used in inductive storage energy systems to transfer large currents to a load with a shorter rise time than a capacitor discharge can produce. A variety of plasma sources have been used, such as flashboards, gas puff guns, carbon guns and the interaction of a laser beam with a solid surface. The parameters of the plasma that are important in the successful operation of the POS include its distribution, concentration, temperature and the species.

Several different forms of carbon gun have been developed as inexpensive sources of plasma for use in laboratory experiments. However, the core of plasma that is produced by the conventional coaxial design is only sufficient to fill a small volume, and in a large POS between twelve and twenty four guns may be required. Any commercial application requiring a compact POS will clearly be difficult to meet by this means.

This paper describes a novel form of gun, in which a polythene insulator separates a pair of aluminum rings. A high voltage pulse applied between the plates induces a surface flashover discharge that travels in a circular path around the inside of the gun. Plasma is injected into the POS region as the discharge moves, creating a more uniform overall distribution. This is illustrated by measurements from a series of suitably located electric probes in a prototype gun and by photographic evidence of the discharge. The electric probes are used to analyse the concentration of plasma at different positions around the POS.

II. CARBON GUN

Conventionally, the carbon gun is constructed from two coaxial conductors separated by a dielectric. A high voltage pulse between the conductors initiates a flashover discharge across the dielectric surface that vaporizes molecules close to the surface. Electric fields accelerate free electrons in the vapour to velocities sufficient to cause ionisation when they collide with the insulator molecules, resulting in further free electrons and positive ions. The plasma formed is propelled away from the insulator surface by thermal pressure, and is accelerated to a high velocity by a force resulting from the interaction of the charged particles with magnetic fields close to the gun.

Early guns produced plasma by flashover of a graphite-coated hard insulator, that needed frequent recoating to prevent surface erosion and consequent plasma contamination [1]. Cable guns [2] use one end of a coaxial cable, with the flashover occurring between the central conductor and the sheath. Recent modifications include the use of nozzles with conical shaped holes to direct the plasma beam [3].

Successful experimental work at Loughborough [4] has produced a coaxial carbon gun that uses a hydrocarbon sleeve insulator between the central copper cathode and an outer anode produced from an aluminum gun case and a copper plate. Flashover across the insulator surface gave plasma that could only be a mixture of carbon and hydrogen ions, with a small amount of sputtering from the copper electrodes. Dense plasma of about $10^{14}$ cm$^{-3}$ and a flow velocity of 8.5 cm·μs$^{-1}$ were measured using electric probes. An optical technique involving capturing an image of the beam by means of the deposit collected on glass plates confirmed that the majority of the plasma was injected within a narrow beam, nominally 30° from the gun axis [5].

The small volume that can be filled by plasma ejected from a conventional gun means that it is often necessary to use at least twelve guns to produce the concentration and distribution required in a POS. The guns, coaxial cable and vacuum connections that are needed in this case require a large vacuum space thus limiting the compactness that can be achieved. The new gun, described in this paper, thus opens the way to a switch that has a better performance, is simpler and can be designed to be more compact than the conventional POS.

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An interesting and novel solution to the problems associated with the conventional carbon gun is shown in Figures 1 and 2. The carbon gun now surrounds the POS, and the gun electrodes are arranged as two equally sized rings with a high density polythene insulator sandwiched between them.

Figure 1. A proposed POS design using a ring carbon gun.

Figure 2. Ring carbon gun showing the funnel clamps, polythene ring and the nail.

In a practical implementation of the novel gun, the circuit of Figure 3 uses a 27.8 μF 30 kV capacitor and a mechanically triggered spark gap SG to discharge current into the gun with a negative high voltage on the cathode. The copper strip line, SL1, is 120 mm wide outside the chamber and reduces to 30 mm inside the chamber, SL2, before terminating on the outside surface of the rings. Gun current measurements are taken using a magnetic pickup probe P located within a tunnel in the strip line SL1.

Figure 3. Pulser circuit.

Embedded in the anode ring is a steel nail, which can be seen in Figure 2, protruding by about 2 mm towards the cathode. Electrons are absorbed into the nail due to their high mobility, as seen in Figure 4, leaving a positive space charge that enhances the electric field strength in this region. Electrons on the cathode are attracted towards this region. Streamers directed towards the cathode may subsequently result in breakdown. If the nail is positioned in the cathode the positive charge will be attracted towards the nail and the anode will absorb the electrons. The electric field will still be greatly enhanced but the charge in the ionisation region reduced, requiring a higher breakdown voltage [6].

Figure 4. Effect of the nail position on the ionisation region.

The breakdown is in the form of a surface flashover that vaporises and ionises the insulator molecules to form plasma, in the same way as in the coaxial gun. Movement of the flashover is considered to be similar to the behaviour of the armature in a rail gun [7, 8]. Current is mainly distributed along the parallel surfaces adjacent to the insulator, with the highest concentration near the edges, as illustrated by region X of Figure 5. Current approaches the discharge point Z, by a number of paths as shown in region Y. This produces a magnetic flux density that interacts with the charged particles to create a J × B
force, with a component in the radial direction to propel the plasma round the ring in a clockwise direction.

\[ J \times B \]

Figure 5. Current distribution and force on the discharge.

Thermal pressure will however force the plasma to expand outwards in all available directions, including towards and beyond the current source. The current finding the lowest impedance path will flow through this region of plasma, producing a magnetic field that creates a second \( J \times B \) force, this time attempting to propel the plasma anticlockwise round the ring. Slots in the two rings immediately anticlockwise of the current source reduce this effect, so that only thermal expansion attempts to force plasma in the unwanted direction.

IV. RESULTS

In an experimental prototype, electric probes were located at 60° intervals and 30 mm from the inner circumference of the gun. A daisywheel arrangement partitioned the ring into 30° segments, to ensure that a signal on the probe must originate from within that segment, as seen in Figure 6.

Figure 6. Daisywheel segmentation.

Figure 7 shows typical probe and gun current waveforms from the prototype, and these confirm that the discharge initiated at the nail travels clockwise through segments 2, 3 and 4 but fails to reach segment 5. The small pulse from the probe in segment 6 indicates the existence of plasma travelling anticlockwise from the nail.

Figure 7. Signals from the plasma and gun current probes in the daisywheel arrangement.

Figure 8. High speed photographs of the discharge from above (left) and horizontal (right).
The series of photographs in Figure 8 are taken over a series of experiments using a Hadland Imacon 468, with the frame rate set at 1μs. Each frame number represents the delay in microseconds from the initial discharge. The photographs show clearly the discharge initiating at the nail and spreading clockwise, confirming the predicted operation of the ring gun. The secondary breakdown that starts to occur close to the current source in Frame 4 is likely to be due to plasma from the initial discharge filling the gap between the two electrodes by thermal pressure.

The waveforms in Figure 7 show a delay between the initial plasma fronts reaching the probes in regions 2 and 3 that indicate the discharge to be travelling at approximately 16 cm μs⁻¹. This speed reduces as the discharge travels further around the ring.

In an earlier experiment, before the introduction of the slots in the two rings, the plasma parameters were investigated using a technique that produces a logarithmic plot of the peak probe current against the probe bias voltage [4] as seen in Figure 9. The gradient of the low voltage sections show the electron temperature to be 9.6 eV, comparable to temperatures measured elsewhere for cable guns [2,3]. Equating this thermal energy to the kinetic energy of the carbon ions enables the plasma flow velocity to be estimated at 1.5 cm μs⁻¹.

![Figure 9. Logarithmic probe characteristics in segments 1, 2 and 4](image)

The break points P, Q and R in Figure 9 are located at the electron saturation currents. Ion collection theory [9] uses this current, the probe area and the plasma flow velocity to predict the electron plasma densities. The densities in segments 1, 2 and 4 were thereby calculated at 1.86 x 10¹⁴, 5.06 x 10¹⁴ and 8.35 x 10¹⁴ cm⁻³.

V. CONCLUSIONS

The aim of the work described in the paper was to produce a circular plasma source, using magnetic forces to propel a surface flashover through 360°. The prototype gun has ejected plasma for over 240° and results from the electric probes and the camera have confirmed that the discharge travels clockwise from the nail. As yet, the current distribution approaching the discharge is over too wide an area and needs to be optimised so that it approaches the discharge point perpendicularly along the inner edge of the rings. This is being achieved by a modification to the present design. In this two copper strips are aligned with their edges parallel, thereby reducing the width over which the current is distributed. The resulting current should then produce a magnetic field that will propel the discharge faster and further than that in the prototype unit. The design will also reduce the secondary emission seen in the photographs.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

PULSED-POWER RESEARCH AT LOUGHBOROUGH UNIVERSITY


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Abstract

This is a companion paper to the other papers at the Conference that emanate from Loughborough. It introduces a few of the other interesting activities that are underway as part of the overall Pulsed Power research activity.

I. INTRODUCTION

Pulsed-power research at Loughborough University began more than twenty-five years ago, with the production and measurement of blast waves from an exploding wire and their subsequent use in impact studies. The work undertaken has increased considerably since then, with the activity now covering a wide range of both experimental and theoretical investigations. Substantial funding for personnel and equipment is received from the EPSRC, EU and EOARD, as well as from various UK government agencies (DERA, etc) and industrial organisations (BAE Systems, etc). Both classified and unclassified work is undertaken and a number of the current unclassified projects are presented elsewhere at this Conference. The present paper provides brief accounts of a few of the other unclassified activities.

II. PHASE TRANSITION VELOCITY [1]

Although the insulator-metallic phase transition that occurs in aluminium powder under shock loading has been explored in several magnetic cumulation experiments, no direct and continuous measurement of the speed at which the transition progresses has however been reported. Experiments were underway at Loughborough using a plane electric gun to accelerate a Mylar foil, which impacted on aluminium powder with 25 μm particles. Figure 1 shows the miniaturised probe that was developed specifically to measure the velocity of the ensuing phase transition. It works by using the newly formed conducting material to short circuit an embedded and uninsulated high-resistance wire that forms part of an external electrical circuit. The advancing phase transition changes the current in this circuit by removing resistance.

Figure 1. The miniaturised probe

The helical coil in Figure 1 is a few mm long, and it is double wound such that the current flows in different directions in the two helices. As a consequence of the very low overall coil inductance, almost no voltage is induced in it via mutual coupling with the electric gun circuit. The probe is wound on a 3.16 mm diameter plastic cylinder from 50 μm diameter manganese wire and is mounted on a BNC connector. Each helix has about 14 turns and a winding pitch of 0.6 mm, with the axial displacement between the two helices being 0.3 mm. Twisted and shielded leads connect the probe to a 25.3 V battery, located inside a Faraday cage. A fast Rogowski coil is used to measure the probe current and a voltage sensor is connected across the battery. During use, the probe is positioned within a small, cylindrical plastic container, with the space remaining being filled by aluminium powder. The axis of the coil is perpendicular to the movement of the transition. A remotely operated pneumatic switch connects the probe to the supply immediately before an experiment, to prevent the initial current of 0.4 A from unduly heating the wire.

Two problems that arose during manufacture of the probe resulted in undesirable modulations in the output current signal. Firstly, it is evident from Figure 1 that the initial 3 mm from the common beginning of the two helices are different from the remainder of their lengths, upsetting the linearity of the relationship between the rate-of-change of current and the velocity of the phase transition. Secondly, misalignment of the helical coil may cause the contact points between the transition front and the coils not to move continuously along helical paths, a phenomenon similar to the 2π-clocking sometimes
evident in helical flux-compression generators. During the experimental programme, several of the probe parameter were varied until the optimum performance was achieved.

The planar electric gun consists of a 26.9 μF capacitor charged to 20 kV and then discharged through a 100 nF transmission system that includes the exploding aluminum foil (thickness 25.4 μm, length 15 mm, width 15 mm) to which the flyer (a 250 μm Mylar-polythene package) is thermally bonded. The flyer is then accelerated to about 3 km s⁻¹ in the 3.2 mm between its initial position and the probe tip embedded in the aluminum powder. Figure 2 shows a typical current signal recorded by the Rogowski coil.

![Figure 2. Probe current: experimental and smoothed](image)

A mathematical technique was used to smooth the experimental results, and the resulting profile was differentiated and used to produce the time variation of the insulator-metallic phase transition shown in Figure 3. The contribution of both unwanted effects described above is clearly evident.

![Figure 3. Characteristics of phase transition](image)

A simple empirical model employing Hugoniot data indicated that the probable conditions attained when the flyer impacts with the powder are a pressure of 45 kbar, a particle velocity of 1.99 km s⁻¹ and a shock velocity of 2.9 km s⁻¹. Earlier work has however consistently recorded a velocity of some 5 km s⁻¹, in good agreement with the present results but well above the velocity theoretically predicted. The difference between predicted and experimental velocities is possibly due to the mechanism responsible for destroying the insulating oxide on the powder particles, which could be a fast low-pressure wave moving ahead of the shock front. Assuming a simple phenomenological model in which the speed of the precursor decayed exponentially, gave good agreement between predicted and measured data for a time constant of 1.465 μs. The velocity data may then be correlated with that portion on the phase transition inside the powder, calculated from the time integral of the velocity (Figure 3).

III. HIGH-VOLTAGE AND HIGH-CURRENT AUTOMATIC CROWBAR [2]

A single-shot crowbar switch has been developed for use in a number of applications where its low cost, simplicity, lack of external components and reproducibility of closure time are of considerable value. The switch is voltage activated and, by not requiring any components carrying the main current, it has negligible effect on the conditions within the circuit. Figure 4 shows the basic form of the crowbar. One or more semiconductors are series-connected between the conductors where the short circuit is required, and they are isolated from these conductors except at the points of connection.

![Figure 4. Crowbar switch arrangement](image)

When a high current passes through the semiconductors, they partially fuse and vaporise. The ensuing phenomena are similar to those in a confined exploding wire, with a conduction path being maintained through the remnants of the semiconductors, vaporised material and hot air. Mechanical pressure builds up within the switch and shock waves may be generated. This leads to a rapid insulation failure and the formation of a number of high-current low-impedance channels that short-circuit the conductors. In an alternative form of the switch, a metallic insert is electrically connected to one of the conductors. The action of the switch forces this through the insulation and into contact with the second conductor, to reduce even further the switch resistance. Both the thickness of the insulating material and the inertia of the moving parts can be varied to adjust the time delay.
between conduction through the semiconductor and the completion of closure.

In one recent application, it was desired to crowbar the current reaching several hundred kiloamperes that was fed to a load by a capacitor initially charged to between 5 and 20 kV. The switch comprised 20 series-connected diodes having a controlled avalanche characteristic and rated at 1 kV 1.5 A. Brass mounting plates were provided at the locations to be short circuited, with three layers of 50 μm Mylar insulation between the diode string and each of the plates, as in Figure 4. The diode string was clamped such that it rested in a groove in one of the plates, and connections to its ends were made through holes in the Mylar. Vent holes were provided in the brass plates near the diodes.

Figure 5 shows current and voltage waveforms when a capacitor charged to 8.45 kV is discharged into a circuit of total inductance 580 nH. After closure of the main switch, the crowbar voltage is approximately an attenuated form of the capacitor voltage and its current is the difference between the exponentially decaying load current and the under-damped and oscillatory capacitor current. Significant current flow begins about 5 μs after the crowbar voltage first goes negative and some 7 μs later the voltage reversal is reduced to less than 1 kV. Experimental results showing the consistency of the breakdown phenomena in the semiconductors have been obtained from more than 50 experiments, with the delay between voltage reversal and completion of closure always being less than 1 μs.

IV. FAST MAGNETO-OPTIC CURRENT MEASUREMENT [3]

Both the detonators and the fast high-current switches used in a number of the research activities at Loughborough generate considerable electromagnetic noise, which makes the accurate measuring and recording of the circuit currents extremely difficult. A range of magneto-optic sensors has been developed for use in such situations based on the magneto-optic Faraday effect and therefore immune to this type of noise. As Figure 6 shows, incoming light to the sensor is transmitted along a 30 m fibre-optic cable from a battery powered laser diode (830 nm, 30 mW) and collimated by a GRIN lens. A polarising lens then sets a polarising plane, which is subsequently rotated inside a rectangular quartz crystal (6 x 6 x 100 mm) by a magnetic field produced by the current under investigation. A second polarising lens analyses the light emerging from the crystal, before a second GRIN lens focuses it into a second 30 m cable. A 700 MHz bandwidth opto-electronic converter then converts the modulated optical output into an electrical signal proportional to the circuit current, after which it is displayed and stored on a fast oscilloscope. The overall rise time of the sensor is about 1 ns.

Figure 5. Voltage (a) and current (b) waveforms from a typical application

In use, the sensor is positioned within a tunnel in the parallel-plate transmission line that carries the input current to, typically, a plasma-opening switch, and adds only about 2 nH to the inductance of the circuit. The considerable benefits evident in such a situation are clear from the comparison in Figure 7 between the results provided by the magneto-optic sensor and an electromagnetic pick up probe.
V. PHYSICS OF EXPLODING WIRES [4]

Exploding wires provide the basis of an established opening switch technique used in many conditioning circuits. Loughborough's interest began during an investigation into a table-top size x-ray source, using a scaled-down version of a plasma-opening switch conditioning circuit. One of the most important parameters of any opening switch is the maximum electric field that can be generated and sustained, and it is often accepted that the highest figure for this is about 20 kV cm⁻¹. However, in a series of experiments, a low inductance 60 nF 30 kV capacitor was discharged with a rise time of 80 ns through a 50 μm copper wire positioned between round electrodes. Figure 8 shows that under these conditions it is possible to generate repeatedly large electric fields up to about 40 kV cm⁻¹, for wires up to 1 cm long. It has been concluded [5] that for insufficiently tamped fuses 'what has historically been identified as a restrick is a direct result of the fuse's trajectory through density-temperature parameter space'.

VI. SUMMARY

This paper has described just a few of the ongoing and unclassified projects in the Pulled Power research program underway at Loughborough University.

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Appendix A – POS Model

A POS MODEL

Short Conduction Time (<1μs) PEOS Model Based on the Naval Research Laboratory Model in "Theoretical modelling of the plasma erosion opening switch for inductive storage applications" [13]

Constants

- Anode radius \( r_a = 6 \text{ cm} \)
- Cathode radius \( r_c = 3 \text{ cm} \)
- Length of switch plasma \( l = 3 \text{ cm} \)
- Plasma density \( n_p = 10^{14} \text{ cm}^{-3} \)
- Drift velocity \( v_d = 7.5 \times 10^6 \text{ cm s}^{-1} \)
- Electron charge \( q_e = 1.6 \times 10^{-19} \text{ C} \)
- Atomic weight \( A_t = 12 \)
- Electron mass \( m_e = 9.11 \times 10^{-31} \text{ kg} \)
- Ion mass \( M_i = A_t M_e = 1.67 \times 10^{-27} \text{ kg} \)
- Generator resistance \( R_g = 0.2 \Omega \)
- Generator rise-time \( t_r = 25 \times 10^{-9} \text{ s} \)
- Generator open-circuit voltage \( V_o = 30\text{kV} \)
- Peak electron relativistic factor \( y_p = 10 \)

Typical Values

- Plasma density \( n_p = 10^{14} \text{ cm}^{-3} \)
- Plasma flow velocity \( v_d = 7.5 \times 10^6 \text{ cm s}^{-1} \)

Conduction Phase

Current is carried across the sheath at the cathode by both the ions and the electrons in a bipolar space charge limited fashion

\[
I_r = \frac{m_e Z}{\sqrt{M_i}} \quad \text{Ratio of ion current to electron current}
\]

\[
I_r = 9.535 \times 10^{-3} \quad \text{Electrons carry most of the current such that the switch current equals the electron current}
\]

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The conduction phase continues until the ion current exceeds a specific value that maintains the sheath at a constant level

\[ I_t = 2 \pi I \text{rc np Qe Z vd} \]
\[ I_t = 1.357 \times 10^4 \text{ A} \]

The bipolar current that can be carried by the switch plasma before conduction phase ends is

\[ \frac{I_t}{I_r} = 1.423 \times 10^6 \text{ A} \]

and the conduction phase when expanded to first order is given by

\[ t_c = \frac{I_t}{2} + \left( \frac{2 \pi I \text{rc np Qe vd to Rg}}{Vo} \right) \sqrt{\frac{M_t Z}{me}} \]
\[ t_c = 7.242 \times 10^{-7} \text{ s} \]

**Erosion Phase**

Once the current exceeds the bipolar current, ions are removed from the sheath faster than they can be supplied by the switch plasma. The sheath expands and opens a gap between the cathode and switch at a rate determined by

\[ \text{chgD} = \frac{I_t}{2 \pi I \text{rc np Qe Z - vd}} \]

The erosion phase is given by the following equation

\[ t_e = \left( 3.75 \times 10^4 \text{ C s}^{-1} \right) \text{to rc Rg} \frac{Vo}{\sqrt{I \text{vd} \left( t_c - \frac{tr}{2} \right)}} \]
\[ t_e = 1.406 \times 10^{-8} \text{ s} \]

The gap grows as dictated by the function

\[ D(t) = \frac{\left( t - t_c \right) - \frac{to^2}{tr} \left( 1 - \exp \left( \frac{tr}{to} \right) \right) \left( \exp \left( \frac{t}{to} \right) - \exp \left( \frac{tc}{to} \right) \right)}{\left( 2 \pi I \text{rc np Qe Rg} \right) \sqrt{\frac{M_t Z}{vo \text{me}}} - \text{vd (tc - t)}} \]
Appendix A – POS Model

The switch voltage during this time is given by

\[ V_s(t) = 1 \times 10^3 \left( \frac{2}{C} \right)^{\frac{2}{3}} \left( \frac{2}{V_o D(t)^2 \left( \frac{1}{I \cdot \frac{R_g}{r}} \right)} \right)^{\frac{2}{3}} \left( 1 + \frac{t}{t_0} \right) \left( 1 - \exp \left( \frac{t}{t_0} \right) \right) \exp \left( -\frac{t}{t_0} \right)^{\frac{2}{3}} \]

The switch current during this time is given by

\[ I_s(t) = 2.7 \times 10^{-5} \left( \frac{I \cdot \frac{V_s(t)^2}{r}}{D(t)^2} \right)^{\frac{3}{2}} \]
Appendix A – POS Model

The gap D does not grow significantly during this phase, and both the switch impedance and voltage remains relatively low, indicating that the erosion phase is not responsible for the fast opening observed experimentally.

**Enhanced Erosion Phase**

The critical current for the enhanced erosion phase to begin is

\[
I_c = \frac{1}{D(t_e + t_c)} \left( 1 \cdot 36 \cdot 10^4 \ \text{W}^{-1} \ \text{A}^2 \right) \left[ \left( 1 V + 1 \cdot 96 \cdot 10^{-6} \ \text{V} \cdot (t_e + t_c) \right)^2 - (1 V)^2 \right]^{\frac{1}{2}} \ \text{rc}
\]

\[
I_c = 1.429 \times 10^5 \ \text{A}
\]

The duration of the enhanced erosion phase is given by the peak electron relativistic factor \( \gamma_p \)

\[
F(\gamma_p) = \left( \frac{\gamma_p + 1}{3} \right)^2 - \frac{2}{3} - \sqrt{\gamma_p + 1 + \sqrt{2}}
\]

\[
t_n = \left( 1 \times 10^{-8} \ \text{s}^{-2} \ \text{C}^2 \right) \ \text{np} \ \text{\AA} \ \text{F(\gamma_p)} \left( \frac{rc}{t_\text{op}} \right)^3
\]

\[
t_n = 4.841 \times 10^{-7} \ \text{s}
\]

The final gap distance \( D \) at \( t_\text{op} = t_2 + t_4 + t_6 \) is given by

\[
D = \left( 1 \cdot 36 \cdot 10^4 \ \text{C} \ \text{s}^{-1} \right) \sqrt{\gamma_p^2 - 1} \ \text{rc}
\]

\[
D = 0.028 \text{m}
\]
Finally, the distance $zd$ that the plasma moves downstream is given by the following

$$y = \left( \frac{tc + te}{tr} \right)$$

$$G(y) = \frac{y^4 - 2y^3 + 15y^2 - 0.4y}{(y - 0.5)^2}$$

$$zd = \frac{\left(1.6 \times 10^{18} \text{ C}^{-2} \text{ m}^{-1}\right) tr^2 \log^2 \ln \left( \frac{ra}{rc} \right)}{np \left( ra^2 - rc^2 \right) At \ I} G(y)$$

$$zd = 0.123 \text{ m}$$
In the early stages of the experimental programme a requirement arose for a dual system to control the chargers, dumps, isolators and closing switches for both the plasma gun and the POS. During the conventional plasma gun experiments (Chapters 5 and 6) a small Glassmann unit charged the 1 µF capacitor and it was intended that a Hartley unit would charge the 27.8 µF capacitor for the POS. Communication between the two systems would have been needed to simplify the user interface and to ensure the correct operating sequence was always followed. In particular, if the charger isolator contacts remain closed during the experiments the stored energy would be dissipated through the mains and laboratory earths, with consequent damage to equipment. In order to prevent this, and to ensure a safe working environment, the control system described below and illustrated in Fig. B.1 was implemented.

![Control System Diagram](image)

**Figure B.1. Control system.**

Implementation of the ring plasma gun needed an enhancement to the pulser circuit that included the larger 27.8 µF capacitor bank and use of the Hartley charger. Several modifications to the control circuit had to be made, resulting in the final system as given in Fig. B.11 and described in the following sections.
B.1 Door Interlock/Safety Features

When high voltages are involved safety procedures dictate that the laboratory doors are closed, therefore the door interlock in Fig. B.2 prevents power being supplied to the control module whenever the door is open. If the door were to be accidentally opened during an experiment the power supply would be immediately turned off, terminating the charging sequence and closing the dump contacts, so that the stored energy discharges safely into the dump resistors. Similarly, a mains supply failure during an experiment would allow the dump contactors to close under the influence of gravity.

A key switch in series with the door interlock prevents unauthorised or accidental charging. The key kept inside the laboratory, where access is restricted, is attached to the cable that shorts the capacitor bank.

Loud noises are experienced in the staircase adjacent to the laboratory that could disturb people, so a beacon and siren are located in the stair well and supplied with 24 V power from the controls immediately prior to an experiment.

After an experiment the capacitor bank is touched with a wand that discharges any remaining energy into the laboratory earth through an aqueous copper sulphate resistor. The shorting cable is re-connected across the capacitor terminals to prevent unwanted voltage recovery from exposing the operator to high voltages.

B.2 Control Module

The control module in Fig. B.2 is the main interface between the operator and the electrical system. Two power supply units (PSUs) inside this module produce the 12 and 24 V supplies for the control relays, tuner, beacon and siren. Closure of both the laboratory door interlock and key switch supplies power to energise the 12 V DPCO relay RL1, which in turn supplies power to the remainder of the system.

The charger voltage is controlled from a ten-turn potentiometer, which is supplied with a 5 V reference voltage from the charger, by returning a voltage that is
proportional to the required output voltage (0 – 30 kV). A voltage feedback from the charger, which is proportional to the actual output voltage, is displayed on a 100 μA FSD analogue meter.

The operating procedure is as follows:

1. INTERLOCKS
   Closure of the door and key switch supplies power to the controls.

2. ISOLATE
   The first command from this switch signals the control interface module to operate and latch the isolator relay, which closes the double-pole isolator contactor and closes the signal path for the next command.

3. CHARGE
   The charge switch sends a signal to close the charger relay in the control interface module and transmit an HV ON signal to the charger. The relay opens the dump contactor, enables a 24 V timer and closes the signal path for the second isolate event. The timer automatically closes the dumps and disables the charger after a preset time, ensuring that the capacitor is only charged for a limited amount of time.

4. ISOLATE
   The second signal from this switch closes the firing relay that opens the isolator contacts and prepares the signal path for the next command.

5. FIRE
   This switch sends a 12 V signal that activates the spark gap, only if the second isolate event has occurred to ensure that the charger and mains are safely isolated.
Appendix B – Control System

Figure B.2. Control module.

B.3 Control Interface

The 12 and 24 V power supply and control signals are transmitted from the control module by a 25-way multi-core cable to the control interface module inside the laboratory. The circuit of Fig. B.3 contains the relays that ensure the correct operating
sequence, operate the firing mechanism and transmit signals to the dump and isolator units through optical fibres.

![Control interface module diagram](image)

**Figure B.3. Control interface module**

The first signal from the isolate button closes and latches the 12 V 3PCO isolator relay RL2, which closes the signal paths to the charge relay RL3 and the charger HV ON. This relay also supplies 12 V to an optical fibre transmitter, through the normally closed contacts of the fire relay RL4, to close the double pole isolator contactor. A 12 V signal from the charge button then closes the charge relay RL3, which is latched by a 12 V supply from one of the timer contacts. This relay closure drives a second optical fibre transmitter that opens the dump contactor, enables the 24 V charge timer and closes the signal path from the isolate button to the fire relay RL4. The second signal from the isolate button sends a 24 V signal to the fire relay RL4 that interrupts the 12 V supply to the isolator optical fibre transmitter, and prepares the signal path for the fire demand. Finally the fire button transmits a 12 V signal to the spark gap solenoid through the fire relay.
B.4 Dump, Charge and Isolation System

The capacitor is charged through the double-pole, normally open, isolator contacts and the current limiting charge resistors in Fig. B.5. The charger is isolated from the high voltage circuit by de-energising the isolator solenoid to open the isolator contacts. After the experiment is complete the single-pole, normally closed, dump solenoid is de-energised, to close the contacts and dissipate all the remaining energy into the dump resistors.

![Diagram of Dump, charge and isolator circuit]

Figure B.5. Dump, charge and isolator circuit.

The contactors and resistors are electrically insulated within high-density polyethylene boxes, held together by nylon screws and silicone sealant, as seen in Figs. B.6 and B.7. In both the isolator and dump contactors, a PVC arm connects the mains solenoid armature to a spring-loaded copper bar, thus providing insulation between the mains supply and the high voltage circuit. The isolator solenoid pulls the copper bar upwards against a spring pressure to close the isolator contacts, whilst in the dump contactor gravity closes the contacts.
To protect the operator, optical fibres link the solenoid drive circuits of Fig. B.8 and the control interface module. Light is emitted by the HFBR1525 transmitters in the control interface module and is transmitted along optical fibre to illuminate the HFBR2524 receivers. These drive small 5 V relays that supply 12 V to larger relays, which in turn supply the 230 V AC to the solenoids.
8.5 Capacitor Voltage Feedback

The capacitor voltage is monitored primarily by the voltage divider in Fig. B.9 that consists of a number of high impedance resistors connected in series that together can withstand the maximum voltage, and a small value resistor at the low voltage end that provides the output voltage. The output is transmitted through the centre conductors of two URM67 coaxial cables to the voltage feedback transmitter circuit in Fig. B.10(a). Here it is converted from a voltage to a frequency signal and transmitted along an optical fibre to the receiver in Fig. B.10(b), where the original voltage signal is regained. A length of URM76 cable transmits the voltage signal to the display unit located outside of the laboratory, where the amplifier circuit in Fig. B.10(c) drives a 1 mA FSD analogue meter that displays a reading of the capacitor bank voltage.

Figure B.9. Resistor stack voltage divider.
Figure B.10. Voltage feedback transmitter (a), receiver (b) and display (c)
C VACUUM SYSTEM

The high level of vacuum required is achieved using a two-stage rotary pump and a diffusion pump as illustrated in Figs. C.1 and C.2.

Figure C.1. Schematic of the vacuum system
C.1 Rotary Vacuum Pump

The Edwards E2M18 rotary vacuum pump is a slotted rotor and sliding vane two-stage system incorporating high and low vacuum stages. Each stage contains a rotor and a stator that together form an integral part of the main shaft. Direct drive is provided via a flexible coupling from a single-phase motor. During each rotation the eccentrically shaped rotor blade and stator sweeps a crescent shaped volume of gas from the inlet port, which is reduced and compressed until eventually being ejected through the outlet valve.

The mechanism is lubricated and sealed by the sliding vane motion that pumps Edwards Ultragrade 19 oil through a gauze filter and a spring-loaded distributor valve to the various moving parts.

During shut down the distributor valve and an external solenoid-operated valve seal the main chambers to prevent air and oil being sucked into the pump. A gas ballast is
used to introduce a small quantity of air into the low vacuum stage during the pumping of condensable vapours to reduce contamination of the oil.

C.2 Diffusion Pump

The diffusion pump heaters, shown in Fig. C.3, vaporise Dow Corning 704(EU) oil that travels upwards through the inner pump system. High pressure forces the vapour through the jet apertures where it is deflected downwards by the baffles. Air from the bell-jar vacuum chamber is captured and forced downwards by the jets, with an increase in pressure achieved at each stage. Finally, the vapour condenses when meeting the water-cooled surface and returns to the reservoir for re-vaporising. Air is released during condensing and is removed by the backing pump (rotary pump).

The oil returning to the reservoir flows from the outside inwards, whilst being heated by the elements underneath the pump. The lighter fractions are vaporised first and travel up the outer jets whilst the heavier fractions are found in the inner jet.
C.3 Vacuum Chamber

The vacuum chamber seen in Fig. C.4 is a large iron bell jar that uses its own weight to seal onto rubber o-rings, inset into slots within the large plastic rings that form the top of the vacuum pump. Two small view ports each hold a three way signal connector that allow signals from the plasma probes to pass between the vacuum and air. The large view port (on the right of the picture below) is used as an observation window during high-speed photography. Current is fed to the plasma guns through two copper strip-lines, 120 mm wide and insulated in heat-shrink, which are connected to three high current feed-throughs at the top of the chamber.

![Vacuum chamber](image)

**Figure C.4. Vacuum chamber.**

C.4 Vacuum Gauges

C.4.1 Low Vacuum – Thermovac Gauge

The Leybold TTR211S thermovac gauge utilizes the thermal conductivity of gases to measure the pressure of the low vacuum side (Pirani principle). A thermocouple and
electronic control circuit maintain the temperature of a filament and the current conducted through the surrounding gas is measured. The gauge output is scaled from 1.9 V to 10 V, as shown in Fig. C.5, which corresponds to a logarithmic scale of $5 \times 10^{-4}$ to $1 \times 10^{3}$ mbar.

\[ V = 0.5585 \ln(P) + 0.143 \]

Figure C.5. Output signal from the thermovac gauge.

C.4.2 High Vacuum – Penning Gauge

The Leybold PTR225 high vacuum gauge is a Penning cold-cathode ionisation gauge where the ions are generated by a gas discharge between two plate electrodes and a second electrode that is located between these. The output from the Penning gauge is given in Fig. C.6.
Appendix C - Vacuum System

If the gauge is operated outside its limits it will be damaged and contaminated, so it is normally triggered by the output of the thermovac gauge. However, in this case the distance between the vacuum chamber and the thermovac gauge prevents the HV ON signal from being achieved, so that instead the toggle switch in Fig. C.7 supplies either 0 V (ON-State) or 15 V (OFF-State) to control the gauge.

Figure C.6. Output signal from the cold cathode gauge

Figure C.7. Vacuum gauge circuit.
C.5 System Operation

The recommended operating procedure is given in the following sections.

1) Starting from atmospheric pressure
   a) Close the high vacuum plate valve and air-intake valve.
   b) Open the roughing and backing valves.
   c) Turn on the cooling water supply and switch on the rotary pump.
   d) When the backing pressures falls to 0.35 mbar or less, switch on the heater.
   e) After a warming up period of 20 to 30 minutes close the roughing valve and gradually open the plate valve.

2) Returning to atmospheric pressure inside the chamber
   a) Close the plate valve.
   b) Open the air-intake valve.

3) Returning to a high vacuum inside the chamber
   a) Close the air-intake valve.
   b) Close the backing valve and open the roughing valve.
   c) When a chamber pressure of 0.35 mbar or better is obtained, close the roughing valve and open the backing valve.
   d) Open the plate valve.

4) Shutting down
   a) Close the plate valve and switch off the heater. Maintain the water supply to allow the pump to cool.
   b) Close the backing valve.
   c) Turn off the rotary pump and water supply. If required the air-intake valve can be opened to return the vacuum chamber to atmospheric pressure. The diffusion pump is normally left evacuated to prevent the pump fluid from absorbing air.
D CARBON GUN MODEL

D.1 Main Program (gun.m)

% Model of the plasma velocity, acceleration and speed from the carbon plasma gun
% used in the experiments at Loughborough University
% P. Stevenson 2000

clear,

% Set global constants

global I,
I = 12000;
% Gun current - Assuming a constant dc current in some cases

global D;
D = 5e-3;
% Radius of polypropylene insulation

global L;
L = 0.09;
% Length of gun

global u,
u = 4*1.6e-7;
% Permeability constant (in air)

global q,
q = 2 * 1.602e-19,
% Charge on a carbon ion

U = 3.5e4;
% Initial thermal velocity of plasma leaving the gun as determined
% from the model given in the chapter on the plasma sources

plateangle = 30*pi/180;
% Angle of the hole in the copper plate

% Components of the initial velocity after expansion through the hole and taking the
% median particle i.e. at half the hole angle

ux = U * cos(plateangle/2),
uy = U * sin(plateangle/2),

m = 12 * 672e-27;
% Mass of a carbon-12 ion

k = 1,
% Record position

x = 3 0001e-3;
% Initial positions in x and y after passing through the

y = 3e-3*tan(plateangle/2);

dt = 0.1e-9;
% Time step

ax = 0;
% Initial acceleration

ay = 0;
% Initial time

while t1 < 1e-6

Displacement(k) = x,
% Record displacement, velocity, acceleration and time

Time(k) = t1,

Velocity(k) = ux,

k = k + 1.

% Current equation to match experimental observations including delay for current
% build-up before plasma production

I = 15430*sin(1 003e6*(t1+0.3e-6))*exp(-129829*(t1+0.3e-6));

B = Magnetic(x,y);
% Magnetic flux density (tesla) due to current segments

F = abs(B * q * uy),
% Force on a moving charged particle due to the magnetic
% field

ax = Acceleration(F,m);
% Acceleration due to the force F on a mass m

Vector = Motion(x,y,ax,ay,ux,uy,dt);
% New position and velocity in the
% x-direction
x = Vector(1,1);  % Update x and ux with the new velocities
ux = Vector(2,1);
y = Vector(1,2);  % Update y and uy with the new velocities
uy = Vector(2,2);

Displacement(k) = x;  % Record displacement, velocity, acceleration and time
Time(k) = tl,
Accel(k) = ax,
Velocity(k) = ux,

tl = tl + dt,  % Increment the time
k = k + 1;  % Increment the record number
end.

D.2 Magnetic Field Sub-function (magnetic.m)

% Function to calculate the magnetic field at a point due to the current
% in the coaxial plasma gun - magnetic field due to spark is not included at this
% time
% P Stevenson 2000

function B = Magnetic(x,y)

% Function called by Magnetic(x,y) where x and y are coordinates relative to the
% origin of the plasma gun. The origin is at the end of the central electrode.

B = UpperField(x,y) + LowerField(x,y) + CentreField(x,y) + SparkLowerField(x,y) + SparkUpperField(x,y);

% Magnetic Field Due to Upper Current Segment

function BUpper = UpperField(x,y)

global I;
global D;
global L;
global u;

% skin depth factor - add 0.2mm to where the current line lies
skin = 0.2e-3,

% The magnetic field inside the gun walls is zero so test the position of x and y and
% determine if the magnetic field needs to be zero. On the axis of the line current
% that magnetic field is also zero
if ((D - y) <= 0) & (x <= 0)
    BUpper = 0;
else
    % B = u*I/(4*pi*r) * (sin(angle2) - sin(angle1))
    angle1 = -atan((L*x)/(D+skin-y));  % * 180/pi for degrees
    angle2 = atan((-x+3e-3)/(D+skin-y)),  % * 180/pi
    anglefactor = sin(angle2)-sin(angle1);
    BUpper = -(u*I/2)/(4*pi) * 1/abs(D+skin-y) * anglefactor;
end,

% Magnetic Field Due to Lower Current Segment

function BLower = LowerField(x,y)

global I;
global D;
global L;
global u;
% skin depth factor - add 0.2mm to where the current line lies

skin = 0 2e-3;

% The magnetic field inside the gun walls is zero so test the position of x and y and
% determine if the magnetic field needs to be zero. On the axis of the line current
% that magnetic field is also zero

if ((D + y) <= 0) & (x <= 0)
    Lower = 0;
else if D + skin + y == 0
    Lower = 0;
else
    % B = u*I/(4*pi*r) * (sin(angle2) - sin(angle1))
    angle1 = atan((L+x)/(D+skin+y)); % * 180/pi
    angle2 = atan((x+3e-3)/(D+skin+y)); % * 180/pi
    anglefactor = sin(angle2) - sin(angle1);
    Lower = -(u*I/2)/(4*pi) * 1/abs(0+skin+y) * anglefactor;
end;

% Magnetic Field Due to Centre Current Segment

function BCentre = CentreField(x,y)

global I,
global D,
global L,
global u;

% The magnetic field inside the centre conductor is zero and on the axis of the
% line current

if (abs(y) < 1e-3) & (x<0)
    BCentre = 0;
elseif y == 0
    BCentre = 0;
else
    % B = u*I/(4*pi*r) * (sin(angle2) - sin(angle1))
    angle1 = -atan((-x+3e-3)/(y)); % * 180/pi
    angle2 = atan((L-x)/(y)); % * 180/pi
    anglefactor = sin(angle2) - sin(angle1);
    BCentre = -(u*I)/(4*pi) * 1/abs(y) * anglefactor;
end;

% Magnetic Field Due to Upper Discharge Current

function BSparkUpper = SparkUpperField(x,y)

global I,
global D,
global L,
global u,

% The magnetic field inside the aluminium gun case and the copper plate should be zero

if x <= 3e-3
    BSparkUpper = 0;
else
    % B = u*I/(4*pi*r) * (sin(angle2) - sin(angle1))
    angle1 = -atan((D-y)/(-x+3e-3)); % * 180/pi
    angle2 = atan((y)/(-x+3e-3)); % * 180/pi
    anglefactor = sin(angle2) - sin(angle1);
    BSparkUpper = -(u*I/2)/(4*pi) * 1/abs(x-3e-3) * anglefactor;
end;
% Magnetic Field Due to Upper Discharge Current

function BSparkLower = SparkLowerField(x,y)

global I,
    global D,
    global L,
    global u,

% The magnetic field inside the aluminium gun case and the copper plate should be zero

if (x) <= 3e-3
    BSparkLower = 0;
else

    B = u*I/(4*pi*r) * (sin(angle2) - sin(angle1))

    angle1 = atan((D+y)/(-x+3e-3)) * 180/pi
    angle2 = atan((y)/(-x+3e-3)) * 180/pi

    anglefactor = sin(angle2) - sin(angle1),

    BSparkLower = -(u*I/2)/(4*pi) * 1/abs(x-3e-3) * anglefactor;

end;

D.3 Motion Sub-function (motion.m)

function Vector = Motion(x,y,ax,ay,ux,uy,t)

%Vector returned with new position and velocity in x and y

Vector(2,1) = Velocity(ux,ax,t),
    Vector(2,2) = Velocity(uy,ay,t),
    sx = Displacement(ux,ax,t),
    sy = Displacement(uy,ay,t),
    p = Position(x,y,sx,sy);
    Vector(1,1) = p(1);
    Vector(1,2) = p(2);

function v2 = Velocity(v1,a,t)
% function to determine new velocity

v2 = v1 + a * t;

function s = Displacement(v1,a,t)
% function to determine displacement

s = v1 * t + 1/2 * a * t^2;

function p = Position(x,y,sx,sy)
% function to determine new position, returns an array x,y

    p(1) = x + sx,
    p(2) = y
The magnetic pickup probe is a multi-turn coil placed inside a copper tunnel or single turn made from both the high voltage and return strip lines, as shown in Figs. E.1 and E.2. Current flowing through the tunnel generates a magnetic field inside the tunnel that induces an emf in the pickup coil at a value proportional to the rate of change of current. The coil is constructed by locating $N$ turns in the threads of a nylon screw (cross-sectional area $A$) to maintain an even gap between each turn. The coil is then electrically insulated from the high voltage by layers of heat shrink and Mylar.

**Figure E.1.** Gun current pickup probe.

**Figure E.2.** Pickup probe parameters.
The intensity of magnetization $H$ and the magnetic flux density $B$ inside the tunnel are given by

$$ H \approx \frac{I}{W} \quad \text{and} \quad B \approx \frac{\mu_0 I}{W} $$

where $W$ is the width of the tunnel. This assumes that the magnetic field inside the tunnel is uniform, which is true when the distance between the coil and tunnel edges is significantly greater than the tunnel diameter.

The total magnetic flux $\phi$ inside the pickup coil is

$$ \phi = BA = \frac{\mu_0 LA}{W} $$

so that the emf $\varepsilon$ induced in a coil of $N$ turns is

$$ \varepsilon = N \frac{d\phi}{dt} = \frac{\mu_0 NA}{W} \frac{dl}{dt} $$

and the current $I$ is obtained by integrating $\varepsilon$ as

$$ I = \frac{W}{\mu_0 NA} \int \varepsilon \, dt $$

This integration is achieved using either an RC circuit, or by numerical integration on a PC using a program such as Mathcad. The oscilloscope sampling frequency must not be exceeded by the signal frequency, otherwise errors may appear during the integration process. The parallel combination of a 330 pF capacitor and 25 $\Omega$ resistance in Fig. E.3 attenuates any signals with a rise time of approximately 8.25 ns, thus removing any frequencies outside of the oscilloscope capabilities. The oscilloscope is protected from exposure to high voltages by a small 300 V telecommunication spark gap and a potential divider, which together limit the maximum voltage to 150 V.
The overall system (including any cables, switches etc.) is calibrated by integrating the original voltage signal twice, which gives a residual value equal to the charge dissipated in the circuit and initially stored in the capacitor, as given by

$$\int_{0}^{t} i \, dt = \int_{0}^{V} C \, dV = CV$$

The Mathcad spreadsheet below shows the process used to calibrate the signals for the first three plasma probes that were constructed for the experiments in Chapter 6. The bias capacitors were charged to -63.4 V giving the total charge stored as -0.317 mC. The multiplying factor is adjusted until the final trace gives a residual charge value that is equivalent to this charge.
Experimental values are retrieved from .prn files and separated into arrays for the voltage recorded from the magnetic pickup coils and the time:

\[
X_1 := \text{data1}(t)
\]
\[
Y_1 := \text{data1}(i)
\]

Offset errors are adjusted by decreasing the voltage values by the product of the average of the first 1000 points (where the signal should be zero) and a small multiplying factor that is needed to give the flat residual waveform in the second integration.

\[
\text{Average}_1 := \frac{1}{1000} \sum_{n=0}^{999} Y_{1n}
\]
\[
Y_1 := Y_1 - 1.05 \text{Average}_1
\]

Magnetic Pickup Probe Signals (before integration)

The probe signals are then integrated using the trapezium rule from the 1200th point onwards at which time the discharge begins, thus reducing any offset error that might initially occur when the signal should be zero and to decrease the computation required.

\[
n := 1200. \text{ rows}(X_1) - 2
\]
\[
Y_{0} := 0
\]
\[
X_{0} := X_{10}
\]
\[
X_{n} := X_{1n}
\]
\[
Y_{1n} := \left(\frac{Y_{1n} + Y_{1n+1}}{2}\right)(X_{1n+1} - X_{1n}) + Y_{1n-1}
\]
This new signal is multiplied by a factor that takes into account the number of turns $N$, coil area $A$, copper turn width $W$ and analog filter attenuation to give the correct current level that integrates (below) to give the residual charge in the capacitors.

$$IY1 := IY1 \cdot 144 \cdot 10^5$$

Probes multiplied by a factor of $144 \cdot 10^6$

The second integration gives a trace that represents the charge dissipated in the probe circuit as a function of time.

$$n := 1 \ldots \text{rows}(IX1) - 2$$
$$IY4_0 := 0$$
$$IX4_0 := IX1_0$$
$$IX4_n := IX1_n$$
$$IY4_n := \left( \frac{IY1_n + IY1_{n+1}}{2} \right) \cdot (IX1_{n+1} - IX1_n) + IY4_{n-1}$$

Probe Current Signals (after integration)

Probe Charge Dissipated (after second integration)
F BEAM SHAPE PROGRAM

% Program to analyse the greyscale scanned glass plates from experiments with the coaxial carbon gun
% Outputs a 3D drawing with six contours holding 4, 8, 16, 32, 64, 96% of the deposit to give an indication
% of the beam shape.

% Written by Paul Stevenson 2001

% Initiate the memory allocations
clear Z;
clear X;
clear Y;

% Open up a figure box and set the axis
figure;
AXIS([0 100 0 278])
hold;

colour = ['y', 'm', 'c', 'r', 'g', 'b', 'y', 'm', 'c', 'r', 'g', 'b'];
colnum = 1;

% Firstly scan the images in to MatLab and convert in to double format

clear A;
clear B;
clear C;
clear D;
clear E;

% Read in image A at 30nm
A= imread('c:\my documents\research\plates\30nm cut 1.tif');
A = double(A),

% Read in image C at 60nm
C= imread('c:\my documents\research\plates\60nm cut 1.tif'),
C = double(C),

% Read in image E at 90nm
E= imread('c:\my documents\research\plates\90nm cut 1.tif');
E = double(E),

% Adjust images to 0 = white format and adjust so that the minimum greyscale becomes zero

% Adjust the matrix A to set zero point and make white be 1
A = 256-A, % Inverts the greyscale
[imax,imax] = size(A), % Measure M x N dimensions of matrix A
m = 0,
n = 0,
Amin = 256;

while m < max
    % Loop around until m = max and then exit loop

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m = m + 1;
n = 0,  % reset n

while n < nmax
  % Loop around until n = nmax and then exit loop
  n = n + 1;
  % Compare value at m, n in matrix A with Amin. If smaller then make equal to Amin
  if A(m, n) < Amin
    Amin = A(m, n);
  end;
end;

% Reduce all elements of matrix A by Amin so that minimum value becomes zero
A = A - Amin;

% Adjust the matrix C to set zero point and make white be 1
C = 256 - C,  % Inverts the greyscale
[max, max] = size(C),  % Measure m*n dimensions of matrix C
m = 0;
n = 0;
Cmin = 256,  % Set initial value at maximum greyscale = Black

while m < nmax
  % Loop around until n = nmax and then exit loop
  m = m + 1;
n = 0,  % reset n

while n < nmax
  % Loop around until n = nmax and then exit loop
  n = n + 1;
  % Compare value at m, n in matrix C with Cmin. If smaller then make equal to Cmin
  if C(m, n) < Cmin
    Cmin = C(m, n);
  end;
end;
end;

% Reduce all elements of matrix C by Cmin so that minimum value becomes zero
C = C - Cmin;

% Adjust the matrix E to set zero point and make white be 1
E = 256 - E,  % Inverts the greyscale
[max, max] = size(E),  % Measure m*n dimensions of matrix E
m = 0;
n = 0;
Emin = 256,  % Set initial value at maximum greyscale = Black

while m < nmax
  % Loop around until m = nmax and then exit loop
  m = m + 1;
n = 0,  % reset n

while n < nmax
  % Loop around until n = nmax and then exit loop
  n = n + 1;
  % Compare value at m, n in matrix E with Emin. If smaller then make equal to Emin
  if E(m, n) < Emin
    Emin = E(m, n);
  end;
end;
end;

% Reduce all elements of matrix E by Emin so that minimum value becomes zero
E = E - Emin;
m = m + 1;
n = 0;
% reset n
while n < nmax
    % Loop around until n = nmax and then exit loop
    n = n + 1,
    % Compare value at m, n in matrix E with Emax. If smaller then make equal to Emax
    if E(m,n) < Emax
        Emax = E(m,n);
    end;
end;

% Reduce all elements of matrix A by Emax so that minimum value becomes zero
E = E - Emax;

% Locate maximum value - darkest point of A
m = 0;
n = 0;
Amax = 0;
while m < nmax
    m = m + 1;
    n = 0,
    while n < nmax
        n = n + 1;
        if A(m,n) > Amax
            Amax = A(m,n);
            AMaxPos(1) = m;
            AMaxPos(2) = n;
        end;
    end;
end;

% Locate maximum value - darkest point of C
m = 0;
n = 0;
Cmax = 0;
while m < nmax
    m = m + 1;
    n = 0;
    while n < nmax
        n = n + 1;
        if C(m,n) > Cmax
            Cmax = C(m,n);
            CMaxPos(1) = m;
            CMaxPos(2) = n;
        end;
    end;
end;
end

% Locate maximum value - darkest point of E

m = 0;
n = 0;
E_{max} = 0;

while m < m_{max}
    m = m + 1;
    n = 0;

    while n < n_{max}
        n = n + 1;
        if E(m,n) > E_{max}
            E_{max} = E(m,n),
            E_{max}_{pos}(1) = m;
            E_{max}_{pos}(2) = n;
        
        end;
    end;
end;

% Sum the greyscale of plate A

sun = sum(A),
total = sum(sun);

% Calculate the summed levels for all the plates at 5%,10%,15%,20%,25%,30%
Percentage = [0.04,0.08,0.16,0.32,0.64,0.96];
ContourLevels = Percentage * total;
% Determine the contour levels for plate A
subtotal = 0,
Level = 1;

while (E_{max} > 0) & (Level <= 6)
    clear CA,
    clear X,
    clear Y;
    clear Z;
    Level

    % Sum all components of matrix A at value A_{max} - output a subtotal value
    m = 0;

    while m < m_{max}
        m = m + 1;
        n = 0;

        while n < n_{max}
            n = n + 1;
            if A(m,n) == A_{max}
                subtotal = subtotal + A(m,n),
            end;
        end;
    end;
end;
% Compare with contour levels
if subtotal >= ContourLevels(Level)
else

en:l,

Appendix F - Beam Shape Program

\[ Z = [\text{Am}_{\text{ax}}, \text{Am}_{\text{ax}}] \]
\[ \text{CA} = \text{contour}(Z, Z); \] % Determine contour coordinates for Amax

% Prepare X,Y,Z data - remove contour information from CA

nepos = 1;
oldpos = 2;
p = size(CA,2);
numberofvalues = CA(2,1);
colunm=0;

% Loop until end of CA reached

while p > 0

% If number has been incremented and reached the number of values in the contour then
% enter if statement

if column = numberofvalues

plot3(Z,Y,X,colour(level)), % Superimpose the contour on the figure

clear X;
clear Y;
clear Z;

column = 0;
if p > 1

numberofvalues = CA(2,oldpos);
end;
oldpos = oldpos + 1;
nepos = 1;

else

X(nepos) = CA(1,oldpos),
Y(nepos) = CA(2,oldpos),
Z(nepos) = 30,
nepos = nepos + 1;
oldpos = oldpos + 1;
column = column + 1;
end.

p = p - 1;

end.

Level = Level + 1; % Increment for next contour level and colour

else

Amax = Amax - 1 % Decrement Amax and repeat loop

end;

end.

% Determine the contour levels for plate C

subtotal = 0;
Level = 1;

while (Amax > 0) & (Level <=6)

clear CC,
clear X;
clear Y;
clear Z;
Level

% Sum all components of matrix C at value Amax - output a subtotal value

m = 0;

while m < Amax

m = m + 1;

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n = 0;
while n < nmax
    n = n + 1;
    if C(m,n) == Cmax
        subtotal = subtotal + C(m,n);
    end;
end;

% Compare with contour levels
if subtotal >= ContourLevels(Level)
    Z = [Cmax, Cmax]
    CC = contour(C,Z),
    % Determine contour coordinates for Cmax

    % Prepare X,Y,Z data - remove contour information from CC
    newpos = 1;
    oldpos = 2;
    p = size(CC,1),
    numberofvalues = CC(2,1);
    column=0;
    % Loop until end of CC reached
    while p > 0
        % If number has been incremented and reached the number of values
        % in the contour then enter if statement
        if column = numberofvalues
            plot3(Z,Y,X,colour(Level));
            clear X,
            clear Y;
            clear Z,
            column = 0,
            % Reset number counter
            if p > 1
                numberofvalues = CC(2,oldpos);
                % Take next number of values
            end
            oldpos = oldpos + 1;
            newpos = 1,
            % Increment old position to miss column
            % Reset counter for new array
        else
            X(newpos) = CC(1,oldpos);
            Y(newpos) = CC(2,oldpos);
            Z(newpos) = 60;
            newpos = newpos + 1;
            oldpos = oldpos + 1;
            column = column + 1;
        end;
        p = p - 1;
    end;
    Level = Level + 1;
    % Increment for next contour level and colour
    else
        Cmax = Cmax - 1
        % Decrement Cmax and repeat loop
    end;
end;

% Determine the contour levels for plate E
subtotal = 0;
Level = 1;

while (Emax > 0) & (Level <= 6)
  clear CE;
  clear X;
  clear Y;
  clear Z;
  Level

  % Sum all components of matrix E at value Emax - output a subtotal value
  n = 0;
  while n < nmax
    n = n + 1;
    if E(n, n) == Emax
      subtotal = subtotal + E(n, n);
    end
  end

  % Compare with contour levels
  if subtotal >= ContourLevels(Level)
    Z = [Emax, Emax]
    CE = contour(E, Z);

    % Prepare X,Y,Z data - remove contour information from CE
    nespos = 1;
    oldpos = 2;
    p = size(CE, 2);
    numberofvalues = CE(2, 1);
    column = 0;

    % Loop until end of CE reached
    while p > 0
      % If number has been incremented and reached the number of values
      % in the contour then enter if statement
      if column == numberofvalues
        plot3(Z, Y, X, colour(Level)); % Superimpose the contour on the figure
        clear X;
        clear Y;
        clear Z;
        column = 0;

        if p > 1
          numberofvalues = CE(2, oldpos); % Take next number of values
          oldpos = oldpos + 1;
          nespos = 1;
        end
        else
          X(nespos) = CE(1, oldpos),
          Y(nespos) = CE(2, oldpos);
          Z(nespos) = 50;
          nespos = nespos + 1;
        end
      end
      % Reset counter for new array
      oldpos = oldpos + 1;
      nespos = 1;
  end
end
oldpos = oldpos + 1;
column = column + 1;
end;
p = p - 1;
end.
Level = Level + 1,
else
Emax = Emax - 1
end.
end;

% Increment for next contour level and colour
% Decrement Emax and repeat loop
G CURRENT DISTRIBUTION PROGRAM

G.1 Main Program (current_distribution.m)

%***********************************************************************************
% 2D procedure to calculate the impedance for the tubes and wedges approach and finally the current flow in each path.
% start point is an equipotential surface (line) and end point is a single point on edge
% Written by P. Stevenson
% First edition 13/3/01 Completed August 2001
% Calls the individual functions that calculate the mutual and self inductances and the resistances
%***********************************************************************************
%***********************************************************************************
% MAIN - Calculates the impedances and current for each tube
%***********************************************************************************
% initialisation of values and memory

clear;
Number_of_tubes = 10; % allocate number of tubes
Number_of_wedges = 20; % and wedges (even number only)
A = 10; % y-axis length (along conductor)
B = 50; % x-axis length (across conductor)
r = 0.1; % radius around end point where
% distribution is assumed linear
X_discharge = 30; % x coordinate of the discharge point
Y_Discharge = 0; % y coordinate of the discharge point
multiple = 1;
Skin_depth = 0.2; % thickness of the current layer ie skin depth
Frequency = 100e3; % frequency of the current
Voltage_Mag = 15000; % magnitude of voltage
Total_Current = 24000; % total measured current through the conductor

%***********************************************************************************
% First function of this program is to determine the current path coordinates
%***********************************************************************************
arc_length = pi * r / Number_of_tubes; % determine the length of the arc between
% the starts of the paths
arc_angle = pi / Number_of_tubes; % determine the angle between the paths
Tube_width = 2 * r * sin(1/2 * arc_angle); % determine the strip width from the linear
% equivalent of the arc length

%***********************************************************************************
% Determine gradient of the lines dividing that divide the wedges
%***********************************************************************************
% start with centre line
% Centre line - intersects both corner points
% % Two arrays are created with the gradients and angles of all the wedge lines
%***********************************************************************************
% Enter the gradient of the middle line using the two corner points
grad_line(Number_of_wedges/2) = A / B,
% Enter the angle of the middle line using the gradient
angle_line = atan(grad_line(Number_of_wedges/2));
% determine the difference between the angles of the lines above and below this line
delta_angle_below_line = angle_line * 2 / Number_of_wedges;
delta_angle_above_line = (pi/2 - angle_line) * 2 / Number_of_wedges;
% starting at the upper edge of the first wedge from the end point determine the gradients
% and angles of the remaining lines
wedge = 1;
% below the centre line the gradients are found by
while wedge < (Number_of_wedges/2)
    grad_line(wedge) = tan(delta_angle_below_line * wedge);
    wedge = wedge + 1;
end.
% above the centre line the gradients are found by
wedge = wedge + 1;
while wedge < Number_of_wedges
    grad_line(wedge) = tan(angle_line + delta_angle_above_line * (wedge - Number_of_wedges/2));
    wedge = wedge + 1;
end.
% firstly determine the coordinates if all the ends of the paths before entering
% the radius r around the discharge point
tube = 1;
% loop around for each tube
while tube <= Number_of_tubes  % loop until all tubes complete
    wedge = 1;
    angle = arc_angle * (tube - 1/2),  % starting angle from discharge point
    delta_angle = angle/(Number_of_wedges-1);  % change in angle required at wedge interfaces
delta_angle_lower = delta_angle * multiple;  % adjust delta angle for interfaces by the multiple
    angle_remaining = angle - delta_angle_lower * ((Number_of_wedges/2)-1);

    delta_angle_upper = 2 * angle_remaining/Number_of_wedges,  % determine delta angle for the upper wedges
    deltaw = - r * cos(angle),  % delta x-coordinate from discharge point
    deltay = r * sin(angle);  % delta y-coordinate from discharge point
    Tube_X(tube,wedge) = X_Discharge + deltaw;
    Tube_Y(tube,wedge) = Y_Discharge + deltay;  % enter start x coord of first filament
    if angle == pi/2
        grad = int;  % determine gradient of first filament
    else
        grad = -tan(angle);
    end.

    % intersection of first filament on y-axis
    int = Tube_Y(tube,wedge) - grad * Tube_X(tube,wedge),

    while wedge < Number_of_wedges  % loop until last filament
        % intersection coordinates of end of filament with wedge boundary

    end.

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Appendix G – Current Distribution Program

```c
if grad == inf % if filament is vertical then x-coordinate remains the same
    int_x = Tube_X(tube,wedge);
else
    int_x = int / (grad_line(wedge) - grad);
end,

int_y = grad_line(wedge) * int_x; % y-coordinate at the intersection with the wedge boundary
Tube_X(tube,wedge+1) = int_x; % stores new coordinates in the tube arrays
Tube_Y(tube,wedge+1) = int_y;

if wedge < number_of_wedges/2 % determine angle of next filament
    angle = angle - delta_angle_lower;
else
    angle = angle - delta_angle_upper;
end,

if angle < pi/2 % determine gradient of next filament
    grad = inf; % if vertical
else
    grad = -tan(angle),
end,

int = Tube_Y(tube,wedge+1) - grad * Tube_X(tube,wedge+1); % intersection of new % filament with y-axis
wedge = wedge + 1;
end;
Tube_X(tube,wedge+1) = 0, % coordinates at end of last filament
Tube_Y(tube,wedge+1) = int;
tube = tube + 1;
end;

% if a tubes leave the boundaries of the conductor then this needs % to be removed from the tubes array

tube = 1;
wedge = 1;
tubenew = 1;

while tube <= number_of_tubes % loop until all the tubes completed
    wedge = 1;

    XMax = Tube_X(tube,wedge),
    YMax = Tube_Y(tube,wedge);
    XMin = Tube_X(tube,wedge);
    YMin = Tube_Y(tube,wedge);

    while wedge <= (number_of_wedges + 1) % retrieve X and Y values from the arrays
        X = Tube_X(tube,wedge),
        Y = Tube_Y(tube,wedge),

        if X > XMax % compare X and Y values with minimum and maximum values
            XMax = X, % stores if values are outside the original values
        end;
        if X < XMin
            XMin = X,
        end;
        if Y > YMax
            YMax = Y;
        end;
        if Y < YMin
            YMin = Y;
        end;

        wedge = wedge + 1;
    end;

if (XMax <= B) && (XMin >= 0) && (YMax <= A) && (YMin >= 0)

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% if the max and min values are inside the limits A, B and 0 then store in tubel arrays
    wedge = 1;
    while wedge <= (Number_of_wedges + 1)
        Tubel_x(tubenum, wedge) = Tube_x(tube, wedge);
        Tubel_y(tubenum, wedge) = Tube_y(tube, wedge);
        wedge = wedge + 1;
    end
    tubenum = tubenum + 1;
    end
end

Number_of_tubes = size(Tubel_x, 1); % determine number of tubes from array tubel
Tube_x = Tubel_x;
Tube_y = Tubel_y;

clear tubel_x;
clear tubel_y;

figure; % open a figure window
axis([0 B 0 A]); % set axis extents to A and B
line(Tube_x', Tube_y'), % draw lines linking the values with
    xlabel(Tube_x), ylabel(Tube_y); % coordinates in Tube_x and Tube_y

%***********************************************************************************
%************* Error of this section
% Next section calls the functions to calculate the self inductance and resistance for each filament
%***********************************************************************************
%
% Resistance
Filament_R = resistance(Tube_x, Tube_y, Number_of_tubes, Number_of_wedges, Tube_width, Skin_depth);
%
% Self-Inductance
Filament_L = self_inductance(Tube_x, Tube_y, Number_of_tubes, Number_of_wedges, Tube_width, Skin_depth);

% Filling the impedance matrix - Z matrix
Tubenew = 1;
    row=1;
col=1;

while Tube_a < Number_of_tubes + 1 % loop for each tube (a)
    Wedge_a = 1;
    while Wedge_a < Number_of_wedges + 1 % loop for each wedge (a)
        xla = Tube_x(Tube_a, Wedge_a);
        yla = Tube_y(Tube_a, Wedge_a);
        x2a = Tube_x(Tube_a, Wedge_a + 1);
        y2a = Tube_y(Tube_a, Wedge_a + 1);
        Tube_b = 1;
        while Tube_b < Number_of_tubes + 1 % loop for each tube (b)
            Wedge_b = 1;
            while Wedge_b < Number_of_wedges + 1 % loop for each wedge (b)
                xlb = Tube_x(Tube_b, Wedge_b);
                ylb = Tube_y(Tube_b, Wedge_b);
                x2b = Tube_x(Tube_b, Wedge_b + 1);
                y2b = Tube_y(Tube_b, Wedge_b + 1);
                z=0;
            end
        end
    end
end

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if (Tube_a == Tube_b) & (Wedge_a == Wedge_b) % determine diagonal components
    z = Filament_R(Tube_a, Wedge_a) + j * (2*p*a*Frequency) * Filament_L(Tube_a, Wedge_a),
else
    z = j * (2*p*a*Frequency) * mutual_inductance(x1a,y1a,x2a,y2a,x1b,y1b,x2b,y2b);
end;

% determine row and column number within filament matrix
row = (Tube_a - 1) * Number_of_wedges + Wedge_a,
col = (Tube_b - 1) * Number_of_wedges + Wedge_b;

Filament_z(row,col) = z; % insert value into matrix

Wedge_b = Wedge_b + 1.
end;

Tube_b = Tube_b + 1;
end;

Wedge_a = Wedge_a + 1;
end;

Tube_a = Tube_a + 1;
end;

% Filling the connection matrix - C and voltage matrix - V

col = 1;
row = 1;
Tube_a = 1;
while Tube_a <= Number_of_tubes
    Wedge_a = 1;
    while Wedge_a <= Number_of_wedges
        row = (Tube_a - 1) * Number_of_wedges + Wedge_a; % determine row position
        C(row,Tube_a) = 1; % column position same as tube number - Insert ones where needed
        Wedge_a = Wedge_a + 1;
    end;
    V(Tube_a,1) = Voltage_Magn, % all voltage values are the same
    Tube_a = Tube_a + 1;
end;

clear Filament_R;
clear Filament_L;

New_Matrix = Filament_z * C; % post multiply by connection matrix
clear Filament_z;

Z = C' * New_Matrix; % pre-multiply by the transpose of C
clear New_Matrix;

I = 2*V; % solve linear set of equations

% take magnitude values
I = abs(I);
% take absolute values
Total_Current = sum(I); % sum total current

Percentage_Current = I/Total_Current * 100 % output to screen percentage current

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% END OF MAIN FUNCTION
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
G.2 Mutual-Inductance Sub-Function (mutual_inductance.m)

%******************************************************************************************
% Development procedure to calculate the mutual inductances for the tubes and wedges approach
% Written by F.Stevenson
% First edition 5/5/01
%******************************************************************************************

function M = mutual_inductance(xla,yla,x2a,y2a,xlb,ylb,x2b,y2b)

%******************************************************************************************
% MAIN FUNCTION - analyses a pair of filaments to determine there geometry
% and calls the require function to calculate the mutual inductance. This
% is returned to the main program as value M
%******************************************************************************************

% initialisation
M = 0;

% Calculate the geometrical equation (y-axis intersection and gradient)
% for the two filaments
if xla == x2a
    % straight line equation for filament (a)
    grada = inf;
    intersa = inf;
else
    grada = (yla - y2a)/(xla - x2a);
    intersa = yla - grada * xla;
end;
if xlb == x2b
    % straight line equation for filament (b)
    gradb = inf;
    intersb = inf;
else
    gradb = (ylb - y2b)/(xlb - x2b);
    intersb = ylb - gradb * xlb;
end;

% ya = grada * xa + intersa
% yb = gradb * xb + intersb

if abs(grada - gradb) < 1e-9
    % if the gradients are equal the filaments are parallel or on the same axis
    % now test whether they are on the same axis by checking the intersection
    % on the y-axis
    if abs(intersa - intersb) < 1e-9
        % filaments intersect the y-axis at the same point so are on the same axis
        M = 0; % mutual inductance is zero
        elseif intersa == intersb
            % Filaments intersect the y-axis at different points so are on different axis
            M = Parallel(grada,intersa,intersb,xla,yla,x2a,y2a,xlb,ylb,x2b,y2b);
        else
            % if neither of the above cases are true then an error exists
            error('y axis intersection fault')
        end;
    elseif grada == gradb
        % if the gradients are different the axis through the filaments must converge
        % either at a point

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% on both of the lines or away from the ends of either one or both
% calculate the intersection point of the filaments when extended to infinity
if grada == inf
    intx = xla;
    inty = (gradb * intx) + intersb;
elseif gradb == inf
    intx = xlb;
    inty = (grada * intx) + intersa,
else
    intx = (intersb - intersa)/(grada - gradb);
    inty = (grada * intx) + intersa;
end;

% Now the geometry needs to be tested to determine whether the filaments meet and
% if not how the filaments converge

d1 = Distance(xla,yla,intx,inty);
d2 = Distance(x2a,y2a,intx,inty),
d3 = Distance(xlb,ylb,intx,inty),
d4 = Distance(x2b,y2b,intx,inty),
Lengtha = Distance(xla,yla,x2a,y2a),
Lengthb = Distance(xlb,ylb,x2b,y2b);
if (abs(d1 + d2 - Lengtha) < le-9) & (abs(d3 + d4 - Lengthb) < le-9)
% converge to a point on both filaments
    M = ConvergeToPoi(xla,x2a,yla,y2a,xlb,ylb,x2b,y2b);
elseif (abs(d1 + d2 - Lengtha) < le-9) & (abs(d3 + d4 - Lengthb) > le-9)
% converge to a point on filament a when b extended
    M = ConvergeOn(xla,x2a,yla,y2a,xlb,ylb,x2b,y2b,intx,inty);
elseif (abs(d1 + d2 - Lengtha) > le-9) & (abs(d3 + d4 - Lengthb) < le-9)
% converge to a point on filament b when a extended
    M = ConvergeOnB(xla,x2a,yla,y2a,xlb,ylb,x2b,y2b,1ntx,1nty);
elseif (abs(d1 + d2 - Lengtha) > le-9) & (abs(d3 + d4 - Lengthb) > le-9)
% converge to a point when both extended
    M = ConvergeExtended(xla,x2a,yla,y2a,xlb,ylb,x2b,y2b,1ntx,1nty);
else
    error('convergence geometry error')
    error('error - filament not parallel or converging')
end;
end,

***************************************************************************

% END OF MAIN FUNCTION
***************************************************************************

function m1 = Parallel(grada,intersa,intersb,xla,yla,x2a,y2a,xlb,ylb,x2b,y2b),

***************************************************************************

% PARALLEL FUNCTION - calculates the mutual inductance of two parallel filaments
***************************************************************************

% determine the geometry of the parallel lines to investigate whether overlapping
% such that delta is -ve
% length of filaments is needed
l = Distance(xla,yla,x2a,y2a);
m = Distance(xlb,ylb,x2b,y2b);
% determine the angle of the line in cartesian from the gradient
if grad == 0
    theta = 0;
elseif grad == inf
    theta = pi/2;
else
    theta = atan(grad),
end;
% test the diagonals between all the end points to determine which is the correct
% diagonal. Calculate the length and gradient of the diagonal.
% firstly find intersection of diagonals from la to 2b and 2a to 1b
diagonal_inter = Intersection(xla,yla,x2b,y2b,x2a,y2a,xlb,ylb); % call function
% diagonal_inter(1) will be zero if an intersection is found
if diagonal_inter(1) == 0 % if intersection found then calculate
    diag_grad = (yla-y2b)/(xla-x2b);
    diag_length = Distance(xla,yla,x2b,y2b);
else diagonal_inter(1) == 1 % else check other diagonals
    % determine intersection of diagonals la to 1b and 2a to 2b
    diagonal_inter = Intersection(xla,yla,xlb,ylb,x2a,y2a,x2b,y2b),
    if diagonal_inter(1) == 0 % if intersection found then
        diag_grad = (yla-ylb)/(xla-xlb),
        diag_length = Distance(xla,yla,xlb,ylb);
    else
        error('no diagonals intersect except on the line')
    end;
end;
% Calculate the angle of the diagonal with respect to the horizontal
if diag_grad == 0
    phi = 0;
elseif diag_grad == inf
    phi = pi/2;
else
    phi = atan(diag_grad);
end;
% Calculate the filament separation and delta variable from the diagonal information
omega = phi - theta, % angle between line and diagonal
delta = diag_length * cos(omega), % overlap variable
d = abs(diag_length * sin(omega)); % filament seperation
% Variable delta, d (filament seperation), filament lengths m and n (length a and
% length b) are all known. The calculation for the mutual inductance can be done
% refer to Inductance Calculations Grover page 45 for the following calculation
% all lengths are in cm
alpha = 1 + m + delta, % variables for calculations
beta = 1 + delta;
gamma = m + delta;
hyperbolic_function = alpha * asinh(alpha/d) - beta * asinh(beta/d) -
    gamma * asinh(gamma/d) + delta * asinh(delta/d);
square_root_function = sqrt(alpha^2 + d^2) - sqrt(beta^2 + d^2) -
    sqrt(gamma^2 + d^2) + sqrt(delta^2 + d^2).
mI = 0 001e-6 * (hyperbolic_function - square_root_function);
%***************************************************************************
% END OF PARALLEL FUNCTION
%***************************************************************************
function mI = ConvergeToPoint(xla,x2a,y1a,y2a,xlb,x2b,ylb,y2b,intx,inty)

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% Appendix G – Current Distribution Program

% CONVERGE TO POINT FUNCTION – calculate the mutual inductance of two filaments that meet at a point

l = Distance(xla,yla,x2a,y2a); % lengths of filaments
m = Distance(xlb,ylb,x2b,y2b);

if (abs(xla - intx) < le-9) & (abs(yla - inty) < le-9)
    if (abs(xlb - intx) < le-9) & (abs(ylb - inty) < le-9)
        R = Distance(x2a,y2a,x2b,y2b);
    elseif (abs(x2b - intx) < le-9) & (abs(y2b - inty) < le-9)
        R = Distance(x2a,y2a,xlb,ylb);
    end,
    end,
elseif (abs(x2a - intx) < le-9) & (abs(y2a - inty) < le-9)
    if (abs(xlb - intx) < le-9) & (abs(ylb - inty) < le-9)
        R = Distance(x1a,yla,x2b,y2b);
    elseif (abs(x2b - intx) < le-9) & (abs(y2b - inty) < le-9)
        R = Distance(x1a,yla,xlb,ylb);
    end,
elseif (abs(x2b - intx) < le-9) & (abs(y2b - inty) < le-9)
    if (abs(xlb - intx) < le-9) & (abs(ylb - inty) < le-9)
        R = Distance(x1a,yla,x2b,y2b);
    elseif (abs(x2b - intx) < le-9) & (abs(y2b - inty) < le-9)
        R = Distance(x1a,yla,xlb,ylb);
    end,
end,

% refer to grover page 50

cos_epsilon = (1.*2 + m.*2 - R^2)/(2*l*m);

m1 = 0.002e-6 * cos_epsilon * (1 * atanh(m/(l+R)) + m * atanh(l/(m+R)));

% END OF CONVERGETOPPOINT FUNCTION

% CONVERGE EXTENDED FUNCTION – calculates the mutual inductance between two filaments that meet at a single point when at least one is extended.

% refer to grover page 52

% filament lengths
l = Distance(x1a,yla,x2a,y2a),
m = Distance(xlb,ylb,x2b,y2b),

% Distance to points on lines from intersection 0

d1 = Distance(xla,yla,intx,inty);
d2 = Distance(x2a,y2a,intx,inty);
d3 = Distance(xlb,ylb,intx,inty);
d4 = Distance(x2b,y2b,intx,inty);

% Test geometry and calculate parameters R1,R2,R3,R4,l,m,u,v accordingly

R1=0;
R2=0;
R3=0;
R4=0;
u=0;
v=0;

if (d1 > d2) & (d3 > d4)
    R1 = Distance(x1a,yla,xlb,ylb);
    R2 = Distance(x1a,yla,x2b,y2b);
    R3 = Distance(x2a,y2a,x2b,y2b);
    R4 = Distance(x2a,y2a,xlb,ylb),
    u = Distance(intx,inty,x2a,y2a),
    v = Distance(intx,inty,x2b,y2b);
elseif (d1 < d2) & (d3 < d4)
    R1 = Distance(x2a,y2a,x2b,y2b);
    R2 = Distance(x2a,y2a,xlb,ylb);
    R3 = Distance(x1a,yla,xlb,ylb);
    R4 = Distance(x1a,yla,x2b,y2b);

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u = Distance(intx, inty, xla, yla),
v = Distance(intx, inty, xlb, ylb),
elseif (d1 > d2) & (d3 < d4)
R1 = Distance(xla, yla, x2b, y2b),
R2 = Distance(xla, yla, xlb, ylb);
R3 = Distance(x2a, y2a, xlb, ylb),
R4 = Distance(x2a, y2a, x2b, y2b);
u = Distance(intx, inty, x2a, y2a);
v = Distance(intx, inty, xlb, ylb);
elseif (d1 < d2) & (d3 > d4)
R1 = Distance(x2a, y2a, xlb, ylb);
R2 = Distance(x2a, y2a, x2b, y2b);
R3 = Distance(xla, yla, x2b, y2b);
R4 = Distance(xla, yla, xlb, ylb),
u = Distance(intx, inty, xla, yla),
v = Distance(intx, inty, x2b, y2b);
end,
alphasqr = (R4*R4 - R3*R3 + R2*R2 - R1*R1);
twocosE = alphasqr / (1 * m);
mI = 0.001e-6 * twocosE * ((u-1)*atanh(m/(R1+R2)) + (v+m)*atanh(1/(R1+R4)) -
u*atanh(m/(R3+R4)) - v*atanh(1/(R2+R3))),

% END OF CONVERGE EXTENDED FUNCTION
%***********************************************************************************
function mI = ConvergeOna(xla, x2a, yla, y2a, xlb, x2b, ylb, y2b, intx, inty)
% Converge at a point on filament a - calculates the mutual inductance
% as the sum of two mutual inductances by splitting the filament a into two
% separate filaments Calls convergeextended function twice with different values
% each time
%mI1 = ConvergeExtended(xla, intx, yla, inty, xlb, x2b, ylb, y2b, intx, inty);
mI2 = ConvergeExtended(intx, x2a, inty, y2a, xlb, x2b, ylb, y2b, intx, inty),
mI = mI1 + mI2;
%***********************************************************************************
% END OF CONVERGE ON A FUNCTION
%***********************************************************************************
function mI = ConvergeOnb(xla, x2a, yla, y2a, xlb, x2b, ylb, y2b, intx, inty)
% Converge at a point on filament b - calculates the mutual inductance
% as the sum of two mutual inductances by splitting the filament b into two
% separate filaments Calls convergeextended function twice with different values
% each time
%mI1 = ConvergeExtended(xla, x2a, yla, y2a, xlb, intx, ylb, inty, intx, inty);
mI2 = ConvergeExtended(xla, x2a, yla, y2a, intx, x2b, inty, y2b, intx, inty),
mI = mI1 + mI2;
%***********************************************************************************
% END OF CONVERGE ON B FUNCTION
%***********************************************************************************
function xy = Intersection(x11, y11, x12, y12, x21, y21, x22, y22)
% INTERSECTION FUNCTION - calculates the intersection of the lines between four
% points and checks if the intersection is at one of the points
%***********************************************************************************
xy(1) = 1, % set return bit to "no intersection found"
% determine gradients of the two lines
if x11 == x12 % if x-values are constant then line is vertical
  gra = inf;
else
  gra = (y11-y12)/(x11-x12);
end,
end;
if x21 == x22 % if x-values are constant then line is vertical
grb = inf;
else
grb = (y21-y22)/(x21-x22);
end,
if gra == grb % if gradients are equal then no intersection
xy(1) = 1 % so return bit left at 1
else
if grb == inf % if filament b is vertical then
x = x21,
inta = y21 - gra * x21;
y = gra * x + inta;
elseif gra == inf
x = x21;
intb = y21 - grb * x21;
y = grb * x + intb;
else
inta = y21 - gra * x21;
intb = y21 - grb * x21;
x = (intb-inta)/(gra-grb), % x-value when intersecting
y = gra * x + inta;
end
% test to see if this intersection value lies on the filament
if abs(Distance(x,y,x11,y11) + Distance(x,y,x12,y12) - Distance(x21,y11,x12,y12)) < le-9
xy(1) = 0;
xy(2) = x;
xy(3) = y;
else
xy(1) = 1;
end;
end;
%***********************************************************************************
% END OF INTERSECTION FUNCTION
%***********************************************************************************

G.3 Self-Inductance Sub-Function (self_inductance.m)

%******************************************************************************
% Development procedure to calculate the self inductances for the
% tubes and wedges approach
% Written by P.Stevenson
% First edition 13/5/01
% Inputs from processor module would be NumberTubes (int), NumberWedges (int)
% and Filament Matrix
%******************************************************************************

function L = self_inductance(Tube_X,Tube_Y, Number_of_tubes, Number_of_wedges, Tube_width, Thickness)
%******************************************************************************
% MAIN FUNCTION - Sums all the self inductances for the network
%******************************************************************************
% initialisation
L = 0;
Tube = 1,
Wedge = 1,
B = Tube_width,
C = Thickness;
**G.4 Resistance Sub-Function (resistance.m)**

```
while Tube < Number_of_tubes + 1  % loop for each tube
    Wedge = 1;
    while Wedge < Number_of_wedges + 1  % loop for each wedge
        x1 = Tube_X(Tube,Wedge);
        y1 = Tube_Y(Tube,Wedge),
        x2 = Tube_X(Tube,Wedge+1);
        y2 = Tube_Y(Tube,Wedge+1);
        length = Distance(x1,y1,x2,y2);  % get length of filament
        L(Tube,Wedge) = 0.002e-6 * length * (log((2*length)/(B+C)) - 1/2);
        Wedge = Wedge + 1;
    end;
    Tube = Tube + 1;
end;
```

% END OF MAIN FUNCTION

G.4 Resistance Sub-Function (resistance.m)

% Development procedure to calculate the resistances for the
% tubes and wedges approach

% Written by P.Stevenson
% First edition 13/5/01

% Inputs from processor module would be NumberTubes (int), NumberWedges (int)
% and Filament Matrix

---

```matlab
function R = resistance(Tube_X,Tube_Y,Number_of_tubes,Number_of_wedges,Tube_width,
Thickness)
```

% MAIN FUNCTION - Sums all the resistances for the network

% initialization

R = 0,
Tube = 1,
Wedge = 1;
B = Tube_width;
C = Thickness;
rho = 2.5e-8;
rho = rho * 100,  % units of ohms cm

while Tube < Number_of_tubes + 1  % loop for each tube
    Wedge = 1;
    while Wedge < Number_of_wedges + 1  % loop for each wedge
        x1 = Tube_X(Tube,Wedge);
        y1 = Tube_Y(Tube,Wedge),
        x2 = Tube_X(Tube,Wedge+1);
        y2 = Tube_Y(Tube,Wedge+1);
```
Appendix G – Current Distribution Program

\[
R(\text{Tube, Wedge}) = \frac{\rho \times \text{length}}{(B \times C)}; \quad \% \text{taken classical resistivity equation}
\]

\[
\text{Wedge} = \text{Wedge} + 1;
\]

end;

\[
\text{Tube} = \text{Tube} + 1;
\]

end.

%******************************************************************************
% END OF MAIN FUNCTION
%******************************************************************************

G.5 Distance Sub-function (distance.m)

function d = Distance(xa, ya, xb, yb)

%******************************************************************************
% DISTANCE FUNCTION - calculates the distance between two points given their x and y coordinates. Uses Pythagoras theorem.
%******************************************************************************

deltax = xa - xb;
deltay = ya - yb;

d = sqrt(deltax^2 + deltay^2);

\% remove sqrt error by assuming that any value below 1e-10 is negligible

if d < 1e-10
    d = 0;
end.

%******************************************************************************
% END OF DISTANCE FUNCTION
%******************************************************************************