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A study of scaling physics in a Polywell device

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A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy (Research)

2016
Declaration of originality

I certify that the work presented in this thesis was undertaken solely during my PhD candidature, and has not been presented for any other degree.

I certify also that this thesis was written by myself, and that all external contributions and sources have been duly acknowledged.

Signature of candidate:

............................................

Scott Cornish
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A PhD thesis is awarded to only one person however as John Donne reminds us “no man is a island”. Without the help of countless others the writing of this thesis would have not been possible. I would like to take this opportunity to extend my utmost gratitude to all of those involved in this great effort.

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As I now come to the close of my PhD work on the Polywell, I am reminded of the introduction to one of my favourite Led Zeppelin songs. Indeed, is this the end or just beginning? Only time will tell.
Should I fall out of love, my fire in the light
  To chase a feather in the wind
Within the glow that weaves a cloak of delight
  There moves a thread that has no end.
For many hours and days that pass ever soon
  the tides have caused the flame to dim
At last the arm is straight, the hand to the loom
  Is this to end or just beginning?

All of my Love - Led Zeppelin
Abstract

The Polywell is an Inertial Electrostatic Confinement (IEC) device that aims to confine ions at fusion energies. The Polywell uses a virtual cathode in place of a metal grid cathode used in regular IEC devices, in which a high voltage is applied to the grid to accelerate ions to fusion energies and confine them in a spherical geometry. The virtual cathode is produced by confining high energy electrons in a magnetic well by mirror reflections, which produces a potential well. Three orthogonal pairs of coils with antiparallel currents are placed equidistant from the centre of the device, such that the six coils make up the faces of a cube. In this way a magnetic well is produced with a magnetic null at the centre of the device and strong magnetic fields near the coils. Spherically symmetric potential wells are also required in order to maximise the degree of ion focusing attained in the core of the device. The formation of deep, symmetrical potential wells is critical to the functioning of the Polywell and is the major focus of this thesis.

This thesis aims to explore how the depth and symmetry of potential wells vary with a number of device parameters. These include injected electron current and electron energy and magnetic field strength. The spacing of magnetic field coils is also investigated. Varying the spacing of the magnetic field coils changes the relative magnetic field strength in the different cusps of the device and hence the electron trapping in these cusps. Electron losses through the cusps represent a major energy loss mechanism and are a major impediment to the potential of the device to eventually reach net fusion energy. The electron trapping is maximised by determining the ideal intercoil spacing. Different sizes of magnetic field coil were used to investigate how increasing the device size improves the electron trapping and potential well formation. It is hypothesized that larger devices are able to trap higher energy electrons and produce deeper potential wells capable of accelerating ions to fusion energies. The scaling experiments with smaller devices are used to estimate the size of device needed to reach fusion energies.

In order to investigate the potential formation multiple secondary electron emission capacitive probes (SECP) were constructed. The use of these probes in the Polywell plasma could give a direct measure of the plasma potential and hence the potential well. However, this type of probe has not been shown to be effective in the highly magnetised non-Maxwellian, non-neutral electron plasma found in the Polywell. A planar vacuum diode within a Helmholtz pair is used to test the applicability of a SECP in such a plasma, with magnetic fields up to 0.35 T, and for electron energies of 100 eV-4000 eV. The plasma potential is accurately measured by the probe when the electron Larmor radius is greater than the probe diameter. When the electron Larmor radius is less than the probe diameter, the measured plasma potential
is underestimated. However, this effect ceases at a finite Larmor radius and the SECP can be used to measure the plasma potential in high magnetic fields using a correction factor.

A small Polywell with a 48 mm average coil diameter is tested with central face magnetic fields up to $\sim 0.5$ T. The effect of magnetic field coil current and electron injection current and electron energy on the development of potential wells is observed. The electron emission current is varied from 150-1680 mA and electron energies range between 150-800 V. These device parameters are tested over a much larger range than previously examined. A linear relationship is observed between potential well depth and injection current. A non-linear relationship is observed between potential well depth and magnetic field strength, with further increases to the magnetic field strength having less effect on the well depth. Investigations are made into the effect of the applied magnetic field current on the amount of emitted electrons that are injected into the device. An analytical model is created to estimate the electron confinement time from the measured potential well depth. From these results, an experimentally derived equation for electron confinement time is constructed, based on the experimental parameters of electron energy and coil current. These results are compared to a similar equation derived from a particle orbit simulation.

A similar setup is used to again test the effect of magnetic field strength and emission current on the potential well depth. However, in the second experiment the two variables are completely decoupled. A nonlinear relationship is now observed between emission current and potential well depth, with the increases to both variables having diminishing returns on the well depth achieved. Electron energies of 200-800 V were used with emission currents of 3-190 mA. More accurate electron emission currents were performed in this experiment. The intercoil spacing is varied to determine the effect of changing the relative magnetic field at the face, corner, and edge cusps of the device. Multiple capacitive probes are used in these cusp locations and at the centre of the device. The use of multiple probes allows the spherical symmetry of the potential wells and the relative electron trapping at the different device cusps to be determined. The effect of a hydrogen background gas on the potential well formation and as a possible source of fuel ions in a fusion capable Polywell is investigated. Three pressures of 0.1 mTorr, 1 mTorr and 10 mTorr, in addition to measurements at a base pressure of 0.007 mTorr were used.

The effect of device scaling is explored by increasing the coil size to an average diameter of 77.5 mm. Based on these results, a geometric progression is used to determine the size of a device needed to reach fusion energies. Two different types of coil housing are used, which demonstrates how the conformal nature of the coil housing to the magnetic fields affect potential well formation. Electron confinement time estimations are made for device configurations that produced reasonably spherically symmetric potential wells. As these estimations rely on a spherical well assumption and the measured injection
current, they are thought to be more accurate than those found in the first experiment.
Publications by the Author

Refereed articles


• S. Cornish and J. Khachan The use of an electron microchannel as a self extracting and focusing plasma electron gun *Plasma Science and Technology* Accepted for publication (7th of June 2015).

• S. Cornish and J. Khachan The dependence of potential well formation on coil spacing and size and the effect of gas pressure in Polywell devices. *Under Internal Review*


Conference proceedings


• Scott Cornish and Matt Carr and David Gummersall and Joe Khachan Capacitive Probe for Plasma Potential Measurements in a Vacuum diode and Polywell Device *15th US-Japan Workshop on IEC Fusion*, Uji Campus of Kyoto University, Japan, Oct 6 – 9, 2013.
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Chapter 1

Introduction

The Industrial Revolution transformed the world and birthed the technological civilization that we benefit from today. Since the end of the Industrial Revolution, global energy consumption has grown by approximately 27 times while the world population has grown by only 7 times[1]. This rapid growth in energy production has primarily been facilitated with coal, oil and natural gas making up at least 85% of this demand[2]. This is an unsustainable path, as all of these resources are distinctly finite. Not revealed by these worldwide statistics is that the energy consumption is not evenly distributed. North America and Western Europe constitute 16.3 % of the world population yet make up 52.7 % of world energy usage, while Asia, Africa and South America make up 83.2 % of the world population and use only 45.8 % of the energy consumed[2]. It is undeniable that the availability of energy and the associated technologies contribute greatly to the standard of living observed within a society.

If all societies globally are to realise the wealth of opportunity that is observed in the more technologically developed countries, a tremendous amount of energy must be created to fill this demand. The main alternatives to hydrocarbon energy are nuclear fission and hydroelectric power. These have each made up around 5% of the energy growth since the Industrial Revolution. The remaining 5% of energy growth is made up from biofuels derived from plant material and other renewable sources such as wind and solar[2].

As hydroelectric power is limited by the geography of the earth, it can not be practically scaled to meet the required energy demands globally. Other renewable energy sources are also incapable of practically meeting base load power demands of the most technologically developed societies of today, let alone the future[3]. Nuclear fission has a number of associated drawbacks such as the high financial and environmental cost of the facilities and fuel. This along with the associated risks of fuel and waste diversion for nuclear weapons production has prevented the technology from becoming a widespread
supply of energy. A potential replacement of our current energy sources is nuclear fusion.

1.1 Nuclear Fusion

Fusion is a process in which two atomic nuclei come together to form a heavier nucleus\cite{4, 5, 6}. In many fusion reactions, the reaction products are in a more stable configuration and require less energy to bind them together than the reactants. As a result, the difference in nuclear binding energy is converted into the kinetic energy of the daughter nuclei. This abundance of nuclear energy has been successfully tapped in the application of nuclear weapons\cite{7}. The fusion or ‘hydrogen’ bomb clearly demonstrates the pinnacle of human destructive force and also the incredible potential of fusion power, should it be harnessed for peaceful purposes.

The coulomb barrier is the main barrier to initiating fusion reactions. This refers to the electrostatic repulsion that occurs between two atomic nuclei. The threshold energy required to overcome the Coulomb barrier is considerably large. Fusion weapons overcome this energetic barrier with the detonation of a smaller fission nuclear weapon which heats the fusion reaction fuel to temperatures on the order of $10^8 K$. This method has been proven as an effective method of initiating a fusion reaction with net energy output, but is impractical for power generation\cite{7} due to its uncontrollable nature.

When gases are heated to thermonuclear temperatures, ionization of the gas occurs and the electrons and atomic nuclei separate. The ionized gas is known as a plasma. We know that gas can be heated to thermonuclear temperatures, but containing the plasma and sustaining the fusion reaction in a controlled manner in order to achieve fusion energy remains an elusive challenge.

1.2 Fusion Reactions

Table. 1.1 documents three of the predominant fusion reactions investigated for power generation. These specific reactions are most interesting due to the combination of high energy released per reaction and low threshold energy. Due to these factors, these are the most likely reactions with which to produce net energy gain with fusion. However, these three reactions all have different attributes that set them apart in terms of their suitability for power generation.
Reaction | Energy Released | Threshold Energy
---|---|---
\(D + T \rightarrow ^{4}\text{He} + n (14.1 \text{ MeV})\) | 17.4 | 4
\(D + D \rightarrow \begin{cases} ^{3}\text{He} + n (3 \text{ MeV}) \\ ^{1}\text{T} + p (2.5 \text{ MeV}) \end{cases}\) | 3.25 | 35
\(D + ^{3}\text{He} \rightarrow ^{4}\text{He} + p (14.7 \text{MeV})\) | 18.2 | 30

Table 1.1: Fusion reactions of primary research interest[6].

The deuterium-tritium (DT) reaction has by far the lowest threshold energy and the second highest reaction energy. However, a lot of the reaction energy is retained by the neutron generated in the reaction. Energy from the fast neutron requires the development of new infrastructure in order to be extracted efficiently. The deuterium-helium-3 (D\(^3\)He) reaction has the highest energy yield, but has a considerably higher threshold energy than the DT reaction. The advantage of D\(^3\)He is that the reaction does not directly produce neutrons, which is known as an aneutronic reaction. Only through side reactions between deuterium atoms are some neutrons produced. Since only a few percent of the energy is transferred to neutrons, the D\(^3\)He reaction is useful as conventional thermal power transfer systems can be used to convert the fusion energy into electricity.

The deuterium-deuterium (DD) reaction is in some ways the poorest contender. It has the highest threshold energy, the lowest energy yield and a significant portion of the energy released is carried by fast neutrons. Despite this, the DD reaction has one major benefit over the other two reactions. Deuterium is abundant in that it occurs naturally in a concentration of 1 out of every 6420 hydrogen atoms. This abundance of deuterium would be enough to supply earth with hundreds of millions, if not billions, of years of energy if harnessed. Deuterium can be extracted from seawater with comparatively light industry and known technology. If this abundant fuel could be used in a small scale fusion power device, it could mean affordable and clean energy for everyone worldwide.

Tritium and \(^3\text{He}\) are both rarely occurring elements. They have to be produced to be useful in a power reactor. Tritium can be made by neutron bombardment in a nuclear reactor using a variety of targets, with the most common being lithium. Tritium itself is radioactive and can decay into \(^3\text{He}\). This method of producing these isotopes is not only costly and exclusive, but ultimately relies on the use of the raw material Lithium. There is a limited supply of naturally occurring Lithium and the mining of it requires heavy infrastructure. This places strong limits on the availability and cost of Lithium.
1.2.1 Reaction Rate

The reaction rate of fusion is given in Equation 1.1[5], where the number densities of the two types of fuel ions are given by \( n_1 \) and \( n_2 \). The fusion reaction cross section \( \sigma \) is the probability of a fusion reaction occurring during a collision between two fuel species. The cross sections for the reactions given in Table 1.1 are shown in Fig. 1.1. Cross sections for more exotic fuels are also given in Fig. 1.1, and are covered in more detail in the advanced fuels section (1.9.1).

\[
R = n_1 n_2 \langle \sigma v \rangle
\]  
(1.1)

Since the cross section is dependent on the relative velocity of the fuel species, the cross section is typically averaged over the velocity distribution of the fuel species. This average is known as the reactivity, and is given in Eqn. 1.1 as \( \langle \sigma v \rangle \). In most fusion plasmas the fuel ions are in thermal equilibrium and the number density can be calculated using the Maxwell-Boltzmann distribution. However, this is not always the case and some devices rely on maintaining a non-thermal equilibrium in order to function.

Figure 1.1: Fusion cross sections for various fuels. The DT reaction has the highest peak cross section at the lowest energy. Reproduced from[8].
1.3 Fusion Devices

The main function of a fusion device is to confine a high temperature plasma. The plasma must be confined in such a way that it does not make contact with the device. If this were to occur, the device would be damaged or destroyed by the plasma. In addition to device damage, the plasma itself would cool down from fusion energies as it rapidly deposits energy in the device material, preventing further fusion reactions. Since the individual plasma particles are charged, the main approach to confining plasmas is to use magnetic or electric fields or a combination of both to control the motion of the particles in the plasma.

1.4 Magnetic Confinement Devices

1.4.1 Toroidal Devices

When a charged particle enters a magnetic field its velocity component which is perpendicular to the direction of the magnetic field rotates around the axis of the magnetic field. The radius of this rotation, or Larmor radius $r_L$, grows smaller as the magnetic field strength increases. Equation 1.2 shows the Larmor radius where $m$ is the particle mass, $q$ is the charge, $B$ is the magnetic field strength, and $v_\perp$ is the velocity perpendicular to the magnetic field.

$$r_L = \frac{mv_\perp}{|q|B} \quad (1.2)$$

If the magnetic field is sufficiently strong, the motion of plasma particles is constrained to magnetic field lines. The magnetic field lines form closed loops in a toroidal device, as shown in Fig. 1.2. This forms the basis of closed magnetic confinement systems.
If the magnetic field is strong enough so that the electrons are tightly bound to the magnetic field lines, then charged particles can loop around the device without end. However, this does not occur in practice as non-uniformities in the magnetic field result in the Larmor radius of confined particles changing radially with the device. This is known as $\nabla B$ drift and the circular motion which would be generated by a uniform field is replaced with cycloid motion[4]. The velocity imparted by the magnetic field gradient to the particles is given by Equation 1.3, where $K_\perp$ is the kinetic energy due to the velocity component perpendicular to the magnetic field.

$$\vec{v} \nabla B = \frac{K_\perp}{qB} \frac{\vec{B} \times \nabla B}{B^2}$$ (1.3)

Drift velocity results in the motion of particles across the magnetic field lines and to the walls of the device. However, the drift velocity is in opposite directions for electrons and ions. To counteract these losses, a poloidal magnetic field is used in addition to the toroidal magnetic field. This produces a helical magnetic field structure and counteracts the drift motion by directing the particles back towards the centre of the device.

This basic ideology has been applied through many unique geometries of vacuum chamber and magnetic field coil shape, and the best results have been found in the Tokamak design. The toroidal motion of the charged particles is induced by external windings. In this way, the plasma acts as the secondary coil of a transformer. In the Tokamak it is the toroidal motion of the plasma which creates the poloidal field.
The most successful Tokamak to date is the Joint European Torus (JET) with a Q factor of 0.62[11].

The planned ITER experiment is a Tokamak which plans for a Q greater than 10 and would represent the first Tokamak to produce net fusion power.

Various plasma instabilities have been found to occur in the Tokamak and other toroidal devices, primarily in the edge of the device. These instabilities are due to the electric and magnetic fields that are created by the plasma, counteracting the applied fields. These instabilities weaken the particle confining properties of the devices. This is perhaps the greatest hinderance to net energy gain for the Tokamak. The only way to counteract these instabilities is to increase the size of the device. This has resulted in a projected plasma radius of 6 m for the proposed ITER experiment. The size of a Tokamak power station would be considerably larger. This has resulted in the criticism that the Tokamak will prove to be too expensive to be a practical power source. It also prevents the use of the Tokamak as a portable power source as there is no known physics that could provide miniaturisation of this type of device.

1.4.2 Open devices

The simplest open magnetic field geometry is that of a single magnetic field coil which creates a point cusp at its centre. As in the closed magnetic field geometry, charged particles can be confined along the magnetic field lines. The main difference is that there exists magnetic field lines that exit the coil and guide particles out of the device. This may seem like a fundamentally inferior geometry to the closed systems, and is indeed the greatest loss mechanism for particles in a cusp confinement system. However, open devices can take advantage of another effect, where particles that travel along the field lines may be reflected back into the device[9]. This effect is known as the magnetic mirror. A magnetic gradient is produced as the magnetic field at the centre of the device is less than that at the ends. Through the conservation of magnetic moment and energy, particles traveling from the centre of the device up the magnetic gradient may be reflected back towards the centre of the device.
1.4.3 The magnetic mirror

One of the simplest and earliest designs demonstrating the magnetic mirror effect is made of two coils with parallel currents, which is known as the Mirror Machine. The magnetic fields produced by this type of device are shown in Fig. 1.3. Particles within the device start at a local minimum of the magnetic field strength $B_{\text{min}}$. As the particles approach the region of stronger magnetic field, they rotate with increasingly smaller Larmor radii, given by Equation 1.2.

$$K = \frac{1}{2} m (v_\parallel^2 + v_\perp^2)$$ (1.4)

The kinetic energy of the particles is given in Equation 1.4. The component of velocity in the di-
rection of the cusp $v_\parallel$ is transferred into rotational velocity $v_\perp$ in the direction across the cusp. If the field keeps increasing, this process will continue until the velocity of the particles become entirely in the rotational direction, and as a result the particle will be reflected back.

Since magnetic fields do no work, the total kinetic energy must remain constant. As long as the Larmor radius is small compared to the spatial variation of the magnetic field, than the magnetic moment given by Equation 1.5 is also conserved[4].

$$\mu = \frac{mv_\perp^2}{2B} \quad (1.5)$$

Equation 1.4 and Equation 1.5 are combined in Equation 1.6 to reveal the relationship between the parallel velocity component and the magnetic field strength.

$$v_\parallel^2 = \frac{2}{m}(K - \mu B) \quad (1.6)$$

It is apparent from Equation 1.6 that the particles are only reflected if $B = \frac{K}{\mu}$. If this condition is met, it is possible to indefinitely trap a particle within such a magnetic field geometry. A particle that begins at the centre of the Mirror Machine device experiences the full magnetic gradient available. The ratio of velocities $v_\perp$ and $v_\parallel$, that result in a reflection for such a particle, is determined to be[4];

$$\frac{v_\perp}{v_\parallel} = \pm \left(\frac{B_{\text{max}}}{B_{\text{min}}}\right)^{-\frac{1}{2}} \quad (1.7)$$

Equation 1.7 describes a line through the centre of the device in velocity space. When rotated around the central axis of the coils, a cone shape is formed. This 3D region is known as the loss cone[9], as any particle within this region of velocity space will not be confined by the mirror reflections. This region can be uniquely described by the angle this cone makes with the central axis, and is given by Equation 1.8.

$$\theta = \sin^{-1} \left(\sqrt{\frac{B_{\text{min}}}{B_{\text{max}}}}\right) \quad (1.8)$$

While this method had been used to confine plasmas, in practice particles are still lost through the cusps over time, as coulomb collisions between particles will cause them to scatter and the magnetic moment to not be conserved. For this reason, even particles that do not originate within the loss cone are eventually scattered into it. Efforts have been made to maximise the amount of mirror reflection occurring and also plug the cusps using electrostatic and magnetic methods[12]. However, the efficiency of particle trapping in devices with magnetic mirroring have not been great enough to achieve fusion energy output.
In addition to the losses of particles down the cusps, these devices are affected by instabilities caused by a build up of plasma pressure $P_{\text{plasma}}$ in the central region. The parameter $\beta$ is used to measure the ratio of plasma pressure to the pressure from the magnetic field $P_{\text{mag}}$.

$$\beta = \frac{P_{\text{plasma}}}{P_{\text{mag}}} \quad (1.9)$$

The $\beta$ for a plasma in thermal equilibrium is given by;

$$\beta = \frac{n k_B T}{\left( \frac{\mu_0 B^2}{2} \right)} \quad (1.10)$$

where $k_B$ is the Boltzmann constant and $\mu_0$ is the magnetic permeability of free space. The arrows in Fig 1.3 show the direction of the magnetic field gradient. Nearer to the coils, the magnetic field grows stronger further out from the centre of the device. This results in a ‘good’ concave curvature of magnetic field lines towards the plasma. In this case, if the plasma is perturbed outwards by a small increase in plasma pressure, it encounters this stronger field region and is pushed back by increased magnetic pressure. This configuration is inherently magneto-hydrodynamically (MHD) stable. In the central region, the magnetic field is decreasing outwards from the device, resulting in ‘bad’ convex curvature. Hence, a small increase in the plasma pressure in this region would cause the plasma to encounter a decreased magnetic pressure. This causes the instability to rapidly grow as there is lessening magnetic pressure holding the plasma as it expands.

### 1.4.4 Minimum-B configuration

A simple minimum-B cusp is shown in Fig 1.3. This configuration is created with two coils of wire. Similar to the Mirror Machine, each coil current is the same in magnitude, but in opposite directions. This simple configuration is commonly known as a spindle cusp. In this geometry the magnetic field in the centre of the device [13] vanishes, as opposed to the original Mirror Machine device. For this reason, the magnetic moment is not conserved and there are no orbits that can indefinitely trap particles, as was possible with the Mirror Machine.

Unlike what is observed in the Mirror Machine the magnetic field curvature is always concave towards the plasma[14, 15] in the minimum-B configuration, and MHD plasma instabilities are avoided. The loss cones in this type of configuration are larger than the Mirror Machine due to the introduction of a line cusp. The line cusp can be seen in Fig 1.3. At the centre plane of the device, there are now magnetic field lines exiting the device. This cusp rotates around in 3D to form a line. This is a much
larger loss region than at the point cusps that exist in the centres of the coils, and essentially makes a line of point cusps. Many minimum-B configurations have been created but none so far have proved effective enough to achieve net fusion power[16, 17].

1.5 Inertial electrostatic confinement

Inertial electrostatic confinement (IEC) is the process of directly confining ions to fusion energies using purely electrostatic methods[18, 19, 20, 21, 22, 23]. The concept was initially developed by focusing electron beams with spherically symmetric anodes. It was proposed that these focused electron beams would produce a virtual cathode at the centre of the spherical electrodes, and that this virtual cathode could be used to confine and accelerate fuel ions to fusion energies. While this arrangement is a practical approach to accelerate ions to fusion energies at low ion densities, it was suggested that it would be unstable at high densities. Later modelling demonstrated that this type of spherical geometry could indeed confine ions at high densities and achieve net fusion power. However, the electron currents required to produce the virtual cathode are of the order of $10^{14}$ A and would be impossible to practically reach.

The next iteration of the IEC device utilised a hollow spherical cathode within a spherical anode. This type of design confines and accelerates ions directly without the necessary formation of a virtual cathode. Although, a much smaller virtual cathode is still produced within the virtual anode created by the physical cathode. This effect is known as ‘multiple wells’.

This style of IEC device formed the basis for much of the following research and is shown schematically in Fig 1.4. The spherical cathode is generally made of a hollow wire grid that is fairly transparent to the confined ions. Ions have been introduced into this type of device using an ion gun (shown in Fig 1.4 (a)) or with a glow discharge (shown in Fig 1.4 (b)), with ions being produced via ionization of a background gas and typically at units to tens of mTorr pressures. In order to achieve fusion, background gases of deuterium or a combination of deuterium and tritium are typical. IEC devices are still actively being pursued in both the USA[24, 25, 26, 27] and Japan[28, 29], and steady state outputs of $10^6 - 10^8$ neutrons per second have been observed.

Another feature of note in gridded IEC systems is the observed star-mode[31], which was named after the prominent collimated beams that emerge from the area between the cathode grid wires. These beams called ion or electron microchannels are also observed in IEC discharges using a hollow cylindrical cathode[32, 33], shown schematically in Fig. 1.4 (c). In this arrangement, a single microchannel is isolated and produced coaxially with the cylindrical cathode.
IEC discharges provide a number of benefits over the previously described magnetic confinement systems. The most apparent benefit is that the ions are easily accelerated to fusion energies by the cathode voltage. Other magnetic systems require different heating techniques such as Radio Frequency (RF) power, Electron Cyclotron Resonance (ECRH), and the most critical of all Neutral Beam Injection (NBI). Due to the limitation of these heating methods, magnetically confined plasma are typically constrained to the use of the DT reaction and plasma temperatures of approximately 5-10 keV. By trivially increasing the accelerating voltage, much higher energies are available to IEC devices and other advanced fuels can be used.

IEC devices suffer fewer plasma instabilities than magnetic systems, as the electric forces inside the non-neutral IEC plasma typically reduce plasma perturbations. For their neutron output, IEC devices are much smaller than their magnetic counterparts, such as the Tokamak. They are currently the best portable steady state sources of 2.5 MeV neutrons. For this reason, they have a number of near term commercial applications, which make up the focus of most current IEC research.

Despite these advantages, the gridded IEC device is unlikely to be able to produce net fusion power. The transparency of the gridded cathode is the fundamental problem that limits its efficiency. Ions generally only make a few passes through the gridded cathode before they impact the grid. However, the fusion cross section is small and ions typically require over 1000 passes before they fuse. This results in a ratio of ion power loss from collisions with the grid to fusion power of $\sim 40$.[34]

We return again to the idea of the virtual cathode, in which an electron plasma is confined in order to produce a negative space charge that confines ions[21, 20]. Since there are no physical wires with which the ions can collide, the major loss mechanism of IEC devices is removed. There have been a number of approaches to developing a virtual cathode and the Polywell device is one of these options.
1.6 The Polywell

The Polywell is a hybrid concept\cite{35, 36, 37, 38, 39, 40, 41} that uses ideas from both IEC\cite{21, 19} and magnetic cusp confinement\cite{13, 15}. However, unlike in previous cusp devices, ions are not intended to be trapped by the magnetic fields. Only energetic electrons are trapped in a cusped magnetic well by magnetic mirror reflections. A sufficiently dense and trapped spatial electron distribution can produce a virtual cathode to form an electrostatic potential well\cite{39}. The depth of the electrostatic potential well can theoretically reach the energy of the injected electrons. The main advantage expected of the Polywell is that ions can no longer be lost to the cathode grid, which is unique amongst IEC devices\cite{22, 19, 32}.

A magnetic well is produced by an electrical current applied to an arrangement of six coils that form the faces of a cube. Pairs of coils situated on the opposite side of the cube have antiparallel currents, just like the spindle cusp described in Fig 1.3. By the addition of two other coil pairs, the large line cusp in the spindle cusp is distorted to form point cusps at the corners of the cube and smaller line cusps in the edges of the device. The point cusps at the middle of the coils remain, however there are now six point cusps corresponding to the six faces of the cube, rather than the two observed in the spindle cusp device. This geometry provides a central magnetic null and a high magnetic field at the coils, thus creating a magnetic well. The coil arrangement with selected magnetic field lines is shown in Fig. 1.5.

![Figure 1.5: 3D depiction of Polywell magnetic fields.](image)

While the Polywell system resolves the ion-grid energy losses found in IEC devices, it does introduce
another energy loss mechanism. Electron losses from the point cusps found at the corners and faces of the device represent a significant energy loss mechanism. However, it has been shown that losses from the line cusps at the edge of the device can be made negligible[42]. For the Polywell to be a viable source of fusion energy, energy lost from electrons exiting the device must remain smaller than the fusion power generated.

1.6.1 Electron confinement

Electron losses from the cusps represent a major energy loss mechanism in the Polywell device. In the case of a low beta plasma, the physics of the electron trapping is described by mirror reflections with a reflection coefficient \( \propto 1 - \frac{1}{B_{\text{max}}} \)[36, 12, 43, 44]. In this mode of operation, the electrons must be confined to a central core of the device such that the average reflection radius of the confined electrons is \( \sim 0.5R \). This creates a potential well that is on the order of the device radius. Thus, the ions are confined electrostatically and are typically reflected on the order of the device radius \( R \).

As previously discussed, cusped geometries are MHD stable as the curvature of the magnetic field lines is always concave towards the plasma [13, 45]. While the Polywell follows this type of geometry and is not susceptible to MHD instabilities, there are still various plasma instabilities that may reduce the effective electron confinement of the device. These instabilities include; the loss-cone instability, the two-stream instability and various gradient driven instabilities.

It has been proposed that by increasing the density of the plasma within the device, the collective diamagnetism of the plasma will exclude the magnetic fields of the cusps. This effect occurs with plasma of \( \beta > 1 \) in the interior of the device and \( \beta = 1 \) at the boundary of the magnetic exclusion[46]. This has the effect of increasing the region of magnetic null within the device. Low and high beta operation and the resultant effect on the magnetic fields are shown in Fig 1.6. The magnetic fields produced by the plasma diamagnetism at high beta form a quasi-spherical geometry with a sharp boundary between the field free region and the high magnetic field region. This is known as the ‘Wiffle Ball’ (WB)[36]. This sharp boundary causes specular reflections in addition to the magnetic mirror reflections and improves electron confinement such that the reflection coefficient is \( \propto 1 - \frac{1}{B_{\text{max}}} \)[46]. Recently, experimental results have shown evidence of improved electron confinement in a Polywell like device operating at high \( \beta \) through x-ray measurements[47].

1.6.2 Fusion Power Density

In all magnetic confinement systems, the upper limit of particle density is determined by the balance of plasma and magnetic pressure \( \beta \). The high beta condition in the Polywell is determined by the electron
density and is given as \cite{48},

\[ \beta = \frac{n_e E_e}{B^2} \]  

(1.11)

where \( n_e \) and \( E_e \) are the electron density and energy respectively. It has also been shown that the electron density required for high beta is many orders of magnitude greater than the electron density required to form the potential well\cite{49}, thus \( n_e \approx n_i \), where \( n_i \) is the ion density at the edge of the plasma. It is thought that ions move radially within the device such that \( n_i \) varies \( \propto \frac{1}{r^2} \), where \( r \) is the radial coordinate. If the ions converge to the core of the device with a radius \( r_c \), then the core ion density can be expressed as \( n_c = \frac{n_i r_c^2}{r^2} \)\cite{48}. For a monoenergetic distribution of identical fuel species, the reaction volume scales as \( V_c \propto r^3 \) and the fusion power scaling can be approximated by;

\[ P_{\text{fusion}} \propto n_c^2 r_c^3 \propto \frac{\beta^2 B^2 R^4}{r_c} \]  

(1.12)

This shows approximately the same fusion power scaling as the quasi-neutral Maxwellian plasma of a Tokamak\cite{50}. In the case of a Tokamak, magnetic pressure is used to confine ions and the loss rates are dominated by ion transport. This is because the energy of the particles can be considered roughly equivalent for a given fuel species, and the ratio of magnetic pressures required by the two species is
\( \propto \sqrt{m_e m_i} \), with \( m_e \) and \( m_i \) being the electron and ion masses. However, in the Polywell, magnetic pressure is used to confine electrons which then electrostatically confine the ions. Since the magnetic confinement of electrons requires lower fields for a given device size or a smaller device for a given magnetic field, this analysis suggests a fusion energy capable Polywell may be more practically achieved than the Tokamak design\[48\].

## 1.7 Experimental Polywells

There is only a small amount of experimental Polywell results published in the peer reviewed literature. This is due to the fact that most of the experimental research has been performed by EMC2 Inc (EMC2), and this company has a non-disclosure policy that has prevented the publication of the bulk of their results. However, prior to 2006 a number of non-peer reviewed technical reports were released along with three patents\[51, 52, 53\]. In addition, two experimental Polywells have been constructed at The University of Sydney (USYD), and these results are available in peer reviewed journals\[42, 54\]. The available results of the EMC2 and USYD experiments are summarised in this section.

### 1.7.1 EMC2 Experiments

In the period between 1994 and 2006 numerous Polywells were constructed and tested by EMC2\[36, 55\]. The operational parameters for a number of their devices are given in Table 1.2.

<table>
<thead>
<tr>
<th>Device</th>
<th>( R ) (cm)</th>
<th>( B_{face} ) (T)</th>
<th>( E_{inj} ) (keV)</th>
<th>( I_{inj} ) (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEPS</td>
<td>35</td>
<td>0.35</td>
<td>5-15</td>
<td>5-10</td>
</tr>
<tr>
<td>PZLx-1</td>
<td>1.5</td>
<td>3.5</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>WB1</td>
<td>2.5</td>
<td>0.08</td>
<td>1-2</td>
<td>4-5</td>
</tr>
<tr>
<td>WB2</td>
<td>2.5</td>
<td>0.13</td>
<td>1-2</td>
<td>4</td>
</tr>
<tr>
<td>WB3</td>
<td>5</td>
<td>0.24</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>WB4</td>
<td>7.5</td>
<td>0.5</td>
<td>15-30</td>
<td>2-4</td>
</tr>
<tr>
<td>WB6</td>
<td>7.5</td>
<td>0.13</td>
<td>12.5</td>
<td>40</td>
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<tr>
<td>WB7</td>
<td>7.5</td>
<td>0.1</td>
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</tr>
<tr>
<td>WB8</td>
<td>15</td>
<td>0.2</td>
<td>2-13</td>
<td>1-14</td>
</tr>
</tbody>
</table>

Table 1.2: Device parameters for various EMC2 devices.\[56, 36, 38, 47\].

The earliest experiment was the High-Energy Power Source (HEPS) device. HEPS was built with funding from DARPA, and was the largest Polywell ever built. Consequently, the power input to the device of \( \sim 150 \) kW was also the largest, with the exception of the recent ‘miniball’ experiment from EMC2 which used MW of injected plasma. Deep potential wells of up to 10 keV were observed, representing a potential well of 80\%\[38\] of the injected electron energy. The HEPS design featured a square vacuum
chamber with the magnetic field coils placed on the outside. This led to a large intersection between the magnetic fields and the walls of the vacuum chamber. Consequently, electron losses from the device were larger than expected.

Subsequent research in the later WB devices were conducted by EMC2 with funding predominately from SBIR grants and the US Navy. WB1 was a comparatively simple device made from permanent annular magnets. The magnetic field from this arrangement produces many magnetic field lines that terminate on the magnet surfaces, increasing electron losses. The line cusps produced in the edges of the device are also larger than those produced with electromagnetic coils, leading to line cusp losses similar to those found in the spindle cusp device.

Copper wire wound coils with square cross sections were used throughout WB2-4[36]. This prevented the large line cusps found in WB1. The coils were placed within the vacuum chamber, unlike the HEPS experiment. This allowed electrons escaping from the point cusps at the corners and faces to recirculate back into the device. The formation of the potential well was observed under a range of varying device parameters, including magnetic field coil and electron injection currents. By applying a voltage to the coils, the Polywell was used to extract electrons from thermionic electron sources, which were placed on the point cusp axes either adjacent to the faces of the coils or at the corners of the device. Neutron rates of $10^6$ n/s were reported with WB4 using DD reactions[36], with a potential well of 10 keV and a coil bias of 12 keV. PZLx-1 was constructed specifically to test the MHD stability of the Polywell coil configuration.

EMC2 returned to the external coil design for WB5. As in the HEPS experiment, electron losses to the vacuum chamber surfaces were large. Repeller plates were added to the experiment to electrostatically plug some of the point cusps. This reduced the electron losses by a factor of 2.5, but also caused increased ion losses as ions were attracted to the plates rather than being repelled like the electrons[36].

The WB6 device was the first to use circular cross section magnetic field coils and minimise the coil interconnects. This was done to reduce the metal surfaces intersecting with magnetic field lines, and thus maximise electron recirculation around the coils. Deep potential wells up to 10 keV were produced and resulted in a reported neutron count of $10^9$ n/s from DD reactions[57, 36]. However, only five device pulses produced a total of 9 measured neutrons, with a the largest count being 3 neutrons reported in a single pulse. This lead to a wide confidence margin in the reported neutron count. Further experimentation was not possible as arcing at the coil interconnects destroyed the device.

Since 2006, two larger devices WB7 and WB8 have been produced. However, unlike for previous devices, further technical reports have not been made available and many of the experimental results are unknown[55]. However, a recent presentation has revealed some of the key results for the WB7 and
WB8 experiments[47]. Neutron rates of $10^5 - 10^6$ were reported for WB7 with much better confidence than the WB6 neutron counts, and no fusion was reported for WB8. The design of WB8 differed from previous designs as there were no connections between the coils. The coils were individually held and powered by supports attached to the chamber walls. This difference was very detrimental to potential well formation and indicated that the coil interconnects were providing a necessary boundary condition for the potential well formation.

In 2015 EMC2 published results of a smaller device known as the 'miniball' (MB). This device utilised solid target plasma injection methods to propel a very high density plasma into a Polywell magnetic field geometry. X-ray measurements were used to determine increased electron confinement in the high $\beta$ operation[47]. However, this device was not reported to have produced a virtual cathode or subsequently confine ions in the manner which the Polywell is designed. As of 2015, EMC2 has not received further funding and is currently not experimenting with any devices.

### 1.7.2 USYD Experiments

Two experimental Polywells have been created by USYD, and key device parameters are shown in Table 1.3.

<table>
<thead>
<tr>
<th>Device</th>
<th>$R$ (cm)</th>
<th>$B_{\text{face}}$ (T)</th>
<th>$E_{\text{inj}}$ (keV)</th>
<th>$I_{\text{inj}}$ (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carr-1</td>
<td>2.8</td>
<td>0.31</td>
<td>6-15</td>
<td>$&lt;1$-$7$</td>
</tr>
<tr>
<td>Carr-2</td>
<td>2.5</td>
<td>0.025</td>
<td>0.05-0.15</td>
<td>1.5-$5.5$</td>
</tr>
</tbody>
</table>

Table 1.3: Device parameters of USYD Polywell devices.[10, 54, 42]

In the first experiment (Carr-1) a teflon frame was constructed on which copper coils were wound. The results using this device represent the first experimental confirmation of potential well formation in a Polywell outside of EMC2. Potential well depths of up to 250 V were observed[42, 10]. This experiment used a hollow cathode plasma source for the electrons. The source was only able to operate at pressures $\geq 10$ mTorr. The results indicated that gas pressure was a major determinate of the potential well depth, with lower pressure being more conducive to potential well formation.

In Carr-2, the coils were made with a circular cross section and a conformal metal casing. This experiment was similar in design to WB6, although much smaller. Potential well formation was observed for a number of device parameters. However, the design of the coil interconnects prevented a high magnetic field from being used, and the potential wells were shallower than previously observed. The electron energy distribution function (EEDF) was determined and showed that the electrons likely form a non-thermal Druyvesteyn distribution[54, 10].
1.8 PIC simulations

Particle In Cell (PIC) simulations using the commercial OOPIC\cite{58, 59, 60} package have been carried out. A Polywell using a DD fuel was simulated under two case studies\cite{61}. It was shown that the potential well decreased when the device magnetic field was increased. It is thought that this may be due to increased ion confinement decreasing the potential well depth. If the ion density is increased beyond the limit required to maintain non-neutrality in the Polywell, than the potential well will be significantly decreased (up to removing the whole potential well if quasi-neutrality is reached). These results suggest that maintaining the ion density below this critical amount is necessary in order to retain potential well depth and accelerate the confined ions to fusion energies\cite{61}.

Also using the OOPIC package, concept studies of a fusion capable Polywell were performed\cite{62, 63}. A number of different fuels were simulated, including the widely used DD and the advanced fuel of p$^{11}$B\cite{64}. A conceptual design study was also undertaken for a $0.25M$ deuterium fueled Polywell with 0.5 m diameter coils\cite{65}.

Recently another PIC simulation has been presented using the SSUBPIC code\cite{66}. These results suggest that biasing the metal housing that surrounds the coils of the Polywell is not only a viable method for extracting electrons, but also results in a much greater electron confinement time than with grounded coils. However, the effect on ions was not simulated.

1.9 Particle orbit theory

Theoretical work has been carried out which examines low beta Polywells\cite{67, 49, 42}. Key predictions from these investigations are summarised in this section. By examining the magnetic field spacing of the coils, it was determined that electron losses from the edge cusps can be made negligible compared to the face and corner cusps by using closer coil spacings. It was also shown that the electric fields that are created by the act of pulsing a Polywell, rather than using a steady state system, do not greatly effect the confinement of electrons. Power losses from the Polywell have been shown to be significantly reduced by increasing the size of the device and by the use of electrostatically plugged cusps.

The claim of electron recirculation was investigated and it was found that there was no significant recirculation due to the magnetic field geometry\cite{49}. Only through electrostatic means, by applying a voltage to the device, was significant recirculation achieved. However, the recirculated electron population spent an order of magnitude more time outside the device rather than inside. Consequently, the vacuum chamber volume must be proportionally larger than the device.
1.9.1 Advanced Fuels

As previously discussed, the DD and DT reaction are the most commonly studied, due significant reaction cross sections occurring at comparatively lower energies. However, there are a number of other possible reactions that have the advantage of being aneutronic. The reaction cross sections for a number of the advanced fuels shown in Table 1.4 are shown in Fig 1.1. Neutrons produced during the reaction are problematic as they cause radiation damage to the reactor materials through neutron activation. Increased reactor shielding is also required to protect workers, and added technological infrastructure needs to be developed in order to extract the energy from these neutrons for useful purposes.

Another advantage of the advanced fuels is the potential use of direct energy conversion[68, 69, 70, 71]. As the energy produced during the fusion reaction is carried in the kinetic energy of charged particles, this energy can be directly converted into electrical current by making the fusion products do work against an electric field[69, 72]. The use of direct energy conversion could lead to large gains in the efficiency of the energy conversion at reduced infrastructure cost[73, 70, 72].

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Energy Released (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p + {}^{11}B \rightarrow {}^3He + \gamma$</td>
<td>8.7</td>
</tr>
<tr>
<td>$^3He + ^3He \rightarrow ^4He + 2p + \gamma$</td>
<td>12.9</td>
</tr>
<tr>
<td>$D + ^3He \rightarrow ^4He + p$</td>
<td>18.2</td>
</tr>
<tr>
<td>$^6Li + ^3He \rightarrow ^2He + p + \gamma$</td>
<td>16.9</td>
</tr>
<tr>
<td>$p + ^7Li \rightarrow ^2He + \gamma$</td>
<td>17.2</td>
</tr>
<tr>
<td>$D + ^6Li \rightarrow ^2He + \gamma$</td>
<td>22.4</td>
</tr>
<tr>
<td>$p + ^6Li \rightarrow ^4He + ^3He$</td>
<td>4.0</td>
</tr>
<tr>
<td>$p + ^{15}N \rightarrow ^{12}C + ^4He + \gamma$</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Table 1.4: Selected advanced fuel reactions. Reproduced from.[10]

IEC devices are well suited to the use of advanced fuels. The ion heating is achieved electrostatically, and higher temperature ions can be achieved by increasing the accelerating voltage of the device to desired levels[69]. This is also true for the Polywell specifically[35]. Tokamak fusion devices are limited to DT fuel as the plasma heating relies on NBI, and this technique can not be used to reach the higher temperatures required by the advanced fuels. Bremsstrahlung losses also increase dramatically at higher Maxwellian temperatures, and the ions in the Polywell device are intended to be far from a Maxwellian distribution.

The Polywell is also better suited to the use of advanced fuels than traditional IEC devices. The reaction products are at much higher energies than the reactant ions and thus easily escape the potential well. They will also be guided by the magnetic point cusps to specific locations where direct energy conversion modules could be placed[39]. This differs from traditional gridded IEC devices, where the
fusion products exit the device in a spherically symmetric volume. The fact that the energy of the fusion products is not deposited in the plasma also means that the Polywell does not achieve ignition. In this way the Polywell is better described as a power amplifier where $P_{\text{fusion \ out}} > P_{\text{electric \ in}}$.

1.10 Criticisms of The Polywell

While we have so far explored many of the proposed benefits of the Polywell device, there are a number of criticisms. The most prominent of these are the ion and electron thermalisation, ion focusing at the core, synchrotron and bremsstrahlung radiation, and the electron cusp losses. These will be briefly explored in this section.

1.10.1 Ion Thermalisation

For the Polywell to achieve net fusion power the ion energy distribution would ideally be monoenergetic and far from a thermal Maxwellian distribution. This is required so that the energy of the majority of ions in the core of the device correspond to the peaks in the fusion reaction cross sections shown in Fig 1.1.

Theoretical analyses have suggested that an initially monoenergetic ion distribution will tend towards a Maxwellian distribution on the time scale of ion-ion collisions\[^74, 75, 76, 34\]. The ratio of the ion-ion collision time $t_{ii}$ and the fusion time scale $t_{fus}$ yields the same results produced by toroidal magnetic confinement schemes.

$$\frac{t_{ii}}{t_{fus}} \sim 10^{-3} - 10^{-2} \quad (1.13)$$

It is thus concluded from this result that the ion distribution will relax into a Maxwellian distribution before fusion can take place. Due to coulomb collisions, some of the initially monoenergetic ions will gain energy (up-scattering) and some will lose energy (down-scattering). The possibility of actively maintaining this distribution by removing the energy gained from the upscattered ions and giving this energy to the down-scattered ions was also investigated\[^34\]. It was shown that the power used to redistribute this energy is always greater than the fusion power and thus such a mechanism could not be effectively employed\[^34, 74\].

Another analysis has shown contradictory results\[^77\]. It has been shown that it is possible for ions to transit the device in a timescale $t_T$ that is shorter than $t_{ii}$, and that edge collisions can passively maintain the initial monoenergetic energy distribution under this condition. Experimental validation of the ion energy distribution has not be published, and this remains an open question.
1.10.2 Core Convergence

It has been argued that the potential well developed in the Polywell will not be able to focus ions in the core of the device\[78\] well enough to gain energy from fusion. Since electrons flow easily along the magnetic field lines of the device, the electrostatic potential will not vary greatly along these field lines. Thus, electrostatic isopotential lines will tend to follow the magnetic field gradient. As the magnetic field lines form convex surfaces towards the core of the device, ions reflected from such a surface would not be well focused to the device core.

A counter-analysis suggests that the assumption that the electrostatic potential follows the magnetic field gradient is incorrect\[79\]. It is argued that electrons are not confined to magnetic field lines as in other magnetic confinement systems due to the magnetic null region. Therefore, the degree of ion focusing is related to how spherically symmetric the potential well is\[80\]. It is also argued that because ions at the edge of the device are low in energy compared to in the core, edge ion-ion collisions will add little transverse momentum to the ions. Thus, the only way a significant amount of transverse momentum can be gained by the ions, resulting in defocusing, is through core collisions\[79\].

1.10.3 Synchrotron and Bremsstrahlung Losses

Any confinement device using magnetic fields has the potential of losing energy via synchrotron radiation. In the Polywell, ions are at their lowest energy at the edge of the device where the magnetic field is greatest\[35\]. For this reason the ion contribution to the synchrotron radiation is thought to be small. However, the opposite is true for electrons in the Polywell. The synchrotron radiation is expected from electrons at the edge of the device. This region of emission is small compared to the device size, thus synchrotron losses are small relative to the total power consumed by the plasma and can be neglected\[35, 76\].

Bremsstrahlung radiation is expected to be a major loss mechanism in the Polywell. The acceleration of electrons by ions is expected to be largest in the core where the ion and electron densities are the greatest. It has been calculated that the timescale of electron-electron collisions $t_e$ is much smaller than the confinement time of electrons in the magnetic cusp. Based on this assumption, a Maxwellian energy distribution for electrons in the core of the device was used to estimate the power losses due to bremsstrahlung radiation $P_{brem}$\[75\]. The ratio of $P_{brem}$ to fusion power $P_{fus}$ is shown in Fig 1.7 for a range of possible fuels. This analysis shows that $P_{brem}$ can be the dominant energy loss mechanism in a Polywell, and that the minimum potential well depth for net fusion power is set by $P_{brem}$ for a range of device parameters. It also suggests that net fusion power with advanced fuels would be impossible due
Figure 1.7: Ratio of power loss from electron cusp losses $P_{\text{losscusp}}$ and bremsstrahlung radiation $P_{\text{brem}}$ to fusion power $P_{\text{fus}}$ versus ion temperature for a range of possible fuels; (a) DD (b) DT (c) D$^3$He (d)p$^{11}$B. Reproduced from[75].

to bremsstrahlung losses, even if power losses due to electrons could be improved[75], as $\frac{P_{\text{brem}}}{P_{\text{fus}}}>1$ for all device parameters, for example in Fig 1.7 (d).

1.10.4 Electron Cusp Losses

Ion thermalisation and bremsstrahlung radiation losses are applicable to all IEC devices. However, the introduction of the virtual cathode in place of the grid cathode introduces power losses from electrons escaping the cusps. Several cusp geometries have been explored and all suffered from cusp leakage that prevented net fusion power. As shown in Fig 1.7, losses from the cusps of a Polywell can form the predominant energy loss mechanism. The Polywell must overcome these electron cusp losses in order to achieve net fusion energy.

The previously discussed WB mode of operation induced by a high $\beta$ plasma offers a possible advantage over other magnetic cusp devices. Electrostatic plugging of the cusps by exiting electrons is another proposed mechanism that could limit the cusp losses. It is also possible for electrons leaving the cusps to recirculate back into the device by following magnetic field lines back into another cusp. While this is an attractive possibility, it is technologically challenging as the magnetic field lines must not intersect with
any of the surfaces within the vacuum chamber. While the vacuum chamber can readily be made larger to accommodate the recirculating electrons, there must exist some supporting structures for the magnetic field coils, which would necessarily introduce surfaces that recirculating electrons would collide with.

1.11 Aims of The Thesis

The main aim of this thesis is to measure potential well formation in a low $\beta$ Polywell and study its relationship with a range of device parameters. As previously detailed the high $\beta$ operation of the Polywell is more likely to be relevant for a device capable of producing net fusion power. However, the apparatus required to probe this region of plasma behaviour is not available at USYD, hence the focus on low $\beta$ operation is chosen. Chapter 2 describes the experimental apparatus used and rationale behind the design.

Chapter 3 describes the characterisation of a capacitive probe diagnostic. The plasma in the Polywell presents unique challenges to conventional probe based diagnostics, since the plasma is non-neutral and non-Maxwellian. The capacitive probe based diagnostic has been used previously in the HEPS experiment, but its use in a non-neutral, non-Maxwellian plasma and the effect of strong magnetic fields have not been thoroughly documented. In order to do this, a planar vacuum diode is constructed within a Helmholtz pair and the capacitive probe is characterised for its use in Polywell experiments.

Chapter 4 describes an experiment that uses a small Polywell with magnetic field strength and electron injection currents greater than previously tested[42, 54]. By expanding the parameter space, we seek to gain more understanding about the potential well formation and attain deeper potential wells than previously observed with small Polywell devices. This experiment aims to show that the potential well depth can approach the electron energy, which has only been shown in a much larger device[38]. A theoretical model is developed to estimate the confinement time of electrons in the device, and a experimentally derived equation for electron confinement time is produced. These results are compared to a particle orbit simulation.

Finally, in Chapter 5 we use a range of inter-coil spacings to vary the relative magnetic field in the cusps. From this we learn more about the electron trapping in the different cusps that exist in the face, edge and corners of the Polywell. Larger magnetic field coils are also used to ascertain the effect of device scaling on the formation of the potential well; from these results a geometric progression is used to predict the size of a Polywell needed to reach fusion energies. Multiple capacitive probes are used to determine the spherical symmetry of the potential well, as this is thought to be an important factor in the degree of ion focusing attained by the Polywell[80]. Lastly a hydrogen gas of varying pressures is used
to determine the effect on the potential well formation and to test the possibility of using a background gas to fuel the device.
Chapter 2

Experimental setup

2.1 Introduction

In this chapter, details are given of the Polywell devices used in this study. In addition, an overview is given of the experimental setup and power supplies used.

The primary aim of the Polywell device is to produce deep potential wells in order to confine ions and achieve fusion. The formation of the potential well and its dependence on device parameters, including electron injection current and a magnetic field strength, the spacing of magnetic field coils and size of device, was a major focus. The formation of the potential well is the main focus in this work. In addition to this, how the depth of the potential well was affected by device parameters, including electron injection current and magnetic field strength, was a major focus. The effect of the physical parameters of the device itself were also of interest.

The experimental setup consists of two main components. The first is the development of a mechanically robust Polywell, due to the higher magnetic fields produced to confine unprecedented high current injected electron beams.

The electron sources for the Polywell were a significant design consideration. A novel hollow cathode electron current was developed for use in the various devices, however, it was found that studies depending on electron injection current scaling could not be met by the electron current range of this gun. Consequently, a standard thermionic emission source was used. Nevertheless, due to the novelty of the hollow cathode gun, the technical details are given in Appendix A.

The second part is the development of a capacitive probe diagnostic which is outlined in the next chapter. The advantages of using the capacitive probe in this device will also be outlined in the next chapter.
2.2 Polywell design

2.2.1 Magnetic field intersection with the field coils

The high magnetic fields used in the Polywell devices, in this work, result in very large repulsive forces between the field coils. Consequently, mechanical robustness is required. To accurately determine the forces on the structure finite element methods or similar would be required. However, it is possible to approximately gauge the magnitude of the repulsive force between two opposing coils by using the following equation for the repulsive force between two magnetic dipoles.

\[ F(x) = \frac{3\mu_0}{2\pi} m_1 m_2 \frac{1}{x^4} \]  

(2.1)

Where \( F \) is the force \( \mu_0 \) is the magnetic permeability of free space and \( x \) is the distance separating the two coils and \( m_1 \) and \( m_2 \) are the magnetic moments of the two coils, given by

\[ m = I_c \pi R^2 \]  

(2.2)

where \( I_c \) is the total coil current and \( R \) is the coil radius. Using typical values found in the experiment of \( I_c = 40 \) kA/turns, \( R = 0.048 \) m and \( x = 0.06 \) m a force of \( \approx 4000 \) N is found. There are also additional constraints on the design, being that the mechanical structure must not impede the electron motion within the device.

Electrons trapped within the outer adiabatic region of strong magnetic field travel along magnetic field lines. For this reason the intersection of magnetic field lines and the device structure should be reduced. In a previous experiment[54] a small Polywell the cross section of the magnetic field coils was made circular in order for this intersection to be minimized. This design presented a significant detriment to the mechanical stability of the device, as the interconnects used had to conform to the circular surface and could not be attached robustly.

In order to achieve a higher level of structural stability wire-spools with a rectangular cross section were used. The assembled spools are shown in Fig. 2.1. The brackets connecting the spools in this design could be bolted through the spool and provided increased mechanical stability.

Particle orbit theory modeling showed trapped electrons generally being excluded to regions outside the regions of intersection that were introduced by changing the cross sectional shape of the field coils[10]. Magnetic fields of \( \sim 1 \) T were produced with these magnetic field coils. Strong magnetic fields are required since electron confinement time depends on the relative size of the electron Larmor radius to the device device dimensions.
2.2.2 Magnetic field intersection with the structural supports

Modeling[49] suggests that electrons predominately enter and leave the faces and corners of these devices due to the existence of magnetic point cusps at these locations. Another set of cusps, however, also exists in the middle of the edges of the Polywell device. In the majority of previous Polywell designs this location forms the practical location of the joining structure, which has been shown to be a significant source of electron loss. This site was the source of arcing that destroyed the WB6 device[36], the only Polywell device claimed to have produced fusion. The design presented in this thesis does not place structural supports within the path of these edge cusps. The brackets that join the edges of the device are joined in the middle of the corner and edge cusp locations minimising electron losses to the structure due to edge cusp losses. A series of 4 square brackets fixed with 8 bolts each join the coils. Each magnetic field coil had 3 mylar sheets that were cut to line the inner surfaces of the frame, shown in Fig. 2.2. Teflon tape was also used on the bottom of the spools, where the mylar sheets joined. The magnetic field coils were wound using 2.24 mm enameled copper wire. The coils were also wrapped in teflon tape in the first experimental setup. However this was found to be unnecessary and was removed in the second experiment.
2.3 Electron Injection

Electron injection is a critical part of the functioning of the device. It was earlier observed\cite{54} that the potential well dependence in the small Polywell was highly dependent on electron injection current. Two types of electron sources were investigated; plasma and thermionic emission. Plasma electron sources produce a discharge from which electrons are extracted. Thermionic electrons are extracted and accelerated from a heated material (tungsten in our case) using electrons and sometimes focussing and magnetic fields to form and electron beam.

2.3.1 Plasma electron guns

A simple plasma electron gun source was developed. Generally it is possible to achieve higher electron currents with plasma electron guns than with filament sources. However, high gun pressures would have been required in order to achieve this and a more sophisticated differential pumping system than that was available would have been required in order to maintain reasonable chamber pressures. Due to this limitation the required high electron currents were less than could be achieved with thermionic emission and the chamber gas pressures achieved with the use of this plasma gun were higher also than desired. The chamber pressure could also not be reasonably decoupled from the electron current and energy.
produced by the plasma gun, placing a restriction on the parameter space required by the experiments. Nevertheless due to its novelty, a brief description of it is given here and further details are given in Appendix A. The plasma electron gun is shown in Fig. 2.3. This type of electron gun uses an IEC discharge to produce an electron microchannel.

![Figure 2.3: Close up photograph of the plasma electron gun](image)

Another advantage of the plasma gun is its simplicity and low maintenances. The specific design of this plasma gun created a higher than normal dependence of discharge current to voltage due to the hollow cathode operating in the abnormal glow mode. Coupling of electron energy and current presented another limitation on the parameter space that was needed for the exploration of scaling performance being conducted in this work. Consequently, a thermionic emission electron source was used, despite the regular replacement of the heating elements and the calibration of its emissive properties each time.
Figure 2.4: Previous experimental setups. Top: Both filament and plasma sources inside the chamber; (a)-Polywell (b)-Plasma electron gun (c)-Filament electron gun (d)-Polywell coil feed-through (e)-Plasma gun high voltage connection (f)-Plasma gun holder. Bottom: Metal tipped langmuir probes and plasma electron gun mounted on the outside of the chamber; (a)-Polywell (b)-Plasma Electron Gun (c)-Cooling fans (d)-Polywell coil feed-through (e)-Plasma gun high voltage feed-through (f)-Metal tipped Langmuir probes (g)-Glass insulator.

Figure 2.4 shows the hollow cathode electron gun placed inside the vacuum chamber to increase the injection current to the Polywell. Also shown in Fig. 2.4 is the original placement of the gun on an external port. Both of these placements resulted in an uncontrolled narrow divergence of the electron beam. Due to this, the electron current available to the Polywell did not significantly increase (less than a factor of 10%) when the plasma gun was moved inside the chamber.
2.3.2 Thermionic electron sources

The first thermionic electron gun that was constructed is pictured in Fig. 2.4 perpendicular to the plasma electron gun. The gun was made of three annular electrodes held together by the tension of two flexed ceramic rods. A tungsten filament was located at the end of the gun, and electrons were extracted from this using the first electrode. The second electrode accelerates the electrons, and the third electrode connects the gun to one of the Polywell field coils, so that the potential on the field coils is the same as the last electrode.

![Thermionic electron gun](image)

Figure 2.5: Top: Close up of filament electron gun; (a)-Extraction electrode (b)-Acceleration electrode (c)-Focusing electrode (d)-Polywell (e)-Ceramic rods (f)-Filament. Bottom: Filament electron gun in operation

The position of the tungsten filament was varied from the outside to inside of the extraction electrode. Slightly larger electron currents were obtained with the filament inside the extraction electrode. It was also found that the largest electron currents occurred when there was no extraction voltage applied. The injection current subsequently increased as both the acceleration electrode voltage and the third electrode/Polywell voltage were increased. Fig 2.5 shows a close up of the filament gun, switched off and in operation.
This arrangement provided lower chamber pressures and greater electron injection currents than were previously obtained using the plasma gun. Consequently the potential wells the formed were deeper than previously observed. Nevertheless, the required high currents could not be achieved with the structured electron gun approach. Consequently, it was found that the required large electron currents could be achieved by using the metal spools of the Polywell as extractors of the electrons from the bare filaments.

Figure 2.6 shows a photograph of four teflon filament holders that were used as the electron gun source for the final experiments and placed the filaments significantly closer to magnetic field spools. The filaments pictured in Fig 2.6 were obtained from "Jaycar" brand 12 V, 50 W, quartz halogen bulbs by removing the quartz covering. The increased size of the magnetic spools of the Polywell as compared the previous small Polywell, along with the sharper edges of the rectangular cross section of the spool greatly increased the amount of current that could be extracted from the filaments. The divergence of the electron beam produced by the teflon filament holders was large without the presence of an applied magnetic field and a lot of the extracted current was collected by the metal spools of the Polywell. However, the magnetic field produced by the coils focuses the beam and allowed more current to enter the Polywell. This effect is discussed in detail in Chapter 4. The lifetime of the filaments when operating at their maximum output was approximately 2 hours of continuous use. For every pulse of the Polywell the filaments were only switched on for a period of 10 s and their total lifetime is practically useful.

2.3.3 Measuring the magnetic field

In order to measure the local magnetic field within the Polywell a very small magnetic field probe was constructed. The probe tip was approximately 2.5 mm by 2.5 mm in size, and was made of a coil of 100 turns of 0.1 mm diameter enameled copper wire. The magnetic field was determined by the induced emf in the probe by the changing magnetic field of the Polywell. A photograph of this probe is shown in

Figure 2.6: Teflon filament holders.
The diameter of this probe was also chosen to fit within the centre bore of the 3 mm Wilmad NMR tubes that are used in the construction of the capacitive probes, detailed in Chapter 3. Holders for capacitive probes of this size allowed magnetic field probe to be accurately held in place and moved from the centre of the device to the corner edge and face respectively, along the magnetic cusp lines. A detailed profile of the Polywell magnetic fields is given in Chapter 5.

### 2.4 Increased Current Polywell

A schematic diagram of the final Polywell setup is shown in Fig. 2.8, which consisted of six coils each with 25 turns. The coils were wound on spools, which had inner and outer diameters of 60 mm and 25 mm, respectively. They were joined together with square metal brackets such that the spools form the faces of a cube. A 7500 µF capacitor bank charged up to 400 V was used to pulse a current into the field coils, which reached a peak value of 1.5 kA. The six coils were connected in series and with the current flowing in the same direction. For this reason, the magnetic fields produced by each coil cancel in the centre of the device. This produced a magnetic well with the maximum field found in the regions surrounding the magnetic field coils.
Figure 2.8: Polywell schematic diagram: (a) Polywell magnetic field coil. (b) Teflon filament holder (only two of four are pictured). (c) Filament. (d) Electrical feedthrough. (e) SECP probe

The Polywell was mounted on an electrical feed-through, which also made an electrical connection with the spools. This enabled a bias voltage to be placed on the device. Teflon brackets were fixed to the four equatorial magnetic field coils. Each Teflon bracket held a 12V, 50W tungsten filament. The aluminium spools that held the magnetic field coils were pulsed with high voltage in order to extract the thermionic electrons emitted from the filaments. A maximum total electron current of 1.7A was extracted from the filaments with a 700 V maximum potential applied between the filaments and the spools. This was achieved with a 150\(\mu\)F capacitor discharged through a MOSFET (IXYS1N450 - ND). A capacitive probe was positioned in the Polywell along the axis of the upper coil. The probe tip could be moved from the coil centre to the device centre along the coil axis.
A photograph of the setup used for the results presented in Chapter 4 is shown in Fig 2.9. In the first experiment a single probe was moved along the axis of the upper magnetic field coil. Slots were cut through the spools of wire that held the magnetic field coils. This was done in order to reduce eddy currents that are induced in the metal frame due to the pulsed nature of the Polywell magnetic field. The magnetic field was not measured before the slots were cut into the frame so the exact reduction in the Polywell frame in unknown. However, the magnetic field of the Helmholtz pair, shown in Fig. 3.6, was measured before and after the slots were cut in the aluminium rings that the coils are attached too. The frame of the Helmholtz pair consisted of aluminium rings attached with aluminium brackets and the magnetic field coils very close to the frame. Before the introduction of the slots, the measured magnetic field was approximately 50% of the theoretically estimated central field of a Helmholtz pair. After the addition of slots comparable to those featured in the Polywell spools the magnetic field increased to approximately 95% of the theoretical value.
2.5 Adjustable coil size and spacing Polywell

2.5.1 Adjusting the coil spacing

In the work outlined in Chapter 5 of this thesis the effect of adjusting the size and spacing of the magnetic fields of the Polywell is examined. The three different coil spacing configurations are shown in Fig. 2.10. Adjusting these parameters was achieved through the use of a number of different stainless steel brackets, shown in Fig. 2.11, that altered the relative spacing of the magnetic field coils. All of the brackets used are of a similar hollow construction so that the edge cusp does not directly impact on the structure of the Polywell device.
The distance between the inner edges of a pair of oppositely facing magnetic field coils, for the closest spacing, was 65 mm. The subsequent larger spacings produced inner magnet distances of 85 mm and 105 mm. The brackets shown in Fig 2.11 were made with screw holes varying in 10 mm increments. The middle bracket shows two sets of hole spaced 5 mm apart. However, only the larger placement was used during the spacing experiment. The largest brackets were used to keep the spacing and intermagnet distance constant for further experiments with magnetic field coils of a larger radius.

Figure 2.11: Brackets used to change the spacing.

2.5.2 Adjusting the coil size

Figure 2.12: Left: Photograph of the Polywell with larger coils. Right: Face plate of magnetic coil has been removed showing how the larger coils were constructed, by using teflon spacers, on top of the same spools that supported the smaller coils.

The radius of the coil was increased for the largest coil spacing. As shown in Fig. 2.12, teflon spacing cylinders and larger aluminium plates were added to the original Polywell frame. The size of the larger coils was also chosen such that the ratios of the magnetic field between the face, edge and corner of the device are similar to those found with the smaller coils when located at the closest spacing. This has
allowed us to demonstrate the effect that scaling has on the potential well formation.

Plasma potential measurements were possible for the base pressure. However, an increase in background pressure resulted in arcing and prevented measurements. Consequently modifications were made to the spools which held the coils, shown in Fig. 2.13. Excessive metal regions inside the coils were reduced. The inner aluminium reel shown in Fig. 2.12 was completely removed and a thin stainless steel covering was placed over the teflon, which is also shown in Fig. 2.13.

The results from experimenting with these different coils spool showed how important the effects of magnetic fields intersecting with the magnetic field coil housing are.

![Figure 2.13: Left: Photograph of the Polywell with larger coils with the inner metal spools removed. Right: Close up photograph of the metal shields that were added to cover the teflon spacers.](image)

Table 2.1 outlines the major dimensions of the different field coils used.

<table>
<thead>
<tr>
<th>Coil Type</th>
<th>Frame Measure (mm)</th>
<th>Coil Measure (mm)</th>
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<td></td>
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<td>Outer Diameter</td>
</tr>
<tr>
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<td>60</td>
</tr>
<tr>
<td>Large Coil</td>
<td>25</td>
<td>93</td>
</tr>
<tr>
<td>Large Coil w/ Reduced Frame</td>
<td>45</td>
<td>93</td>
</tr>
</tbody>
</table>

Table 2.1: Table of coil dimensions.
2.5.3 Multiple Probe Arrangement

The second experiment used multiple probes in order to measure the plasma potential along the face, edge and corner cusps of the Polywell, and the centre. An adjustable teflon probe holder was constructed that could be used for multiple Polywell coil spacings. Fig. 2.14 shows the final setup, on the larger Polywell coils. As in the first experiment, similar tungsten filaments were used as an electron source. All of the radial probes were generally placed the same distance from the centre. The radial position of the probes was determined by the effect the magnetic field has on the collection area of the probes. This effect is explained in more detail in the next chapter.

Figure 2.14: Final arrangement using multiple capacitive probes; (a)-Face cusp probe (b)-Corner cusp probe (c)-Edge cusp probe (d)-Centre probe (e)-Teflon probe holder for face and centre cusp (f)-Teflon corner probe holder (g)-Teflon edge probe holder (h)-Corner and edge probe pitch adjustment screws (i)-Corner and edge translational position adjustment screws.

Figure 2.14 shows the setup containing multiple probes for the work presented in Chapter 5. The probe holder allowed multiple probes to be translated along the face corner and edge cusps of the device. Capacitive probes were placed at these positions for plasma potential measurements. The same holder was used to position the probe for magnetic fields characterisation.
2.6 Vacuum Chamber and Experimental Schematic

Figure 2.15 shows a schematic diagram of the experimental setup. The vacuum chamber used for the experiments was cylindrical, which was 480 mm in length and 360 mm in diameter. The vacuum system consisted of an Alcatel - 2012A rotary backing pump in conjunction with a Leybold Heraeus Diff 170 L oil diffusion pump. Three valves were used to isolate the oil diffusion pump and allow pumping with the rotary pump directly. The Pressure Gauge used was a Pfeiffer full range Cold-Cathode PKR 251. In the final Polywell experiment hydrogen gas was introduced with a MKS mass flow controller. A Bertan 205A - 05R DC high voltage power supply was used to charge a square high voltage pulse generator. Two pulse generators were used to time the triggering of the square pulse and the high current power supply for the magnetic field coils.

![Schematic diagram of experimental setup.](image)

2.7 Power Supplies

2.7.1 High Current Pulse Power Supply

A high current power supply was used to power the magnetic field coils. Two 7.5 mF capacitor banks connected in series, each consisted of five 1.5 mF capacitors connected in parallel. The maximum charging voltage was 450 V for each bank giving a maximum 900 V output. Protection diodes prevented the
reverse charging of the capacitor bank by an induced back emf. The discharge of the capacitors was achieved by using a Silicon Controlled Rectifier (SCR) in series with the magnetic field coils.

The charging power supply consisted of a high voltage transformer with 12 parallel output taps of 450 VAC, 6 parallel rectification circuits were used to charge each capacitor bank. Two relays controlled the charging and firing circuits. These relays also connected the charging power supply and disconnected the output and dump circuits. Which were made from the heating element of bar heaters.

The coil current is plotted in Fig. 2.16. The resulting magnetic field is approximately constant in the region of the 0.3 ms square pulse of electron input current.

![Graph showing Polywell Coil Current vs Time](image)

**Figure 2.16: Timing of Polywell magnetic field and Polywell Voltage.**

The maximum obtainable current was 1.7 kA in the 25 turn magnetic field coils. This equals 42.5 kATurns and a maximum face cusp field of approximately 1 T. The circuit diagram of the power supply is shown in Fig. 2.17.
2.7.2 Square High Voltage Pulse Generator

The capacitive probes which were used to measure plasma potential required a short pulse in order to capacitively couple to the plasma. The maximum output voltage of the power supply was determined by the high voltage capacitor which was rated to 3 kV. The square pulse was achieved by using four high voltage MOSFET’s connected in parallel capable of up to 3 A output current. The dump circuit was controlled by an electronically isolated solenoid that provided a crowbar connection to earth via a heating element from a radiant bar heater.

The output voltage was connected to the metal frame which held the magnetic field coils of the Polywell, via a high voltage feed through. The electron emission current was varied by controlling this voltage and the heating voltages of the four filaments placed at the centre of the equatorial face cusps,
which are shown in situ in Fig 2.9 and Fig 2.14. The square output is shown in Fig 2.16 along side the Polywell magnetic field coil current for comparison and in Fig 3.6 with the capacitively coupled probe voltage. Plasma potential measurements were taken during the square pulse. The circuit diagram for the square high voltage pulse generator is shown in Fig 2.18.

Figure 2.18: Circuit diagram of the square high voltage pulse generator.
Chapter 3

Capacitive Probe Diagnostic

3.1 Introduction

A number of probe based diagnostics have been used in Polywell experiments. Biased Langmuir probes\cite{54} have been used to measure the plasma potential in the Polywell. The analysis of the Langmuir probe current-voltage curves, which determines plasma potential in the non-neutral plasma, requires assumptions to be made about the electron energy distribution function (EEDF)\cite{54}. The bias voltage for the experiments planned in this thesis is up to 1 keV, and the plasma potential within the device is expected to approach this value. A probe driver is also required to sweep the voltage on the probe beyond the plasma potential in a microsecond time frame. This represents a significant technological challenge.

An emissive probe has been used to measure the plasma potential of an electron plasma\cite{81}, and could in principle be used to measure the plasma potential in the Polywell. However, the high filament temperature required reduces the lifetime of the probe. This requires a change of filament, resulting in a possible variation of probe characteristics. These limitations can be circumvented by using a capacitive probe.

A capacitive probe has been used previously to measure the plasma potential in a Polywell with an electron plasma\cite{38}. Similar SECP probes have been used in a non-equilibrium plasma quasineutral plasma from a "Q" machine\cite{82} and a thermalised electron only plasma in a Tokamak\cite{83}. However such a probe has not been characterised in a non-equilibrium electron only plasma such as that found in the Polywells studied in this thesis. Magnetised plasmas have also been explored using the SECP\cite{84} however the range on magnetic field has not reached the strengths of the Polywell describes in this thesis and the effect of the magnetic field has not been thoroughly characterised.

Since there has been no rigorous analysis of the perturbation of measured plasma potential with strong magnetic fields, or the effect of a non-equilibrium electron plasma on the probe behaviour, this
This chapter aims to characterise these effects on a capacitive probe. This is achieved by using a planar vacuum diode, as the physics of the planar vacuum diode is well understood[85]. In a planar vacuum diode the electron energy can be many keV and the pressure sufficiently low so that the electron mean free path is greater than the interelectrode distance[86]. Consequently, the maximum electron energy is equal to the applied potential difference between the electrodes[85], which is similar to a Polywell device operating with an electron plasma. A strong magnetic field is imposed by placing the vacuum diode in a Helmholtz pair. The results obtained from this setup should show the suitability of the capacitive probe for plasma potential measurements in the Polywell.

3.2 Capacitive probes

There are two main types of capacitive probes. The first type can be made of a metal disk and constructed into the wall of a plasma device[87]. These probes have no contact with the plasma, but produce a transient signal due to the formation of image charges with the plasma. This type of capacitive probe has been used to determine some plasma parameters on non-neutral electron plasmas[88, 83]. However, it cannot be used to determine the local plasma potential due to limitations in their construction. The other type of capacitive probe is the secondary emission capacitive probe (SECP)[84, 89].

The construction of the SECP is very similar to a traditional cylindrical Langmuir probe with an additional glass sheath surrounding it. The glass prevents any direct contact between the plasma and the probe tip. The SECP has been shown to measure the plasma potential in a similar way to a thermionic emissive probe operating in the limit of strong emission[89]. For electrons with energy between 100 eV and 2 keV, the secondary electron emission coefficient in pyrex glass[90] is \( \lambda > 1 \). A transient beam of electrons striking the glass will result in secondary electron emission by the glass surface, which causes the surface of the probe to reach the plasma potential. The metal tip of the probe capacitively couples to this voltage, thereby giving a direct measurement of the plasma potential.[91, 92]

The main limitation of the SECP is that it relies on the electrons of the plasma to cause sufficient secondary emission of electrons from the glass surface so that the surface of the probe can saturate to the plasma potential. If the electrons do not have sufficient energy or the electron current to the probe is too small there will be insufficient secondary emission and the probe will not saturate to the plasma potential. In this chapter the cutoff values of electron current and energy are determined for the SECPs used in this thesis.

Another limitation of emissive probes in general is perturbation of the plasma potential due to the probes emission. The high input impedance of the capacitive probe reduces the perturbation of the
plasma in comparison to an emissive probe operating at high filament temperatures in order to obtain the plasma potential[82]. This is due to a smaller emission current drawn from the plasma by the capacitive probe[91].

![SECP schematic diagram](image1)

Figure 3.1: SECP schematic diagram: (a) Probe electrode/tip. (b) Insulating material. (c) Central conducting wire. (d) Coaxial shield. (e) Pyrex glass tube. (f) Foil for calibration. (g) Follower circuit.

3.3 Capactive probe construction

The capacitive probe design was based on that of Wang[89]. The probe schematically shown in Fig. 3.1 consisted of a 2.9 mm wide coaxial cable inserted into a 3 mm bore Wilmad pyrex NMR tube. The tip of the probe was a cylinder 1.4 mm radius and 3 mm in length. The probe was connected to a follower circuit that consisted of an OPA627 high impedance op-amp. The voltage from the follower circuit was measured using a Rigol DS1204B Oscilloscope. The probe could be used without the follower circuit by directly connecting it to the oscilloscope. However, the frequency bandwidth of the probe became wider when the output of the probe was connected to the follower circuit. This resulted in a constant voltage measurement by the probe for the 300 µs pulse used in the calibration. A photograph of the capacitive probe is shown in Fig 3.2.

![Close up photograph of secondary electron capacitive probe (SECP)](image2)

Figure 3.2: Close up photograph of secondary electron capacitive probe (SECP); (a)-Probe Tip (b)-Teflon disk (c)-Coaxial cable (outer shield visible) (d)-Pyrex NMR tube.
3.4 Follower circuit

A series of seven follower circuits were constructed for the final experiment with multiple probes. A diagram of the circuit is shown in Fig. 3.3. The system of the follower circuit and oscilloscope provides a capacitance to earth that is additional to the capacitance of the probe. This forms a capacitive divider, and the voltage measured by the inner electrode $V_1$ is less than the voltage on the outside of the glass $V_2$, shown in Fig. 3.1. The ratio of $\frac{V_1}{V_2}$ was determined by covering the probe with a foil electrode and measuring the probe and foil voltages.

The voltage measured with the probe was multiplied by this factor (150) to obtain the floating potential. The follower circuit used for a single probe in this chapter and in the first experiment had slightly different components, which increased this factor to 5950. As a result, the signal-to-noise ratio observed with the final follower circuit was less than that of the original circuit. Typical signal to noise ratios obtained with the first follower circuit were 20 and increased to 100 with the second follower circuit. The measured voltages $V_1$ and $V_2$ correspond to the foil and probe voltages, respectively. These measurements are presented for both follower circuits in Fig. 3.4.

![Figure 3.3: Circuit diagram of probe follower circuit](image-url)
3.5 The Vacuum Diode

Validation of the use of the SECP in the Polywell was achieved by measuring the plasma potential in a planar vacuum diode, shown schematically in Fig. 3.5. The diode plate consisted of a $50 \times 50 \text{ mm}^2$ parallel anode and cathode plates separated by 26 mm. A 12 V 100 W tungsten filament was inserted through a hole in the centre of the cathode plate. The anode voltage was pulsed from 100–4000 V, resulting in a beam of electrons with energy equal to that of the anode potential.

![Figure 3.5: Planar vacuum diode schematic diagram: a; Helmholtz coils. b; Anode. c; Cathode. d; Filament e; Capacitive probe. f; Translational probe holder.](image)

A 100 mm diameter Helmholtz pair, coaxially positioned with the central axis of the diode, was used to measure the response of the SECP to an applied axial magnetic field. The magnetic field generated...
by the Helmholtz pair in the region the diode was placed was measured using the magnetic field probe described in Chapter 2. A current range of 240–2400 A produced a respective magnetic field range of 0.035–0.35 T at the centre point of the Helmholtz pair axis and along the interelectrode distance, with a 1% variation in magnetic field. However, the field varied at most by 9% along the paraxial line at the edge of the diode (as defined by the edges of the metal plates that made up the diode) and by 5% radially from the central axis to the edge of the diode. The capacitive probe was inserted into the top of the diode and held vertically by a movable arm. The centre of the probe tip was aligned with the central axis of the diode. The probe was moved along the central axis of the diode by using a micrometer with 50 µm resolution. A photograph of this setup is shown in Fig 3.6. The background pressure of the vacuum diode was 0.02 mTorr.

Figure 3.6: Photograph of vacuum diode setup.

3.6 Use of the SECP in the vacuum diode

3.6.1 Diode plasma potential

Presented in Fig. 3.7 is the measured plasma potential, 2 mm from the anode plate of the vacuum diode as a function of time and for a range of filament temperatures. The potentials were corrected for the capacitive coupling between the probe and the diode plates in the absence of thermionic emission from the filaments. Such a correction is necessary as without it the measured signal overestimates the plasma potential, as the signal due to the electric field generated by the plates and the plasma are added together when the plasma is present. This was done by subtracting the probe signal obtained with no emission
from the probe signal obtained when the filament was heated. This method has previously been applied to emissive probes[93].

![Graph showing plasma potential and anode plate voltage](image)

Figure 3.7: The plasma potential measured at 2mm from the anode by the SECP as the filament voltage was varied by increments of 0.5V to a maximum of 12V. The emission currents for the various filament temperatures are also indicated.

The filament temperatures were controlled by applying 2 - 12 V across the filaments in 0.5 V increments. However, the emission current reached a maximum value of 10 mA at and above 8.5 V, which is indicative of space charge limited flow. As such, a space charge limited 1D diode model was used for a comparison with the spatial potential profile along the diode axis[85]. Also note from Fig. 3.7 that a saturation value of the potential was obtained for a diode emission current of 7.5 mA, which established a lower current limit for measuring the plasma potential with 0.8 keV energy electrons. There was no observable signal at diode currents less than 0.1 mA.

### 3.6.2 Vacuum diode with a magnetic field

The measurements of the plasma potential along the diode axis are shown in Fig. 3.8. Note the low value of the potential compared to the expected value from the space charge limited 1D model (shown by the...
solid line) for anode potentials below 500 V. As was shown in Fig. 3.7, the electron energy and current must reach a threshold value in order for the probe potential to saturate to the true plasma potential. Evidently from Fig. 3.8, the electron emission current and energy must be greater than 3.0 mA and 500 eV, respectively. By qualitative inspection of Fig 3.7 it can be seen that the results of the probe were consistent with the theoretical estimates made by the 1-D model when the diode current is greater than 3.0 mA, which corresponds to a diode voltage of 500 V.

The effect of applying an axial magnetic field to the diode is also shown in Fig. 3.8. There was no significant difference in the measured plasma potential with an applied magnetic field of 0.035 T, except at anode voltages less than 500 V. At 500 eV the Larmor radius of the electrons is smaller than the probe diameter which causes the collection area of the probe to become larger and the plasma potential to be underestimated. This effect has been documented with metal tipped Langmuir probes and is likely to occur with the capacitive probe also[85].

The magnetic field was also applied at a strength of 0.35 T, with corresponding Larmor radii less than the probe diameter for all diode voltages. This resulted in an increase in the magnitude of the underestimation of the actual plasma potential with decreasing anode voltage. This is possibly due to a larger Larmor radius for electrons and a reduction of the effective collection area of the probe at the higher voltages. Arcing prevented measurements of plasma potential in the presence of the 0.35 T magnetic field when the probe was 15 mm away from the filament. There was arcing at greater distances for anode potentials greater than 1000 V. Consequently, there are fewer data points for the 0.35 T results than obtained at 0.035 T and with no magnetic field.

Figure 3.8 shows a reduction in the difference between the measured plasma potentials with and
Figure 3.9: The plasma potential measured in the diode with an applied magnetic field, which varied from 0.017 T to 0.35 T. The Larmor radii of the electrons at the probe position is also indicated. The Larmor radius is infinite with no applied magnetic field and a minimum of 0.38 mm at 0.35 T. The anode voltage was 1 kV and the diode current 7.5 mA

without an applied 0.35 T magnetic field for increasing diode voltages and currents. This is possibly due to the increase in electron current density striking the probe rather than the increasing Larmor radius. To test this implication, the diode voltage and current were held constant as the magnetic field was increased, as shown in Fig. 3.9. The plasma potential was measured 2 mm from the anode with increasing magnetic field strength applied to the diode. At the anode the plasma potential must reach the potential of the anode, as this is a boundary condition for the planar diode. The close proximity of the probe to the anode ensured that the measured potential would be close to the anode voltage. Thus, very little deviation of the plasma potential due to the effect of the magnetic field was expected at this position. It is shown in Fig. 3.9 that there was an underestimation of the plasma potential at this position for electron Larmor radii less than 3 mm, which is also the probe diameter. However, the lower limit of the measured potential occurs at a Larmor radius of <0.4 mm. Further reduction in the Larmor radius does not further reduce the measured potential.
3.7 Conclusions

These results indicate the suitability of the SECP for plasma potential measurements in a high energy non-neutral electron plasma, such as that in the Polywell. The probe can be used in the presence of a magnetic field, however consideration must be given when the strength of the magnetic field causes the Larmor radius of the plasma electrons to become less than the probe diameter. In this case the plasma potential of the probe will be an underestimate of the true plasma potential by up to 50%. Since this effect is limited, a capacitive probe can be placed in a high magnetic field region of the Polywell such that the Larmor radius of the electrons is $< 0.4 \text{ mm}$ and the factor of underestimation (which was approximately 2) will remain constant. By using this method, the plasma potential in the strong field region of the Polywell can be determined. The plasma potential can still be determined in a moderate magnetic field region corresponding to a Larmor radius $0.4 \text{ mm} < r_L < 3 \text{ mm}$. However, as the magnitude of underestimation is changing in this region, the uncertainty of the plasma potential is greater.
Chapter 4

Increased Current Polywell

4.1 Introduction

The increased current Polywell described in Chapter 2 is used here to test the effect on potential well formation for a range of coil currents and electron injection currents. The planned range of both these currents, and the electron energy, is considerably larger than has been previously examined with a small Polywell[54, 42]. By increasing the parameter space of the experiment, a greater understanding can be achieved on the relationship between these device parameters and well formation. Another main objective is to determine if the potential well depth can approach the injected electron energy. This is the theoretical maximum well depth, as at this depth all of the kinetic energy of the electrons will have been transferred into the potential energy of the well. Previous experiments with small Polywells have only demonstrated potential wells that are a small fraction of the injected electron energy.

The potential well formation will be observed through plasma potential measurements using the capacitive probe described in the previous chapter. Measurements will be taken at the centre of the device as well as at two radial locations, with a single capacitive probe which is translated along the central axis of a coil. The aim of taking radial potential measurements is to investigate the spatial profile of the potential wells in order to compare their features at different electron energies and currents.

We aim to determine an equation for the confinement time of electrons based on the electron energy and confining magnetic field strength. In order to achieve this an analytical model based on the measured depth of the potential well will be developed in order to estimate the confinement time of electrons in the device. A single particle simulation of electrons within the device will be compared to the experimental confinement time estimations.
4.2 Plasma potential measurements

4.2.1 Oscilloscope traces of plasma potential

The plasma potential measured at the centre of the Polywell device for increasing magnetic field strength is shown in Fig 4.1. The measured potential was equal to the potential bias applied to the spools of the Polywell in the absence of applied coil current, as would be expected in the interior of a hollow conductor. The low density of the unconfined electron beam was insufficient to greatly perturb this vacuum potential. The capacitive probe was able to measure up to 150 V plasma potential. This differs from the vacuum diode experiment where measurements were not possible at this voltage. This is likely due to the increased electron current available with this setup.

Figure 4.1: Plasma potential at the centre of the Polywell for increasing magnetic field coil currents of 0 A, 380 A, 750 A, 1150 A and 1560 A for (a) 150 V and (b) 700 V Polywell bias voltage
There was a reduction in the measured potential upon the application of current to the field coils, which is shown in Fig. 4.1 for bias voltages of 150 V and 700 V. These voltages correspond to electron energies of 150 eV and 700 eV respectively, as the bias voltage applied to the Polywell accelerated and extracted the electrons from the filaments. The positioning of the probe tip at the centre of the magnetic well, and an electron current much larger than the threshold minimum, ensured that the true plasma potential was measured (as explained in Chapter 3). This reduction in measured potential is an indication of the formation of a potential well, as such a reduction could only be caused by an increase in electron density. The plasma potential at the centre was lower for increasing magnetic field strength, for all bias voltages. The magnitude of this plasma potential was nearly the full 150 V bias voltage, while at 700 V the magnitude only reached approximately half the bias voltage. The implications of this are discussed in detail in section 4.4.

The effect of the orientation of the probe relative to the magnetic field could not be determined in the vacuum diode due to the geometry of the setup. However, this was possible in the Polywell and there was no observable change in the measured plasma potential due to the probes orientation.

4.2.2 Radial potential measurements

Plasma potential measurements at 0 mm, 10 mm, and 20 mm from the centre along the axis of a coil are presented in Fig. 4.2. There is a minimum in the plasma potential at the centre of the device, which indicates the formation of a potential well. The concept of a potential well was introduced in section 1.6. The errors depicted in Fig 4.2 and Fig 4.3 are due to the noise in the voltage output by the capacitive probe shown in Fig 4.1. The upper and lower limits of the signal shown in Fig 4.1 correspond to the upper and lower error bars of the measured plasma potential. Other sources of error such as the uncertainty in the measured voltage of the oscilloscope were negligible compared to the noise in the signal. The lower error bars in the measured plasma potential at 20 mm are larger than the other error bars. This is due to the plasma potential being underestimated by up to a factor of 2 in the presence of a strong magnetic field, as shown in Chapter 3.
The electron Larmor radius at 10 mm was greater than the probe diameter, resulting in a true measure of plasma potential at this position. However, the Larmor radius was smaller than the probe diameter at the 20 mm position. Consequently, as was shown in the previous chapter, the measured plasma potential at this point would have been lower than the true plasma potential causing a greater uncertainty. Also note that the distance from the centre of the device to the inner edge of a spool was 32.5 mm not 20 mm, thus the full spatial extent of the potential well is not shown. It is expected that the plasma potential approached the bias voltage at the coil boundary.

The plasma potential measurements shown in Fig. 4.3 were obtained by varying the electron emission current while keeping the bias voltage on the Polywell constant. Larger electron injection currents produced correspondingly deeper potential wells. The effect of varying the emission current was considerably more pronounced than the effect of varying the magnetic field strength.
Figure 4.3: Radial profiles of plasma potential as a function of electron emission current, showing the change in the potential well, for a Polywell bias voltage of 250 V

4.2.3 Summary of results

There was a more pronounced change in the potential well depth when the injection current was increased than when the magnetic field was increased. The relationship between the depth of the potential well and the injected electron current and magnetic field strength is summarised in Fig. 4.4. The errors depicted in Fig 4.4 and Fig 4.5 are due to the uncertainty in the measured plasma potential. As the potential well depth was determined by subtracting the measured plasma potential in the centre of the device in the presence of a magnetic field from the case where no field was applied, the uncertainty is greater than that in Fig 4.2 and Fig 4.3 as the uncertainty of both plasma potential measurements is additive.

A linear dependence of the potential well depth on emission current has been shown in previous work[54] for a Polywell of similar size and a bias voltage similar to the lowest voltage described here. However, the emission current range was 1.5 - 5.5mA for 100 V bias on the Polywell. Here we have extended this range to 100 - 360 mA at 250 V, and have shown in Fig. 4.4 that the linearity also applies to this higher current range. In addition, the higher emission currents have enabled larger potential well depths to be obtained than in a previous experiment with a similar small Polywell[54]. That is, a maximum potential well depth of 135 V for a bias voltage of 150 V and emission current of 150 mA in this experiment, compared to 35 V with a bias of 122 V and a current of 5.4 mA.
It was also suggested[54] that there is a linear dependence of potential well depth on the magnetic field strength at the centre of the coil faces. However, this was deduced from a magnetic field range of 0.016 - 0.026 T for a bias voltage of 100 V. Here we present a non-linear dependence, as shown in Fig. 4.5, with coil currents to a maximum of 1500 A, which corresponds to a magnetic field of ~0.5 T at the centre of the coil faces, for bias voltages of 150, 250, 420 and 700 V. In the work presented here, there was a sharp increase in the potential well depth as it varied from 0V-106 V as the Polywell magnetic field was increased from 0 - 0.13T. However, as the magnetic field was increased further to 0.13-0.5 T, the potential well depth increased at a much slower rate from 106 - 135V, which is consistent with previous work.

In the high magnetic field region the potential well depth appears to be linear with coil current. However, the gradient of this linear relationship increases with increasing bias voltage or electron energy. The formation of a potential well has the effect of reducing the number of emitted electrons that arrive within the Polywell due to electrostatic shielding[38]. This has been experimentally confirmed in a larger Polywell[38] where only 10% of the emitted electrons entered the device once the potential well was established. This explains the non-linear behaviour observed in potential well depth and also explains why the non-linearity is more apparent at the lower energies. At electron energies of 150 V, the confinement of electrons at high magnetic fields was sufficient to form a potential well depth which was close to the energy of the electrons. This was compared to well depths achieved at 700 V which was only half the
electron energy. These combined observations indicated that electrostatic shielding had more effect on the potential well depth at lower electron energies, as there was greater non-linearity in the relationship between potential well depth and magnetic field strength at 150 V than 700 V.

![Figure 4.5](4.5.png)

Figure 4.5: Potential well depth at the centre of the Polywell for increasing magnetic field coil currents of 0 A, 380 A, 750 A, 1150 A and 1560 A. A range of Polywell bias and emission currents are listed in the legend.

The limiting case of this behaviour is approached by the 150 V results. The theoretical limit of the potential well is equal to the electron injection energy. It would be physically impossible for the potential well to exceed the electron energy as additional electrons would not have sufficient energy to enter the Polywell once the electrostatic potential energy produced by the well was equal to their kinetic energy. This is an example of space charge limited flow.
4.3 Electron Injection

In the absence of a magnetic field, a large fraction of the emission electrons are collected by the metal spools of the coils. However, there are two competing effects that must be included in the interpretation of the measurements on the potential well formation and electron confinement time when the magnetic field is introduced. Firstly, there is an increase in the electron current entering the device with increasing magnetic field since the electrons that were previously collected by the metal spools are guided into the interior of the device. Secondly, an increasing fraction of electrons are repelled away from the outside of the device, with increasing magnetic field, due to magnetic mirror reflection.

In order to test the effect the magnetic fields have on the injection current, the capacitive probe was replaced with two intersecting metal plates 20 mm in diameter, biased at the same voltage as the Polywell. The relatively large surface area of the plates resulted in the collection of electrons that entered the device. Presented in Fig. 4.6 is the measured dependence of the electron current collected by the plate on the current in the coils. Note that although there is an increase in the current entering the device with the introduction of a magnetic field, there is a reduction of the collected current with a further increase in the current of the coils. Nevertheless, there was an increase in the potential well depth with increasing coil current, as shown in Fig. 4.5.

![Figure 4.6: Current collected by a central plate for increasing magnetic field coil currents of 0 A, 380 A, 750 A, 1150 A and 1560 A. The emission current from the filaments was kept constant at 45mA for □ 150 V and 95mA for □ 250 V.](image)
4.4 Estimations of confinement time

4.4.1 Analytical Model

Previous work has analytically estimated the confinement time of electrons within the Polywell using the measured plasma potential\([38]\), and a similar approach is taken in this experiment. We assume that the electron cloud is spherical with a radius \(R\), which is equal to the outer coil radius (30 mm), with an additional 5 mm for the brackets holding the coils. The charge distribution is also assumed to be of uniform density \(\rho\). The electrostatic potential that is formed by such a charge distribution is \(V(r)\), where \(r < R\), is given by Equation 4.1\([94]\).

\[
V(r) = \frac{\rho}{6\epsilon_0} \left( R^2 - r^2 \right) + \frac{\rho R^2}{3\epsilon_0}
\]  \tag{4.1}

When no magnetic field is present, electrons will transit the device in time \(t_T\).

\[
t_T = \frac{2R}{\sqrt{\frac{2\mathcal{E}}{m_e}}}
\]  \tag{4.2}

The density due to unconfined electrons \(\rho_u\) can be obtained from the electron emission current \(I_e\) and Polywell volume, as follows;

\[
\rho_u = \frac{1}{10} \frac{3I_e t_T}{4\pi R^3}
\]  \tag{4.3}

Note that the factor of ten included in the denominator in Equation 4.3 comes from previous observations that only 10\% of the emitted electrons enter the Polywell once the potential well has been established\([38]\). The density \(\rho_c\) that is required to form the observed potential well depth \(V_d\) was obtained from Equation 4.1, where \(r = R\);

\[
V_d = V(0) - V(R) = \frac{\rho_c R^2}{6\epsilon_0}
\]  \tag{4.4}

\[
\rho_c = \frac{3V_d\epsilon_0}{R^2}
\]  \tag{4.5}

The confinement time \(t_c\) is determined by multiplying the transit time by the ratio of unconfined and confined densities. The predicted number density of electrons \(n_e\) varied from approximately \(3 \times 10^7\) \(\text{cm}^{-3}\) - \(9 \times 10^7\) \(\text{cm}^{-3}\) as the Polywell voltage varied from 150 - 700 V.
Figure 4.7: Estimates of the confinement time of electrons within the Polywell device for a range of Polywell parameters. ○ - Particle orbit theory simulation, □ - Experimental model, △ - Experimental model with changing electron injection. The dashed line shows the time it takes for an electron to cross the device without any confinement.

$$t_c = \frac{\rho_c}{\rho_u} t_T$$ (4.6)

From the above analysis it can be seen that the confinement time is proportional to the potential well depth. Any change in the confinement time produces a corresponding increase in density and thus potential well depth. The estimated confinement times are presented in Fig. 4.7.

### 4.4.2 Single Particle Simulation

Particle orbit theory was also used to estimate the confinement times of electrons in this device. The model that was used has been previously described in detail[67]. In this model the trajectories of 420 electrons, of energy equal to the bias voltage, are calculated. Once an electron reaches the boundary of the Polywell device it is considered lost. Fig. 4.8 shows the proportion of electrons that remain in the Polywell as a function of time. Aside from a small population of electrons that are indefinitely trapped within the timescale of the simulation, the proportion of electrons remaining in the Polywell follows an exponential relationship.

As in previous work[67] an exponential of the following form was fitted to the data using the curve
fitting tool box in MATLAB. Here the proportion of electrons that remain within the Polywell $N(t)$ decays exponentially with a time constant that depends on the electron energy or Polywell bias voltage $V_p$ (eV), the Polywell radius $R$, the total current in the Polywell coils ($I_p$) and a fitted parameter $b$.

$$N(t) = \exp \left(-b \frac{V_p^{\frac{3}{4}}}{\sqrt{I_p R^2}} t\right)$$

(4.7)

The constant $b$ varied for the different Polywell parameters used in the simulation. The mean of $b$ was $9.3 \times 10^4$ with a standard deviation of $6 \times 10^5$. Previously[67] the constant $b$ was determined to be $2.0 \times 10^6$ with a standard deviation of $6 \times 10^5$.

The difference between these is likely due to the larger spacing of coils in this experiment than the coil spacing used in the previous[67] simulation. In this simulation the magnetic fields of the Polywell are approximated by a single coil of wire located at the centre of the actual coils which contained multiple turns. Due to the small radius of this Polywell and the larger coils, the distance from the centre of the coils to the inner edge of the Polywell was $\frac{4}{5}$ of the Polywell radius. This is much larger than the original[67] simulation where the coils were placed so that this distance was $\frac{1}{4}$ of the Polywell radius. Although the value of the constant is different, the uncertainty of $b$ is similar with both coil spacings.

Equation 4.8 shows the confinement time $t_c$, which is the reciprocal of the time constant of the exponential decay in Equation (4.7).

$$t_c = 1 \times 10^{-5} \frac{\sqrt{I_p R^2}}{V_p^{\frac{3}{4}}}$$

(4.8)

Both estimates of confinement time are shown in Fig. 4.7. The results are of the same order of magnitude. However, there is a larger deviation between the results as the strength of the magnetic fields increased, for all electron energies. In Fig 4.7 the errors in the confinement time estimated from the analytical model are due to the uncertainty in the measured plasma potential, while the errors in the confinement time estimations from the single particle model are due to the uncertainty of the exponential fit. The confinement times estimated by the experimental model change only by a small amount over the range of magnetic field strengths, while the particle orbit simulation predicts that the magnetic field has a much greater effect on the confinement time. This trend is most apparent when the electron energy is lowest.

One likely reason for this disparity is the same reason that non-linearity was observed in potential well depth with increasing magnetic field strength, as shown in Fig. 4.5. As the potential well forms, less of the emission current enters the Polywell and this amount is likely to change depending on the depth
Figure 4.8: The crosses show the proportion of electrons still within the Polywell as a function of time within the particle orbit simulation. The results of the simulation are fitted with an exponential decay that is shown as the solid line. Each line represents different Polywell parameters of varying voltage and currents of; (a) 150 V, 38 kATurns (b) 150 V, 9.5 kATurns (c) 700 V, 38 kATurns, (d) 700 V, 9.5 kATurns.

of the well. At lower electron energies the depth of the potential well approaches the electron energy, thus the screening of injected electrons would be greater than at higher energies where the potential well depth was approximately half of the electron energy. However, the experimental estimate of confinement time assumed that 10% of the emission current enters the Polywell regardless of the potential well depth.

As shown in Fig. 4.6, the current that entered the interior of the Polywell (called the injection current) decreased with increasing current in the coils, although the emission current from the filament remained constant.

The collecting plate represents a perturbation to the electric field in the device, and consequently the measured injection current will differ from that in the absence of the collection plate. However, the relative changes to the injection current are assumed to be reliable since the perturbation to the electric field that results in electron emission from the filament are negligible. It was found that the injection current changes approximately by a factor of 2 from the minimum to maximum coil currents. This factor was applied to the confinement time estimations from the experimental model, and the results are shown in Fig. 4.7. With the correction factor applied, the results showed a closer relationship to the simulated confinement times. However, the results still show a lower predicted confinement time than the simulations. This may be due to the perturbation of electric fields inside the device by the formation of a potential well, resulting in the repulsion of electrons from within the device. Such a perturbation is not considered by the simulation.
4.4.3 Experimental Confinement Time Equation

This section details the development of an equation for the confinement time of electrons within the device, based on the experimental results. The following equation was obtained by substituting Equation 4.3 and Equation 4.5 into Equation 4.6.

\[ t_c = \frac{40V_d\varepsilon_0\pi R}{I_e} \]  

(4.9)

This equation will be expressed in terms of Polywell bias voltage \( V_p \) and Polywell coil current \( I_p \), in order to compare with Equation 4.8. The emission current \( I_e \) increased as the Polywell bias voltage increased, as shown in Fig. 4.5. The effective emission current also decreased as the magnetic field of the Polywell increased, due to magnetic reflections, as shown in Fig. 4.6. These relationships were fitted with a power law, resulting in the following equation;

\[ I_e = 9.0 \times 10^{-4}V_p^{1.5}I_p^{-0.3} \]  

(4.10)

Similarly, the potential well depth \( V_d \) increased, as both the Polywell bias \( V_p \) and Polywell coil current \( I_p \) increased, as shown in Fig 4.5. A power law was fitted to the data, with the following equation being a result of averaging the results of the individual data sets.

\[ V_d = 1.2 \times V_p^{0.5}I_p^{0.2} \]  

(4.11)

Substituting Equation 4.10 and Equation 4.11 into Equation 4.9 yields an experimentally obtained expression for the confinement time of electrons within the Polywell device. This equation is in terms of the physically meaningful parameters of Polywell radius, bias and coil current.

\[ t_c = 1.5 \times 10^{-6}\frac{R\sqrt{I_p}}{V_p} \]  

(4.12)

This equation for confinement time varies from the one derived from particle orbit simulations given by Equation 4.8. The main difference is that the confinement time scales linearly with the device radius and is also inversely proportional to the Polywell voltage. Both equations of confinement time suggest a square root dependence on the coil current.
4.5 Conclusions

A Capacitive probe was used to measure the plasma potential in a Polywell device and potential wells were observed to have formed within the Polywell. The filament emission current and thus the electron injection current into the Polywell were varied. The effect on the depth of the potential well was observed. The injected electrons were extracted from the filaments with a positive bias placed on the Polywell. The magnitude of the Polywell bias and thus the electron energy was also varied. The capacitive probe was moved axially from the centre of the device to the edge, and consequently the spatial formation of the potential well was observed.

The potential well depth increased linearly as the electron emission current was increased. However, a non-linear relationship was observed for an increasing magnetic field strength. The non-linearity was greatest when the bias voltage or electron energy was lowest. This indicated that as the potential well formed, external electrons were electrostatically repelled from the device. Since the emission current increased with bias voltage, the effect of bias voltage alone on potential well formation could not be determined. A decoupling of these parameters was achieved in the experiment detailed in Chapter 5. It was also observed that increasing the filament emission current had a substantially greater effect on the potential well depth than increasing the magnetic field strength of the Polywell.

The confinement time of electrons within the device was estimated by a simple experimental model and a particle orbit theory simulation. The estimated confinement times were of the same order of magnitude, but indicated a different pattern of behaviour. This difference in behaviour and the non-linearity observed with increasing magnetic field strength is thought to be due to the number of emitted electrons entering the Polywell decreasing as the potential well developed. It was also found that increasing the magnetic field strength of the Polywell can cause a focusing of the emitted electrons and an increase to the injected electron current. However, mirror reflections of emitted electrons also increased with increasing magnetic field, limiting the effect of electron focusing on injection current.

This work extends previous work with small Polywell devices[42, 54] and has shown that the potential well depth can approach the electron energy, which has only been previously shown for a much larger Polywell[38]. Estimations of confinement time based on experimental results were made for the first time with a small Polywell and were shown to be consistent with estimations of confinement time from particle orbit simulations.
Chapter 5

Adjustable coil size and spacing Polywell

5.1 Introduction

In this chapter, results are presented that show the dependence of the potential well formation on coil size, spacing, and background gas pressure. An improvement in the cleanliness of the chamber (by baking, for example) resulted in greater accuracy and consistency of results, specifically the electron emission current. The effects of magnetic field strength and electron emission current on potential well formation are also presented, and are fully decoupled unlike the previous experiment.

The main focus of the experiment was to observe the effect of changing coil radius and spacing between coils on the potential well formation, which also allowed predictions to be made on potential well depth increases with device size. Also, due to the improved vacuum performance of the second experiment, with an order of magnitude lower base pressure than the experiment described in Chapter 4, more accurate readings of the electron emission currents were obtained, producing generally lower measurements than those from the first experiment. This indicated that outgassing had a significant effect on the emission current. Due to this improvement, the effect of gas pressure on the formation of potential wells was able to be examined. This experiment produced radial potential measurements, which were taken along the three magnetic cusp axes of the Polywell device, corresponding to the centre of the edge, corner and face. These radial probes allowed for the symmetry of the potential well to be examined.

This experiment attempts to answer various questions that are useful in determining if the Polywell is capable of fusion. Mainly to see how improvements can increase the electron trapping capability of the device, and use the relationships found to predict the necessary scaling needed for fusion energies. As such, the relative magnetic field strengths in the different cusps were examined for their potential to trap electrons. Comparisons in coil size and spacing can give us an idea of how increasing the size of the Polywell could improve its performance. Considering the need for fuel in the future, ions would
need to be introduced into the system. It was found that the easiest way of doing this was analysing the effects of adding a background gas and examining the effect of gas pressure on potential well formation. The motivation for characterising the symmetry of the potential well comes from the understanding that more symmetrical potential wells are thought to improve ion focussing and ion trapping. Additionally, an incidental result found by changing the shape of the spool which held the coils has implications for future experimental setup and possible improvements in coil design to maximise the potential well depth.

5.2 Magnetic field characterization

The magnetic fields were characterized for the four coil spacing and size combinations used throughout the experiment. The combinations included the spacing and coil size used in the first experiment, the same coil size with two larger spacings, and then larger coils placed at the largest spacing of the smaller coils. The magnetic field was measured along three lines, taken from the centre directed towards three different points, which we have called the face, the edge and the corner. These points correspond to the inner spatial cube formed by the coils, with the face position being located at the centre of a coil. The edge position was taken at the middle of an edge, and the corner position taken at a vertex. The maximum face field was located inside a coil. These lines follow the three magnetic cusp axes, and the measurements extended outside the device. The positions of the magnetic field probe correspond to the location of the capacitive probes depicted in Fig 2.14.

![Figure 5.1: Magnetic field strengths along the three types of cusps of the different magnetic field coil arrangements, with the maximum coil current of 41 kATurns](image)

As the spacing of the coils was increased, it was found that the field strength along the face cusp increased and the field strength along the edge and corner cusps decreased. Also, as the spacings increased, the peaks of the magnetic field were shown to be more spread out. This effect was more apparent for the
measurements taken at the edge and corner cusps. The results are shown in Fig. 5.1.

The larger sized coils were used to test the effect of scaling on potential well formation. For these coils the magnetic field at the face of the device was found to have decreased while the field at the edge and corners had increased. The difference between the strongest and weakest fields in the three different cusps is similar to that observed with the configuration using the smaller coils at the closest spacing. In order to determine the effect of scaling on potential well formation the results from these two magnetic field configurations are compared in the section 5.8.

5.3 Central plasma potential for changing magnetic field coil strength and electron emission parameters

5.3.1 Changing coil spacing

Coils with average radius of 24 mm were used in three different spacings in order to test the effect of coil spacing on the plasma potential at the centre of the potential well. The distance between a pair of coils began at 65 mm and was then increased to 85 mm and 105 mm.

![Figure 5.2: Central plasma potential for the three coil spacings for a range of coil and emission currents with a 200 eV electron energy, listed in legend.](image)

Fig. 5.2 shows the central plasma potential for three electron emission currents as the coil current was also adjusted. Increasing the electron emission current caused deeper potential wells. However, the effect of increasing either the electron emission current or the coil current is nonlinear with diminishing returns on the potential well depth achieved. Of the three spacings, the deepest potential wells were found at the closest coil spacing. There was also less change in the potential well depth as a function of electron emission current as the coil spacing was increased. While the potential well depth is greatest for the higher emission currents at the smallest spacing, the potential well depth is greatest for the lowest
emission current at the largest spacing.

It is thought that the decrease in plasma potential as the coil current was increased was due to an increasing number of trapped electrons. However, it is possible that some of the measured drop in plasma potential is due to the electron beams formed by the filaments. These beams would have been focused by the magnetic field, thereby increasing electron density and decreasing plasma potential. Since the larger coil spacings are predicted to have poorer electron trapping capability, the fact that the emission current has less of an effect at these spacings also suggests that these potential drops may have been partially due to focused electron beams rather than trapped electrons.

The errors depicted in the plasma potential in Fig 5.2 and all further figures in this chapter are due to the noise in the voltage output by the capacitive probe, as was discussed in Chapter 4. Other sources of error such as the uncertainty in the measured voltage of the oscilloscope were negligible compared to the noise in the signal. This uncertainty is noticeably smaller than that presented in Chapter 4. This was due to the reduced signal to noise ratio provided by the redesigned follower circuit described in Chapter 2.

### 5.3.2 Changing coil size

Larger magnetic field coils with an average radius of 38.75 mm were used to test the effect of scaling the device size on the central plasma potential. Two types of spools were used for these larger coils. Initially the larger coils were placed over the same frame that held the smaller coils used in the previous spacing test. This caused shallower wells, which were not expected. It was suspected that the increased metallic areas may have been negatively affecting the potential well depth, so the spools were modified to remove most of the extra metallic surfaces. This was found to have a large effect on the depth of the potential well. The central plasma potentials for both spools containing the larger coils were tested with three electron emission currents and increasing coil currents. These are shown in Fig 5.3.

The relationship between the central plasma potential and the electron emission current with the applied coil current was much the same as was observed with the smaller coils. Much deeper potential wells were observed when the spools with reduced metal surfaces were used. This indicated the importance of designing coil frames that are conformal to the magnetic field. The reduced metal spools also produced a larger spread in the measured plasma potentials as the electron emission current was varied. This was similar to the effect found when the spacing was decreased for the smaller coils. However, unlike what was found in the comparison of the smaller coils, the plasma potential is considerably lower for all electron emission currents with the reduced metal spool.
5.3.3 Higher electron energies

Higher electron emission energies of 400 V and 800 V were used across all previously outlined coil size and spacing configurations to see how these higher energies would affect electron trapping in the device. The central plasma potentials obtained for the coil spacing tests, for voltages of 400 V and 800 V, are shown in Fig 5.4 and Fig 5.5 respectively. The plasma potential was measured over the same range of electron emission currents that were previously used.

At both electron energies the lowest potential wells were observed at the closest coil spacing, as was the case at 200 V. The nonlinear trend was most apparent at 800 V, with potential well depth increasing at a decreasing rate with electron emission current. For example, at 800 V the largest two emission currents of 110 mA and 190 mA result in very similar potential well depths. The trend of plasma potential decreasing with increased coil spacing observed at 200 V was also observed at these higher energies. The effect is more pronounced at 400 V than either at 800 V or 200 V. The reasons for this are not immediately apparent, but suggest some interplay with electron energy and magnetic field parameters, which could be a topic for further research.
Fig 5.4: Central plasma potential for the three coil spacings for a range of coil and emission currents with a 400 eV electron energy.

Fig 5.5: Central plasma potential for the three coil spacings for a range of coil and emission currents with a 800 eV electron energy.

Fig 5.6 and Fig 5.7 show the central plasma potentials of the larger sized coils with the two types of spools at the higher electron energies of 400 V and 800 V respectively. The plasma potentials are given for the same range of emission and coil currents used throughout this experiment.

As was the case at 200 V, the reduction of the metal surfaces by interchanging the spools increased the potential well depth. Although, this effect is most apparent at the lowest electron energies, clearly shown when Fig 5.6 and Fig 5.7 are compared to Fig 5.3. The reduction of the metal surfaces of the spools used to house the coils resulted in them intersecting less magnetic field lines. Thus, electrons travelling along these magnetic field lines were no longer lost to the surface of the spool, which resulted in a deeper potential well.

The spread of central plasma potentials, in terms of electron emission current, do not change significantly at these higher energies. The relationship of electron emission current and central plasma potential is more linear than was the case with the smaller coils. This is particularly true for the reduced metal...
coils. The largest two emission currents, of 110 mA and 190 mA, resulted in a much deeper potential well. When the same increase in current was applied to the smaller coils the plasma potential increased by only a small amount. This indicated that the maximum potential well depth that may be achieved is dependent on the size of the Polywell. Therefore, the size of the Polywell is as much a limiting factor of potential well depth as the magnetic field strength or emission current.

![Figure 5.6](image1)

Figure 5.6: Central plasma potential for the two varieties of larger coil spools for a range of coil and emission currents with a 400 eV electron energy.

![Figure 5.7](image2)

Figure 5.7: Central plasma potential for the two varieties of larger coil spools for a range of coil and emission currents with a 800 eV electron energy.

5.4 Central Plasma Potential with a Background Hydrogen Gas

5.4.1 Changing coil spacing

The previous central plasma potential tests that used the smaller coils in three different spacings were repeated with the addition of a background gas. To begin with the base pressure of the vacuum chamber was 0.007 mTorr. Hydrogen gas was then introduced into the vacuum chamber using an MKS mass.
Central plasma potential measurements were taken at the base pressure as well as at 0.1 mTorr, 1 mTorr and 10 mTorr of hydrogen gas. Fig 5.8 and Fig 5.9 demonstrate this relationship for the three coil spacings, at voltages of 200 V and 400 V respectively. In both cases an emission current of 22 mA was used.

The effect of pressure is similar at 400 V and 200 V. Only a small difference was observed in potential well depth between the base pressure and the lowest hydrogen gas pressure. However, the potential well depth is greatly reduced at the two highest pressures. It is hypothesised that ions were produced via ionization of the background gas and that these ions would move into the potential well and thus reduce its depth. This effect can be referred to as the well being washed out, and is explored in more detail in the radial plasma potential measurements section.

Figure 5.8: Central plasma potential measurements for the three coil spacings with a variety of pressures for three coil spacings for a range of coil currents and a 200 eV electron energy.

At 400 V there was no difference within experimental error in the plasma potential for the two largest pressures, shown in Fig 5.9. This differs from observations at 200 V that showed potential well depths as significantly lower at 1 mTorr than at 10 mTorr. For both energies, 200 V and 400 V, the plasma potential at the lowest two pressures grow closer in value as the coil spacing was increased. The plasma potentials measured at each gas pressure are changed by coil spacing in similar ways at both energies.
5.4.2 Changing coil size

To investigate the effect of changing coil size on plasma potential with a background gas, the previous test was conducted with the larger coils. They were tested with the same range of coil and emission currents, as well as the same range of chamber pressures. While two types of spools were previously used when testing with the larger coils, measurements were not possible with the spool without reduced metal due to arcing.

Measurements taken using the reduced metal spools at 200 V and 400 V are presented in Fig 5.10. The depth of the potential well decreased as the background gas pressure was increased. Although, the magnitude of this decrease is not as large as was observed with the smaller coils. The pattern previously observed in the smaller coils, where at 200 V the highest pressures showed a significant difference in plasma potential compared to no significant difference for the same pressures at 400 V, was also observed with the larger coils. These effects resulted in a reduced spread of plasma potential as the gas pressure was increased at 400 V compared to 200 V. This is likely due to the fact that the ionization cross section decreases from 200 eV to 400 eV electron energy, and indicated that at even higher electron energies gas pressure would have a further reduced effect.

Figure 5.9: Central plasma potential measurements for the three coil spacings with a variety of pressures for three coil spacings for a range of coil currents and a 400 eV electron energy.
5.5 Plasma Potential for increased electron emission current

5.5.1 Changing Coil Spacing

The effect of increasing emission current from that tested in the previous section is explored here with the smaller coils and their prior spacing configurations. Figure 5.11 shows the central plasma potential for a range of electron emission currents at 200 V electron energy. The plasma potential was measured at two pressures for comparison, which were the base pressure of 0.007 mTorr and the lowest hydrogen pressure of 0.1 mTorr. Higher emission currents were achievable at 0.1 mTorr that were unobtainable at the base pressure.

The current applied to the coils was only 16 kATurns, which was 40% of the maximum coil current used in sections 5.3 and 5.4. This coil current was chosen due to an observation made in the first experiment, in which the electron emission current decreased as the magnetic field strength was increased. Since the magnetic field was 40% of the maximum while the filaments were at maximum temperature, the maximum emission current increased from 22 mA to 31.25 mA at the base pressure, and up to 42 mA at the higher pressure. The emission current was reduced by reducing the filament temperature and keeping the magnetic field constant. In contrast, in the previous section a constant emission current was maintained by reducing both the filament temperature and the magnetic field.
It was shown in the previous section that an increased gas pressure decreased the potential well depth. This was thought to be caused by the ions in the system washing out the well. This relationship was observed again for emission currents up to 19 mA. However, as emission currents were increased from 19 mA, the relationship was inverted and the higher pressure generally produced deeper potential wells.

The maximum electron emission current obtained at the higher pressure was greater than that obtained at the base pressure. The increased current is presumably due to ionisation of the background gas, which provided a source of electrons in addition to the emitted electrons. The combination of higher emission current and pressure produced the deepest potential wells at all coil spacings. Hence the effect of ions washing out the potential well was compensated by the increased emission currents.

A similar test was conducted with the reduced magnetic field, except with an electron emission energy of 400 V, which resulted in the maximum emission current increasing from 98 mA to 138 mA.
at the base pressure and up to 210 mA at the higher pressure. Central plasma potential measurements from this configuration are shown in Fig. 5.12. The pattern of behaviour of the plasma potential is very similar to that which was observed at the lower voltage, except in the case of the second spacing where the central plasma potential is deeper with the addition of hydrogen gas for all emission currents. This anomalous result could be explored by further experiments that determine the dynamics of ions in the system.

The relationship of a closer coil spacing producing deeper potential wells was more apparent at the electron energy of 400 V. This indicated that the relative magnetic field strengths of the device are more critical as the electron energy is increased. The result observed at the closest spacing is compatible with the theory of electron trapping as discussed in the previous experiment, where the potential well is expected to grow deeper at a decreasing rate with increasing emission current. The theory predicts that deeper potential wells prevent more of the emitted electrons from entering the Polywell. It was found that the relationship between the plasma potential and the electron emission current was considerably more linear for the largest coil spacing. A linear relationship is more in line with the hypothesis that part of the potential drop at the centre may be due to electron beam focusing rather than electron trapping.

5.5.2 Changing Coil Radius

![Graph showing plasma potential vs emission current for two varieties of larger coil spools with a lower coil current of 16 kATurns and increased emission current for two pressures and a 200 eV electron energy.]

Figure 5.13: Central plasma potential for two varieties of larger coil spools with a lower coil current of 16 kATurns and increased emission current for two pressures and a 200 eV electron energy.

To test the effect of increased electron currents with device scaling, coils were used in conjunction with the two types of spools previously described. The first test in the previous subsection was repeated with the larger coils, using the same range of emission currents and an electron emission energy of 200 V. This is shown in Fig. 5.13. As was the case in the previous subsection, the magnetic field strength was only 40% of the maximum, resulting in higher emission currents. Only base pressure plasma
potential measurements are given for the larger coil with the reduced metal spool, as arcing prevented measurements with the larger coils on the spools without reduced metal surfaces. The higher currents allowed for by the higher gas pressure increased the magnitude of the potential well, as was the case with the previous test of coil spacing.

The potential well was found to be considerably deeper with the spools with reduced metal surfaces for both pressures. Also the relationship between plasma potential and emission current is considerably more linear with the larger coils, when compared to the smaller coils. This indicated that the non-linear relationship observed with the other smaller coil may be due to electron losses to the frame rather than the potential well building up and excluding additional electrons, as has been previously theorised. This hypothesis is supported by the fact that the lowest plasma potential observed with the smaller coils is much greater than that observed with the reduced metal spool or the theoretical minimum plasma potential of 0 V.

![Larger Coils − 400 V](image1)

Figure 5.14: Central plasma potential for two varieties of larger coil spools with a lower coil current of 16 kATurns and increased emission current for two pressures and a 400 eV electron energy.

To test the effect of increasing the electron energy with device scaling, the central plasma potential for the base pressure is shown in Fig. 5.14 with an applied voltage of 400 V for the two types of spools. Increasing the coil size in conjunction with the reduced metal spools at 400 V resulted in the magnitude of the potential well depth increasing more than in the case of 200 V.

As in the case of 200 V, the plasma potential is greatly reduced by the reduction of the metal surfaces. However the magnitude of this effect is reduced, compared to the previous case of 200 V. The increasing linearity of plasma potential versus electron emission current with the larger coils is also apparent at 400 V. However, the magnitude of this effect is also reduced compared to the previous case of 200 V. The reduced magnitude of both of these effects suggest that there are more electron losses to the spools at the higher electron energy of 400 V. This is to be expected as the Lamor radius is greater at the higher
voltage and the electrons are more likely to spiral into the spools than be reflected back into the centre of the device as the energy is increased.

It is important to note, that even at a moderate pressure of 0.1 mTorr, the depth of the plasma potential was similar to that achieved at the base pressure of 0.007 mTorr. This implies that it is possible to fuel the Polywell, while maintaining deep potential wells, with the simple addition of a background gas.

5.6 Radial Plasma Potential Measurements

In this section multiple radial plasma potential measurements were taken in order to gauge the symmetry of the potential well. The effect of emission current, coil current and gas pressure on the symmetry of the potential well was investigated. These parameters were varied for the three coil spacings used for the central plasma potential measurements made in the previous sections. Larger coils were also used in conjunction with the two types of spools in order to test the effect of scaling on the symmetry of the potential well. The radial potential measurements also gave an indication about whether the corner, face or edge cusp had the greatest trapping of electrons.

A three dimensional (3D) representation of the potential well was created in order to better visualise the changes of the symmetry of the potential well. The 3D representations use a square surface where the height was set by the plasma potential. The plasma potential at the corners of the square were set by the plasma potential measured at the centre, face, edge and corner positions. To complete the representation, a linear interpolation was assumed between the corners. Selected emission currents, coil currents and gas pressures are presented for all coil spacing and size configurations, to demonstrate how these affect the symmetry of the potential well. In this meaning of symmetry the potential well would me most symmetric when the potential in the edge corner and face are equal.

The results presented in this section were found by using four probes simultaneously. With one in the centre of the device and another three in the edge, face, and corner radial positions. A total of seven probes was used but it was found that the measured plasma potentials deviated from those measured when only a single probe was being used. However, this effect was not observed when only four probes were used. Thus four probes were used as simultaneous measurements reduced errors due to variation between pulses and there was no measurable perturbation in the plasma potential compared to using just one probe.
5.6.1 Changing coil spacing

The radial position of the probes was selected due to previous observations made, in which the plasma potentials measured by the capacitive probes were affected by the presence of a magnetic field (see section 3.6.2). The measured plasma potential was underestimated when the Larmor radius of the electrons became less than the probe tip diameter. The magnitude of underestimation increased as the magnetic field increased. However, the magnitude of the underestimation increased at a decreasing rate, and eventually ceases to increase at a finite magnetic field strength. The magnetic field at the radial positions was always large enough to ensure that the magnitude of underestimation was in the constant region. Three radial probes were used, which were positioned for the smallest, middle and largest coil spacings at a radial distance of 30 mm, 35 mm and 45 mm respectively. The radial probes were placed along three axes aligned with the magnetic cusps, which start at the centre of the device and end at the centre of the faces, edges and the corners.

![Figure 5.15: Radial plasma potential for the three coil spacings for a range of coil currents and an emission current of 22 mA, with a 200 eV electron energy at the base pressure.](image)

An emission current of 22 mA and a range of coil currents were used with the smaller coils in the three spacings, to gauge its effect on the symmetry of the potential wells. The central potential alongside the plasma potential measured at the three radial locations is shown in Fig 5.15. The radial plasma potentials shown in Fig 5.15 indicate that not only were the potential wells made deeper as the coil spacings became closer, but they also became wider. The width of the potential well was determined by the difference between the radial plasma potential and the central plasma potential. This is because the plasma potential must return to 0 V at the filaments. Even though the plasma potential in this region was not measured it is possible to infer how the well is shaped beyond the radial probes positions due to its boundary condition. Hence wells which exhibit a smaller difference between plasma potentials in the radial position and the centre have a flatter bottom and wider profile than wells which have a
greater difference between the radial potential and the central potential. Narrower potential wells are more desirable for fusion by increasing ion focusing. This result suggests that a balance in spacing may need to be found to optimize central potential well depth, symmetry and well width.

The symmetrical nature of the potential well degraded as the coil spacing or coil current was increased. Particularly the plasma potential in the face of the Polywell device diverged from that measured in the other cusps at the largest spacing. However, in the case of the closest spacing it was the corner cusp potential that diverged the greatest. The decreased plasma potential in the radial positions of the device may likely be due to an increased electron density caused by more electrons being trapped in a particular cusp. This hypothesis explains why the plasma potential measured at the face cusp diverged more as the coil spacing was increased, since the magnetic field strength decreased at the corner and edge and increased at the face, and stronger magnetic fields have been shown to increase electron trapping.

The errors depicted in Fig 5.15 for the central plasma potential are due to the noise in the signal from the capacitive probe, as previously discussed. However, the radial plasma potentials in Fig 5.15, and in all subsequent radial plasma potential measurements in this chapter, have a greater uncertainty as the plasma potential in underestimated in the presence of a strong magnetic field. This is discussed in detail in section 3.6.2. There is uncertainty in this factor of underestimation and this causes a greater uncertainty in the radial plasma potential measurements.

To better visualise the potential well as the coil current and spacing was increased with an electron emission current of 22 mA, a 3D depiction of the potential wells is shown in Fig 5.16. It can be clearly seen in this depiction that as the coil current of the device was increased the asymmetry of the potential well increased. Once again the closest spacing of coils produced the lowest plasma potential measurements at the centre of the device. However, the potential well is generally the deepest when measured from the radial position with lower coil currents and especially for the middle spacing.
Figure 5.16: 3D depiction of potential well structure for the three coil spacings with a moderate emission current of 22 mA and a range of coil currents at base pressure of 0.007 mTorr.

The smaller coils were used with a current of 16 kATurns in the three coil spacings and with a range of emission currents, to gauge these effects on the symmetry of the potential wells. The central and radial plasma potential measurements are shown in Fig 5.17. These results indicated that the symmetrical nature of the potential well degraded as the emission current was increased, similarly to the case of increasing coil current. However, the deepest central potential was observed at the greatest emission current. Once again this suggests a balance between electron current and central potential must be found for the best fusion performance.
As in the previous case where the coil current was varied the greatest variation in plasma potential occurred at the face cusp at the largest spacing and at the corner cusp at the closest spacing. This supports the hypothesis that more electrons were trapped in the cusp with the strongest magnetic field, and that having a similar magnetic field in both the corner and face cusps result in the most symmetrical potential well possible.

In the following two figures three dimensional depictions of the potential wells are given for the lowest and highest emission current regimes, for all three spacings represented in Fig 1.17. In Fig. 5.18 a 3D depiction of the potential wells is presented at the lowest emission current of 3.13 mA. The asymmetrical nature of the wells became more apparent as the spacing between the coils was increased. The depth of the potential well at the centre of the device was greatest in magnitude for the closest coil spacing. However, the depth of the potential well measured from the radial positions of the device to the centre did not vary much as the coil spacing was increased.

Figure 5.18: 3D depiction of potential well structure for the three coil spacings with a lower emission current of 3.13 mA and a current of 16.25 kATurns.
Figure. 5.19 shows a 3D depiction for the largest electron emission current of 31.25 mA. As in the case of the lower emission current, the magnitude of the potential depth at the centre of the device was greatest for the closest coil spacing. The asymmetrical nature of the potential well is also greater for all coil spacings than with the lower current. However, the depth of the potential well measured from the edge of the device is significantly deeper for the middle coil spacing. Along with this, the middle coil spacing was also the most symmetrical potential well.

![Figure 5.19: 3D depiction of potential well structure for the three coil spacings with a higher emission current of 31.25 mA and a coil current of 16.25 kAmpTurns.](image)

### 5.6.2 Changing coil size

In this section larger coils were used to determine the effect of scaling on the symmetry of the potential well. Radial plasma potential measurements were also taken with both types of spool, for a range of coil currents and an emission current of 22 mA. The results are plotted in Fig. 5.20. These results show deeper potential wells with the spools with reduced metal, compared to the potential wells observed with the smaller coils. However, the spools with a larger metal surface resulted in shallower potential wells than those observed with the smaller coils. This once again indicates the importance of the shape of the spools which hold the coils on the depth of the potential wells observed.

More symmetrical potential wells were observed for the larger coils with both spool types than with the smaller coils. Due to the negative effect of the metal surfaces a comparison of the results at the closest spacing with the small coils and the larger coils with reduced metal surfaces best illuminate the effect of scaling on the shape of the potential well. In the case of the closest spacing, the plasma potential in the face cusp diverged from the other cusp measurements by the greatest amount. However, there is no significant divergence between the face and corner cusps with the larger coils, and the differences in the relative magnitude of magnetic fields in the various cusps were similar with the larger coils and smaller coils at the closest spacing. These results indicated that the symmetry of the potential wells is not only...
effected by the proportion of magnetic fields in the cusps, but also by the overall volume of the device.

The internal volume of the device was the same with the larger coils and the smaller coils at the largest spacing. However, the magnetic field produced by the larger coils increased at the corner and decreased at the face as the coil size was increased, for a fixed coil current, and the plasma potential measured in the corner cusp increased and the face cusp decreased. This supports the hypothesis that the relative magnetic field strength of the cusps with each other affect the electron trapping which occurs at each cusp.

![Graph showing plasma potential vs. coil current for larger coils and larger coils with reduced metal.](image)

Figure 5.20: Radial plasma potential for the two types spools for a range of coil currents and an emission current of 22 mA with a 200 eV electron energy at the base pressure of 0.007 mTorr.

A 3D depiction of the potential well with the larger coils, for a range of coil currents and an electron emission current of 22 mA, is shown in Fig. 5.21. The reduction of metal surfaces of the spools resulted in considerably deeper potential wells, as measured by both the central plasma potential or by the difference between the radial and central plasma potentials. When the 3D depiction of the potential well for the closest spacing shown in Fig. 5.16 is compared with the larger coils, it can be clearly seen that the potential wells became deeper and more symmetrical as the coil size was increased.
Figure 5.21: 3D depiction of potential well structure for the two types of larger coils with a moderate emission current of 22 mA and a range of coil currents at the base pressure of 0.007 mTorr.

In order to test the effect of varying the emission current, the larger coils were used with a coil current of 16 kATurns. These results are shown in Fig. 5.22. Once again the plasma potentials were deeper and more symmetrical than those observed with the smaller coils. As the emission current was increased, the divergence of the corner cusp from the other cusps became more apparent. The strength of the magnetic field at the corner was known to have been increased by the use of the larger coils. Therefore, these results support the hypothesis that as the magnetic field in a cusp is increased the electron trapping in that cusp is also increased.

The potential wells shown in Fig 5.22 and Fig 5.20 produced by the larger coils, are narrower than those compared to the smaller coils at the closest spacing. This demonstrates the important result that the potential wells are improved in symmetry as well as width as the device size was scaled up. Both of these attributes are important for confining ions for fusion.
Figure 5.22: Radial plasma potential for the two types of larger coils for a range of emission currents and a coil current of 16 kATurns with a 200 eV electron energy at the base pressure of 0.007 mTorr.

Figure 5.23 shows the 3D depiction for three of the emission currents used with the larger coils without the reduced metal spool. The most symmetrical potential wells were observed at the lowest emission current of 3.25 mA, and the least symmetrical well at the highest current of 31.25 mA. This is the same trend that was observed with the smaller coils.

The effect of reducing the metal surfaces of the spools is demonstrated in Fig 5.24 with the same three emission currents shown with the reduced metal spools. The 3D depictions show that the potential wells were significantly deeper with the reduced metal spool in terms of the magnitude of the central potential measurements and in terms of the difference between central and radial position measurements. However, there was no significant change in the symmetry of the potential well with the reduced metal spools. This result suggests that the metal surface reduces the overall depth of the well by increasing electron loss, but the symmetry of the potential well is most affected by the relative magnetic field strength of the cusps.
Radial plasma potentials were taken with higher gas pressures and the same coil spacings previously used in order to determine the effect of gas pressure on the symmetry of the potential well. Figure 5.25 shows radial plasma potential measurements for the three coil spacings using the small coils with a background hydrogen gas of 0.1 mTorr for a range of coil currents.

The radial measurements show more symmetrical potential wells than compared to those found with the absence of a background gas, which is shown in Fig 5.15. However, the plasma potential at the centre of the device was slightly increased in the presence of the background gas. Both of these effects are hypothesised to be due to ions entering the potential well, smoothing it out and also reducing its depth. The relative radial plasma potential measurements also changed with the introduction of the background gas. Unlike the case with no background gas, the relative radial plasma potentials can not be used to infer
information about the electron trapping, as the dynamics and spatial distribution of ions in the potential well are not known.

As the coil current was increased, the asymmetry of the potential well was also increased. Fig. 5.26 shows the 3D depiction of the potential well with an emission current of 22 mA, over the range of coil currents used for the three coil spacings. Once again, the closest coil spacing produced the lowest plasma potential measurements at the centre of the device. However, the potential well is deepest when measured from the radial position with lower coil current, particularly at the middle coil spacing. This trend was also observed at the base pressure.

![Figure 5.26: 3D depiction of potential well structure for the three coil spacings with a moderate emission current of 22 mA and a range of coil currents with increased pressure of 0.1 mTorr.](image)

In order to test the effect of varying the electron emission current on the radial plasma potential at
the higher pressure, the coil current was reduced to 16 kATurns for the three coil spacings. The results are shown in Fig. 5.27. Compared to the case at base pressure shown in Fig 5.17, the potential wells are more symmetric and deeper. The most symmetrical and deepest potential wells were observed at the closest coil spacing.

Figure 5.27: Radial plasma potential for the three coil spacings for a range of electron emission currents and a coil current of 16 kATurns with a 200 eV electron energy at an increased pressure of 0.1 mTorr.

In order to demonstrate the effect of a background gas on the symmetry of the potential well, 3D depictions are presented for the test with a 0.1 mTorr background gas. This is shown in Fig. 5.28. A lower emission current of 3.13 mA was also used for all three coil spacings, as shown in Fig 5.23. The main difference that the introduction of the hydrogen gas caused was an improvement in the symmetry of the potential well structure. This effect is most notable at the largest coil spacing. Although the symmetry of the potential well was improved, the depth of the potential well was slightly decreased compared to observations at the base pressure.

Figure 5.28: 3D depiction of potential well structure for the three coil spacings with a lower emission current of 3.13 mA and a coil current of 16.25 kATurns with increased pressure of 0.1 mTorr.

The higher emission current test of 31.25 mA is presented in Fig 5.29 for the three coil spacings.
and a gas pressure of 0.1 mTorr. The symmetry of the potential well structure was improved with the addition of the hydrogen gas at this larger emission current. However, the potential well became more asymmetric with an increase in emission current, as was the case with the radial potential measurement at the base pressure. However, this effect is lessened in magnitude at the higher pressure.

In order to test the effect of scaling with higher pressures on the symmetry of the potential well, the larger coils were used with the same emission and coil currents used previously. Radial plasma potential measurements using the larger coils with reduced metal surfaces are shown in Fig 5.30. No radial plasma potential measurements were taken at higher pressures when the larger coils without reduced metal surfaces were used as arcing prevented measurements. Deeper potential wells were observed with the larger coils than that observed at all spacings using the smaller coils.

Unlike with the case at base pressure, the symmetrical nature of the potential well did not improve...
as much as the coil size was increased. This indicated that the effect of the background gas and the subsequent ions produced has more impact on the shape of the potential well than the increase in coil size. Figure 5.31 shows the 3D depiction of the potential well for three of the emission currents used with the larger coils. In this case there were no significant change in the symmetry of the potential well as the emission current was increased. However, the potential wells became significantly deeper and wider as the emission current was increased.

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**Figure 5.31:** 3D depiction of potential well structure for the larger spools with reduced metal surfaces for a range of emission currents at an increased pressure.

The changes in the 3D potential well structure as the coil current was varied with the larger coils with the reduced metal spools are shown in Fig 5.32. It is clear from this depiction that the deepest potential wells, based on the central potential, were attained at the highest coil current. However, the potential wells are more symmetrical and slightly narrower for the lowest coil current.

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**Figure 5.32:** 3D depiction of potential well structure for the larger spools with reduced metal surfaces for range of coil currents at an increased pressure.
### 5.7 Confinement time estimations

Another way that the electron trapping capabilities of the Polywell device can be quantified is by making estimations of the electron confinement times. A method for making confinement time estimations was detailed in the previous chapter. This method is reapplied to specific cases detailed in this experiment. Due to the improved measure of electron emission currents made possible by the reduced outgassing of this experiment, the estimates are thought to be more accurate than those made in the previous chapter.

One of the key assumptions in this method of estimating the confinement times is that the potential well is close to a spherically symmetric charge distribution. From the radial potential well measurements provided in this chapter, it is clear that this assumption is not valid for a wide range of experimental configurations. For example, all of the potential wells observed at the larger two spacings at low pressure are significantly asymmetrical. The density of ions was not determined and only the electron density was considered in this method of estimating confinement time, which also prevented its use for pressures higher than the base pressure.

In Chapter 4 the potential well depth \( V_d \) was determined by the difference in the plasma potential with and without the applied magnetic field at the centre of the device. However, the radial measurements allow for the potential well depth to be determined by the difference between the radial potential and the potential at the centre, both with the magnetic field applied. This is a more realistic depiction of the spatial profile of the potential wells. For this reason it is thought that this method of determining the potential depth will result in a more accurate estimate of the electron confinement time. Thus the potential well depth \( V_d \) was determined by taking the difference between the central plasma potential and an average of the three radial plasma potential measurements.

The potential well was sufficiently symmetrical at the closest spacing using the smaller coils and

![Figure 5.33: Confinement time and electron reflection estimates for a range of emission currents](image-url)
with the larger coils with both types of spool. The electron confinement time was estimated at these Polywell configurations and the results are plotted in Fig. 5.33 for a range of emission currents. The estimated confinement times were considerably larger than those estimated in the last chapter. This was primarily due to the significant reduction in measured emission currents, while the measured potential well depths were similar. The estimated confinement time is proportional to the potential well depth and inversely proportional to the emission current. However, the potential well depth was observed to increase at a decreasing rate as the emission current was increased. This relationship is manifested in the confinement times decreased with increasing emission current. The confinement time of electrons increased substantially as the device size was increased and as the metal surfaces of the spools were reduced. In this case the uncertainty in the confinement time estimation is from the uncertainty in the plasma potential measurements used in calculating the confinement time.

Also plotted in Fig 5.33 is the estimated average number of reflections made by the electrons within the device. This was calculated by dividing the estimated confinement time $t_c$ by the time it takes electrons to make a single pass across the device $t_T$. Since the estimated confinement time is linearly dependant on the width of the device, increasing the spacing between the coils in order to use the larger coils caused a corresponding increase in the confinement time of the electrons. Because of this, the number of reflections is more instructive than the total confinement time when considering the improvement of electron trapping by changing the coil configuration. On the basis of this measure, the effect of reducing the metal surfaces was greater than increasing the device size in improving the electron confinement. The number of electron reflections increased by a much smaller amount compared to the estimated confinement time.

The relationship between coil current and electron confinement time is shown in Fig 5.34. As with emission current, the nonlinear relationship between potential well depth and coil current is expressed in the relationship of decreasing electron confinement time with increasing coil current. Similar trends were observed in the confinement times for the different coil configurations, as was depicted in Fig 5.33. These results suggest that the profile of the coils and the spools which hold them is critical to the performance of the device.
5.8 Scaling law

The effect of scaling on the depth of the potential well was determined by comparing the central plasma potential of the smaller coils at the closest spacing and the larger coils used on the spool with reduced metal surfaces. The points of comparison are shown in Fig 5.35. These configurations were chosen as the relative magnetic fields at the cusps and the amount of metal surfaces used on these spools were the most proportionally similar of all coil size and spacing configurations used throughout the experiment. A geometric progression is used to estimate the effect further increases to device size would have on the central plasma potential. This method was chosen as it is based on the assumption that further increases of the same amount to the radius of the coils would have the same effect on the potential well depth. As only two device sizes were tested in the experiment, no other assumptions have any evidence on which to base non-linear potential well depth with device scaling. The use of a geometric series or recursion relation in this way is not particularly justified by any physics but was used as it contains only the one previously mentioned assumption, while other methods would contain more assumptions.

Despite the similarities, the magnetic field was strongest at the corners for the larger coils while the magnetic field was the strongest at the face for the smaller coils. Also, while the metal surfaces on the spools were reduced as much as the experimental design would allow for on the larger coils, the metal surfaces were still larger relative to the coil size in comparison with the smaller coils. It was also found that the reduction of metal surfaces resulted in a significant increase to the potential well depth when the two types of spools used with the larger coils were compared. For these reasons, the effect of scaling on the potential well depth could be underestimated and the scaling factor $k$ used in Equation 5.1 could be overestimated.

The electron emission current was also found to be a significant variable in the magnitude of the
potential well. For this reason the electron emission current is scaled to the volume of the Polywell in order to estimate the effect of only device scaling. By taking this approach the ratio of emission current to volume is kept constant. The internal volume of the Polywell was increased by a factor of 4.2 with the increase in coil size (this factor was calculated by using the outer coil radius). Vertical lines drawn on Fig. 5.35 show the points that were used for comparison in the development of the scaling law for maximum potential well depth. In the cases of 400 V and 800 V the emission currents used were not exactly 4.2 times. Therefore in these cases the plasma potential was estimated by the closest emission current which was measured. This is indicated by the vertical lines in Fig. 5.35.

Figure 5.35: Comparison of the central plasma potential for the smaller coils at the closest spacing and the larger coils with reduced metal surfaces at the base pressure. The vertical lines highlight the points used in the geometric series later in this section.

The geometric progression shown in Equation 5.1 was used to extrapolate the central plasma potential with device size, with \( P_n \) being the plasma potential. The first two iterations of the geometric series \( P_1 \) and \( P_2 \) were determined from the plasma potentials measured in the experiment, notably the points highlighted by the vertical lines in Fig. 5.35.

\[
P_n = P_{n-1} \times k
\]  

The scaling factor, \( k \), was calculated by Equation 5.2 for the three different electron energies by using these points. These results are summarised in Table 5.1.

\[
k = \frac{P_2}{P_1}
\]  

Also shown in this table are selected iterations of Equation 5.1 that correspond to the plasma potential reaching less than 10 % of the electron energy. This corresponds to a potential well depth greater than 90 % of the electron energy. The increase in device radius for each iteration \( n \) in Equation 5.1
was determined by Equation 5.3, where $R_1$ and $R_2$ are set by the radius of the small and larger coils respectively.

$$R_n = (R_2 - R_1) \times (n - 1) + R_1 \quad (5.3)$$

Each iteration of Equation 5.3 produces an increase in device radius that is the same as the increase that was used between the two coil sizes. The emission current for the predicted iterations in Table 5.1 was determined by Equation 5.4 and increases proportionally to the increase in device volume. The initial emission current $I_1$ was set by the emission current used with the smaller coils. As previously described, the scaling factor $k$ could have been overestimated. This indicates that for the predicted iterations, the device radius $R_n$ and emission current $I_{n+1}$ may have been overestimated.

$$I_{n+1} = I_n \times \frac{R_{n+1}^3}{R_n^3} \quad (5.4)$$

<p>| Electron Energy 200 V — $P_1 = 112$ V — $P_2 = 89.6$ V — $k = 0.800$ |
|-------------------------|-------------------|-------------------|</p>
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<th>n</th>
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<th>Central Potential ‘$P_n$’ (V)</th>
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<td>112</td>
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<tr>
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<td>89.6</td>
</tr>
<tr>
<td>9</td>
<td>1.657</td>
<td>142</td>
<td>18.79</td>
</tr>
</tbody>
</table>

<p>| Electron Energy 400 V — $P_1 = 272$ V — $P_2 = 220$ V — $k = 0.809$ |
|-------------------------|-------------------|-------------------|</p>
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<tbody>
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<td>24</td>
<td>272</td>
</tr>
<tr>
<td>2</td>
<td>0.135</td>
<td>38.75</td>
<td>220</td>
</tr>
<tr>
<td>11</td>
<td>11.676</td>
<td>171.5</td>
<td>32.66</td>
</tr>
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</table>

<p>| Electron Energy 800 V — $P_1 = 643$ V — $P_2 = 556$ V — $k = 0.865$ |
|-------------------------|-------------------|-------------------|</p>
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<td>61.89</td>
<td>245.25</td>
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</tr>
</tbody>
</table>

<p>| Electron Energy 12500 V — $P_1 = 12500$ V — $k = 0.825$ |
|-------------------------|-------------------|-------------------|</p>
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<td>13</td>
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<td>201</td>
<td>1,233</td>
</tr>
</tbody>
</table>

Table 5.1: Summary of predictions from the geometric series.

The last section of Table 5.1 looks at a theoretical electron energy of 12.5 keV, which was signif-
icantly higher than the highest tested energy of 0.8 keV, and theoretically capable of reaching fusion energies. In this case, the scaling factor used was an average of the three experimentally determined scaling factors and the initial emission current was estimated by the trend observed between emission current and electron energy for the three measured energies. These results indicate that in order to reach fusion capable ion energies of approximately 11 keV, the device size must be increased to approximately 200 mm. An electron energy of 12.5 keV is a somewhat arbitrary choice and was chosen as at an energy ion energy of 11 keV the fusion cross section for the DD reaction is $\tilde{0}$.01 barns and for DT is $\tilde{1}$ barns (see Fig 1.1) and the fusion rate could be practically measured. However, even at somewhat lower energies, and obviously at even higher energies, the Polywell would also be fusion capable.

5.9 Conclusion

The spacing experiment showed that the deepest potential wells are observed when the magnetic field strengths at the cusps are most similar i.e. when the well is most symmetrical and the electron losses are dominated by losses at the cusp with the weakest magnetic field strength.

The potential well depth increased with emission and coil currents. However, this relationship is nonlinear, with the potential well depth increasing at a decreasing rate for both current variables. This indicated that in order to achieve deeper potential wells, a larger device is required and that the maximum potential well depth is determined by device size as much as it is determined by the emission and coil currents.

The use of two types of spools for the larger coils demonstrated that the amount of metal surfaces surrounding the coils had a great effect on the potential well depth. The larger coils used with the spools with reduced metal surfaces demonstrated that deeper potential wells could be achieved by increasing the device size. By comparing the results of the two device sizes, a tentative scaling law for the maximum potential well depth with device size was obtained. This led to a prediction of device size necessary to achieve fusion energies. The symmetry and width of the potential well was also found to increase with device size.

The effect of a background gas on the potential well formation found that increasing gas pressure resulted in shallower potential wells. However, the use of a moderate gas pressure of 0.1 mTorr resulted in potential well depths that were only slightly reduced in depth compared to the base pressure of 0.007 mTorr for the same emission current. Ultimately, the higher gas pressure of 0.1 mTorr achieved higher emission currents and potential wells that were deeper and significantly more symmetrical than found at base pressure. This result indicated that the use of a moderate gas pressure may not only be a
possible way to fuel the Polywell, but may also be preferable for potential well formation.

In summary, these results indicated that it is possible to construct a Polywell with an approximate coil radius of 200 mm which would be capable of reaching fusion energies. In theory the symmetry and width of this potential well would also continue to improve due to its larger size, and may result in considerable ion focusing and ion trapping. The results of this experiment also suggest that it would be possible to fuel this Polywell simply by the addition of a background gas pressure of approximately 0.1 mTorr.
Chapter 6

Conclusions and Future Work

A capacitive probe has been characterised for use in a high energy non-neutral electron plasma. The effect of strong magnetic fields on the probe has also been determined. It was shown that the plasma potential measured by the capacitive probe is underestimated once the Larmor radius of electrons within the plasma is reduced to less than the probe tip diameter. The magnitude of this underestimation increased as the Larmor radius was further decreased. However, the magnitude of underestimation stopped increasing once the Larmor radius reached a critical value. By placing the probe in a region of the Polywell such that the Larmor radius of electrons is below this critical value, a simple correction can be applied to the plasma potential measured by the probe to determine the true plasma potential. From these results it was determined that the capacitive probe diagnostic is suitable for use within Polywell experiments.

A mechanically robust Polywell was constructed so that the parameter space of magnetic field strength and electron emission current and electron energy could be increased relative to previous experiments using small Polywell devices[42, 54]. By using increased magnetic field strengths, the relationship between potential well and magnetic field strength was shown to be non-linear, as progressive increases to the magnetic field produced smaller increases to the well depth. It is thought that this non-linear behaviour is due to the deeper potential wells, formed by the stronger magnetic fields, electrostatically shielding electrons from entering the device. Greater potential well depths were observed compared to those observed in previous experiments using small Polywells, and it was shown that the potential well depth could approach the electron energy in a small device.

Electrons were produced from a thermionic emission source consisting of four tungsten filaments, with one placed at four of the face cusps. The depth of the potential well was shown to be more strongly correlated with the electron emission current than the magnetic field strength of the device. A linear relationship between electron injection energy and potential well depth was shown at an electron energy
of 250 eV. In future work further increases to the electron emission current may provide a nonlinear relationship, similar to that with magnetic field strength, if the potential well depth at 250 eV electron energy can be made closer to 250 V. A possible source of error in emission current measurements could have been the presence of outgassing. It was noticed that outgassing from the experiment increased as the filaments were heated.

The electron current that was injected into the Polywell was found to be less than the emission current of the filaments. Initially the electron injection current was found to increase with the application of magnetic fields. The magnetic field caused a focusing of the electron beams formed from the filaments and shielded the emitted electrons from collisions with the outer surface of the coils, resulting in more electrons entering the device. However, the electron injection current was found to decrease with a further increase to the magnetic field. This was thought to be due to increased mirror reflections on the outside of the device. This should be a consideration in future experiments in order to maximize the efficiency of electron injection.

An analytical model was created to estimate the confinement time of electrons within the device. The results of this model were used to create an experimentally derived equation for confinement time of electrons based on the injected electron energy and applied coil current. This equation suggests that the electron confinement time is inversely proportional to the electron energy and proportional to the square root of the magnetic field strength. These estimations were compared to confinement times produced from a single particle simulation of the electrons within the device. The confinement times produced by both methods were of the same order of magnitude. However, the confinement times from the simulation were consistently larger than those determined experimentally, and the simulation predicted electron confinement time to scale more strongly with electron energy. One possible reason for these discrepancies is that the single particle model does not take into account the electrostatic effect of the potential well on the electrons. The analytical model also relies on the assumption that the potential well is spherically symmetric. The symmetry of the well was not determined in this experiment as radial potential measurements were only taken along one of the axis of symmetry of the device. It is suggested that future potential well measurements be taken along the three axes of symmetry that exist within the Polywell so that the validity of this assumption can be determined. This is also important for future experiments investigating ion trapping, as the degree of ion focusing achieved is related to the spherical symmetry of the potential well.

A Polywell with adjustable coil spacing was used to determine the effect of different magnetic field ratios in the different cusps of the Polywell. A system of baking out the chamber allowed for better accuracy of electron emission currents and control of the vacuum pressure, which also allowed the effect
of pressure on the formation of the potential well to be determined. Three radial probes were used in this experiment that measured the plasma potential along the three magnetic cusps and axes of symmetry of the device, allowing the spherical symmetry of the potential well to be determined. As in the first experiment, a nonlinear relationship was observed between potential well depth and increasing magnetic field strength. However, unlike the first experiment, a non-linear relationship was also observed with potential well depth and electron emission current. This is likely due to the increased accuracy of the emission current measurements available from the cleaner chamber.

The results from varying the coil spacing indicate that closer coil spacings produce the deepest and most symmetrical potential wells. As the coil spacing was increased, the plasma potential measured at the faces of the device was lowered and the potential at the corners increased. This indicated that the magnetic field strength at a cusp is proportional to the amount of electron trapping in that cusp. The deepest potential wells were found at the closest coil spacings, where the magnetic field at the cusps are closest in magnitude. This suggests that electron losses are dominated by the cusp which has the lowest magnitude of magnetic field. The plasma potential at the edge cusp did not diverge for any coil spacing. These results indicate that for future Polywell experiments it would be ideal to set the coil spacing so that the magnetic field strength is equal at the face and corner cusps. Future experiments could also be designed with faraday cups placed outside the device on the three different cusp axes to directly measure electron losses, as the spacing and magnetic field is varied. This would give a more direct measurement of these effects.

The effect of increasing device size on the formation of potential wells was investigated by increasing the coil radius. These results showed that the potential well depth that is achievable for a given electron emission and magnetic field strength increases with device size. The symmetry of the potential well was also significantly increased with the larger device. By using a geometric progression, the minimum device size to reach fusion energies was estimated, assuming a geometric scaling of device performance. A future experiment that follows these coil size and spacing recommendations should be able to achieve fusion. It was also found that the degree to which the coil housing conforms to the magnetic fields has a significant effect on the achieved potential well depth. To maximise this effect it is suggested that future experiments use circular cross section coils rather than the square cross section coils used in this experiment.

A background gas was introduced into the system, and the pressure was varied in order to quantify the effect on potential well formation. Previous results using a high gas pressure indicated that pressure would have a considerable effect on potential well formation. It was found that hydrogen gas pressures of \( \geq 0.1 \) mTorr significantly reduced the depth of the potential well. However, a gas pressure of 0.1 mTorr
was shown to only slightly reduce the potential well depth. At this pressure the symmetry of the potential well was also improved. These results suggest that future experiments could fuel the Polywell with a background gas at this pressure.

While there is potential for using a background gas to fuel the Polywell, there are possible problems with this method of fueling. Ideally ions are to be formed at the edge of the potential well so that they will have the maximum energy at the core of the device. Ions created through the ionisation of the background gas will be created all throughout the potential well not just at the edge. This will reduce the number of ions in the core that have sufficient energy to fuse. Charge exchange reactions will also provide an additional loss mechanism as the fast neutrals produced will not be confined to the device. These effects will likely reduce the ion temperature that can be achieved in the core of the device than if all the ions were created at the edge of the device without a background gas. For these reasons, future experiments may benefit from the use of ion guns placed at the edge of the potential well. Although much has been learned about the behaviour of electrons in the Polywell and the potential well formation, the behaviour of ions in the device still requires investigation. Useful diagnostics for use in a future Polywell experiments to determine ion behaviour could be ion-doppler spectroscopy and laser induced fluorescence.

There is also potential to use higher dimensional polygon geometry such as a dodecahedron rather than the cube geometry used in this thesis. Increasing the number of coils in this manner has the effect of increasing the volume of the magnetic null inside the device. This would be expected to increase the electron confinement in a similar manner that high $\beta$ operation would, as discussed in Chapter 1 of this thesis. However, increasing the number of coils also increases the number of point cusps and thus the surface that electron may be lost through, thereby reducing electron confinement. Future experiments using larger coil numbers may help find the optimal balance between null volume and coil number.
Chapter 7

Bibliography


Appendix A

Novel plasma electron gun

A.1 Introduction

A new and simple type of electron gun is presented. Unlike conventional electron guns, which require a heated filament or extractor, accelerator and focusing electrodes, this gun uses the collimated electron microchannels of an Inertial Electrostatic Confinement (IEC) discharge to achieve the same outcome. A cylindrical cathode is placed coaxially within a cylindrical anode to create the discharge. Collimated beams of electrons and fast neutrals emerge along the axis of the cylindrical cathode. This geometry isolates one of the microchannels that emerge in a negatively biased IEC grid. The internal operating pressure range of the gun is 35 - 190 mTorr. A small aperture separates the gun from the main vacuum chamber in order to achieve a pressure differential. The chamber was operated at pressures of 4 - 12 mTorr. The measured current produced by the gun was 0.1 - 3 mA (0.2 - 14 mA corrected measurement) for discharge currents of 1 - 45 mA and discharge voltages of 0.5 - 12 kV. The collimated electron beam emerges from the aperture into the vacuum chamber. The performance of the gun is unaffected by the pressure differential between the vacuum chamber and the gun. This allows the aperture to be removed and the chamber pressure to be equal to the gun pressure if required.

A.2 Background of plasma electron guns

Plasma cathode electron guns are used in a variety of applications, from electron tubes[95] to plasma welding[96]. For this reason, electron guns must operate at a variety of pressures and currents. Many plasma-cathode electron guns create a dense plasma discharge using a hollow cathode,[97] often with the aid of a magnetic field[98]. In standard hollow cathode electron guns, the hollow cathode is generally a cup shape, and the anode is a plate with an aperture[97, 99, 100]. Even when this is not the case,
the plasma is strictly used as a source of electrons[101, 102], from which electrons are extracted by an electrode[103]. Typically the extracted electrons are accelerated and focused by additional electrodes in order to form a beam. A magnetic field can also be used to focus the beam[97, 98].

This type of electron gun design requires a discharge in the hollow cathode and exclusion of a discharge from occurring in the extraction, focusing and acceleration electrodes. To avoid breakdown of the gas in the extraction region of the gun, two steps are taken. The first is to have a lower pressure in the extraction region, often achieved by differential pumping. Secondly the extraction electrode, along with additional focusing and accelerating electrodes, are placed close together to reduce the breakdown voltage further.

Another common type of electron gun is the heated filament electron gun. These guns work by extracting thermally excited electrons from a heated filament. The upper operating pressures of this type of gun are limited as the gas will destroy the filament. When the target region of the electron beam requires a high pressure, differential pumping of the electron gun segments is required.

The electron gun presented in this appendix formed an electron beam by using an open ended cylindrical cathode to provide the discharge. The cathode was located coaxially within a cylindrical anode. This produced collimated electron microchannels, due to the electrode geometry. This effect was initially observed in the field of IEC[19, 22, 32], in which ions are electrostatically confined by a spherical and gridded electrode. Neutrons are produced via fusion reactions between the confined ions. Beams of electrons and fast neutrals were observed leaving the open spaces of the gridded cathode[104, 105]. The same effect was seen when using the cylindrical cathode in a pressure range of 10 - 100 mA[33]. However, only one microchannel was formed through the central axis of the cylinder. By exploiting this microchannel, an electron gun that did not rely on differential pumping or an extraction electrode to extract current from the plasma was constructed. Focusing and accelerating electrodes or focusing magnetic fields were also not required to create the beam, although these features are pervasive in other plasma cathode electron gun designs[106, 107, 98].

### A.3 Experimental Setup

The plasma electron gun shown in Fig. A.1 is of a noticeably simple design. The cathode used was an open ended cylinder. Different from other hollow cathode guns, in which the body of the gun forms the well known cup shaped hollow cathode. The cylindrical cathode in this gun was coaxially encased within a closed cylindrical anode, with the only opening being the aperture. The electron gun relied on the formation of electron microchannels along the central axis of the cylindrical cathode to create the
beam. Because of this there was no requirement for a pressure differential between the discharge and beam target. However, a pressure differential was achieved by adding the required gas through the gun, and allowing it to diffuse into the target region via an aperture.

The electrode configuration of the gun was a 2\(\frac{3}{4}\) inch stainless steel tee piece, with a length of 125 mm and a 35 mm inner diameter. The two end flanges of the tee piece consisted of the gas feed-through and a metal plate with a central aperture. Three plates with of aperture sizes of 5 mm, 7.5 mm and 10 mm were used. The respective gas flow rates used were 10 sccm, 20 sccm and 30 sccm, for each aperture size. These correspond to target region pressures of 4 mTorr, 8 mTorr and 12 mTorr respectively. The target region pressure depended only on the flow rate of the hydrogen, not the aperture size. However smaller apertures created a larger pressure inside the gun for a given flow rate of hydrogen.

A 35 kV electrical feed-through was placed on the side flange of the tee piece, on which a cylindrical cathode (37 mm long and with an inner diameter of 27 mm) was mounted. The cathode was operated at a high voltage of negative polarity, all other metal parts of the experiment including the vacuum chamber were grounded. All of the metal pieces used in the gun were stainless steel. A glass insulator was placed in the port of the vacuum chamber to prevent the electron beam from being attracted to the chamber. In all of the experimental results shown in Fig. A.2, A.3, A.4 and A.5 a 50 mm long 26 mm diameter piece of glass was used. However, longer and thinner pieces of glass were tested in order to examine the effects
that the glass insulator had on the beam.

The discharge of the gun was powered with a 25 kV 45 mA regulated direct current power supply. The electron gun was only operated in a continuous mode and was not pulsed. To measure the pressure in the gun, the electrical feed-through was removed and replaced with a Pfeiffer type PKR - 251 full range cold cathode/pirani gauge. The internal chamber pressure was measured with a Speedivac model-812 Pirani gauge and the PKR - 251, when it was not in use on the gun. The vacuum chamber used was cylindrical, 2 m tall with a 0.4 m diameter and a domed top. The pumping system consisted of a Pfeiffer Balzer type TPH - 510 turbopump, in addition to a rotary backing pump. This arrangement achieved a background pressure of 0.2 mTorr. The internal pressure of the gun was varied between 35 - 190 mTorr, resulting in chamber pressures of 4 - 12 mTorr. Hydrogen was used for the gun characterisation. However nitrogen was used in one instance to test the effect of a different gas. The beam current was measured using a grounded copper plate placed 135 mm away from the gun aperture.

A.4 Results and Discussion

A.4.1 Current Characteristics:

![Figure A.2: Electron beam current as a function of discharge current for a range of electron gun pressures](image)

Figure A.2 and Fig. A.3 show the beam current as a function of discharge current and discharge voltage respectively. The ratio of the current measured by the plate to the discharge current was inversely
proportional to the discharge voltage, as shown in Fig. A.4. Due to the symmetry of this discharge, it was expected that the electron beam emerging from one side of the cylindrical cathode should contain approximately half of the discharge current. Consequently the maximum achievable beam current attained by the largest aperture is expected to also be 50% of the discharge current. The current that is measured by the plate is an underestimate of the beam current due to electrons being ejected from the surface of the plate. To obtain an estimate of the amount of underestimate of the current, the cylindrical cathode was placed inside the vacuum chamber. One end of the cylinder faced the vacuum chamber wall while the other end faced the current measuring plate. It was expected that the plate would measure approximately half of the discharge current. However, the emission current that was measured was lower than half of the discharge current by a factor of approximately 2 for a 2 kV discharge voltage, increasing to a factor of approximately 4 at 12 kV.

![Graph showing electron beam current as a function of discharge voltage for a range of electron gun pressures.](image)

Figure A.3: Electron beam current as a function of discharge voltage for a range of electron gun pressures.

The difference between expected and measured currents is due to surface emission of electrons created by the impact of fast neutrals, which were also present in the electron beam. The fast neutrals were produced via charge exchange reactions between fast ions and the background gas, as shown in Fig. A.1. Ions that were produced in the rear half of the gun were traveling in the direction of the cathode and aperture. When these ions undergo a charge exchange reaction, fast neutrals are produced that travel in the direction of the aperture. Some of these fast neutrals exited the gun via the aperture with the electron beam. All beam currents quoted in the results section of this appendix are the current measured directly...
by the plate, unless specifically stated. This is due to uncertainty in the spatial density profile of the fast neutrals and the effect of the electron gun aperture on reducing their incidence on the plate.

The current increased linearly for both discharge current and discharge voltage for all pressures and apertures. For aperture sizes of 10 mm and 7.5 mm a larger beam current was observed for increasing gun pressure, for a given discharge current and voltage. The 5 mm aperture showed the opposite characteristic of increasing beam current for decreasing gun pressure. Possibly indicating an optimum pressure for the formation of microchannels between 95 - 130 mTorr.

![Figure A.4: Ratio of beam current to discharge current as a function of discharge voltage.](image)

The 7.5 mm aperture was used to study the effect of nitrogen as the discharge gas. The results are shown in Fig. A.5. The discharge characteristics changed slightly in terms of discharge voltage, but the overall efficiency of the gun did not change. This suggests that the majority of the electron population was produced at the cathode by secondary emission and not by ionization of the background gas. Consequently, the majority of the electrons are expected to have the full discharge energy by the time they reach the field free region of the target area. As a result, a larger cathode would probably produce a larger current for a given voltage. Using a power supply that can produce a larger current may also be an effective way of increasing the gun output. From Fig. A.2 and Fig. A.3 it can be seen that the discharge current rose rapidly in terms of the discharge voltage, and this effect was reduced by decreasing the pressure. This result indicated that the plasma was operating in the abnormal glow discharge mode, and indicated that increased arcing was likely to occur by further increasing the voltage. Arcing was
observed in some instances.

Figure A.5: Electron beam current for close and far collection plates.

The amount of beam loss from the aperture of the gun to a grounded copper plate 130 mm away was measured by putting a 12 mm diameter circular plate 8 mm away from the aperture of the gun. The result is shown in Fig. A.5. There was no appreciable difference in the beam current for gun pressures of 60 mTorr and 80 mTorr with the 7.5 mm aperture, indicating no beam loss in the arrangement. However a significant decrease in the current measured on the plate was observed at a pressure of 95 mTorr. An increase in current on the close plate would be expected if the beam was striking the glass insulator, or diverging once it emerged into the chamber. The decrease is possibly caused by the radial profile of the fast neutrals changing with the pressure inside the gun. If more fast neutrals are striking the plate for an equivalent electron current then the measured current would decrease.

The largest beam current measured was 3.5 mA, for a discharge current of 45 mA. This is a current efficiency of 8%, or 14 mA and 31%, if the correction is made for the underestimate in the measuring method. Other electron guns have a current efficiency of between 30-100% [98, 99, 102, 108] and will produce a current of 14 - 45 mA for a discharge current of 45 mA. Due to the production of a symmetrical electron microchannel emerging from either side of the cathode, half of the discharge current will be traveling towards the back of the gun. This half of the current is never expected to emerge from the aperture, hence the absolute maximum current efficiency for this style of gun was expected to be at most 50 %. There are no error bars on Fig A.2 to Fig A.6 and Fig A.9 as potential sources of error shown
as inaccuracies in the electronic measurement systems were small and the error bars would not extend beyond the markers used to plot the data.

![Graph showing beam diameter vs. distance from glass](image)

**Figure A.6: Total electron beam width, up to 100mm from the insulating glass**

### A.4.2 Beam Characteristics:

A phosphorescent screen was placed at a distance of 150 mm from the aperture and 100 mm from the 50 mm long glass insulator. The beam showed a bright circular region, which increased in intensity towards the centre. The pattern and beam width was found to be independent of the size of the aperture used. The screen glowed brighter overall the wider the aperture used due to a larger electron current and energy. Since the beam width was not dependent on the aperture, the effect of the glass insulator was considered. The 26 mm diameter glass insulator was replaced with two smaller diameters of glass, 19 mm and 12 mm. Fig. A.6 shows the total width of the beam at three distances from the end of the glass insulator for the three different widths of glass. A photograph of the beam is shown in Fig A.7
The beam width given in Fig. A.6 was determined by using a metal ruler with a phosphorescent powder coating in the markers, shown in Fig. A.8. The smaller diameter glass produced a correspondingly narrower electron beam and the angle of beam divergence decreased for decreasing diameters of glass. The angle of divergence was $10^\circ$, $8^\circ$, and $8^\circ$ for the 26 mm, 19 mm and 12 mm diameter insulators. There
was no difference in the measured current for the two largest diameters of glass but there was a decrease in the current for the 12 mm diameter glass, by a factor of approximately $\frac{2}{3}$.

Figure A.8: Total electron beam width, up to 100mm from the insulating glass

The 50 mm long glass insulators were replaced with a 200 mm long 19 mm wide glass insulator. This reduced the beam width by approximately half at a distance of 100 mm and considerably reduced the angle of divergence to 2.5°. However, the current was also reduced by a factor of 2. This behaviour indicated that the glass had a focusing effect on the beam, probably due to the accumulation of surface charge. If the glass was only masking the electron beam then a decrease in current would be expected between the 26 mm and 19 mm pieces of 50 mm length. However, this was not observed. Additionally the decrease in current from the long piece of glass would be much larger if the glass had not resulted in some focusing. Other plasma electron guns can have smaller beam widths of 10 mm\cite{101}, or 2 mm\cite{106} with the aid of a magnetic lens. Other beams are wider\cite{109} with a total width of 120 mm. It should be noted that the reported beam width was the full width at half maximum (FWHM) of the beam. The total width of the beam is recorded as the phosphorescent markings were unable to indicate the internal structure of the beam, only the edges of the beam were distinguishable. This can be seen in Fig. A.8.

The beam energy was determined by deflecting the beam by a pair of 60 mm diameter Helmholtz coils, with the centre placed 80 mm away from the aperture of the electron gun. The energy of the beam was determined by the strength of the magnetic field and the amount of resulting deflection. This result is shown in Fig. A.9. The beam energy was equal to the discharge voltage, within the errors of the experiment. The equality of these energies is consistent with the hypothesis that most of the electrons produced in this discharge were produced at the cathode, and not by ionization. This hypothesis is also supported by the earlier result that used nitrogen as the discharge gas, shown in Fig. A.5.
An electron microchannel from an IEC plasma device has been used as an electron gun. This style of electron gun is simpler than conventional plasma cathode electron guns. It does not require an additional extraction, focusing or accelerating electrodes, or a magnetic field for the discharge or beam focusing. Due to the lack of these additional electrodes, the target pressure can be as high as the interior gun pressure, which was varied from 35 - 190 mTorr, while the target pressures varied from 4 - 12 mTorr. The pressure differential was created by feeding gas into the chamber via the electron gun. The current produced by the gun was measured as between 0.1 - 3 mA, for discharge currents of 1 - 45 mA and discharge voltages of 0.5 - 12 kV. However the actual current was found to be higher than the measured value due to the presence of fast neutrals in the electron beam. After allowing for this reduction, the actual range of beam currents varied from 0.2 - 14 mA. Using the corrected values this gun produced 5% of the discharge current for the smallest aperture and up to 31% for the largest aperture. While this design of electron gun is on the lower end of efficiencies of typical plasma electron guns, it is of considerably simpler design than typical electron guns.

![Figure A.9: Electron beam energy as a function of the discharge voltage](image-url)