The dependence of the virtual cathode in a Polywell$^{\mathrm{TM}}$ on the coil current and background gas pressure

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Floating potential measurements have been carried out on a Polywell$^{\mathrm{TM}}$ inertial electrostatic confinement device that uses magnetic cusps to trap electrons and establish a virtual cathode. In particular, the dependence of the floating potential on the coil current and background gas pressure was studied. The magnetic field coils were driven by a pulsed current supply and it was found that the virtual cathode could only be established within a narrow range of currents. In addition, it was shown that the magnitude of the floating potential increased with decreasing background gas pressure. It is conjectured that the depth of the virtual cathode and its lifetime are dependent on the magnitude of the injected electron current.

THE POLYWELL CONCEPT

The Polywell$^{\mathrm{TM}}$ fusion reactor concept was first invented by Bussard in 1983, and patented in 1989, 1992 and 2006 [1–3]. It is a fusion reactor concept that combines elements of inertial electrostatic confinement (IEC) [4–6] and magnetic confinement fusion. Spherical cathode grids are used in IEC systems to create electrostatic potential wells in order to confine energetic ions for nuclear fusion[7–10]. These systems have suffered from substantial energy loss due to ion collisions with the metal grid. The Polywell$^{\mathrm{TM}}$ concept[11–17] aims to replace the physical cathode with one that is formed by trapping energetic electrons in a magnetic cusp arrangement. The potential well would then accelerate monoenergetic positive ions to the centre [18], where the ions would either collide with other high energy ions to produce fusion or scatter through the well, at which point they will fall back in to the well, resulting in ion confinement.

The magnetic field configuration is created by pairs of opposing current loops each creating a cusp. In a cube configuration, these point cusps are arranged so that they sit around the faces of a cube, one pair on each axis. The magnetic field is zero at the center due to symmetry, creating a null point (Fig 1). Magnetic flux that enters the Polywell$^{\mathrm{TM}}$ through the coil faces is balanced by the fluxes leaving through the spaces between the coils. As a result there is a magnetic mirror effect, along the three orthogonal axes, on a particle located at the center. This field configuration has been labeled a wiffle ball by Bussard[14]. During operation, electrons are confined by reflection from the wiffle ball magnetic field configuration. Moreover, the number of collisions of electrons and ions with the magnetic field coils is greatly reduced due to deflection by local fields, which loop around the coils. The magnetic field geometries in the Polywell$^{\mathrm{TM}}$ are inherently MHD stable because they are everywhere convex toward the centre [11]. Collisional scattering and direct propagation through the field cusps is conjectured to be the major loss mechanism for electrons in the Polywell$^{\mathrm{TM}}$.

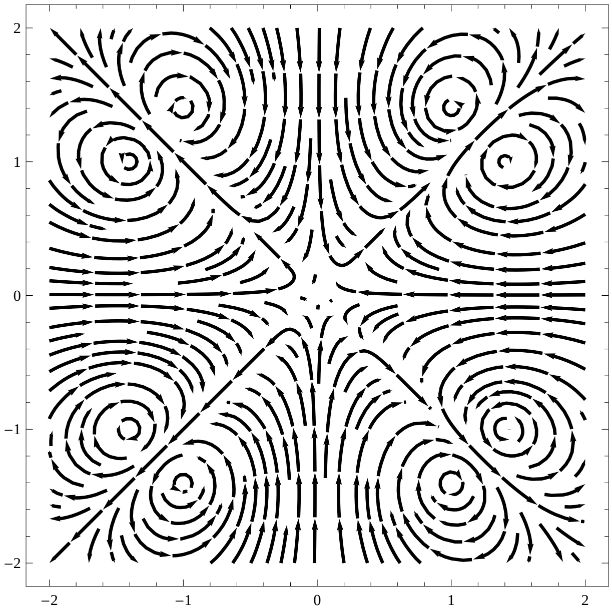

FIG. 1: Magnetic field lines inside the polywell when viewing the plane intersecting 4 of the 6 coils, in the cube configuration.

The overriding aim of all Polywell$^{\mathrm{TM}}$ and IEC research is to produce deep and sustained potential wells. Moreover, for the purpose of producing fusion, the dependence of the well depth on gas or ion density must be determined. To this end, in this paper we present results that give the dependence of potential well depth on background gas pressure. In addition we investigate the dependence of well depth on current in the magnetic field coils. These results have not been presented in previous literature about the Polywell$^{\mathrm{TM}}$.

EXPERIMENTAL SETUP

The Polywell$^{\mathrm{TM}}$ consisted of 10 turns of enamelled copper wires wound on 6cm diameter Teflon reels. The inner faces of opposing reels were separated by 6cm, as shown in Figure 2. The coils were driven by a pulsed current power supply that consisted of a 7.5mF capacitor bank, which

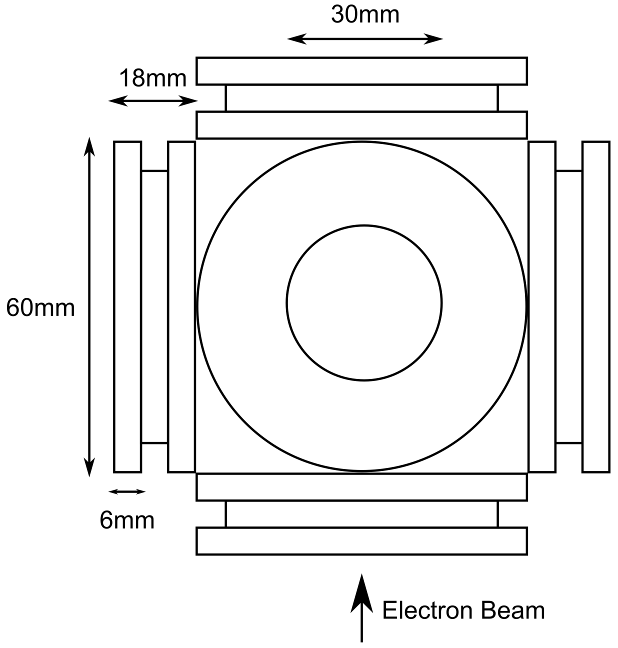

FIG. 2: Schematic of our polywell design, constructed from six identical circular teflon pieces. They have a major diameter of 6cm, and a hole punched out the middle with diameter 3cm. A groove 6mm wide and 6mm deep is cut around the outer edge to accomodate the copper wire. The six teflon pieces are held in place by aluminium angle brackets where two teflon pieces meet at an cube edge.

could be charged to a maximum voltage of 450V. The capacitors were discharged through a triggered silicon controlled rectifier in series with the field coils. A maximum peak current of 2.5kA was achieved with a pulse shape as shown in Figure 3. The peak current was varied between 200A and 2.5kA by changing the charging voltage applied to the capacitors.

Although this experiment is physically much smaller in scale than the original experiments by Krall and Bussard (known as the HEPS experiment [13]), the coil and power supply parameters have been deliberately designed to be in the same magnetic field regime. In the HEPS experiment the peak field in the cusps was 0.15T. Whereas in the smaller scale Polywell^{TM} described in this article the peak field in the cusps is 0.25T at currents of order 2kA and ten turns of wire in each coil, in fact slightly larger than in HEPS. However, it would be inappropriate to make direct comparisons between our device and that of the HEPS experiment because the physical scaling laws are currently unkown. Although Bussard and Krall [3, 11, 13, 14] claim to know the physical scaling laws, these results have not yet been published in the open peer reviewed literature.

The Polywell^{TM} was held by an aluminium cross beam, in the middle of a vacuum chamber 420mm in diameter. Electrons were supplied in a single, collimated monoenergetic beam from a cylindrical hollow cathode [19, 20].

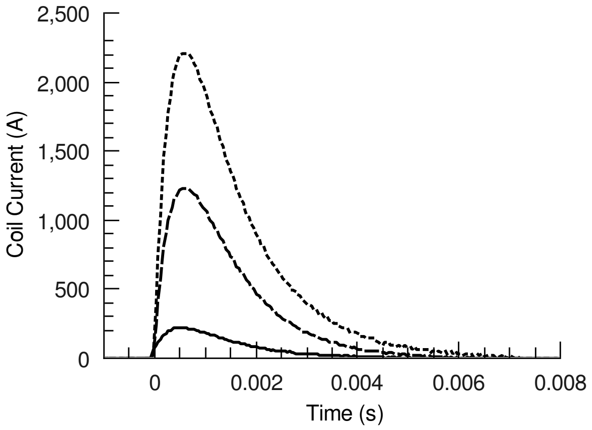

FIG. 3: Calibration of the current profiles through the polywell coils. These current pulses are attained by varying the voltage on the capacitor bank between 50V and 450V, giving a maximum current of nearly 2.4kA.

This method has many advantages over other possible electron guns, mainly its simplicity. The generation, acceleration and focusing of the electron beam all happens conveniently in one step whereas in a conventional electron gun setup, each of these processes has to be done separately. Bussard's most successful Polywell^{TM} (WB6) used the filament method to generate electrons. Their Polywell^{TM} was floated to a high positive voltage to accelerate the electrons, and attract them to the general polywell region, but was not capable of focussing them in to a beam. The fact that the polywell was floated up meant its coil power supply needed to float as well, creating a great deal of complexity in the custom built power supply design. This ultimately led to many uncontrollable arcing issues that destroyed Bussard's WB6 device [14].

By using a cylindrical hollow cathode the electron beam generation process is greatly simplified and simultaneously negates the need to float the polywell for electron acceleration, thus reducing the required complexity for the coil power supply. Although there are other anticipated beneficial effects of floating the polywell, this is left for another experiment because of the additional technical complexity required.

The electron energies were equivalent to the voltage supplied to the cathode, which was powered by a high voltage power supply delivering up to 20kV, in currents ranging from 1-20mA. The lowest beam energy possible was fixed at 6keV, determined by the lower limit of plasma breakdown in our operating pressure range. The hollow cathode was located 10cm from the polywell face, and the angle of beam incidence could be varried arbitrarily.

The reduced risk of arcing from the polywell to the chamber (potentially destroying the polywell structure and coil power supply) allows operation at pressures above Bussard's arcing limit [14]. However the hollow cathode also places a lower limit on the operating pressure due to the conditions required for plasma breakdown. Hence in this experiment pressures are limited to greater than 15mTorr. In future experiments this limit can be overcome by moving the hollow cathode to an adjacent injection chamber allowing a substantial pressure differential to be maintained, and subsequently allowing much lower operating pressures to be achieved.

A single ended langmuir probe was mounted on a flexible bellows allowing motion along the radial components of the Polywell. The floating potential on the langmuir probe was measured with a high voltage probe (Tektronix P6015) connected to an oscilloscope input (Tektronix TDS 2024B). Note that we will use the floating potential as a qualitative parameter to confirm the existence of a virtual cathode and its lifetime. No further interpretation of the results can be made at this stage because the electron energy distribution function is unknown and the discharge may not satisfy the quasineutrality condition since electrons are being injected into the confining space. Measurements of electron density and energy distribution will be left for future work. The pulsed nature of the electron confinement introduces a non-locality to the langmuir probe measurement, and thus presents a limitation on spatial resolution. The measurement of negative floating potentials in the confining region will also be referred to as a potential well, but a measurement of the true depth of the well will be left for future work.

The electron beam current was obtained from the cathode power supply, and pressure was measured using a Pirani gauge accurate to 10^{-4} Torr. The experimental error for each of these quantities is on the order of 5%. The current in the Polywell$^{\mathrm{TM}}$ coils was measured using a current transformer (IRF/60/D12) placed around one of the leads of the pulsed current supply.

RESULTS AND DISCUSSION

The dependence of potential well formation on magnetic field strength, gas pressure and electron injection energy was measured. Potential well formation as a function of magnetic field strength was measured by varying the current in the Polywell coils. Floating potentials of up to –250V were obtained for periods of several milliseconds, confirming the presence of a virtual cathode stable for at least on the millisecond time scale.

Figure 4 shows the two types of floating potential measurements observed in the pulsed magnetic field. For each current pulse shown in Figure 4 (a), there is a corresponding potential well profile displayed in Figure 4 (b). Figure 5 shows a range of potential wells measured over the 20-200A range of currents in the Polywell$^{\mathrm{TM}}$ coils.

Note that there is a non-linear increasing potential well depth in the range from 0 to ≈100A in Figure 5 (a), we will label this regime as class 1. For currents greater than ≈100A there is a linear decrease in potential well depth, designated as class 2. An example of the pulses leading to the class 1 potentials is shown as a dashed line in Figure 4 (b), whereas the class 2 data is shown as a solid line. The peak current in class 1 results is in phase with the minimum of the potential well. However, the class 2 results display a linearly increasing phase shift between the peak current and the potential well minima, as seen in the solid line data in Figure 4 (b).

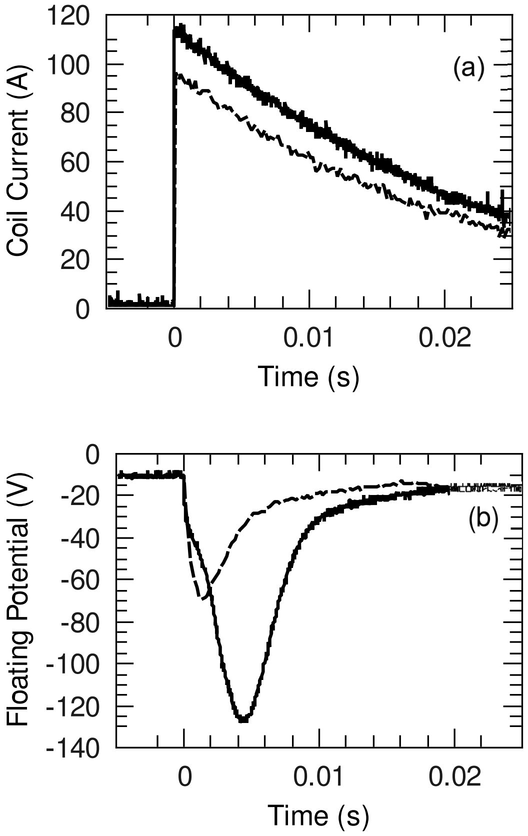

FIG. 4: Two typical potential well profiles. For a given current profile shown in (a) the corresponding potential well measured on the langmuir probe is shown in (b).

For the class 2 results that subsequently drift further out of phase with increasing coil current, the appearance of the minima always coincides with the class transition current of 100±10A, leading to the interpretation that this threshold is the peak magnetic field above which potential wells are no longer stable. When the peak magnetic field (and the equivallent coil current) is above this threshold, potential well formation is generally not observed until after the field has decayed down to the threshold value, producing an apparent phase shift.

A likely explanation for the observed magnetic field threshold is that the magnetic mirror effect will be active from both inside and outside the Polywell$^{\mathrm{TM}}$. The mag-

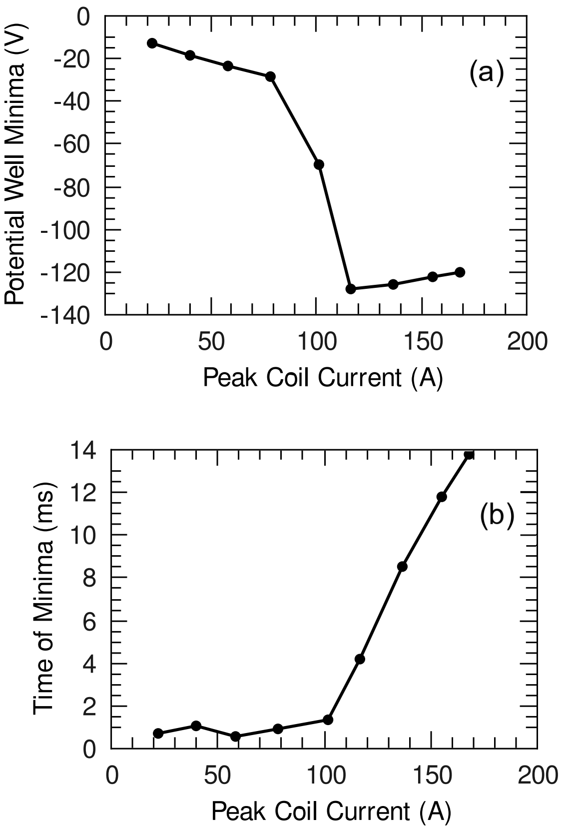

FIG. 5: (a) displays the minimum well depth observed as the peak coil current is varied from 20A up to 170A. For each current pulse measurement in (a), the corresponding time of the well minimum is plotted in (b).

netic mirror effect approach to fusion is based on the adiabatic invariance of the magnetic moment μ. First principles dictate that as long as the spatial variation of the magnetic field B is small with respect to a complete cyclotron orbit, μ will be a constant of motion [21]. Therefore, adiabatic invariance is satisfied if

$$\frac{v}{L_m} \ll \omega_c \tag{1}$$

where v is the particle velocity, L_m is the scale length for spatial variation of the magnetic field, and ω_c is the cyclotron frequency [21]. At the magnetic null in the middle of the Polywell$^{\text{TM}}$, the cyclotron radius becomes infinite and inequality (1) is not satisfied. However, in between the magnetic null and the polywell coils there is a transition point where the inequality is satisfied, and μ is an invariant of motion. When μ is invariant, the condition for reflection in a magnetic mirror [22] is approximately dependent on the ratio of the relatve magnetic field strengths:

$$\frac{B_0}{B_m} = \sin\theta_m \tag{2}$$

where B_0 is the weakest magnetic field point at which inequality (1) is satisfied [23], and B_m is the peak magnetic field located in the centre of the Polywell's coils. θ_m defines a loss cone in phase space, where particles with a velocity inside this loss cone will be lost from the system. Particles with a velocity outside the loss cone, are reflected from the coil face back into the centre of the device. Since μ is not invariant in the centre of the device, particles are diffused throughout veloctiy space every time they pass through the centre of the well. Hence many electrons are likely to undergo a substantial number of mirror reflections before escaping through a loss cone, leading to a net build up of trapped energetic electrons.

However, note that the mirror ratio equation (2) is only dependent on a difference between the magnetic fields and hence also applies to the magnetic mirror outside the Polywell$^{\text{TM}}$. The injected electrons are initially far away from the polywell, but as they approach the coil faces eventually transition into a region where inequality (1) is satisfied and μ is invariant. A fraction of the injected beam with velocities outside the loss cone are reflected from the Polywell$^{\text{TM}}$ faces. This idea predicts that there will be a threshold point where a potential well can no longer form since a substantial portion of the injected electron beam is now reflected and no-longer enters the device, explaining the observed phenomena.

Although the loss cones on either side of a single coil are identical, the unique geometry within the Polywell$^{\text{TM}}$ leads to a potentially greater number of mirror reflections in the core of the device, and hence is theoretically conjectured capable of forming substantial potential wells.

Gas pressure and injection energy

Potential well formation as a function of injected electron energy was measured at three pressures (15mTorr, 25mTorr and 35mTorr), whilst keeping the peak coil current constant at 625±25A. Figure 6 shows the results for only two lower pressures, since potential wells completely disappeared at 35mTorr in all data sets. As pressure is decreased from 25mTorr to 15mTorr, the potential wells are consistently deeper, suggesting that the achiveable well depth is dependent on pressure.

Because of the relatively high background gas density, it is likely that neutral gas is being ionized by the incoming electron beam and the newly created ions decrease the potential well created by the electrons. At pressures of 20mTorr, the ionisation mean free path is $\approx$ 5m. Although this is much larger than the size of the chamber, electrons were trapped for many milliseconds in the Polywell$^{\text{TM}}$ core. This implies that the distance they travelled is larger than the mean free path and hence the production of ions by the trapped electrons must be considered as a mechanism for reducing the well depth. Thus, increasing the background gas pressure would predict a reduction in the

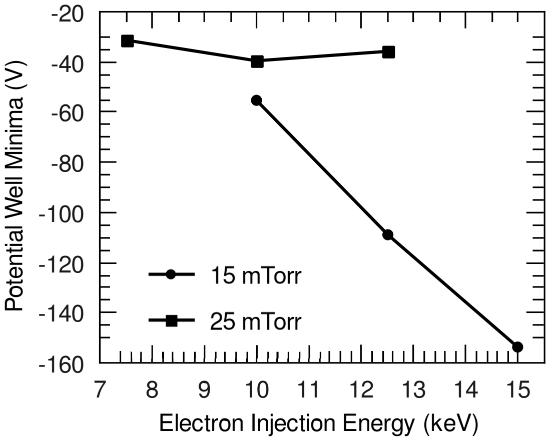

FIG. 6: Well depth as a function of injection energy, at a constant coil current of 625±25A. Data was measured at two different pressures, 15mTorr and 25mTorr. Well depths at 35mTorr were deemed too small to be significant.

attainable well depth, explaining the observed results.

It should be possible to reduce the background gas pressure in to a regime where background gas ionisation is not significant enough to greatly reduce the potential well created by the electrons. However this would need to be balanced with the need to operate at higher ion densities for larger fusion reaction rates.

Krall and Bussard [13] reported that it is possible to attain potential well depths equal to the energies of the injected electron beam, which would predict potentials on the order of kVs in our experiment. Although there is a near linear increase in well depth with respect to injection energy in the 25mTorr data set in Figure 6, the magnitude is lower by two orders of magnitude.

However the Krall and Bussard experiment [13] used electron guns with energies of 5-10kV at 5-15A, whereas the hollow cathode in our experiment produced comparable energies limited to 10mA in steady state operation. The factor of 100 difference between the experimental well depths found by Krall and Bussard [13] and our experiment is approximately equivalent to the difference between the injection currents used, making electron injection current the likely limiting factor. This strongly suggests future Polywell$^{\mathrm{TM}}$ designs will need to be capable of supplying significantly greater injection currents if we are to achieve the deep potential well depths required for IEC.

CONCLUSIONS

The dependence of the virtual cathode lifetime on coil current and background gas pressure has been measured in a Polywell$^{\mathrm{TM}}$ IEC device. It was shown that stable virtual cathodes were produced for several milliseconds. The lifetime of the cathode was derermined by the shape and duration of the coil current. Consequently, this implies that currents of increasing duration will increase the lifetime of the virtual cathode.

It was also shown that the virtual cathode does not form outside of a narrow range of coil currents in this design. We conjecture that this is due to deflection of the electron beam from the coil faces.

Producing significant fusion reaction rates will require substantially deeper potential wells. We expect that improved performance can be observed in a Polywell$^{\mathrm{TM}}$ of this design by increasing the magnitude of injected electron current, and decreasing the background gas pressure. Both of these goals could be achieved by moving the electron gun to an adjacent chamber where differential pumping can be used to maintain a substantial pressure difference. In addition, it will be technically easier to generate large electron currents from a plasma source than the alternatives such as thermionic emission.

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