Potential Well Structure Associated with the Periodically Oscillating Plasma Sphere (POPS)

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I. Abstract

This study investigates concepts behind inertial electrostatic confinement (IEC) fusion. Increasing overall fusion output requires sufficient plasma temperature, confinement, and density. Operating an IEC device using a new scheme called the periodically oscillating plasma sphere (POPS) may solve many problems that limit other IEC systems to low gain. Here, the POPS concept is introduced. Measurements pertaining to potential well formation and charge density are taken and analyzed. These measurements confirm that conditions can be created for POPS to exist.

II. Introduction

IEC offers a highly efficient means of producing fusion power. IEC produces fusion by confining plasma with either electrostatic fields or a combination of electrostatic and magnetic fields. These electrostatic fields form a potential well structure that can confine ions. Figure 1 displays an IEC device in operation.[1]

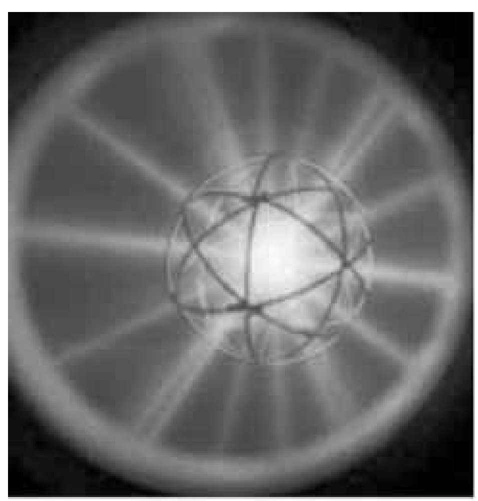

Figure 1: Fusion in an IEC Device

IEC's approach differs from the more mainstream fusion technique, magnetic confinement, which is limited by particle and energy diffusion across a magnetic field.[2] Therefore, IEC devices can be made much smaller (~ 1 centimeter to 1 meter). In magnetic confinement, the average plasma density and subsequently fusion power:

$$\mathbf{P \propto n^2} \qquad \textbf{(1)}$$

where P = fusion power and n = plasma density scale upward in real space.[3] Increasing a magnetic confinement device's size results in higher fusion output power.[1,4] In contrast, one can show using Poisson's equation:

$$\nabla 2\varphi = \varepsilon o \rho \quad (2)$$

where φ = potential (V) and ρ = charge density (C/m^3) that the net fusion power for an IEC device scales as the inverse of the device radius.[5] Decreasing an IEC device's size also results in higher fusion output power.[1,4] However, one problem of making an IEC device small is vacuum breakdown between electrodes. It is very difficult to achieve field strength approximately 50-100 kV/cm without causing arcing. The maximum field strength is governed by the Paschen curve. Because IEC does not require large magnets and has the convenient size of a basketball, an IEC device achieves a high-power fusion density in a lightweight, compact device.

If one wishes to increase fusion output power, one must increase the average plasma density.[3] Typically, IEC devices have a low-average plasma density, which results from the gradient scale length for the electric field not being greatly different from the effective plasma Debye length[2] — a measure of the plasma shielding length.[3] Debye length equals:

$$\lambda = ((KT_e)/(4\pi ne^2))^{1/2} \quad (3)$$

where λ = Debye length, K = Boltzmann's Constant, T_e = electron temperature, n = density, and e = charge of electron. This paper will illustrate the theory behind a new method of operating IEC devices that may enhance IEC performance. Here, an oscillating plasma sphere that periodically compresses the plasma to high densities and temperatures replaces the usual ion beam setup. This new method is POPS. The following pages detail data pertaining to potential well structure to verify that conditions can be created for POPS to operate.

III. Potential Wells

IEC uses strong electric fields to accelerate and confine ions for fusion. It differs from pure electrostatic confinement by overcoming Earnshaw's plasma confinement limit.[6] This limit states that a single charge acted on by electric forces alone cannot rest in stable equilibrium in a static electric field.[6] IEC accomplishes this by having neutrals interact and allowing the inertia of the ions to be propelled into the center of the device.

IEC devices often consist of two hollow, concentric, semi-Gaussian electrodes. The innermost electrode is permeable to charged particle flow, where the flow produces a steady saturated electrostatic potential well capable of confining oppositely charged particles.[3] Electrons injected symmetrically into the hollow, concentric, semi-Gaussian anode produce a negative potential well at its center. This potential well confines positively charged ions.[3]

The IEC device that was used in collecting data for the experiments discussed here consists of two grids, noted as the middle and outer grids with respect to their position from the center of the device. The purpose of these grids is to create a spherical ion source internal to the device by ionizing the background gas.[8] The middle and outer grids are anodes.

To increase electrons into the system, electrons are extracted from six electron guns located at the edge of the device's grounded shell, which acts as a cathode. Inside the grounded shell, an extractor grid acts as an anode. This grid spreads the electrons from the electron guns uniformly over the inside of the grid, which from Poisson's equation forms a harmonic oscillator potential inside the grid.[2] The electrons are farther dispersed as they move toward the outer and middle grids. Likewise, these electrons ionize the background gas that was backfilled into the system.[9]

IV. Periodically Oscillating Plasma Sphere (POPS)

The POPS concept can be derived from a combination of one-dimensional fluid equations for ions and Poisson's equation.[2] As discussed earlier, if the charge density is uniform, meaning the electrons from electron guns are spread uniformly within the extractor grid, then a harmonic oscillator potential forms:

$$\varphi = \varphi_o(1 - (r/r_{grid})^2) \quad (4)$$

where φ = electrostatic potential and r^{grid} = the radius of the extractor grid. The ion dynamics from this harmonic oscillator potential can be calculated from the following equations:

$$\partial n_i/\partial t + (1/r^2)\partial/\partial r(r^2 n_i v_i) = 0 \quad (5)$$

which is the conservation of mass, where n_i = ion density, t = time, and v_r = ion radial velocity;

$$(m_i n_i)\partial v_r/\partial t + (m_i n_i v_r)\partial v_r/\partial r = q_i n_i Er - \partial P_i/\partial r \quad (6)$$

which is the fluid equation of motion, where qi = charge of an ion, E_r = radial electric field, and P_i = ion pressure;

$$P_i/(n_i)^{5/3} = \text{constant} \quad (7)$$

which is the ideal gas law;

$$(1/r^2)\partial/\partial r(r^2 E_r) = 4\pi(q_i n_i - en_e - en_b) \quad (8)$$

which is the Poisson equation, where e = charge of an electron, n_e = thermal electron density, and n_b = background electron density generated by the grid and electron guns;

$$E_r = -\partial\varphi/\partial r. \quad (9)$$

A set of self-similar solutions exists for these equations. However, the calculation of these self-similar solutions is beyond the scope of this paper. These solutions reduce the problem to the following ordinary differential equation for the plasma radius:

$$d^2a/dt^2 + (4\pi q_i^2 n_b/m_i)a = (n_o(a_o/a(t))^3 - n_e)a + (2P_o/m_i a_o n_o)(a_o/a(t)). \quad (10)$$

[3]

If one ignores the right-hand side of equation (10), it reduces to a simple harmonic oscillator equation. When the potential on the extractor grid is large compared with T_o, which is the initial temperature, equation (10) reduces to a simple harmonic oscillator equation, except in the region of $a(t)/a_o << 1$:

$$d^2a/dt^2 + (4\pi q_i^2 n_b/m_i)a = 0. \quad (11)$$

Phase locking of all of the ions in the system is achieved by driving the system near one of the resonances.[2] The lowest resonance is:

$$\omega = 2\omega_h = 2(4\pi q_i^2 n_b/m_i)^{1/2}. \quad (12)$$

A harmonic oscillator driven at resonance will phase lock to the driver.[2] In this IEC system, the oscillation in n_b can be provided by oscillating the extractor grid potential.[2] From examining the equations, one notes that because the ions phase lock and motion pertaining to a simple harmonic oscillator is independent of amplitude, all ions with a phase-locked period of oscillation simultaneously arrive at the center as the plasma collapses upon itself.

V. Experimental Setup

The experimental device consisted of a 12-inch-radius stainless steel, spherical, vacuum shell that was grounded. Mounted to six outside ports on the spherical, grounded shell were six electron guns. On the inside wall of the spherical, grounded shell was the stainless steel extractor grid. The extractor grid was made of fine molybdenum mesh and was mounted close to the wall of the spherical, grounded shell near the six ports, where electrons would be emitted from the six electron guns. Inside the extractor grid was the 4-inch radius stainless steel outer grid. The outer grid was a spherical, semi-Gaussian anode biased with respect to the grounded shell. The outer grid had approximately 95 percent transparency. Inside the outer grid was the 2.5-inch-radius stainless steel middle grid. The middle grid was a spherical, semi-Gaussian anode biased with respect to the grounded shell. The middle grid had approximately 90 percent transparency. Separate voltage regulated power supplies maintained well-filtered stable anode potentials between each electron gun, extractor grid, outer grid, and middle grid. The vacuum system consisted of a turbo pump (150 liters/sec) in conjunction with a liquid nitrogen cold trap. This was backed up by a mechanical roughing pump. This vacuum system provided a base pressure less than 1×10^{-8} Torr.

The operating voltages and currents were as follows. The electron guns were consistently operated at 10 V and ~ 5.8 A. Any attempt to take the electron guns to a higher power resulted in melting the electron guns. The extractor grid over each electron gun was consistently biased at 100 V. The current found in each extractor grid varied between which electron gun it covered. These differences can be attributed to how each electron gun was manufactured. Yet the current differences had no affect on creating a uniform electron distribution. The current differences affect only the total current being supplied to the plasma. The current found in each extractor grid varied between ~ 60 mA and ~115 mA. Potential well data was taken by varying the middle grids. Therefore, the outer grid was consistently biased

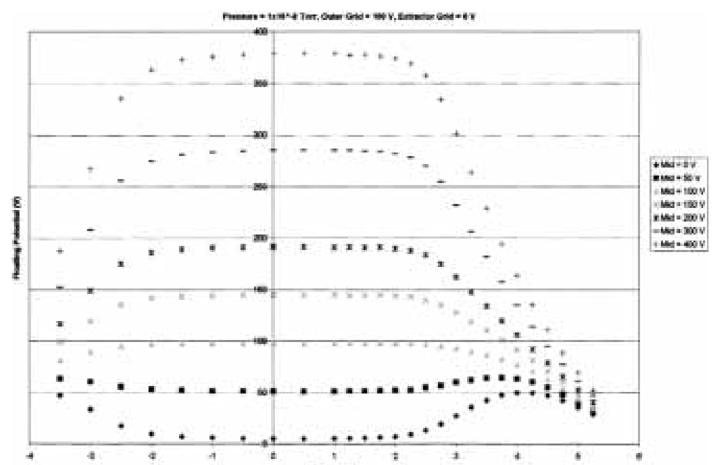

Figure 2: Vacuum Field Potential Versus Radial Position

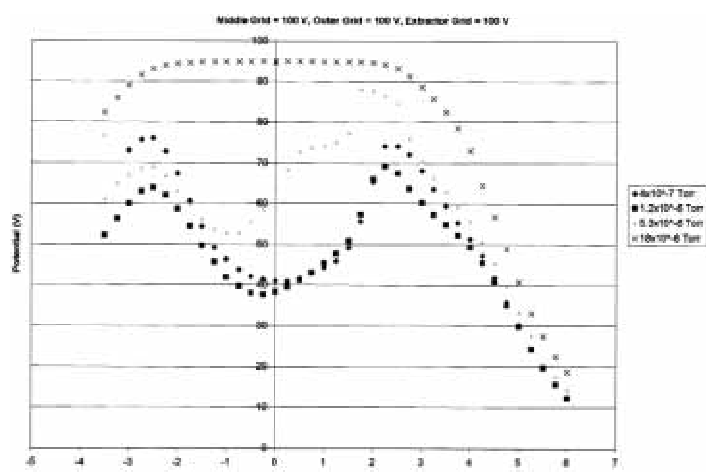

Figure 2: Vacuum Field Potential versus Radial Position

at 100 V, and the middle grid was biased at 0 – 400 V. Never was the extractor grid or any other grid driven at an oscillating potential. These experiments were set up only to verify if the proper conditions for POPS could be created.

Data pertaining to the potential well structures was collected using a hot emissive probe. The hot emissive probe consisted of a tungsten filament spun into braided copper wire that was shielded with nonconducting alumina tubing. The hot emissive probe was consistently heated with a heater current equal to 960 mA. At this current the tungsten filament emitted electrons, and the plasma potential could be measured using the hot emissive probe. The tungsten filament loop extended approximately one-third of an inch outside of the alumina tubing. The entire probe consisting of the tungsten filament and the alumina tubing was ~20 inches. For taking measurements of the potential well profile, the hot emissive probe could be moved to different radial positions across the diameter of the IEC device. From this, one could view how the potential profile changed with radial position. Likewise, one could construct plasma density using the data collected on the potential well profiles and Poisson's equation.

VI. Results

Figure 2 illustrates the vacuum field potential versus radial position for varying middle grid potentials. A vacuum field occurs when there are no electrons being injected into the system via the electron guns and there is no backfilling the system with any gas. Therefore, the operating pressure for this particular experiment was very low ($1x10^{-8}$ Torr). Only the outer grid is biased at 100 V, and the middle grid is biased at varying potential indicated in the graph. For middle grid potentials greater than or equal to the outer grid potential, one notes a consistent filling of the potential well that would exist at the center of the device. This is the result of there being relatively no negative space charge from the emitted electrons existing at the center of the device. Furthermore, for middle grid potentials less than the outer grid potential, one notes a consistent widening of the potential well that would exist at the center of the device. One also notes that in this case the potential decreases as one moves from the radial position of the outer grid (radius = 4 inches) toward the center of the device. This is simply the result of going from 100 V on the outer grid to a lesser potential on the middle grid. Yet, when one gets to the radial position of the middle grid and continues inward toward the center of the device, one notes a consistent potential across the center of the device. This is simply the result arrived at earlier for the middle grid potential greater than or equal to the outer grid potential.

Figure 3 illustrates the plasma potential versus radial position for different pressures. Here, each grid (extractor grid, middle grid, and outer grid) is biased at 100 V. This graph shows the potential well structure's dependence on pressure as one moves a hot emissive probe radially across the diameter of the IEC device. The pressure used for these plots correspond to a low, medium, high, and very high operating pressure. The pressure used in each of these plots was $4x10^{-7}$ Torr, $1.2x 10^{-6}$ Torr, $5.3x10^{-6}$ Torr, and $18x10^{-6}$ Torr. At low pressure ($3x10^{-7}$ Torr), one sees a very smooth, parabolic potential well, which is essential for confining ions. This plot demonstrates that there are sufficient electrons being injected into the center of the device to create the potential well structure. If one measures the depth of the potential well, which is defined as the change in plasma potential from the relative minimum near the center of the device to the relative maximum near the middle grid wire (~ 2.5 inches from the center of the device), one finds this depth equal to approximately 35 V. If the pressure is increased to $1.2x10^{-6}$ Torr, the plasma potential starts becoming less smooth. More importantly, the potential well becomes more shallow. Here, the plasma potential has decreased to approximately 30 V. If the number of electrons being injected does not increase while the pressure increases, then the potential well will decrease because there are more ions being created from electrons ionizing an increased amount of background gas. With increased pressure ($5.3x10^{-6}$ Torr), the plasma potential becomes very chaotic. The potential profile in the graph lacks all of the smoothness associated with the potential well profile occurring at $4x10^{-7}$ Torr. Likewise, in this graph it is very difficult to determine the potential well depth. If one measures the potential well depth from the relative minimum near the center to the relative maximum on the left-hand side of the plot, one finds a well depth of approximately 15 V. However, on the right-hand side, it is difficult to discern if a potential well has formed completely due to the large number of ions in the system. One must question the stability of this potential well. Lastly, if one increases pressure to $18x10^{-6}$ Torr, there is no potential well structure. This is what one expects with all of the ions in the system. All of the ions completely fill in the potential well.

The POPS scheme requires a harmonic oscillator potential and a uniform density of electrons

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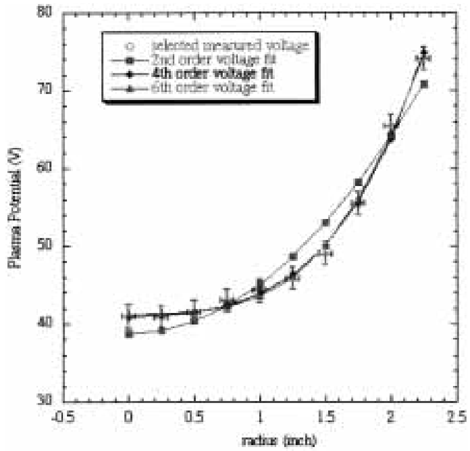

Figure 4: Plasma Potential with Polynomial Fitting

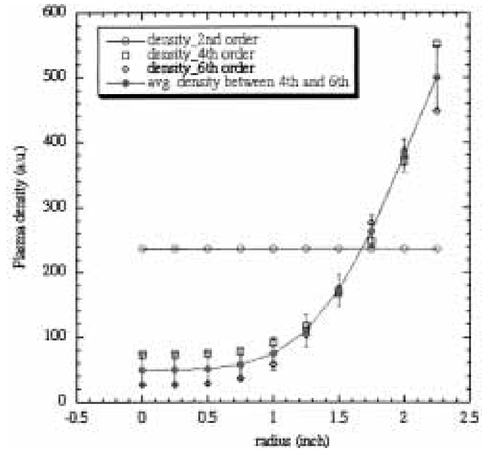

Figure 5: Plasma Density Profile with Polynomial Fitting

to be present in the system. In Figure 3, there was a symmetrical, parabolic, and deep potential well formed, which could satisfy the requirement of a harmonic oscillator potential. To verify if this is a uniform density of electrons existing throughout the system, one would have to utilize the Poisson equation, where one could construct the plasma density from the data collected about the potential well profiles. Using a technique employed by Nebel and Park at Los Alamos National Laboratory, where even order polynomials are used to fit the potential profile, one may subsequently arrive at the density profile. (See Figures 4 and 5.) Figure 4 is the potential profile taken at $4x10^{-7}$ Torr, which was plotted in Figure 3. However, it is fitted with even order polynomials. Figure 5 is the subsequent density profile calculated using the potential profile plotted in Figure 3, but fitted with even order polynomials. Figure 5 illustrates that the electron density is uniform throughout the system. This is necessary for the POPS scheme to be employed.

VII. Conclusion

This paper has described an IEC device and indicated some of the current problems (especially low plasma density) involved with operation of such a device. A possible solution to the low plasma density problem is a new means for operating an IEC device, POPS. We have examined the ion dynamics equations needed for modeling POPS, which allows for a periodical collapse of all of the ions in the system to a point at the center of the IEC device. This collapse is achieved by placing all of the ions in the system within a parabolic potential well that is driven at a resonant ion frequency. Eventually, all of the ions in the system phase lock to the driver because all of the ions in the system have the same frequency of oscillation, which is independent of their energy.[2]

There are certain conditions necessary for POPS to occur. These include having a harmonic oscillator potential within the IEC device and a uniform density of electrons within the extractor grid. In examining if one can create these required conditions for POPS to occur, it has been experimentally verified that one can create deep parabolic potential wells needed for confining ions, and one can also create a uniform density of electrons within the extractor grid. Although this paper demonstrates that one can create conditions necessary for POPS to occur, this paper does not provide any direct evidence that POPS is actually taking place. Providing direct evidence that POPS is actually taking place by measuring the ion frequency and amount of neutrons produced per second is the subject of current research.

VIII. Acknowledgments

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