THE PENNSYLVANIA STATE UNIVERSITY
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DEPARTMENT OF MECHANICAL AND NUCLEAR ENGINEERING

A METHOD FOR ACTIVE SPACE CHARGE NEUTRALIZATION IN AN INERTIAL ELECTROSTATIC CONFINEMENT (IEC) NUCLEAR FUSION DEVICE

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ABSTRACT

Recent inertial electrostatic confinement (IEC) fusion concepts are discussed and their shortcomings noted. Ion space charge is substantiated as a significant hindrance to high efficiencies, so a method for space charge neutralization in an ion-injected IEC device is proposed. An electrostatically-plugged magnetic trap is used to confine electrons in the core region of a planar electrostatic trap for ions. The electrons act to dynamically neutralize the space charge created by converging ions for the purpose of increasing achievable core density and fusion rates. An electrostatic trap utilizing this method of neutralization is termed the plasma-core planar electrostatic trap, or PCPET. COMSOL Multiphysics 4.3 is used to model the electromagnetic fields of the PCPET and compute lone ion and electron trajectories within them. In the proper configuration, ions are shown to be stably confined in the trap for many hundreds of oscillations, potentially much longer. Electrons are confined virtually infinitely in the central electrostatically-plugged cusp. For both species, upscatter into source electrodes seems to be the dominant loss mechanism. Adjusting the electron energy and behavior in the core to provide the optimum neutralization for ions is discussed. Ion synchronization behavior can be controlled with RF signals applied to the anode. Two operational modes are identified and discriminated by the state of ion synchronization. Further experimentation is needed to determine which mode produces the optimal neutralization and fusion rate. An experimental prototype PCPET is constructed out of 3D-printed PLA and machined aluminum.

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ACKNOWLEDGMENTS

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Chapter 1

Introduction to Inertial Electrostatic Confinement (IEC) Fusion

A novel method of plasma confinement for fusion applications involves the primary use of electric fields (as opposed to magnetic fields) to accelerate and trap charged particles. First studied in the 1960s by Robert Hirsch and Philo Farnsworth [Hirsh, 1967], the simplest configuration consists of a single spherical mesh cathode concentric within a larger, spherical vacuum chamber that is grounded, as shown in Figure 1. In this thesis, the single-grid configuration is referred to as a traditional or first-generation IEC device.

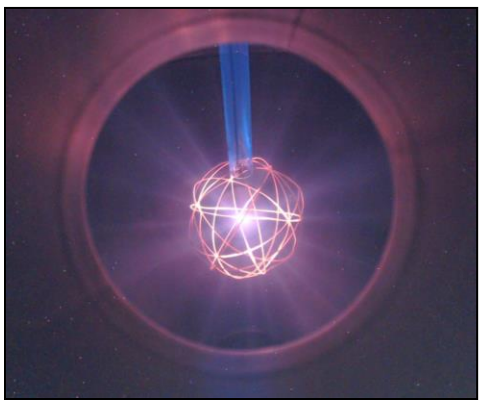


Figure 1: A traditional "fusor" IEC device [FuseNet, 2017]

When a very large negative electric potential, typically negative tens to hundreds of kilovolts, is applied to the cathode, a "potential well" results, as shown in Figure 2. This well can confine ions with energies as high as the cathode potential in electron volts on oscillatory trajectories through the cathode grid. In this discussion, "ions" usually refers to positive deuterium ions, as deuterium (D–D) is the most common fusion fuel studied in recent experiments. Other fusion fuel combinations include deuterium–tritium (D–T), deuterium–helium-3 (D–^{3}He), and proton–boron-11 (^{1}H–^{11}B). Of these, D–T fusion reactions have the largest cross-section at relevant energies [Miley, 1974], though the radioactivity of tritium makes its use more problematic in IEC experiments.

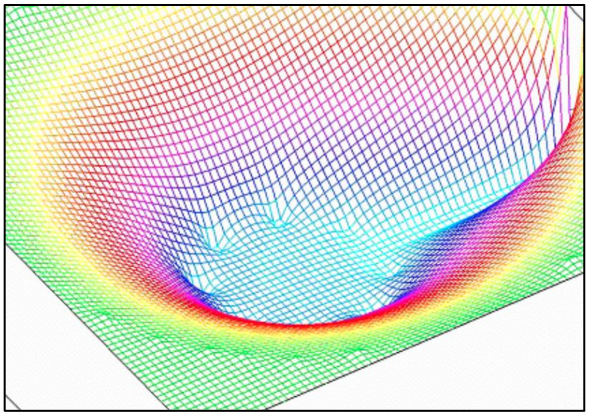


Figure 2: Electric potential map of a traditional ion-injected fusor [McGuire, 2007]

Positive fuel ions are created from a dilute neutral gas throughout the chamber volume by a type of glow discharge between the grounded vacuum chamber and the low-potential cathode [McGuire, 2007]. Typically, the dilute gas is deuterium (D_2) at a pressure of a few milliTorr. These ions are accelerated towards the cathode where they may pass through gaps in the cathode grid and intercept ions coming from other regions of the chamber. The spherical compression of cascading ions leads to a high-density core in the center of the cathode. It is in this region where high-energy ions can fuse, elastically scatter, or miss other ions entirely. Ions that miss or scatter can exit the cathode through another gap, where the radial electric field slows them and re-accelerates them to the cathode for another pass. Ions that fuse produce MeV-energy nuclei, which easily surmount the keV potential well before imbedding themselves in the chamber walls. As with any fusion scheme, neutrons tend to be the largest radiation concern with IEC devices, since they are of high-energy and can easily pass through the chamber walls and the surrounding atmosphere. IEC fusion distinctly differs from other fusion concepts in that it does not seek “ignition”—that is, using high-energy fusion products to heat the fusing ions. The fusion products are free to stream outwards, making IEC a strong candidate for direct energy conversion [Moir, 1977].

Overview of Thesis

This thesis first addresses the recent attempts to improve on the performance of the traditional IEC device. Chapter 2 discusses the problems that must be solved in these attempts, if the fusion efficiency is ever to reach levels of high applicability. The second-generation IEC devices reviewed in Chapter 3 show many commonalities that illustrate the requirements for more efficient IEC fusion. Ion space charge is substantiated as a fundamental hindrance to performance, so Chapter 4 outlines the conceptualization of an IEC design that attempts active neutralization of space charge. The concept is termed the plasma-core planar electrostatic trap, or PCPET. Chapter 4 also includes simulations done with the PCPET in COMSOL Multiphysics, which confirm its similarities to other advanced IEC designs. However, experimentation on a prototype is needed to truly test the functionality of the PCPET. Chapter 5 outlines the construction of the first PCPET prototype, and concludes with plans for initial experimentation in April 2017. The implications of IEC technology are reviewed briefly in Chapter 6, after conclusions concerning further studies with the PCPET.

Chapter 2

Problems with Traditional IEC Experiments

The “traditional” IEC configuration, unfortunately, is plagued by a number of fundamental problems that hinder it from having a Q-value (E_{out}/E_{in}) higher than about 10^{-4}, even at high input powers and precise geometry [McGuire, 2007]. Even at high input power, the fusion rate of these devices is often unusable. In other words, to scale the fusion rate to magnitudes useful for non-power applications, the input power would have to be unrealistically large. The fundamental problems that restrain the efficiency of first-generation IEC devices are discussed in this chapter.

Ion Grid Impact

The foremost problem with single-cathode IEC devices is high-energy ion impact with the cathode grid [Miley, 2014]. Grid wires introduce asymmetry in the potential well (see Figure 2) and defocus ions, causing them to build up angular momentum about the center of the device and quickly intercept a grid wire. Another major problem is the high voltage stalk supporting the cathode, which is actually the primary defocusing mechanism for ions [Miley, 2014]. A large number of ions wind up impacting the stalk, which is at the same potential as the cathode.

Ion impacts with cathode materials not only remove energy from the system, but also convert it to heat in the cathode. Heating of the cathode can lead to unwanted thermionic emission and distortion/melting of the grid wires. As shown in the next chapter, electrostatic ion optics or magnetic shielding must be employed to discourage ions from impacting the cathode. This increases ion lifetime and improves the efficiency of the device.

Operation Pressure

Traditional IEC devices are operated in the milliTorr range [McGuire, 2007], which provides sufficient neutral density for plentiful ion production through ion and electron impacts with deuterium molecules—a sort-of glow discharge between the chamber and cathode. However, the mean free path for a deuteron in 1 mTorr of deuterium gas is less than a meter [Rohlf, 1994]. Thus, an ion might complete only a few dozen oscillations through the cathode before it impacts a neutral gas molecule. A large energy sink in traditional IEC devices is charge exchange collisions [Isler, 1994], in which a high-energy ion impacts a neutral gas atom. This results in a high-energy neutral and a thermalized (and useless) ion. The neutral impacts a surface and the energy is lost as heat. Another possible outcome of an ion–neutral collision is fusion of the ion and the atom's nucleus. Though much less probable than charge exchange, these "beam–background" fusions actually comprise the majority of the fusion output with traditional IEC devices [Miley, 2014].

Ion collisions with neutral gas and the cathode grid/stalk result in an ion lifetime of only about 1–10 oscillations through the well. Thus, most ions undergo not nearly enough high-energy collisions with other ions to fuse before their energy is lost as heat. The ion lifetime must be dramatically improved if a significant fraction of the ions are to fuse, and a useful fusion output is to be obtained.

Beam–Background vs. Beam–Beam Reactions

As mentioned in the previous section, beam–background reactions are a prevailing interaction in IEC devices. They include beam–background fusion, which is a large portion of the fusion output in traditional IEC devices due to the high background gas pressure. Beam–background must be distinguished from beam–beam fusion, which occurs in the center region of the cathode where high-energy ion trajectories intersect. It can be shown that beam–background fusion output scales linearly with the "total ion current"; that is, the ionization current multiplied by the average number of ion recirculations through the cathode [Miley, 2014]. Beam–beam fusion output scales with the square of the total ion current. Thus, to achieve much higher fusion outputs, it is desirable to maximize beam–beam reactions rather than beam–background. McGuire proved that it would be nearly impossible to reach breakeven fusion rates simply by scaling beam–background reactions because charge exchange is so much more probable than beam–background fusion [McGuire, 2007].

Significantly reducing the background neutral density allows much higher ion lifetimes and minimizes undesirable beam–background reactions, such as charge exchange. By increasing the ion lifetime, beam–beam reactions become the more dominant process. However, beam–beam reactions are hindered by another fundamental problem, space charge.

Space Charge Limitations

Space charge in the context of IEC devices refers to the ability of charged particles to distort an external electric field when present in sufficiently high densities. In the core region of an IEC device, high ion densities are desirable for high fusion rates. However, the high ion densities can result in inflation of the electric potential in the core region, raising it by several kilovolts under some conditions. This "spike" in the core potential repels oncoming ions such that their velocity in the high-density region is lower, lowering the probability for fusion. It also acts to defocus the ions from radial paths, lowering their confinement time and imparting angular momentum to the ions about the center of the device.

Ion space charge places a fundamental limit on achievable ion densities/temperatures and is extremely detrimental to IEC device performance. It would seem the only way of mitigating the space charge effect is to introduce electrons to the core, which would be attracted to the space charge of the ions. The electrons could oscillate through the potential spike in the same way the ions oscillate through the potential well. If enough electrons are introduced, they may create a space charge of their own, which serves to counteract that of the ions, and create a potential well within the potential spike created by the ion space charge. Ions could then oscillate in this second potential well. In theory, an infinite series of alternating potential wells and spikes could be created, nested within each other. Hirsch termed these structures “poissors”, and hoped their formation would result in mitigation of the space charge problem and thus high fusion rates [Hirsh, 1967]. Unfortunately, when the ions and electrons collide with each other and develop angular momentum, the poissor structures are hindered. Only one nested potential well has been observed experimentally in a single cathode device, termed the “double well” [Miley, 2014]. The production of this double well as the ion current increases in a traditional fusor is shown in Figure 3.

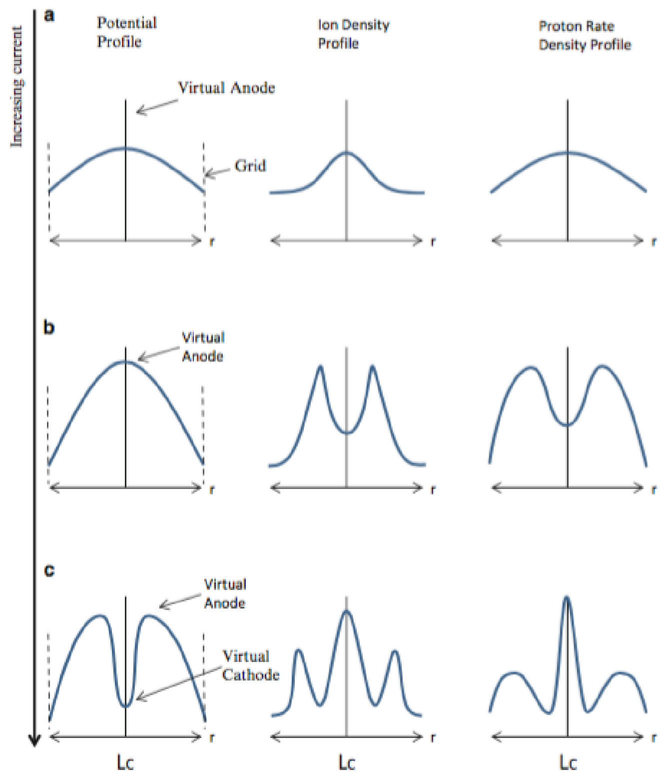


Figure 3: Double potential well in a traditional IEC device cathode [Miley, 2014]

Streaming Electrons

Yet another problem with single-cathode IEC devices are electrons streaming from the cathode to the grounded chamber walls. Electrons can be emitted from the cathode region in many ways. The foremost is high-energy ion impacts with the cathode, which sputter electrons from the grid as well as contaminant ions. Electrons can also be thermionically emitted from the cathode, when it is heated to high temperatures by continuous ion impacts. Electrons can also be produced from ionization events inside the cathode. Electrons emitted from the outer surface of the cathode will be accelerated outward to the grounded vacuum chamber, where their impact represents a loss of energy equal to that of the cathode potential in electron volts. Electrons produced in the interior of the cathode may see the ion space charge and be attracted to the core, though it has been shown experimentally that electron density in the core is orders of magnitude lower than that of ions [McGuire, 2007]. Streaming electrons represent a significant energy drain in traditional IEC devices. For more efficient operation, streaming electron losses must be mitigated.

Chapter 3

Second-Generation IEC Experiments

The "second-generation" IEC devices differ from traditional IEC devices in that they attempt to solve some or all of the problems outlined in the previous chapter. The ultimate goal is to greatly improve ion lifetimes, such that a significant fraction of ions fuse before they are lost. Beam–beam reactions thus dominate over beam–background, and the fusion rate becomes proportional to the square of the ion current. This proportionality is critical for scaling to useful fusion outputs without requiring high power input. Some second-generation IEC devices relevant to this thesis are described in the following sections.

McGuire's Multi-Grid IEC [McGuire, 2007]

Studied under Dr. Ray Sedwick, the multi-grid IEC concept uses multiple, concentric grids to produce an electric field configuration that focuses ions to the core and inhibits streaming electrons. In the multi-grid concept, 4–5 concentric wire grids lie within each other. The innermost grid is biased positively with respect to the second innermost grid, the main cathode. The outer grids are biased slightly above the vacuum potential produced by these two grids to provide a focusing effect. The potential map of such a device is shown in Figure 4.

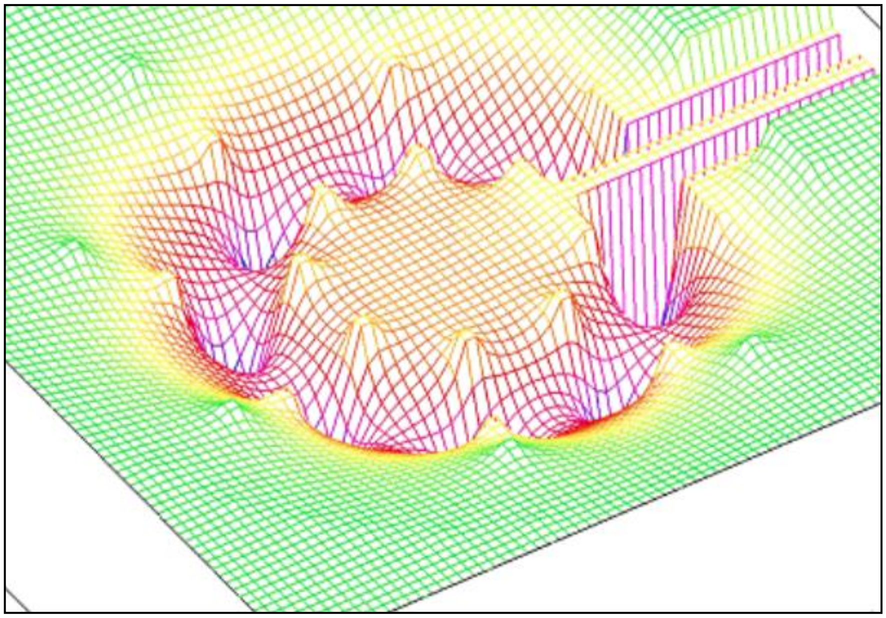


Figure 4: Multi-grid 2-D electric potential map [McGuire, 2007]

Biasing the innermost grid positively serves two functions. First, it eliminates streaming electron losses from the core. Since the grids are in each other's "shadow" as seen from the core, ions deflected off radial paths will tend to impact the innermost grid before any others. Thus, most electron emission comes from the innermost grid. However, the electric field outside the innermost grid now serves to reflect electrons back to the core region, rather than accelerate them away to the chamber walls.

The second function of the positive innermost grid is ion focusing. Since the ions are decelerated as they approach the core region, the field asymmetry of the grid now serves to focus ions radially rather than defocus them, limiting angular momentum buildup. Additionally, the focusing effect of the innermost grid is stronger than the defocusing effect of the cathode, because the ion travels slower in the focusing region and thus spends more time subject to the focusing fields. The asymmetric effect of the feed through electrode is also somewhat alleviated in the multi-grid arrangement.

The improved ion optics of the multi-grid device can keep lone ions from impacting any surfaces for thousands to millions of oscillations through the core. Now, only impact with neutral molecules limits an ion's confinement time. This can be solved, as mentioned in previous sections, by reducing the background pressure to the microTorr range.

With confinement time greatly increased, the physics of the ion-injected IEC device change dramatically. When large numbers of ions are confined together for so long, a collective behavior begins to emerge. This "bunching" phenomenon is explained in the subsequent section.

Synchronized "Bunching" Phenomena

Increasing individual ion confinement time from 1–10 passes to 10^4–10^7 passes reveals a completely new operation regime of ion-injected IEC devices. When a large amount of ions recirculate together in the trap, they quickly (within ~50 passes) begin to exhibit collective behavior. It is understood that a two-stream instability in the colliding ion beams serves to group stably trapped ions into "bunches". The effect is only observed if the electrostatic trap satisfies the kinematic criterion. This criterion states that increasing an ion's total energy increases its oscillation period. Most ion traps satisfy the kinematic criterion, including the multi-grid.

In the multi-grid, each beam path (grid opening) contains two ion bunches, which simultaneously collapse to the core from opposite directions. On a slightly longer timescale, bunches in each beam line also become synchronized with bunches from every other beam line. The result is a multitude of ion clouds that oscillate in the potential well, each collapsing to the core region at the same time. Simulation screen shots showing the bunching phenomena are shown in Figure 5. This bunching phenomenon, observed in simulations and experiments, greatly changes the physics of IEC devices. The spatial density can no longer be analyzed as steady-state, and attempting to neutralize the collapsing ion bunches becomes much more complex.

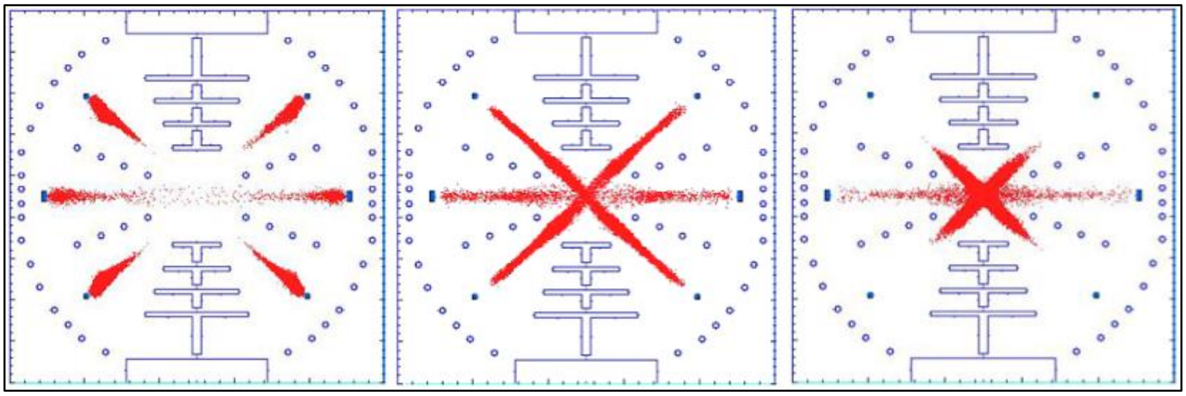


Figure 5: Long-lived, stable synchronization at over 2,500 passes (0.01s) [McGuire, 2007]

Ion bunching complicates the scaling laws between ion injection current and fusion output. At such high ion lifetimes, one could make the assumption that confinement is completely limited by space charge. In other words, there is a maximum population of ions that can be contained in the trap. If additional ions are introduced, space charge instabilities will tend to eject them from the system after a few passes to return to the equilibrium number. Were this assumption correct, core densities and fusion rate would be completely independent of ion injection current. Changing the input current would simply change the time required to reach the maximum ion population, and the ion current could be reduced to a mere trickle once steady-state was reached, to the rate needed only to replace the ions undergoing fusion.

This assumption is more or less valid at low ion currents, typically in the microamp range. Once steady-state is reached, most ion losses are from upscatter into the anode. At higher injection currents, in the milliamp range, the system becomes much less ordered. When ions are flooded into the trap in this way, rather than group the ions into bunches, the instabilities tend to violently eject ions from the system. The confinement time becomes so low that newly introduced ions do not have enough time to join any collective behavior, and the synchronization effect becomes very weak. The counter-streaming ion beams also tend to filament, severely lowering the core density and defocusing ions into grid wires. Figure 6 shows a snapshot at steady-state of the low current (left) and high current (right) cases in the multi-grid IEC.

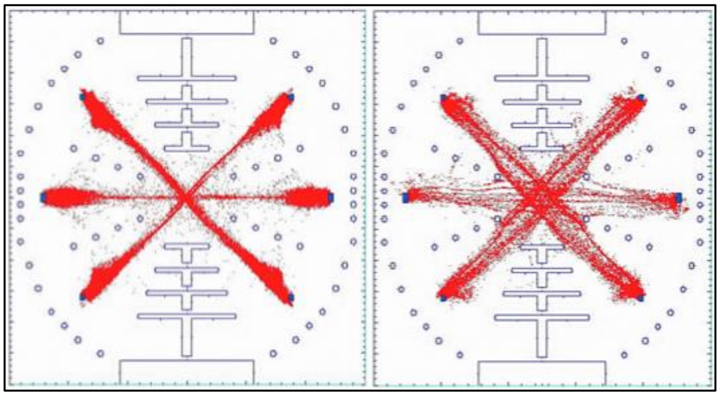


Figure 6: Steady-state ion map at 1 mA (left) and 100 mA (right) injection current [McGuire, 2007]

This disorder at high injection currents is not good for IEC projects looking into ultra-high current pulses to explore beam–beam reaction scaling. Since beam–beam reactions scale with the square of the ion current, these projects look to see if that scaling holds at higher injection currents, which would be critical for eventual high-output devices. Unfortunately, the multi-grid experiments show that forcing such a large population of ions into the trap severely cripples their confinement time. So while a high injection current device may reach high fusion rates, it would actually be further below breakeven than a low-current device. Again, this reinforces the speculation that space charge is the ultimate hindrance to high efficiencies. Not only does it place a limit on trapped ion population in the device, but it also limits the achievable densities and temperatures in the core region during the bunches' simultaneous collapse to the core.

In summary, the multi-grid IEC concept utilizes multiple, concentric grids that serve as electrostatic optics to greatly improve ion lifetimes. The multi-grid IEC device would also run at very low pressures, typically in the microTorr range, to prevent ion losses through charge exchange and other beam–background interactions. These conditions drastically improve ion lifetimes from 10 to well over 10,000 passes. In optimal conditions this number may grow to many millions of passes. At such high lifetimes, the ions tend to self-organize into bunches, a process McGuire called synchronization. In this regime of operation, low ion injection current is sufficient since space charge places a fundamental limit on ion population, core density, and confinement time. Though it prevents free electrons from streaming to the anode, the multi-grid concept does little to inject and confine electrons to the core, where they are needed to mitigate the fundamental hindrance to ion density: space charge.

Periodically Oscillating Plasma Sphere (POPS) [Park, 2005]

At this point it is appropriate to introduce the POPS concept, which has some relation to the synchronization behavior observed in multi-grid experiments. Proposed by Barnes and Nebel [Barnes, 1998], the periodically oscillating plasma sphere, or POPS, refers to the behavior of an ion cloud immersed in a spherical harmonic oscillator potential well. In the Barnes and Nebel proposition, a radially uniform electron density in vacuum forms the potential well. An ion cloud of sufficiently low density will oscillate in the well with a frequency independent of amplitude. The ions can be induced to collectively collapse to the core, boosting the achievable densities. This behavior is similar to that observed by ions in a grid-produced potential well at high confinement times, as shown in the multi-grid experiments.

In their experiments, Barnes and Nebel used an electron-injected IEC device to produce the electron background within the volume of the central grid. This device was similar to the multi-grid configuration, but with opposite electrode polarities to focus high-energy electrons to the central core region rather than ions. The potentials of the grids can be tuned to produce a nearly uniform electron density within the central grid. This produces the negative potential well needed for the experiment, until enough ions accumulate in the well that it is destroyed.

Barnes and Nebel ran their experiments at pressures of a few microTorr, at which the potential well is destroyed on a timescale of 0.5–5 ms. Fortunately, this is much longer than the POPS oscillation period of a few microseconds. Before the well is destroyed, the number of ions in the well steadily builds from ionization of a low-pressure neutral gas. When the space charge of these ions grows to sufficiently perturb the electron space charge, the well is effectively destroyed. The POPS oscillations can be observed in the ions present after the formation but before the destruction of a stable potential well.

However, Barnes and Nebel noted an additional constraint on producing the POPS oscillations: an external perturbation to phase-lock the ion motion. One might think the oscillations should shown self-synchronization due to the ion kinematics, as in the multi-grid experiments. However, the harmonic trap produced by the electrons does not satisfy the kinematic criterion; that is, the ion bounce frequency is independent of ion energy. This explains why there is no mention of the self-synchronization effect in Barnes and Nebel's experiments, and an external perturbation is needed.

By introducing an external perturbation to the vacuum potential at resonances of the POPS frequency, the ions could be forced into synchronization behavior on a timescale shorter than in multi-grid experiments. Barnes and Nebel achieved this by adding an RF offset of 5–10 V to the inner grid during the experiment. The voltages used in the POPS experiments (hundreds of volts) are typically much lower than those used in IEC experiments (hundreds of thousands of volts), but the fundamental physics are identical. The ion dynamics are thus that of a driven harmonic oscillator, described by the Mathieu Equations. When the voltage modulation is applied at the fundamental resonance—twice the POPS frequency—the slightest perturbation drives the ion orbits unstable, eventually ejecting them from the well. Ejection of ions from the well serves to prolong the ion density buildup in the well, thus prolonging the life of the potential well. This effect is important in further POPS investigations to improve device efficiency.

Barnes and Nebel also considered the effectiveness of the electron background in responding to a simultaneous collapse of ions to the core region. The electrons must move to neutralize the space charge of the converging ions to prevent the ions' mutual repulsion that slows and defocuses them. This will be relevant in Chapter 4 where neutralization is discussed.

Klein's MARBLE Concept [Klein, 2011]

Klein's Multiple Ambipolar Recirculating Beam Line Experiment (MARBLE) resembles a linear analog of the multi-grid device, but with multiple stages of ion focusing. The MARBLE concept is unique in that it offers a way to confine both ions and electrons of different energies on the same beam line. This is done with an alternating series of anodes and cathodes, as shown in Figure 7.

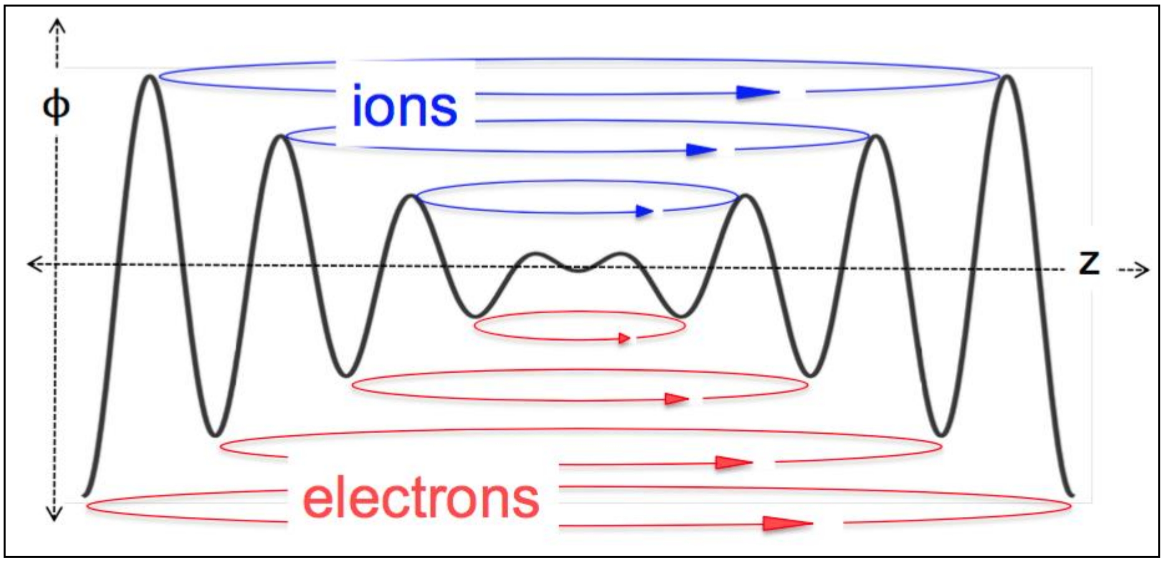


Figure 7: Potential distribution along MARBLE axis [Klein, 2011]

The MARBLE concept also utilizes a modest axial magnetic field (~200 gauss), which constricts electrons to axial travel. This is useful because it turns the potential peaks into electron Penning traps (see Figure 8) for ionization of a neutral gas. Low-energy electrons are constrained to oscillate at the potential peaks, where they may impact and ionize neutral gas atoms. Ionization creates more trapped electrons as well as ions that can fall into the potential well. The Penning-trapped electrons also serve to help neutralize ion space charge at the potential peaks, where the ion velocity is slowest and collisions are most probable.

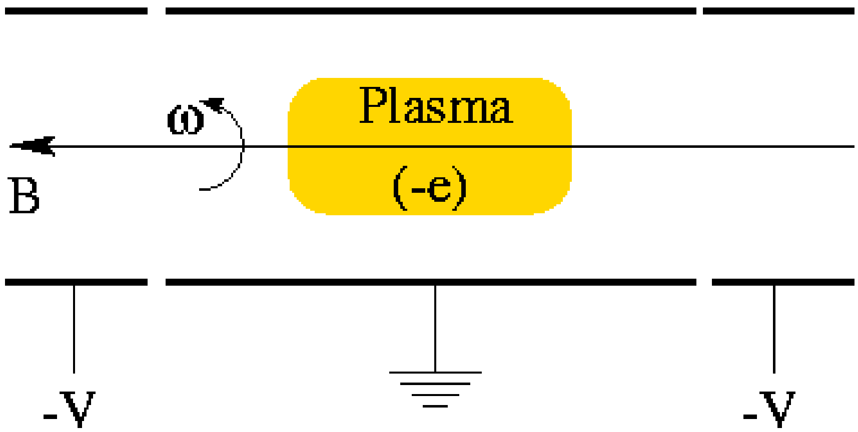


Figure 8: An electron Penning trap [PPPL, 2000]

Another innovation of the MARBLE configuration is that it reduces the average energy lost per particle. High-angle ion scattering occurs most often at the potential peaks, where the ions are slowest. However, an ion scattered out of the trapping space at a potential peak will often impact the next lowest anode, rather than a cathode. This constitutes a loss of energy corresponding to the potential difference between the two anodes, which is much less than that between the anode and a cathode. Thus, the average energy expenditure per ion lost is much lower than in typical IEC devices. Figures 9 and 10 show more of the MARBLE concept.

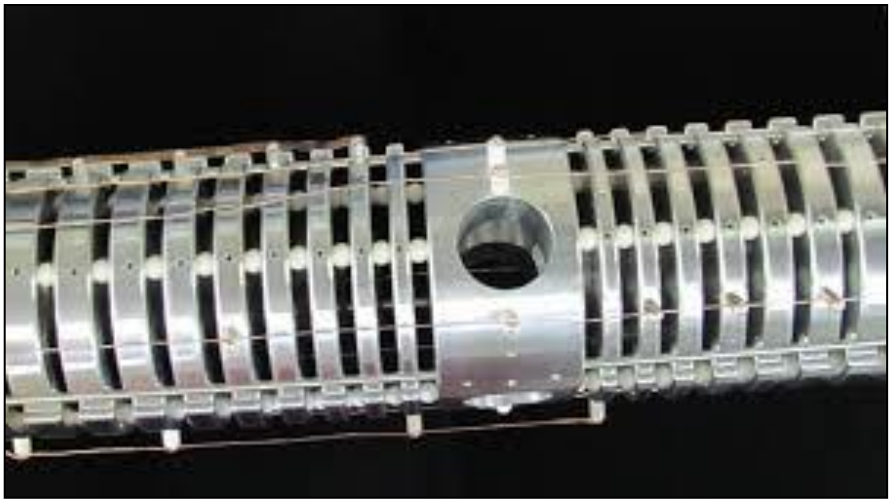


Figure 9: MARBLE-1 device with ceramic spacers between electrodes [Klein, 2011]

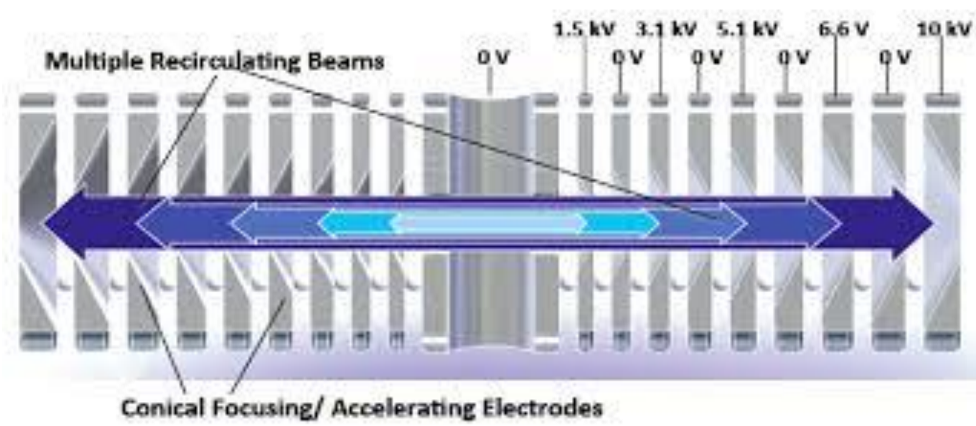


Figure 10: MARBLE-1 cross-section [Sedwick, 2013]

The MARBLE-1 device, as shown in Figures 9–11, was quickly built and ran experiments for only a few weeks before funds were exhausted. Nevertheless, encouraging results were obtained. Electron populations form easily with no external injection, and the electron density in the Penning traps can be controlled with the strength of the magnetic field. The optimal B-field is ~200 gauss to limit space charge distortion of the potential peaks.

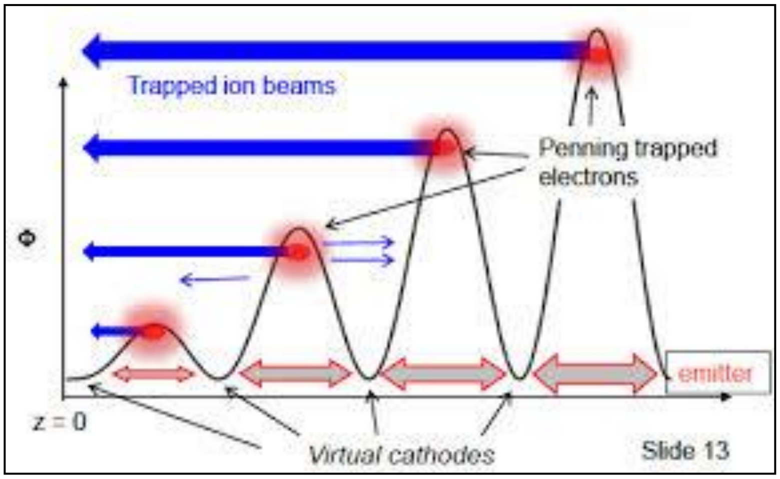


Figure 11: Axial potential distribution in MARBLE-1 [Klein, 2011]

The MARBLE concept may be an effective way of increasing the ion population in IEC devices as the ion turning region can be extended to any number of stages. Electron confinement along the beam path helps reduce space charge effects at the ion turning regions. However, electrons are not injected or confined to the core so the ion population is still fundamentally limited by core space charge as in the multi-grid IEC.

Planar Electrostatic Trap (PET) [Knapp, 2015]

While the ability to contain multiple, independent, ambipolar beams allows the MARBLE device to contain more ions than a typical linear IEC device, further increasing the trapping space is always desirable. If a cross section of the MARBLE device were rotated about its central axis, one winds up with a planar electrostatic ion trap, as shown in Figure 12. In this arrangement, the ions oscillate through the device center, but also develop a small amount of tangential energy through collisions. This causes them to spread angularly throughout the trap, as shown by the red ion trace in Figure 12. The potential map of the cross-sectional cutting plane in Figure 12 is shown in Figure 13. It is identical to that in the MARBLE-1 device, but is axisymmetric about the vertical axis rather than the horizontal.

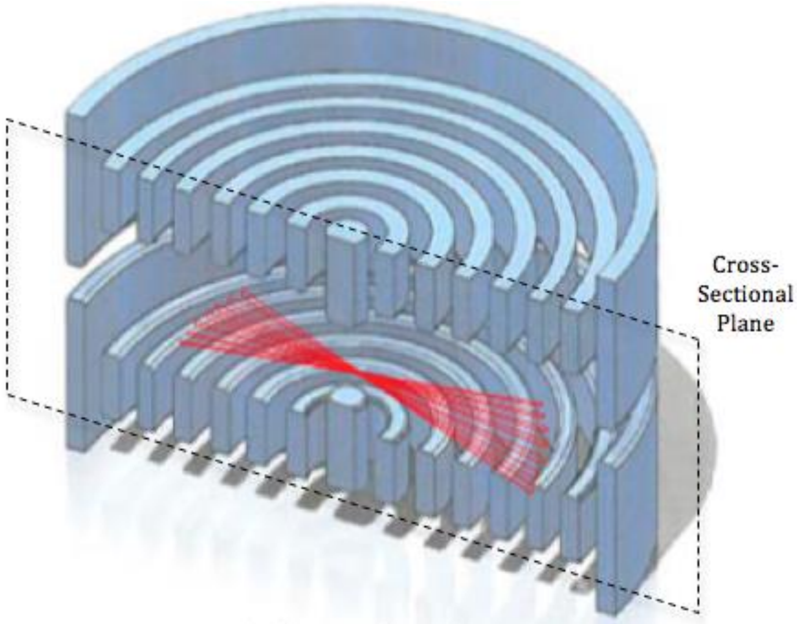


Figure 12: Planar electrostatic ion trap (halved) [Knapp, 2015]

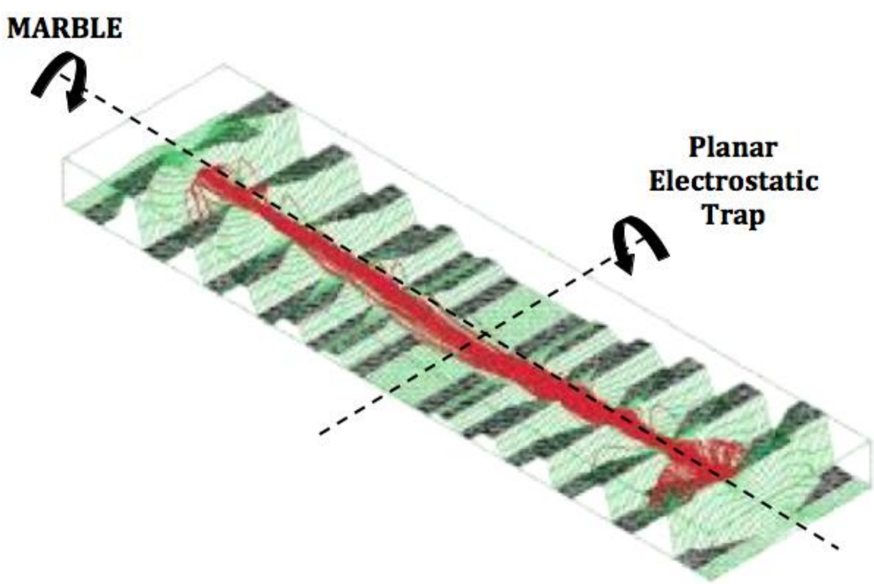


Figure 13: Electric potential map of cross-sectional plane in Figure 12 [Knapp, 2015]

The planar configuration has nearly the same confinement properties as the MARBLE concept, but provides more trapping space to hold a greater population of ions. Maximizing the ion population is desirable to maximize the net ion current through the core. Simulations show that individual ions can be confined as long as 16 seconds (>10^7 passes) in the planar trap—given there are no collisions with background neutrals and the ion population is well under the space charge limit. Simulations show that the former assumption is valid at background pressures under 10^{-4} Pa (0.75 μTorr).

Sixteen seconds should be more than enough confinement time for the synchronization behavior to take effect as in the multi-grid experiments, but there is little reference to the synchronization behavior in literature on MARBLE or the planar electrostatic trap. A reference to bunching behavior is presented in a poster about the MARBLE-1 device [Klein, 2011], in which it is noted that autoresonance of the ions was used as a diagnostic during testing. Similar to the POPS experiments, this diagnostic involved applying a low-voltage, sinusoidally oscillating potential to the central electrode. At the appropriate frequency, this oscillating perturbation can induce the bunching behavior in the trapped ions. The oscillating bunches capacitatively drove a signal on a second electrode from which the ion behavior could be analyzed. It was noted by Klein that the ions could self-bunch spontaneously in some conditions. These conditions were probably similar to those in which self-bunching was observed in the multi-grid experiments, i.e., high confinement time and ion population.

Conclusions to Be Drawn

The requirements for more efficient IEC devices are evidenced by the similarities between second-generation experiments. Low background gas pressure is critical to mitigate ion impact with thermal neutrals. Ion optics must be utilized to drastically slow the rate at which ions are defocused into electrode surfaces. The MARBLE concept employs electrons with an axial magnetic field to mitigate space charge along the beam path and provide an ion source through Penning-trapped electron impacts with neutrals. These modifications serve to dramatically increase ion confinement time and net ion current to the core in second-generation IEC. However, these conditions naturally result in a synchronization behavior between the trapped ions that causes them to group into bunches. The counter-streaming bunches simultaneously collapse to and reemerge from the core region. This behavior is understood to originate primarily from a two-stream instability in the counter-streaming ion beams, and is observed in both multi-grid and MARBLE experiments and simulations.

Synchronization behavior among ions can emerge naturally after many hundreds to thousands of individual ion oscillations in the potential well, given the majority of ions are allowed to oscillate for this time. However, synchronization behavior may be induced on a faster timescale if an external perturbation is applied at a resonant frequency of the ion bounce frequency. This external perturbation could be a slight modulation in the voltage of a participating electrode. Stimulation at the resonance frequency was employed in the MARBLE device as a capacitive diagnostic technique, but it was noted the synchronization behavior could be observed naturally in some conditions—most likely those which led to very long confinement times with a large trapped ion population.

The concept of stimulating ion synchronization behavior is also presented in the periodically oscillating plasma sphere (POPS) concept. The theory is applied to an ion cloud within a uniform cloud of excess negative charge, such as that created in the core of an electron-injected IEC. The electron cloud potential well produces nearly infinite confinement time for ions since there are no solid grids for the ions to intercept. In the POPS concept, a periodic stimulus such as that previously described is applied to the inner grid of the electron-injected IEC, inducing the synchronization behavior between ions trapped in the potential well. Without the periodic stimulus at the resonant frequency, self-synchronization would not occur with POPS because the potential well does not satisfy the kinematic criterion. POPS experimentation was limited by the lifetime of the potential well created by electron injection, which was about two orders of magnitude longer than the ion oscillation (POPS) period.

The synchronization effect is an integral consideration in future IEC concepts. Reactions in the core can no longer be modeled as steady-state beam interactions, but are pulsed as the majority of confined ions collapse simultaneously to the core. This ion dynamic also complicates space charge neutralization in the core. Without synchronization, a constant ion density in the core creates a space charge that may continuously attract electrons for neutralization. With synchronization, ion density is negligible in the core until the collapse phase of the oscillation, when it spikes and decays rapidly. It is unclear how electrons, if introduced to the core region, would react to such sudden spikes in density.

The second-generation IEC experiments also show that the fundamental hindrance to high fusion rates is space charge. Confinement time can be successfully extended such that many ions have time to fuse before being lost. Multiple stages of electrostatic lenses can be used to focus ions to the core and expand their turning region. Synchronization behavior, whether natural or induced, seems advantageous as it enhances confinement time and forces all the ions to the core at the same time. However, it is also a drawback since the density spike creates a space charge potential spike that slows and defocuses impinging ions. This results in a broader, less dense, and colder core, detrimental to fusion rates. In order to reach the high ion densities and temperatures required for high fusion output, the collapsing ion bunches must be neutralized as they approach the center. A method for achieving this condition comprises the remainder of this thesis.

Chapter 4

A Plasma-Core Planar Electrostatic Trap

In order to achieve the high fusion rates required for practical IEC applications, the repulsive space charge of the ion bunches inevitably produced at high confinement times must be neutralized as the bunches approach the center of the device. Otherwise, the bunches will tend to decelerate and defocus each other during their convergence, leading to lower ion densities and velocities in the compression phase than could be achieved with proper neutralization.

Common sense would dictate that the easiest way of promoting neutralization of the bunches is to provide ample electron density in the core region. Since electrons are so much lighter than ions, they should be easily and quickly accelerated to the regions of high ion density on a timescale faster than the ion transit through the core. As the ion bunches converge, the space charge should pull the electrons inward as well, providing the necessary neutralization. It was shown by Barnes and Nebel in their work with the POPS concept that this assumption is not entirely true due to the electrons' angular momentum. As with all plasmas, the ability to damp out electric field fluctuations depends on many factors, primarily the electron density and temperature. Simulations of the POPS phenomena showed that finite energy electrons were not able to fully neutralize the core during a POPS collapse; in fact, the central electron density was nearly two orders of magnitude lower than the ion density during the collapse phase.

Though the concepts presented in the previous chapters provide means to prevent electrons from streaming to the anode, the only ones that forcefully inject electrons to the core are the electron-injected IEC concepts, including the POPS concept and the Polywell. These concepts use the potential well created by electron space charge to accelerate and confine ions, which intrinsically provides an abundance of electrons for neutralization. Fusor-type electron-injected IEC concepts (like that used in the POPS concept) require unrealistically large currents (10^{14} A) to achieve breakeven at useful fusion energy output [Miley, 2014]. The Polywell concept employs magnetic fields to increase the fusion volume, but suffers from electron losses and high power requirements.

These intrinsic difficulties may prevent any IEC device from reaching breakeven by using solely electron space charge to confine ions. Thus, it is of interest to explore ways in which electrons can be confined in the core of an ion-injected IEC device. These electrons are employed solely to combat space charge effects, rather than accelerate and confine ions. A novel concept for providing these electrons is presented in the following sections, and is termed the “plasma-core planar electrostatic trap” or PCPET. The first two sections discuss some concepts related to the PCPET.

The Saddle Point Potential

One may infer that the simplest way of confining both electrons and ions to a single core is with an electrostatic saddle point potential. A 2-D saddle point potential is shown in Figure 14. Ions are confined in one direction, while electrons are confined in the other, purely electrostatically. This configuration is essentially an ion-injected IEC in one direction, and an electron-injected IEC in the other. Both ions and electrons are accelerated to the same point, the saddle point. However, both species must be restricted to travel only in their respective directions, or they are not confined. For the ions this is not a huge problem; the potential can be modified far from the core so that an ion’s inertia prevents it from being significantly defocused.

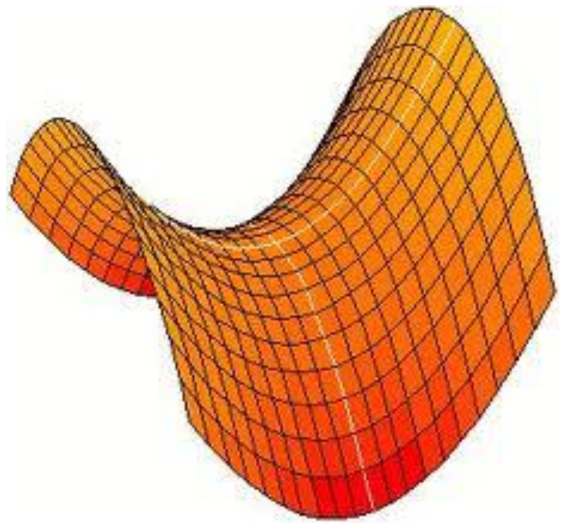


Figure 14: 2-D saddle point electric potential map

The electrons can be confined to travel in a single direction with magnetic fields. Since electrons are so much lighter than ions, magnetic fields in the core region can be tailored such that they prevent electrons from straying, but do not significantly affect the ions. This configuration then becomes very similar to an existing plasma confinement scheme, the electrostatically-plugged magnetic trap, which is discussed next.

Magnetic Electrostatically-Plugged Confinement [Ware, 1969] [Dolan, 1994]

Initial fusion research efforts focused on magnetic cusp confinement of plasma. These concepts take advantage of the fact that charged particles can be reflected from regions of stronger magnetic field. Thus, high-energy charged particles can be confined in a region bounded by strong magnetic fields, as in the magnetic bottle of Figure 15. However, if particles scatter into a certain region of velocity-space called the “loss cone” [Fitzpatrick, 2011], they can escape through the magnetic cusps. Particle collisions constantly scatter particles into the loss cone, so magnetic cusp devices suffer from chronic “leakage” of particles out of magnetic cusps.

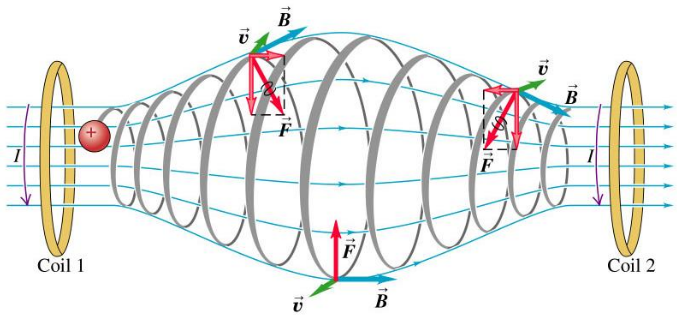


Figure 15: A magnetic "bottle" plasma trap [Wesley, 2004]

In order to prevent some of the particles from leaking out of the system, the cusps could be "plugged" electrostatically by placing high-voltage electrodes outside of the mirror region (outside of the coils in Figure 15). If the electrodes were biased negatively with respect to the coils, then high-energy electrons escaping through the cusp would be repelled by the electrode, and forced back through the cusp into the plasma region. Ions escaping through the cusp would still be lost. This constitutes a preferential loss of ions over electrons from the magnetically confined plasma, causing the plasma to develop an excess of electrons and depress its potential with respect to the coils. The negative space charge attracts ions to the plasma, reducing their loss rate through the cusps. The plasma becomes more and more negative until the loss rates of electrons and ions equalize. In addition, the excess electrons in the plasma will tend to drift to the outer surface of the plasma, where they form a thin sheath in which a potential drop of several kilovolts can be established. The bulk plasma remains quasi-neutral and can be magnetic and electric field-free [Dolan, 1994]. In this way, MEPC with electron plugging is similar to the Polywell concept. The sheath potential drop reflects high-energy ions to the plasma and is denoted ϕ_i in Figure 16, which shows an electrostatically plugged spindle cusp and its radial potential distribution at the ring cusp. The deviation from the vacuum potential (dotted line) caused by the presence of the plasma is denoted as $\phi(x)$. The depression of potential in the gap in the center of the anode, $\Delta\phi$, is caused by electron space charge. The potential difference between the anode and cathode is denoted ϕ_A. It is assumed that the magnetic coils and the surrounding vacuum chamber are at the same potential as the anode.

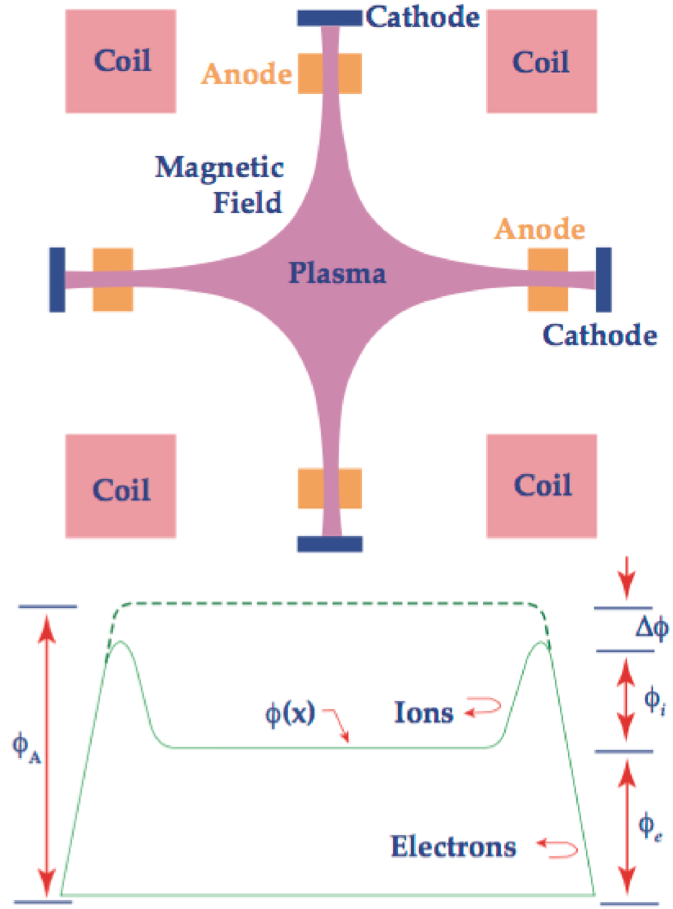


Figure 16: An electrostatically-plugged biconic (spindle) magnetic trap [Dolan, 1994]

The primary energy drain in MEPC is leakage of plasma ions through the anode gaps. Ions are created by ionization of a neutral gas at the plasma boundary. These ions fall into the potential well where they gain an energy equivalent to $e(\Delta\phi + \phi_i)$ before entering the bulk plasma. The ion energy distribution will quickly thermalize due to collisions. Ions with energy greater than $e\phi_i$ will be able to exit the plasma through the anode gaps, where they accelerate to energy $>e(\phi_i + \phi_e)$ before impacting the cathode. Ions with energy greater than $e(\Delta\phi + \phi_i)$ can escape through the electron sheath if the magnetic field is weak, but this is rare since ions will often be lost through the anode gap before exceeding energy $e(\Delta\phi + \phi_i)$.

An electrostatically plugged magnetic trap has many similarities to a saddle point potential with magnetic fields to keep electrons on their confining beam path. In MEPC, electrons are confined by the magnetic field and plugging electrodes, whereas ions are confined by the negative space charge of the electron sheath surrounding the central plasma. The main problem with MEPC is that it requires very strong magnetic fields with voltages ≥400 kV to approach breakeven performance, due to the strong electron space charge in the anode gap [Ware, 1969].

The Plasma-Core Planar Electrostatic Trap

This thesis proposes the use of MEPC to create either a steady-state or dynamic plasma in the core region of a planar electrostatic trap, with the primary purpose of mitigating space charge problems in the core. The voltages applied to the electrodes and magnets of the MEPC element as well as the strength of the magnetic field determine the properties of the neutralizing plasma, such as temperature, density, and charge composition. This discussion will focus on COMSOL Multiphysics simulations of a preliminary PCPET design for fusion purposes.

The preliminary PCPET schematic is shown in Figure 16. The electrodes are axisymmetric about the central (dashed) axis, just like the planar electrostatic trap. The MEPC magnets, which could be permanent or electromagnetic, serve as the focusing anode. As shown in the multi-grid experiments, locating a focusing anode within the acceleration cathode dramatically increases ion confinement time and prevents electrons from streaming out of the core region. Whether or not the ions in the trap are synchronized, the central plasma electrons can be used to neutralize the space charge in the core and yield stronger ion convergence. A number of properties can determine the neutralization abilities of the plasma electrons, which is the subject of a later section.

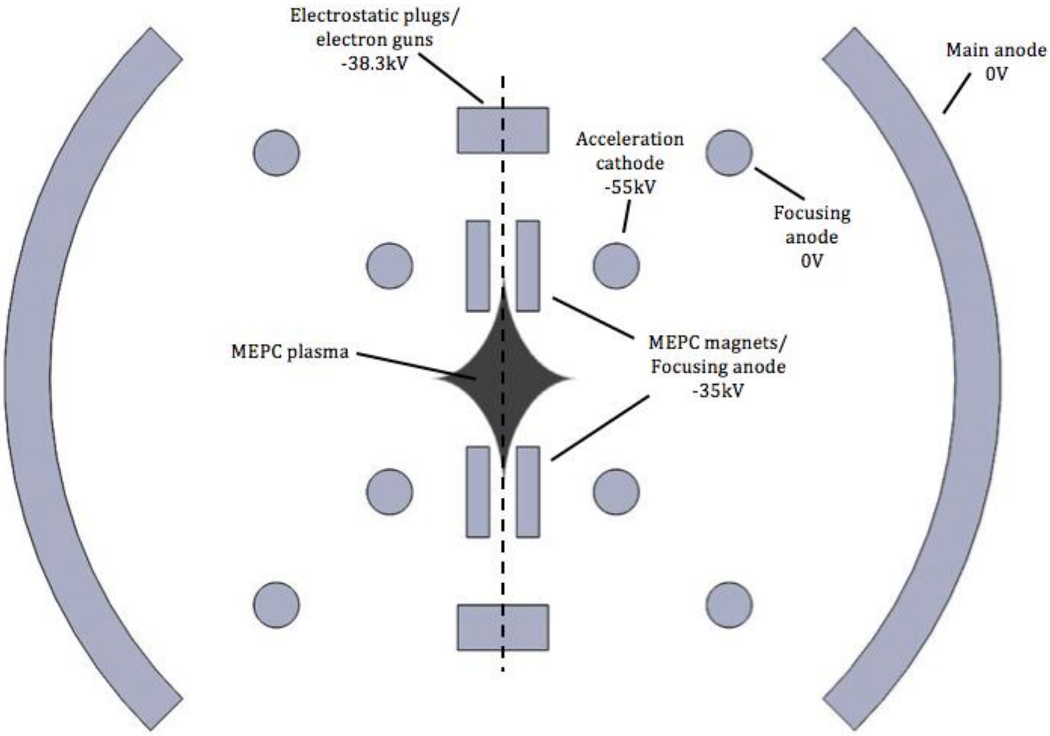


Figure 17: A plasma-core planar electrostatic trap (PCPET)

COMSOL Multiphysics Simulations with Ions

COMSOL Multiphysics was used to explore various axisymmetric electrode geometries for the plasma-core planar electrostatic trap. The Electrostatics, Magnetic Fields, and Charged Particle Tracking modules were used to numerically solve the electromagnetic fields of the trap and deuteron trajectories within them. The goal was to optimize confinement time and core energy of deuterium ions generated within the ionization region. The planar traps modeled were 20–40 cm in diameter, large enough to avoid electrical breakdown problems but small enough to fit in an average vacuum chamber. A 2D-axisymmetric, triangular meshing was used with maximum cell size ~15 mm^2 and minimum <0.5 mm^2 near the electrodes. The largest voltage used in the simulations was 55 kV in order to accelerate the deuterons to energies appropriate for D–D fusion. D–T fusion has a higher fusion cross-section at these energies, but due to tritium's larger mass, its use may interfere with the synchronization effect. The possible use of other fusion fuels is discussed in a later section. It was found that ion trajectory solutions closely converged at time steps under 20 ns; a time step of 5 ns was used for all ion simulations reported in this thesis.

First, the 2D multi-grid geometry was recreated to ensure the software was working properly and accurately modeled charged particle movement in IEC devices. The simulation showed excellent confinement for the full 100 μs simulation time and agreed with previous multi-grid experiments. The solution is shown in Figure 18.

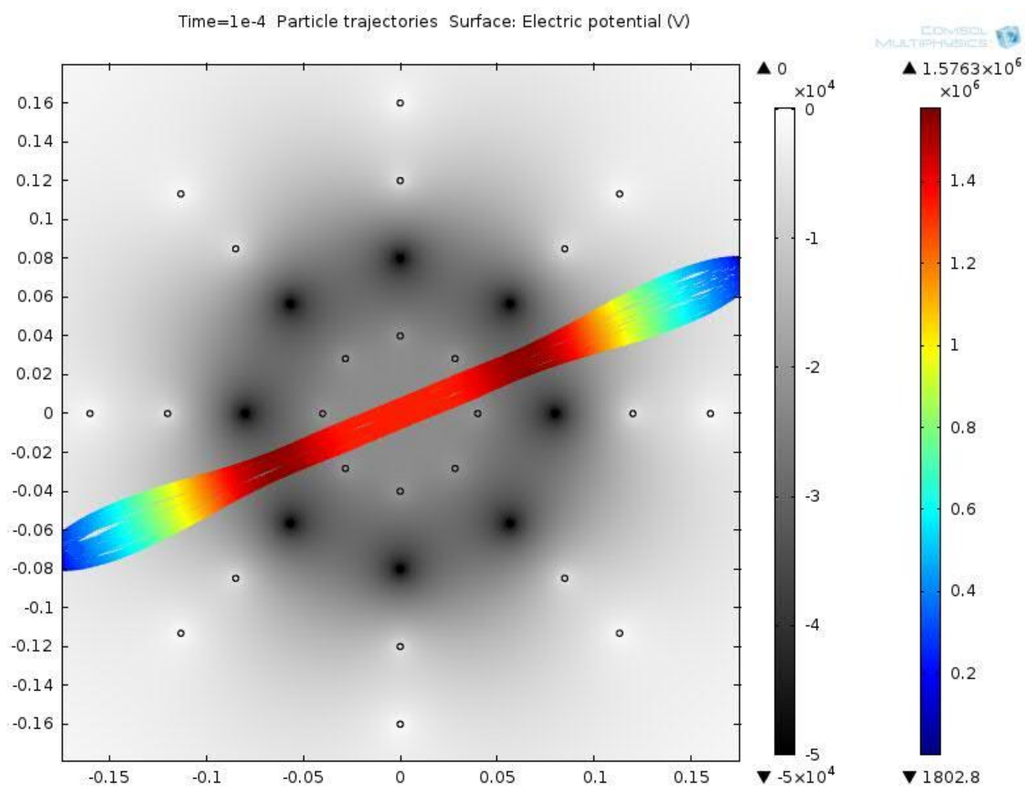


Figure 18: Stable deuteron trajectory in the multi-grid at 100 microseconds (>350 passes)

Rigorous simulations were carried out with the planar analog of the MARBLE configuration shown in Figure 13; however, this configuration was eventually swapped for a more simplistic design that showed similar if not superior confinement properties. This design is that shown in Figure 17. The outer electrode is curved to have its focal point at the center of the device. As in the multi-grid experiments, the central MEPC magnets are biased positively to the acceleration cathode to prevent streaming electron losses and improve confinement. A number of other configurations showed good confinement. However, the subject of this thesis is the effectiveness of the plasma core, rather than the precise optimization of the electrode optics, which is left for later study.

Figure 19 shows the stable confinement of a deuteron in the discussed PCPET geometry at 100 μs (>450 passes). Ion energy in the core is approximately 30 keV. Computing time placed a practical limit on the maximum length of the simulation time, but the stability of the orbits suggest confinement times comparable with those of the multi-grid and PET experiments. Deuterons generated within a ~17° altitude angle of the device plane showed this stable confinement. Deuterons generated slightly outside of this region could show stable confinement, but most often impacted the MEPC magnets or the acceleration cathode after a few passes. Most ion losses are upscatters into the anode due to slight missteps of the solver over hundreds of passes through the core. Interestingly, though the solver does not include ion–ion interactions, scattering is, in a way, approximated in the simulation by the small numerical errors of the solver. Furthermore, the error is largest in the core, where scattering is the most frequent.

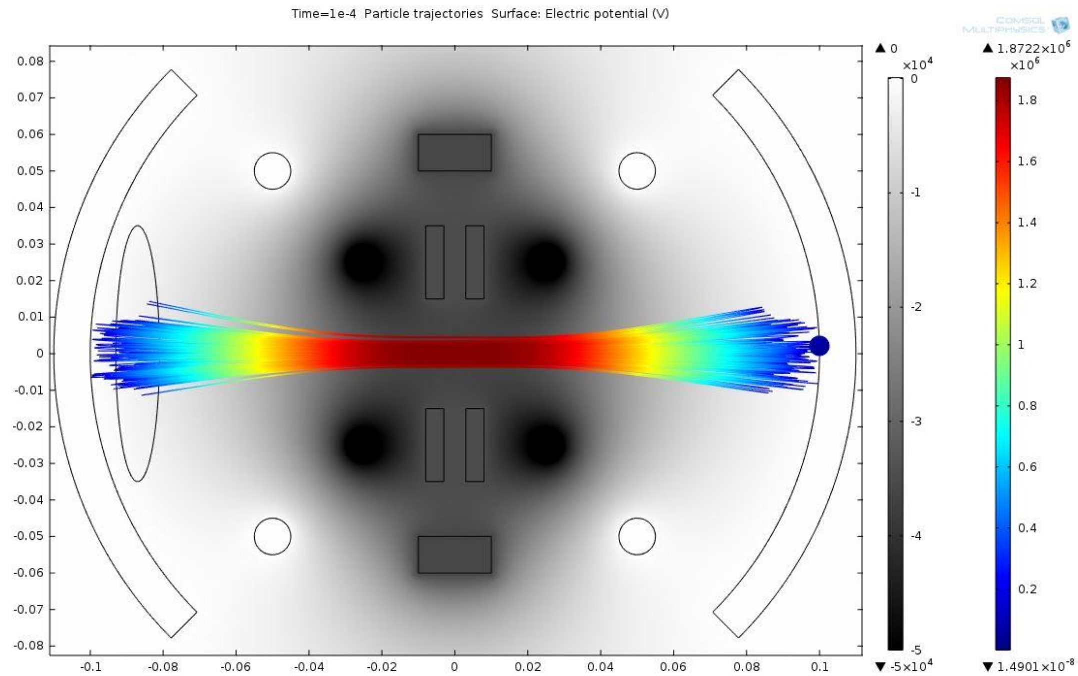


Figure 19: Stable deuteron (blue dot) trajectory in the PCPET with no central plasma at 100 microseconds (>450 passes)

It is of interest to determine the effect of the central MEPC plasma on individual ion trajectories. This plasma could be quasi-neutral, as in steady-state MEPC experiments, or primarily electrons, similar to the pulsed electron-injected IEC in the POPS experiments. The approximate electric field disturbances caused by the presence of these plasmas were incorporated into the simulation. The central ovals represent the region of plasma. Despite kV-scale perturbations, neither a quasi-neutral nor uniform electron plasma showed any significant effect on ion confinement. Some simulations even showed increased stability, as in Figure 19. However, the presence of the plasma did tend to defocus ions from the core, as shown in Figure 20.

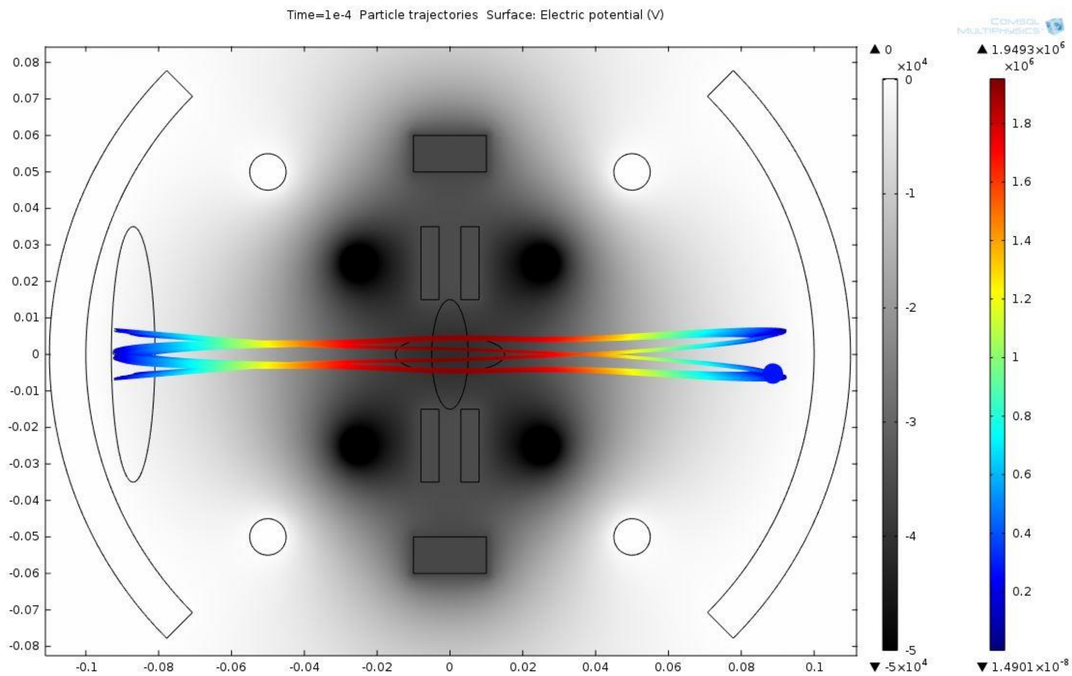


Figure 20: Unusually stable deuteron (blue dot) trajectory in the PCPET with uniform electron plasma (n~5 × 10^{14}) at 100 microseconds (>450 passes)

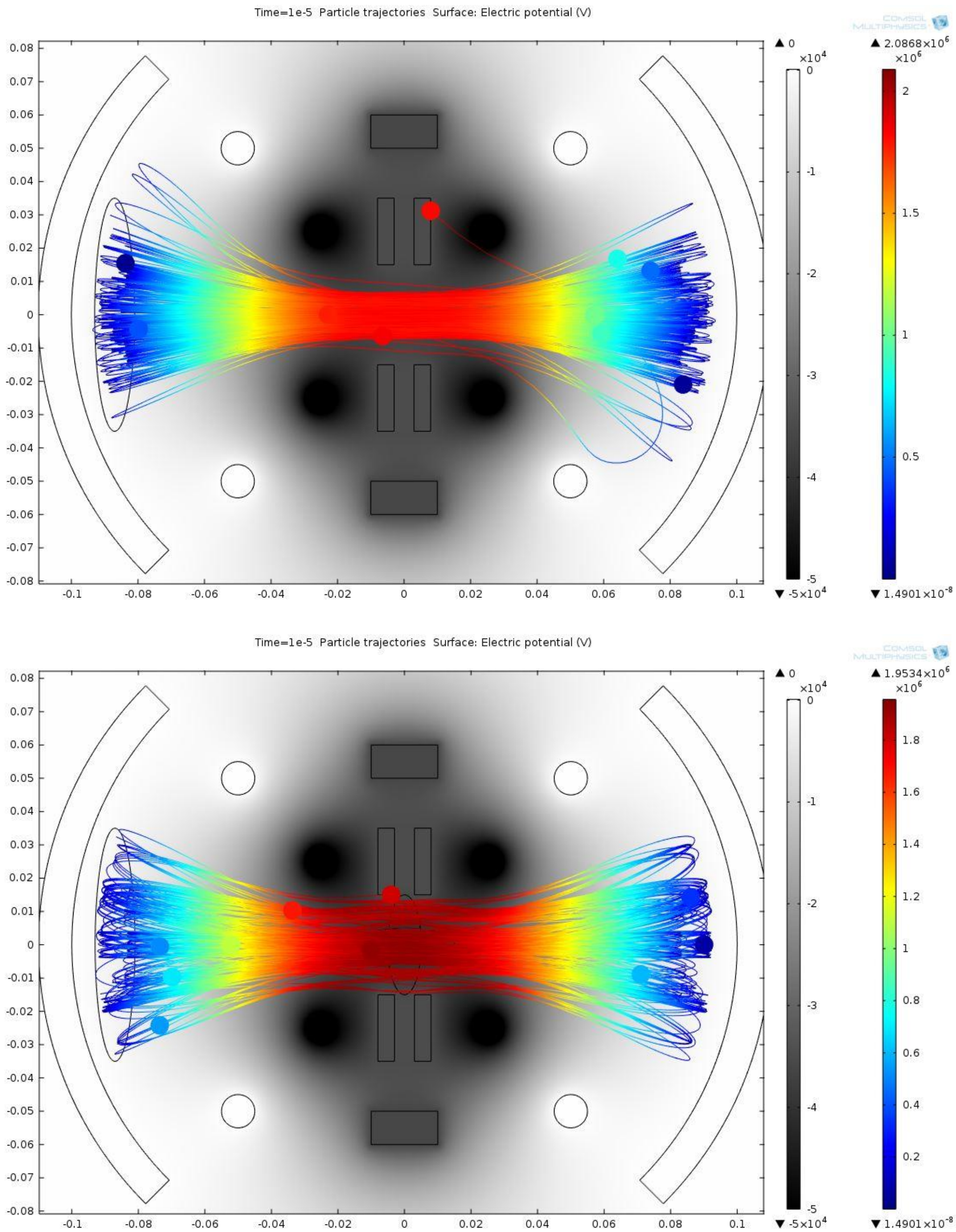


Figure 21: Ten deuterons at 10 microseconds (50 passes) in PCPET without plasma (top) and with uniform electron plasma (bottom)

If the trap is to be operated at low pressures, incorporating a Penning trap ion source like in MARBLE may be desirable. To simulate this, a gap was made in the center of the anode and an additional electrode at −1 kV added outside of the anode. With the addition of a local, weak magnetic field, low-energy electrons could oscillate in the gap and produce ions to feed the trap.

Unfortunately, the field asymmetry caused by the gap crippled the confinement properties of the PCPET design. Figure 22 shows how a single deuteron becomes unstable with the field asymmetry in less than 100 passes. A wire mesh at ground potential could be placed over the gap to remove the asymmetry, but would intercept some of the recirculating electrons. Nevertheless, this would probably be the best configuration for a Penning trap ion source in the PCPET.

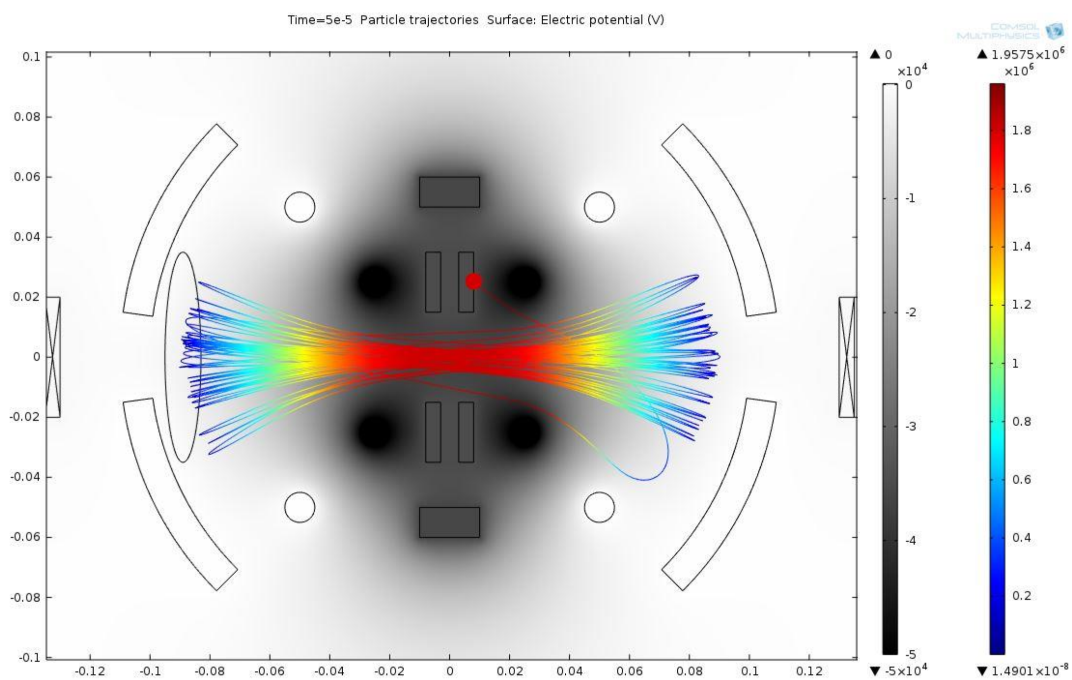


Figure 22: Unstable deuteron trajectory in PCPET with Penning trap ion source

Finally, the magnetic fields produced by the MEPC magnets were incorporated into the simulation. These fields were not included in previous simulations because it was assumed they were not strong enough to have any significant effect on the ion trajectories, while they dramatically increased computing time.

As shown in Figure 23, the MEPC magnets could create two types of magnetic traps: a magnetic bottle or a biconic cusp. Both types are capable of trapping charged particles, and are differentiated by the relative polarities of the magnets.

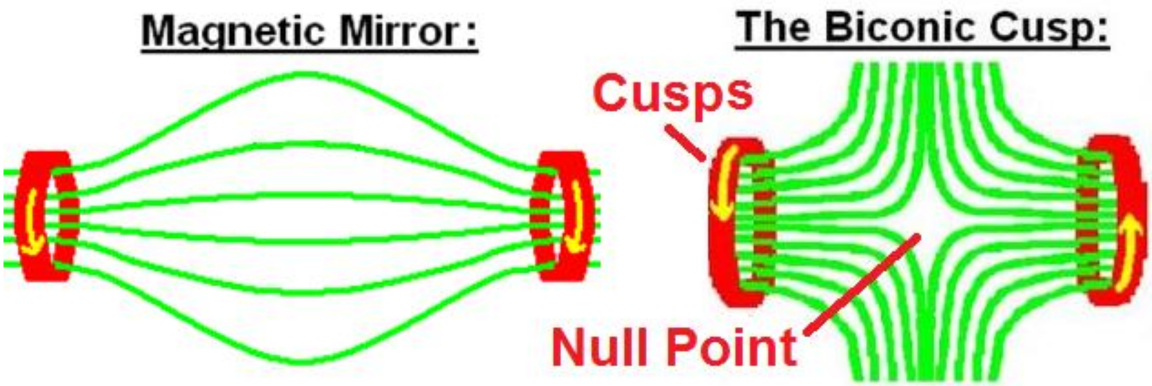
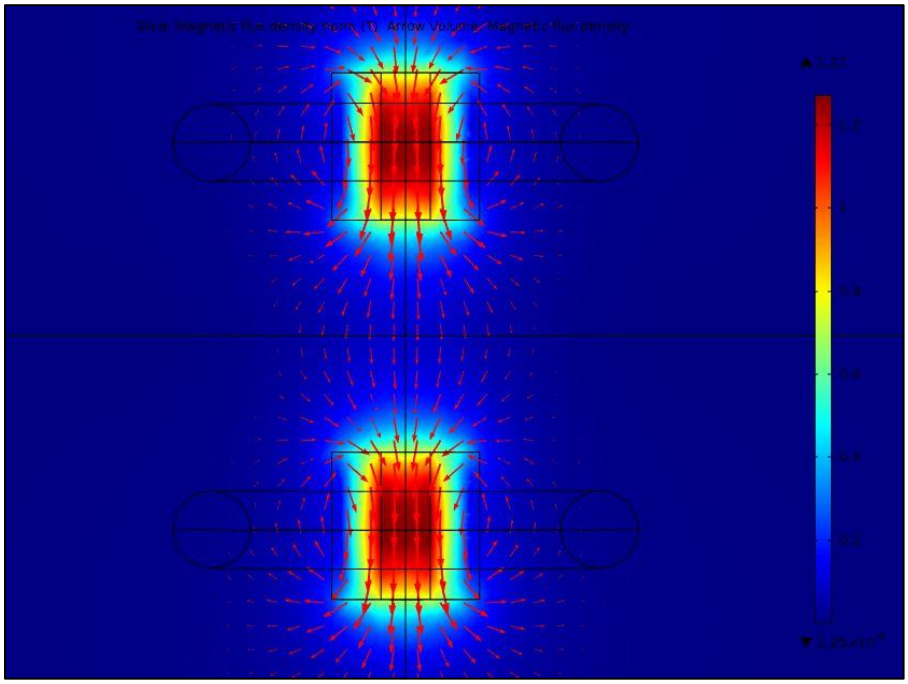


Figure 23: A magnetic bottle (left) and a biconic/spindle cusp (right)—both capable of trapping charged particles with the magnetic mirror effect [Fusion Adv., 2015]

The magnetic fields were created in COMSOL by running 15,000 amp-turns through each magnet cross-section, creating a flux density of ~1 T at the point cusps. The type of magnetic trap created is determined by the direction of current in the bottom magnet. Figure 24 shows the magnetic field created at the axisymmetric plane under these conditions for each type of magnetic trap. Figure 25 shows the trajectory of a deuteron in the PCPET in each type of trap, as well as the trajectory with no magnetic fields.



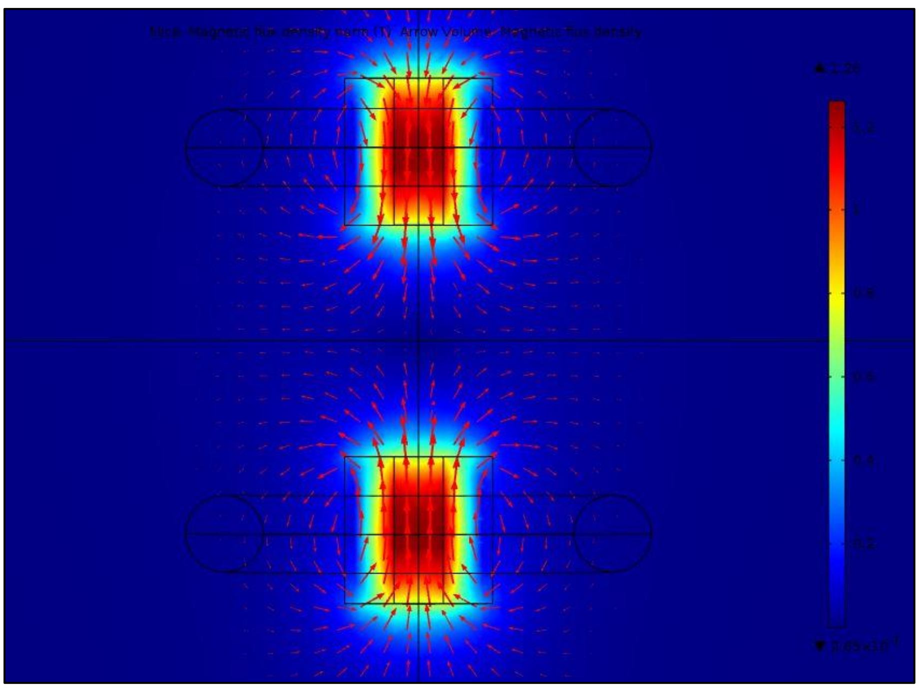
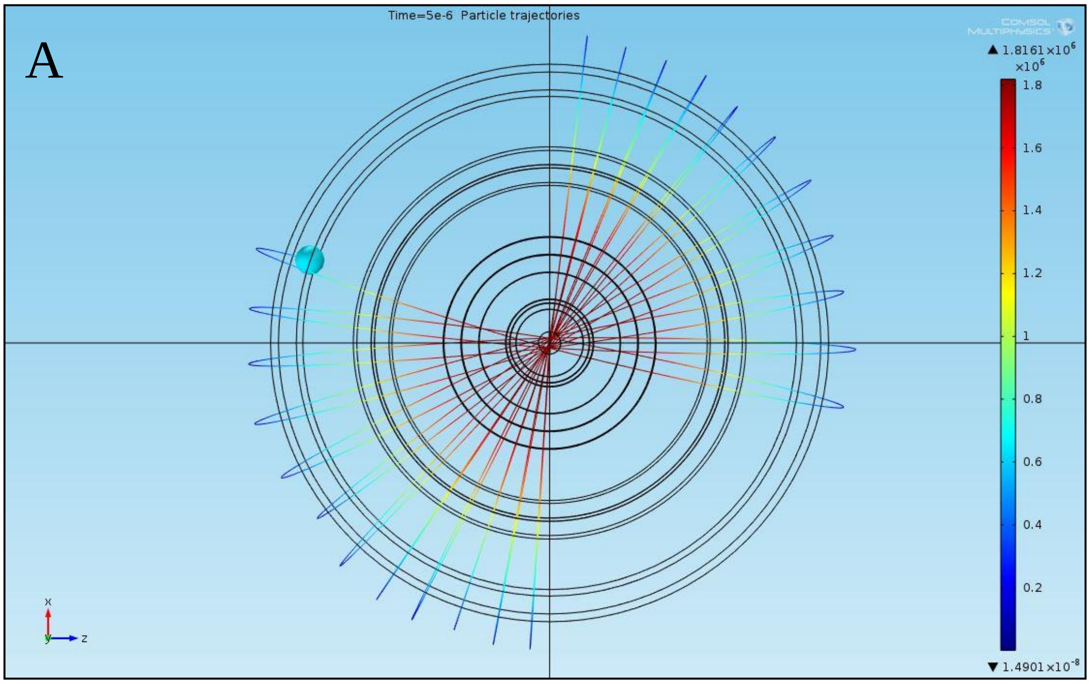


Figure 24: Central magnetic field topography in PCPET using magnetic bottle (top) and biconic cusp (bottom)


A
Time=5e-6 Particle trajectories
▲ 1.8161×10^6
×10^6
1.8
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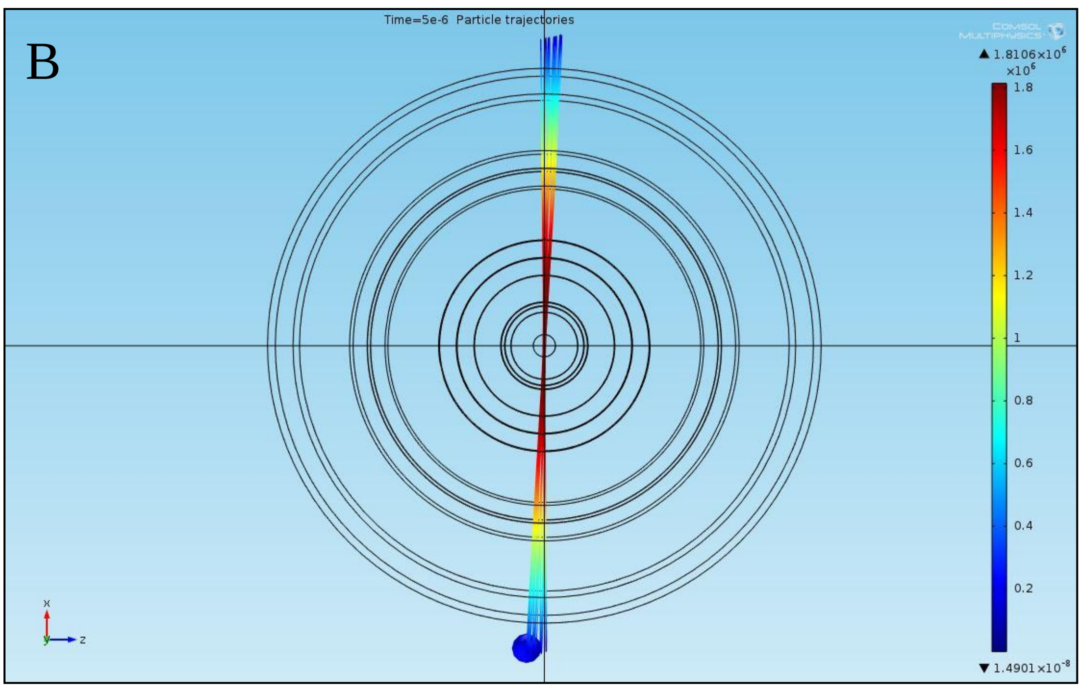
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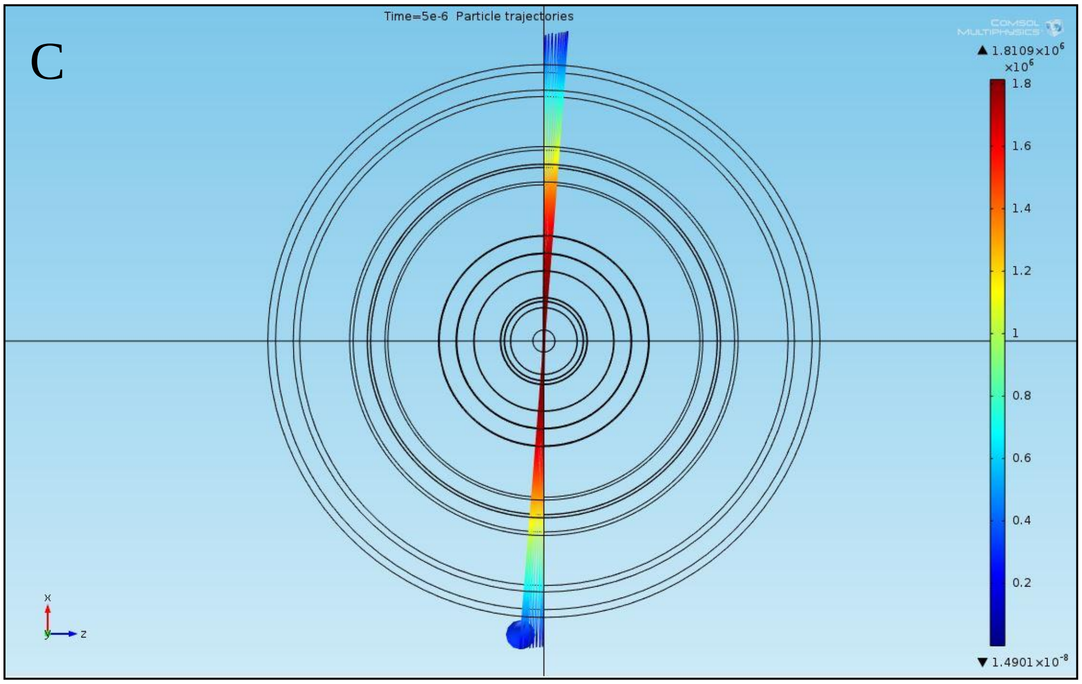

Figure 25: Deuteron trajectory at 5 microseconds (25 passes) in the PCPET with magnetic bottle (A), biconic cusp (B), and no magnetic field (C). Deuteron starts at rest near center of ionization region.

As one can see from Figure 25, the magnetic mirror configuration is undesirable because the strong axial magnetic field in the core region causes the ions to quickly build up angular momentum. Even if the deuteron starts at rest, it builds up enough angular momentum to orbit the trap in about 7.5 μs (30 passes). Angular momentum of ions is detrimental to IEC performance because it enlarges the core region and impairs confinement. Angular momentum buildup in the biconic cusp configuration is similar to that of no magnetic field. One can see from Figure 25 how the central convergence is reduced with increased angular momentum. Thus, the biconic cusp is favored from the point of view of ion kinematics.

In summary, COMSOL Multiphysics simulations show that ion confinement in a PCPET trap can be similar to that in the multi-grid and planar electrostatic trap configurations. Electric field disturbances caused by the central plasma do not seem to inhibit ion confinement, though they may broaden the core. A biconic cusp field should be used for central plasma confinement to prevent imparting undue angular momentum to the confined ions. In the next section, the electron behavior in the MEPC region will be simulated.

COMSOL Multiphysics Simulations with Electrons

With the ion behavior well understood, it is now necessary to explore the electron behavior in the PCPET. Electrons are introduced primarily by thermionic filaments on the electrodes outside of the MEPC magnets. The electric field accelerates the electrons through the magnets into the magnetic trapping region. As shown in the previous section, a biconic cusp trap is preferable to a magnetic bottle to prevent ions from building up angular momentum. Although the biconic cusp trap has the additional spindle cusp through which electrons could be lost, this is not a concern because the spindle cusp is electrostatically plugged by the acceleration cathode. Thus, electron losses should be limited to upscatter into the external emitter and drift to field lines that graze the inside of the magnets. The sole purpose of the electrons is to mitigate the positive space charge created by convergence of ions to the core.

COMSOL Multiphysics was used to simulate electron behavior in the PCPET. The time step was reduced to 0.1 nanoseconds to account for the electrons’ higher velocities. Sufficient trapping occurred with 5,000 amp-turns in each magnet. Figure 26 shows how an electron emitted from an outside electrode is trapped in the PCPET. Confinement time is only limited by upscatter due to the electrostatic plugging effect. Anywhere an electron can escape the magnetic confinement, an electric field exists to reflect the electron back to the trapping region. These favorable conditions should allow trapping of an electron population that serves to actively neutralize the ion space charge.

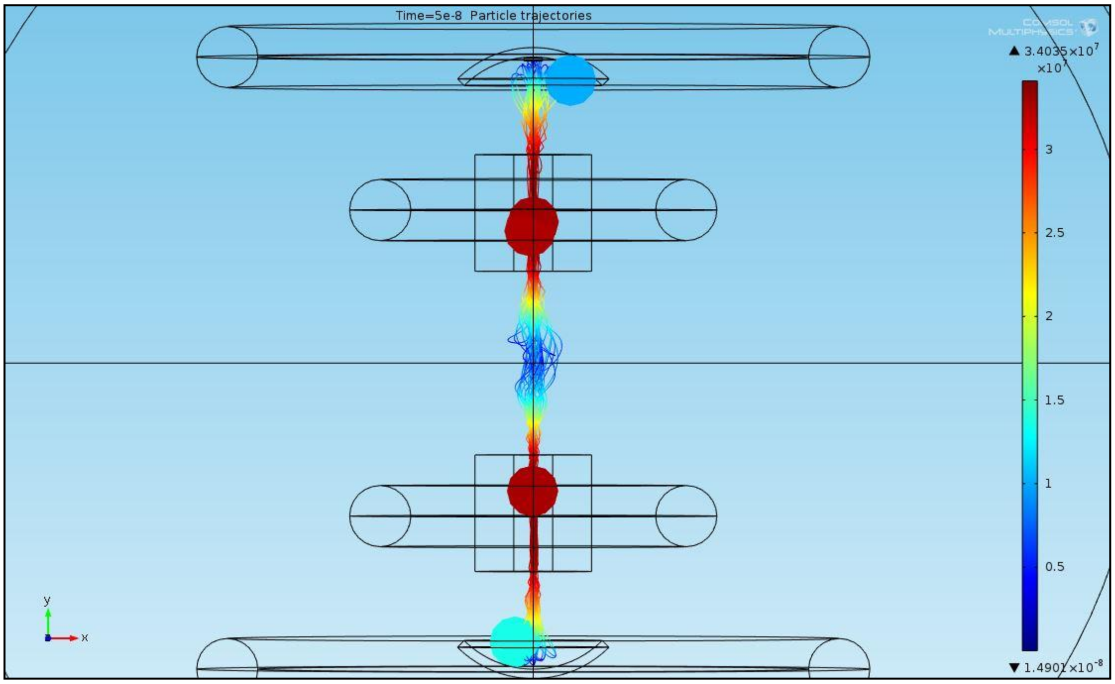

Figure 26: Confinement of five electrons in PCPET core near axis at 50 ns

Two types of electrons exist in the PCPET. The first type are those near the central axis, which oscillate from end to end in about 5.5 ns through the center of the device, as shown in Figure 26. The electrons slow considerably in the center due to the depression in potential there. With sufficient electron current, the central potential may depress so much as to reflect the electrons entirely, such that they never pass through the center.

The second type of electrons are those born or scattered away from the device axis, as in Figure 27. These electrons' trajectories are radially deflected by the diverging magnetic field in the core region, and do not pass through the center. Rather, they are reflected by the spindle cusp and electric field, oscillating between the center plane and the plugging electrode.

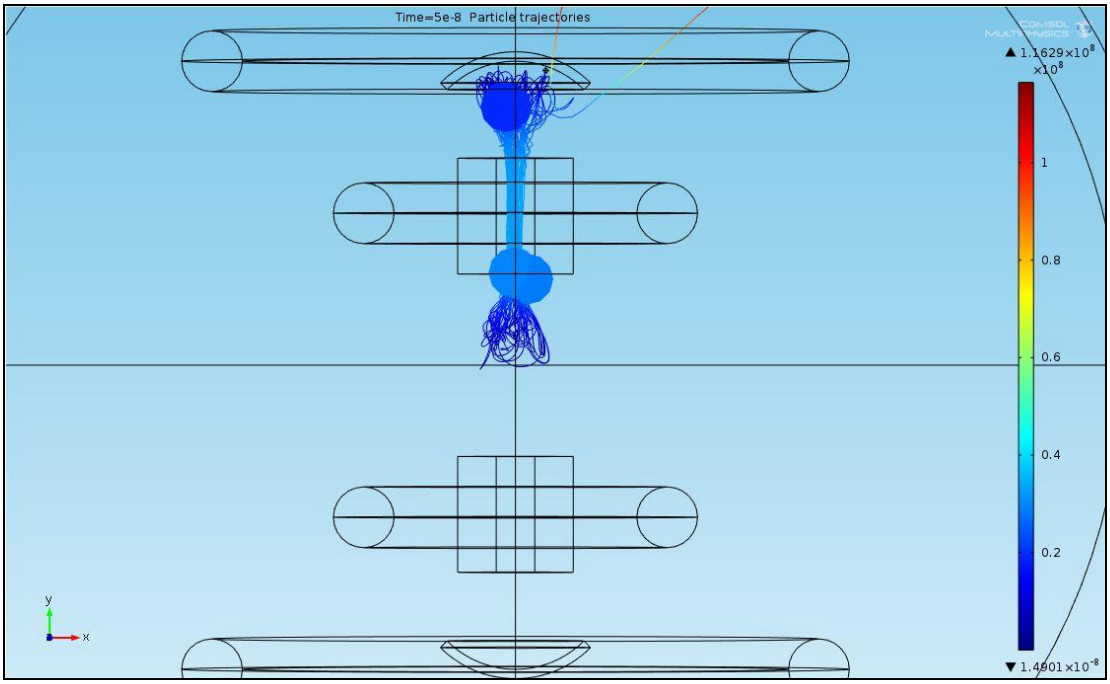

Figure 27: Confinement of five electrons in PCPET core away from axis at 50 ns

At sufficient electron currents, very few electrons may actually pass through the center plane. The vast majority will oscillate between the center plane and the external electrode, with a traverse time of about 3ns. If the electric potential of the external emitter is made more negative, more electrons may be energetic enough to pass through the center and the average energy of electrons in the core is increased. If the potential is made more positive, the energy of electrons in the core is reduced and the electron density in the center becomes lower. Thus, the external electrode potential can be tuned to control the electron energy and density in the core region.

Central Plasma Design

The purpose of confining a plasma to the core region is to provide electrons for neutralization of ion space charge. Whether or not the recirculating ions are in a synchronized state, the plasma electrons should react to and shield out any positive space charge created in the core. The extent of neutralization can be related to the local Debye length and plasma frequency in the core. The smaller the Debye length, the more effective the neutralization. Ideally, the Debye length should be much smaller than the core diameter, i.e., on order of micrometers. If the ions are in a synchronized state, the local plasma period should be much shorter than the ion transit through the core (a few ns). The Debye length and plasma frequency are calculated from the electron properties, since it is assumed any ions in the plasma are too massive to react on the nanosecond timescale of core transit. The mathematical approach agrees with this intuitive reasoning. Minimizing the Debye length suggests high density and low temperature. Abundant, cold electrons will clearly provide the best neutralization by moving quickly to the regions of positive space charge.

The electron temperature in the core can be controlled by adjusting the voltage on the external electrode/emitter. By tuning the potential just below that of the center of the device, the electron temperature could be reduced to just a few eV in the core. The electron current from the emitters controls the central density. However, the electron density cannot simply be increased arbitrarily. Electron space charge will depress the potential in the core, and the external emitter voltage must be adjusted accordingly to ensure electrons are energetic enough to populate the core. At still higher currents, the Debye length approaches the core diameter and the plasma becomes quasi-neutral. That is, low-energy ions will begin to accumulate in the core as well. As the density increases further, the plasma will grow in size to the limits of the magnetic trap. At such low temperature, the plasma will quickly reach high beta values, but this has little effect on the neutralization properties of the plasma since the core is relatively magnetic field-free no matter the plasma beta.

A plasma with temperature <100 eV and density 10^{19} m^{-3} satisfies the Debye length and plasma frequency requirements for effective neutralization. Such a plasma should be attainable with modest magnetic field strength and electron current. However, maintaining such a large temperature difference between the central plasma and recirculating ions could prove difficult. Indeed, one of the primary critiques with IEC devices is that the fusion energy output will never exceed the energy needed to maintain the non-Maxwellian plasmas. This is discussed in the next section.

Ion Effects on Central Plasma

As noted in the previous section, maintaining the temperature difference between the central plasma and the recirculating ions could be the biggest hindrance for the PCPET. As the high-energy ions pass through the plasma, they interact with electrons and low-energy ions to which they transfer energy and momentum. If this energy transfer is not negligible over many hundreds or thousands of passes, then it must be concluded that the plasma ruins the confinement of the trap.

Transport of high-energy ions through low-energy plasma has been studied for applications in neutral beam heating. Magnetically confined plasmas can be heated by injection of high-energy neutrals, which immediately ionize and then gradually transfer their energy to the bulk plasma. Anderson et al. [Anderson, 2011] measured the lifetime of fast deuterons in 400 eV plasma of density 10^{19} m^{-3}. By observing fusion rates, it was found the 25 keV ions classically slowed to beneath fusion-relevant temperature (~8 keV) in about 4 ms. Therefore, it can be concluded from these studies that fusion-energy ions have a lifetime on order of a millisecond in low-energy plasma. For deuterons with an initial energy of 25 keV, this corresponds to a penetration distance of ~5500 m.

If multiple ion passes through the central plasma in the PCPET can be modeled as accumulated transport through plasma of equivalent density, then the deuteron lifetime can be estimated as ~70 ms or 275,000 passes. Thus, the plasma limitation on ion lifetime is potentially less than that of the ion optics and charge exchange. However, this analysis ignores any higher-order effects due to the ion convergence in the plasma. A spindle cusp-contained plasma is generally MHD stable due to the concave magnetic fields, but beam-plasma instabilities may still be initiated.

The preceding basic analysis suggests that energy transfer between the recirculating ions and central plasma may not be a problem in the PCPET. Moreover, the slight plasma heating that does occur will primarily work to raise the electron temperature [Anderson, 2011], which is regulated by the external electrode potential. The core electron temperature is maintained at the desired energy as overheated electrons escape the point cusps, surmount the potential hill, and lightly impact the external electrodes.

Possible Use of Other Fusion Fuels

One of the advantages of electrostatic confinement is the ability to easily achieve ion temperatures suitable for burning a variety of fusion fuels. The use of different fuels would allow different fusion isotopes to be created, and the use of aneutronic fuels would be extremely favorable to eliminate radioactivity concerns. The IEC is also a strong candidate for direct conversion—the use of strong electric fields to convert fusion product kinetic energy directly into electrical energy.

The concern with using other fusion fuels in advanced IEC lies in the synchronization effect. D-D synchronization is simple because all ions in the system have the same mass. But most fuels, including the aneutronic, require the presence of two species with different masses. Each species would have a different bounce frequency, so inter-species synchronization could not occur. Each species would synchronize only with its own kind, and the two species' bunches would reach the core at different times. Inter-species fusion would only be significant when the core convergence phase of the species' oscillations overlapped. For the aneutronic p–^{11}B reaction, this would occur at most once every 11 proton oscillations.

It may be possible to restrict the ion synchronization effect by applying a RF voltage signal to the main anode. The RF signal causes temporal changes in the vacuum potential near the anode. These changes can cause the trap to violate the kinematic criterion if the RF frequency is not a resonant of the ion bounce frequency. Thus, no synchronization could occur. Restricting the bunching behavior may be desirable for any number of reasons, including avoiding the asynchronous problem with multi-species fusion. Restricting synchronization may also improve neutralization by eliminating the need for rapid temporal reactions of the plasma. Conversely, a constant ion current through the central plasma may be more prone to beam-plasma instabilities. Experimentation is needed to evaluate the stability of the asynchronous and synchronous modes and determine the potential of using fuel with varying mass.

Chapter 5

PCPET Prototype

To test the improved convergence of an actively neutralized ion trap, a prototype PCPET device was constructed [Sporer, 2017]. The axisymmetric geometry of the device is identical to that presented in Figure 16, except for the outer electrode. A solid outer electrode would prove difficult to machine and would visually obscure the device interior. Therefore, the prototype uses eighteen rings of 18 AWG aluminum wire, spaced ~1 cm apart, as the anode. This configuration is shown via COMSOL Multiphysics to have similar stability characteristics to the solid anode, as shown in Figure 28.

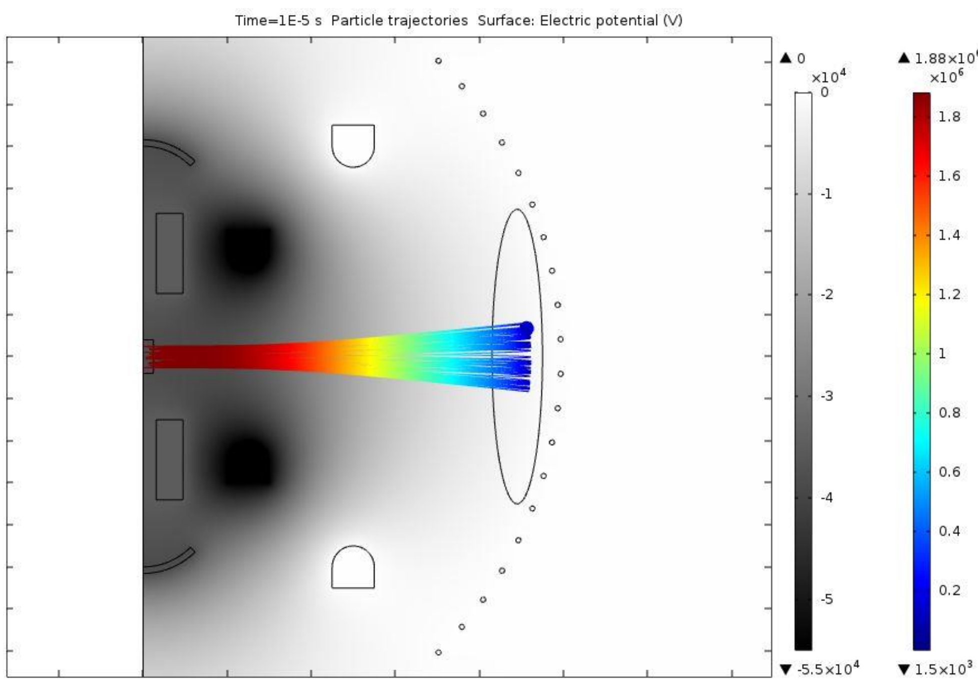

Figure 28: Single deuteron at 10microseconds in PCPET with wire anodes

The four ring-shaped, inner electrodes were machined on a lathe from 6061-T6511 aluminum bar stock. Aluminum was chosen over other easily workable metals for several reasons. First, Al has a relatively high work function, which should limit emission of extraneous particles like electrons. Al is also resistant to corrosion due to its self-protecting oxidation layer, making it easy to clean (ultrasonically), though this oxidation layer may also adsorb gasses and prolong the pump-down process. Aluminum is generally considered a good material for high vacuum.

Two permanent, nickel-plated, neodymium magnets create the central magnetic trap, and double as the central electrodes. The magnets were chosen to have a magnetic field strength topography resembling that generated in previous COMSOL Multiphysics simulations.

An assembly of 3D-printed PLA plastic frame pieces holds the various electrodes and magnets in place. While the ideal dielectric material for a HV plasma device would be ceramic, plastic turns out to be a great material for first prototypes. 3D printing allows for the complex and intricate shape of the support frame, and PLA plastic supposedly performs surprisingly well in vacuum. A plasma group from PPPL tested 3D-printed PLA in high vacuum in the vicinity of plasma, and found no increase in the background signal as low as 1 μTorr [Zwicker, 2015]. With proper cleaning, hopefully similar levels of vacuum can be achieved with the plastic PCPET frame pieces.

The electrodes and frame were thoroughly cleaned with isopropyl alcohol before being bonded with small amounts of vacuum-grade epoxy (Hysol 1-C). The two halves of the frame then enclose the anode frame and are fastened with plastic pins (see Figure 29). The assembled device is 22 cm (8.66 in) in diameter and height, not including any high voltage attachments or electron emitters/reflectors. The entire device is now ready to be outfitted in a vacuum chamber.

Figure 29: PCPET prototype disassembled (left) and assembled (right)

At the time of submission of this thesis, the PCPET prototype was being installed in a suitable vacuum chamber for initial testing. Plasma properties will be measured optically through a standard window port to see if ion density is enhanced with the permanent magnets (as opposed to aluminum duplicates). Initial experiments will be run with hydrogen or helium; however, the vacuum chamber being used is self-contained and portable, so movement to a radiation-shielded room may eventually allow experiments with deuterium. Direct measurement of fusion rate would be the most useful diagnostic with the PCPET prototype.

Experiments with the PCPET prototype will also demonstrate the usefulness of 3D-printed PLA in a high-vacuum and plasma environment. Obviously the plastic may outgas profusely and melt at high temperatures, but if suitable levels of vacuum can be reached, even for short periods, 3D-printing may prove an indispensable tool for IEC prototyping, and plasma experimentation in general.

Chapter 6

Conclusions & Implications

Inertial electrostatic confinement (IEC) provides a method to easily trap and heat charged particles for nuclear fusion applications. Unfortunately, the traditional IEC configuration is inherently limited in both efficiency and power output. Numerous alterations have been made to mitigate problems with the traditional IEC configuration, and much progress has been made. However, even once most problems are eliminated, the efficiency of advanced IEC devices are still fundamentally limited by the achievable ion population and density in the trap. This limit is imposed by space charge due to the insufficient neutralization of ion plasma in the device.

A novel approach for improving the neutralization in ion-injected IEC devices involves the active injection and confinement of electrons to the center of the device, to create a dense, neutralizing plasma in the core region. Enhanced neutralization allows for higher ion densities and populations, and consequently higher fusion rates. The described concept is termed the plasma-core planar electrostatic trap, or PCPET. The PCPET uses permanent or electromagnets to create an electrostatically-plugged biconic cusp in the device center, where ions converge in their oscillations through the planar trap. Electrons are injected into the trap to create the neutralizing plasma for the ions.

The PCPET may run in different modes of operation depending on how the synchronization behavior of ions is controlled. Synchronization will tend to emerge naturally, but can be encouraged or restricted with RF signals applied to the anode of the trap. It is unclear which mode will result in the greatest fusion output. Further experimentation is needed to verify the expected behavior of the trap and determine which mode of operation is most efficient. A first prototype has been constructed utilizing 3D-printing with experimentation set to begin in April 2017 [Sporer, 2017].

The use of other fusion fuels in the PCPET may be possible, but the effect of differing ion masses on the synchronization behavior must be considered. Use of different fuels would allow for production of different particles. Aneutronic operation with a fuel like p–^{11}B would be extremely favorable.

A breakeven IEC fusion device would be *incredibly* more valuable than any other fusion machine. Cheap construction, flexible sizing, and direct conversion would allow for modular units running at powers of kilowatts to megawatts, instead of large and expensive reactors running at many gigawatts. If aneutronic fuels could be utilized, radioactivity regulations would be much less stringent and even lower power devices could be made for a variety of portable applications.

High-output IEC fusion also has many near-term applications, particularly in space propulsion. The vacuum of space makes IEC particularly simple there, eliminating the need for any pumps or chambers. Kilowatt-power IEC engines could reduce the transit time from Earth to Mars by nearly half that possible with chemical propulsion [Hammond, 2000]. IEC engines have specific impulses as high as 100,000 s [NASA, 2015] due to the extreme velocities (>12,000 km/s!) of the fusion products ejected for thrust. A Q > 2 IEC engine using aneutronic fuel could expel half its fusion products as thrust, while using the direct conversion to extract energy from the other half, propelling the spacecraft and powering it.

High-energy neutrons and protons from fusion can be used for a number of other purposes, including production of medical isotopes and non-destructive probing of materials. Currently, great cost comes with producing medical isotopes in bulk at specialized fission reactors or particle accelerators, as well as with the decay of many of the short-lived nuclei during transportation to hospitals. Low-power IEC fusion devices could produce isotopes for hospitals onsite, on demand, with similar radiation concerns as X-ray machines. Several PET isotopes can be produced from irradiation of nitrogen and oxygen with the 14.7 MeV protons from D–^{3}He fusion [Miley, 2014].

A number of researchers have studied the use of neutrons from an IEC fusion device for neutron activation analysis (NAA). NAA with IEC allows for a reactor–detector combination capable of identifying both fissile material and chemical explosives. More detailed descriptions of IEC active detection systems can be found in [Miley, 2014].

IEC fusion has an incredibly bright future and a wide range of applications, if only it can be made more efficient. The ultimate efficiency goal would be breakeven, where a fusion reactor may generate net energy. If problems with space charge could be mitigated, such efficiency boosts may be possible and the aforementioned technologies made a reality. Unfortunately, IEC has received significantly less attention from the fusion community in recent decades, partially because the advent of superconductors has reinforced exploration of magnetic confinement systems like the tokamak and stellarator. Many in the fusion community have dismissed IEC with calculations showing its inability to reach breakeven, but some assumptions in these calculations become questionable in the highly non-thermal plasmas of advanced IEC devices like the PCPET. As such, IEC is best studied experimentally. Even assuming IEC fusion will never reach breakeven, the multitude of its applications makes IEC research more than worthwhile.

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