Study of Ion Microchannels and IEC Grid Effects Using the SIMION Code[+]

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ABSTRACT

The design of the cathode grid for a spherical inertial electrostatic confinement (IEC) fusion device is described based upon the results of SIMION, an electric field and ion trajectory program. Cathode grids of varying radii and geometric transparency were simulated with this code. Two-dimensional models of energetic ions in the IEC that were produced with SIMION show the formation of ion microchannels and the Star-mode. The SIMION results also show that smaller, less transparent grids produce smaller cores and more focused ion channels.

INTRODUCTION

Inertial Electrostatic Confinement (IEC) fusion systems have been studied experimentally for many years. Initial work was done by Hirsch [1] and is continuing today with studies by Miley [2] at the University of Illinois (UIUC), Anderl [3] at Idaho National Engineering Laboratory (INEL) and Fonck [4] at the University of Wisconsin (UW). Spherical IEC devices with a single cathode grid have produced 10^7 n/s from the D-D fusion reaction. While this neutron production rate is acceptable for such applications as neutron oil-well logging [5] and other nondestructive evaluation applications [6], a greater neutron yield would make IEC devices more competitive with advanced neutron accelerators.

The IEC device in its simplest form consists of a hollow, spherical, cathode grid inside a spherical vacuum chamber. An insulated, high voltage feedthrough supplies power to the grid, and a small amount (10^{-4} - 10^{-2} Torr) of either hydrogen or deuterium gas is fed into the chamber. When voltage is applied to the grid, the gas becomes an ionized plasma. The positive ions are accelerated toward the grid, where many pass through because of the cathode's high geometric transparency. Most of the ions recirculate through the center of the chamber, where they can collide and fuse with other ions.

Experimental studies [7] have shown that the fusion neutron production rate is increased when the IEC is operated in a regime known as the Star mode. This mode is characterized by beams of light emanating from the center of the chamber and passing through the holes in the grid, as seen in Fig. 1. The light results from interactions of the positive ions with both the electrons and the neutral background gas. This implies that the beams of light are actually concentrations of ions (and electrons) within the plasma. For this reason, the beams have been named ion microchannels.

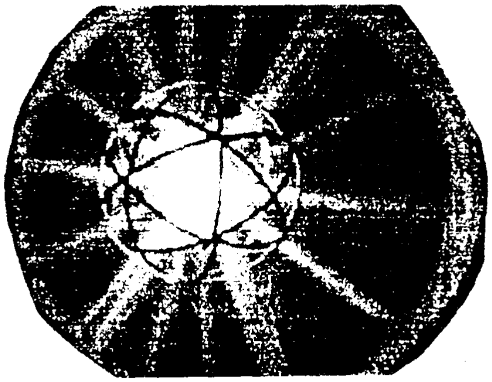

Fig. 1. A photograph of the IEC operating in Star mode. Ion microchannels pass through the holes of the cathode and converge in the center.

Since the Star mode produces a greater fusion rate than other modes of operation, it is important to study this regime, both experimentally and computationally. Many computer programs have been written or adapted to study the plasma in an IEC chamber, including IXL [8], PDS-1 [9], and NNF. These codes are useful for calculating such properties as the ion density, electric potential, and fusion rate. However, these codes are one-dimensional simulations and cannot represent the non-uniform, three-dimensional plasma of a Star mode discharge. In the present study, a particle trajectory code is used to analyze the microchannels of the Star mode.

USING SIMION TO MODEL THE IEC

SIMION is an electric field and ion trajectory program developed at Idaho National Engineering Laboratory. Its

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primary uses are to model ion focusing equipment such as Einzel lenses, ion traps, and mass spectrometers. Electrodes in SIMION are defined on a point-by-point basis in a rectangular coordinate system in either two or three dimensions. Once the electrodes are defined, the program solves Laplace's equation with a finite-difference method to determine the electric potentials due to the electrodes.. SIMION uses these potentials to calculate the forces on ions and determine their trajectories. This code cannot determine the electric potentials produced by a plasma.

There were some key reasons for using SIMION. First, many geometric shapes can be used with this program, making it easy to produce a model of the IEC. Second, SIMION can be enhanced by implementing user subroutines. These routines can enhance the calculation of ion trajectories, or be used to write useful information to an output file. Third, the program runs on a PC, which is more convenient than a mainframe. Finally, it is possible to simulate several ions at a single time, accounting for coulomb forces between the charged particles. However, this slows the program significantly. Fig. 2 shows a sample plot of the ion trajectories in the IEC. Here the paths of the ions closely resemble the ion microchannels of the Star mode.

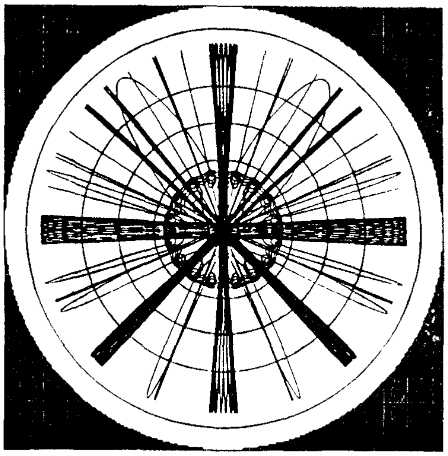

Fig. 2. A SIMION model of ion paths in the IEC. The trajectories resemble ion microchannels. The center region can be considered to represent the core.

However, there are also limitations using this program to model an IEC device. First, SIMION can only model the potentials created by the electrodes. Next, the program cannot model electrical insulators. All points in the system are either electrodes (treated as solid shapes) or are non-electrodes (treated as transparent regions). Finally, it can only model ion collisions with the electrodes. It cannot model ion and neutral gas collisions, which is a major ion scattering mechanism in the IEC. In spite of these limitations, the results from SIMION provide good insight about the formation of microchannels and how grid design affects the central core.

GRID DESIGN CONSIDERATIONS

The main task at hand was to use SIMION to model different cathode grids in the IEC. The grid radius and number of wires used in the grids, which determines the geometric transparency, were varied. The chamber radius was constant at 7.7 cm and the voltage was fixed at -30 kV. For each grid design, a series of ions were started at a certain radius with no initial kinetic energy. Each ion was stopped after it collided with the cathode, or after 2.5 microseconds, whichever came first. As each ion crossed the y-axis, its position was written to a data file. The average deviation from the center was calculated from this file and this value was called the ballistic core radius (BCR). Results from two-dimensional SIMION calculations are plotted in fig. 3 and illustrate that the BCR increases with the grid radius and the physical transparency.

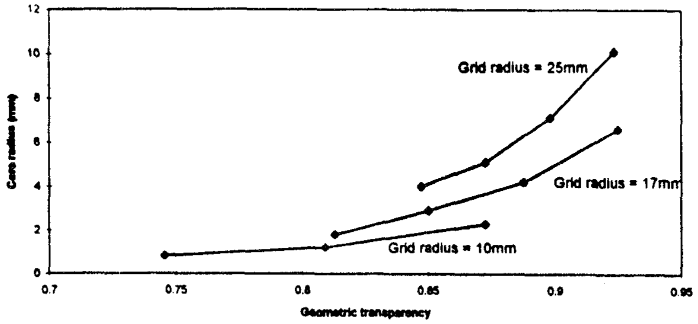

Fig. 3. Calculated core radius vs. grid radius and geometric transparency.

These values for the BCR compare well with experimental observations. Tzonev and Satsangi at UIUC [10] found the core to have a 3.0 mm radius by measuring the light intensity from the center of the IEC.

The BCR serves as an indication of how well the ions are trapped in the microchannels. A smaller BCR has narrower ion channels, which means that the ions are less likely to deviate from the center of the chamber. This also implies that there is a greater ion density within each microchannel,. A larger core indicates wider, less-focused, lower density ion microchannels.

Another important aspect of grid design is the physical or geometric transparency. This value is defined as the fraction of the surface area of the grid that is open space. As the transparency decreases, there is more cathode surface area present to intercept ions. This increases the number of ions that collide with the grid, decreasing the number that are trapped and travel in the microchannels. In short, a lower transparency decreases the ion density in the micro channels and decreases the fusion rate. When the transparency of the grid is less than 0.85, over 40% of the ions, a significant fraction, collide with the grid, reducing the number of ions available in the micro channels.

The two factors, grid radius and transparency, play an important role in the formation of ion microchannels and in determining the fusion rate. Smaller, less transparent grids can produce smaller ballistic cores, which have a greater ion density. However, with these grids, more ions collide with the cathode and do not contribute to the fusion process. Larger, more transparent grids allow more of the ions to travel in microchannels, but the channels are wide and diffuse. The ion density within these channels is lower and would decrease the volumetric fusion rate. There should be an optimum transparency and grid radius which produces the largest fusion rate. Unfortunately, SIMION cannot calculate the fusion rate of the IEC system. However, it can graphically represent the IEC in two (and three) dimensions, show the effect of cathode design on the formation of ion microchannels, and provide some quantitative numbers for the BCR, which may be difficult to measure experimentally.

MICROCHANNEL FORMATION WITH SIMION

Although the theoretical basis for ion microchannels formation has been reported previously [11], the graphical output of SIMION can be used to describe microchannels further. As seen in Fig. 2, the cathode in the IEC produces concave equipotential lines whose shapes are due to the potential of the individual grid wires. These lines will defocus ions as they approach the grid from the outside. But once an ion is inside of the grid, it "sees" convex field lines, which focus the ion toward the center. The net result is that ions that do not initially collide with the cathode, or do not pass so close to the grid that their trajectory is distorted, continue to travel within the microchannel.

This picture of channels assumes that the ions are born near the chamber wall where the electric potential is greater and the perturbation of the electric field due to grid wires is small. If, on the other hand, the ion starts near the grid where there is a small electric potential accelerating it toward the center. This ion will have a small amount of momentum and may be attracted by an individual grid wire. If this happens the ion will be deflected away from the center of the channel where it can either collide with the grid or go into an orbit that is not in any specific microchannel.

Fig. 4 depicts the difference between these two cases. The ions in the first case (left side of Fig. 4) start near the wall and form microchannels. The ions in the second case (right side of Fig. 4) start close to the grid. These ions do not form separate and distinct microchannels. instead they pass through the grid while traveling in a greatly curved path. These paths are similar to the results of Moses [12]. who used Mathematica to plot ion trajectories in an IEC device. His simulation also started the ions close to the grid, which resulted in a de-focusing of the ions.

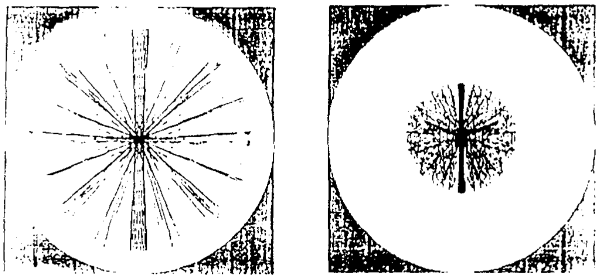

Fig. 4 SIMION plots of ion trajectories starting at different radii. Ion channels form only when ions start far from grid.

There are three different ways that an ion can collide with the grid in SIMION. The first is to run directly into the cathode without passing through the center. The second method is to pass through the grid a few times without being trapped in a microchannel before colliding with a wire. The third way is to pass through the core a few times while remaining in one microchannel before it collides with a wire. The ion could also remain trapped in a microchannel indefinitely. For this instance, a small user program is needed to stop the ion after a certain period of time. Table 1 shows how many ions collided with the grid and the manner in which they collided. This data is for a 91% transparent grid at -30 kV. Note that more high energy ions that start near the wall remain trapped in the channels compared to the low energy ions that start near the grid.

Table 1. Distribution of collision types for high and low energy ions.

	High E ions (26 kV)	Low E ions (12 kV)
Ions collide directly with grid	8.8%	8.8%
Ions not in one channel and collide w/ grid	19.2%	25.6%
Ion in one channel, but collide with grid	28.8%	55.2%
Ions in channel, do not hit grid	43.2%	10.4%

Thus it is concluded that for ions to remain in the microchannel, they must be the high energy ions that start near the chamber wall. Low energy ions that start near the grid do not remain in the channels. This implies that increasing the density in the ion channels will increase the number of high energy ions which will increase the fusion rate.

CONCLUSIONS

In this study. we have used the SIMION code to model ion transport in a has spherical, gridded IEC device. Some of the key results of this study are the following: First, the calculations have shown how the spherical IEC grids can confine ions into microchannels. Second, calculations of the ballistic core radii for various grids and have shown that smaller, less transparent grids produce smaller cores. Finally, these calculations have shown that the transparency must be kept at a reasonably high level (>85%) to maintain a large number of ions in the channels. In conclusion, we have demonstrated in this work that SIMION calculations have been useful to design cathode grids for IEC devices.

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