COMPUTATIONAL STUDIES OF COLLISIONAL PROCESSES IN INERTIAL ELECTROSTATIC GLOW DISCHARGE FUSION DEVICES

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Computational studies of the Inertial Electrostatic Confinement (IEC) devices have yielded amazing results. An analytical model of charge exchange collisions in the IEC plasma has been developed to include ion time-of-flight and fusion neutron generation rates. Results from the model simulating 10 mA of D_2^+ ion current in a 30-cm diameter IEC device at 50 kV match the experimental results of 10^6 fusion neutrons per second. The model has also been used to find the effects of grid diameter on neutron yield and show that it scales as diameter^{-0.4058}. This factor is very close to the experimental scaling factor of diameter^{-0.4171}.

INTRODUCTION

The Inertial Electrostatic Confinement (IEC) concept is being employed to make a portable fusion neutron source. In an IEC fusion device, a deuterium plasma is initiated in a system with a spherical hollow cathode grid and a spherical vacuum vessel serving as the anode [1]. When sufficient voltages are applied to the cathode, the deuterium ions can fuse together. One branch of the fusion reaction produces 2.45-MeV neutrons; which can be used in a variety of industrial applications including non-destructive evaluation of coal, airline luggage, and munitions [2].

The Fusion Studies Laboratory at the University of Illinois at Urbana-Champaign (UIUC) is currently working with Daimler-Chrysler Aerospace to develop commercial IEC neutron sources. The primary experimental vessel at UIUC for this research has been named the A-device. It is a 30-cm diameter spherical vacuum chamber, which approximates the desired size for a portable neutron source (fig. 1). Presently, the IEC A-device can generate 10^6 neutrons per second when operated at 50 kV and 10 mA.

Figure 1. (left) Picture of 30-cm diameter spherical IEC A-device in operation. (right) Close-up view of the Star mode glow discharge through a viewing port.

An important aspect of the spherical IEC device is the Star mode discharge. Discovered at UIUC, this unique discharge mode allows ions to pass through the holes of the

hollow cathode without direct losses to the cathode grid wires (fig. 2) [3]. As a result, ions could theoretically recirculate indefinitely through the IEC device, increasing the number of fusion reactions. However, collisions between ions and other species in the plasma (other ions, thermal background gas, fast neutrals, and electrons) can dislocate an ion from the preferred Star mode ion beam and send it on a collision course with the cathode grid. Further studies of the many different collisions are needed to be able to improve the yield of a commercial IEC neutron source.

Figure 2. Diagram showing equipotential surfaces of the IEC cathode grid and their focusing effect on a beam of ions in the Star mode discharge.

COMPUTATIONAL STUDIES AT UIUC

Two different computational approaches are being developed at UIUC to model various collisions in the plasma of the spherical IEC device. The first approach involves modeling only charge exchange collisions as fusion rates, energy distributions, and ion transit times are calculated. The second approach involves many different collisions; including charge exchange, ionization, molecular dissociation, and fusion. This model will be a comprehensive simulation of an IEC plasma when it is completed.

Unfortunately, results from this second approach, the IONTRAC program, were not made available at the time of writing. This paper will focus on the results from the first approach, the Analytic Charge Exchange (ACE) program. [3]

CHARGE EXCHANGE COLLISIONS

Charge exchange (CX) collisions occur when a fast (above thermal energy) ion collides with a neutral background gas particle and an electron is transferred from the neutral particle to the ion. This process results in a fast neutral (formerly ion) and a thermal energy ion (formerly neutral). Instead of viewing the collision as a transfer of

charge, the process can be thought of as a transfer of kinetic energy from the ion to the background gas particle.

There are three different CX reactions whose cross sections are readily available. [4]

Of these reactions, only the first two were considered for the ACE program, primarily to keep the model simple by involving only one ion specie in each reaction.

The curve-fits of the cross sections for the equivalent hydrogen reactions were found in Janev. [4] Although it is easy to convert the formulas for use with deuterium, finding cross section fits exclusively for deuterium simplifies and speeds up the calculations. The Chebyshev fits from Janev were plotted on the appropriate deuterium energy scale (fig. 3) and were fit to a 6th order polynomial function of the natural logarithm of deuterium energy. The coefficients of the polynomials appear below in table 1.

Figure 3. Plot of the charge exchange cross sections for D^{+} on D and D_2^{+} on D_2 .

Table 1. Coefficients for charge exchange cross sections used in the ACE program (valid from 0.5 eV to 100 keV).

$$\sigma = \sum_{n=0}^6 a_n (\ln(E(\text{eV})))^n \text{ cm}^2$$

n	D^{+} CX (eq. 1)	D_2^{+} CX (eq. 2)
0	6.24967882 E-15	1.35660436 E-15
1	- 3.47012922 E-16	- 1.96548177 E-16
2	- 5.64994294 E-17	1.87262829 E-16
3	- 8.29919141 E-18	- 2.5692072 E-17
4	2.91334306 E-18	1.0573025 E-17
5	- 2.18376695 E-19	- 6.30570489 E-19
6	4.68748873 E-21	1.2351316 E-20

ANALYTIC CHARGE EXCHANGE MODEL OF THE IEC A-DEVICE

The Analytic Charge Exchange (ACE) program considers a one-dimensional view of an ion beam in the IEC device. For this model, it is assumed that the beam has a constant cross-sectional area across the device and that none of the ions in the beam directly strike the grid (100% effective transparency). In this model, the only time an ion is lost is after it has charge-exchanged inside the cathode grid region. In this circumstance, there is a strong tendency

for the newly created thermal ions to be attracted directly toward a cathode grid wire. Another assumption includes a vacuum electric potential profile that ignores the plasma potential effects. Finally, the model does not determine the initial ion positions; an initial distribution is set by the user.

Once the device parameters are selected, the deuterium ions that start at the chamber wall (anode) are "marched" through the device, passing through a large series of cells. At each cell location, the number of CX collisions that occur within that cell is calculated. Ions that do not CX advance to the next cell, increasing their energy as they move toward the cathode. Ions that do CX are placed in the next cell and continue as new ions with thermal energy. The process continues until all of the ions are lost due to CX collisions within the cathode grid region.

Significant improvements to the ACE model have been implemented since DeMora's MS thesis [3] was completed. Some improvements include the choice of modeling either D^{+} or D_2^{+} collisions, tracking ions as they pass completely through the cathode grid to the other side of the device, and allowing simulation of multiple ion passes. Also, the ACE program now includes routines to calculate fusion rates for ions and fast neutrals, and to calculate the ion time-of-flight at each cell location.

Two factors that affect the number of CX collisions are the background gas pressure in the IEC device and the energy of the ions. The CX cross section is largest at low energies, and is much larger for D^{+} than it is for D_2^{+} . Also, an increased pressure provides more targets for the ions to have CX collisions. The increased number of collisions reduces the energy of the ions in the system, which leads to lower ion confinement times and lower fusion rates.

Using IEC A-device conditions of 50 kV, 10 mA, and 4-cm grid diameter, the background gas pressure is about 4.6 mTorr. At this pressure, CX collisions occur quite frequently for the case of D^{+} ions. In their first pass through the IEC, about half of the ions CX within the cathode region and are lost (fig. 4). After only 4 passes, most of the remaining ions have lost a large amount of their original potential energy (fig. 5) and the fusion rate from subsequent passes becomes negligible. For D_2^{+} ions with a smaller CX cross section, it takes about 20 passes for most of the D_2^{+} ions to lose their energy and be lost to the grid.

Figure 4. Plot of deuterium ion (D^{+}) energy distributions on their first pass through the grid of the IEC. Almost half of the ions charge-exchange inside the cathode region and are eventually lost.

Figure 5. Plot of deuterium ion (D^+) energy distributions after 4 passes through the center of the IEC. After 4 passes, there are very few D^+ ions at an energy to produce fusion.

In an effort to model various cathode grid sizes with the ACE program, another assumption was needed to correlate the background gas pressure to the grid diameter. It was assumed that the $p \cdot d$ term for Paschen break down of a plasma (where d is the distance between the electrodes) remained constant for various grid sizes. This led to an increase in the operating pressure as the grid diameter increased (because the distance between the anode and cathode decreased). This in turn increased the number of CX collisions. Consequently, the average ion time-of-flight decreased as the grid diameter increased. (fig. 6) This trend occurs for both D^+ (not shown) and D_2^+ ions. The ion time-of-flight plays an important role in determining the overall fusion rate.

Figure 6. Plot of average D_2^+ ion time-of-flight in the IEC as a function of grid diameter. Increased grid size means higher operating pressure, more collisions, and shorter time-of-flight.

CALCULATING FUSION RATES WITH ACE MODEL

The ACE program is able to calculate the fusion rate from ions and from the fast neutrals that are produced by the CX collisions. In an ideal low pressure case, one could expect all of the fusion reactions to come from ions because there would not be many fast neutral particles to fuse. However, in a typical IEC A-device Star mode discharge, the pressure is high enough to produce many fast neutrals at sufficient energies to be a major contributor to fusion in the IEC.

When scaling the fusion rates with the grid diameter, it is important to note that the pressure increases as the grid

size increases. This means that there are more background gas particles for the ions and fast neutrals to fuse with, leading to seemingly increased fusion rates (fig. 7 and 8). However, it is important to note that these rates are based on a fixed number of ions (10^9) starting at the chamber wall. These rates have not yet been normalized to current, and they assume that all of the ions start at the chamber wall, which is a very optimistic scenario.

Figure 7. Plot of fusion rate based on 10^9 D^+ ions in the IEC system. About two-thirds of the fusions come from fast D neutrals.

Figure 8. Plot of fusion rate based on 10^9 D_2^+ ions in the IEC system. D_2^+ ions and fast neutral D_2 molecules contribute to fusion almost equally. These rates are lower than those for monatomic D and D^+ ions (fig. 7).

In order to normalize these fusion rates to the applied current, the average ion time-of-flight and one bold assumption are needed. The bold assumption is that all of the applied current in the IEC (typically, 10 mA) manifests itself only as ion current that becomes lost to the cathode grid. This means that for 10 mA of current, $6.24 \cdot 10^{16}$ ions are lost per second due to CX collisions within the cathode grid region. If the ion time-of-flight is only 10^{-6} seconds, then there must be $6.24 \cdot 10^{10}$ ions lost every 10^{-6} seconds to provide the 10 mA of ion current. The fusion yield based on current is shown in equation 4 below and is plotted for the D^+ and D_2^+ cases at 50 kV in fig. 9.

$$\text{Fusion}(i_{(mA)}) = \frac{i_{(mA)} \times 6.24 \cdot 10^{15} \times \text{TOF}_{(s)}}{X_{(\# \text{ of ions})}} \times \text{Fusion}(X_{(\# \text{ of ions})}) \quad (4)$$

Figure 9. Plot of fusion rates normalized to 10 mA of ion current using the average ion time-of-flight. The graph of D_2 fusion closely matches experimental results (10^6 neutrons/sec at 50 kV, 10 mA, and 3.4-cm diameter grid).

COMPARISON WITH EXPERIMENTS

Amazingly, the normalized neutron yield from D_2 fusion matches experimental values achieved in the IEC A-device, specifically the yield of 10^6 neutrons per second at 50 kV and 10 mA (using a 3.4-cm diameter grid). Furthermore, curve-fits were applied to the normalized neutron rates to find the relationship between neutron yield and grid diameter. For the D case, the yield scaled as diameter^{-0.3876}. For the D_2 case, it scaled as diameter^{-0.4058}. In experiments with eight different in the A-device, the yield was originally scaled to $\exp(-0.142 \cdot \text{diameter})$ [3]. When applied to a "power" scaling, the experimental grid scaling was diameter^{-0.4171}. The power functions are very close to each other, as seen in fig. 10.

Figure 10. Plot of D_2 fusion rate from ACE model on the same scale as experimental fusion scaling parameters from eight different cathode grids tested in the IEC A-device.

These results of the ACE model are significant in that they directly match experimental values for neutron yield and share practically the same scaling with grid diameter as eight different cathode grids. Previous attempts at using a charge exchange program to model fusion rates in an IEC device did not quite match their experimental counterparts. [5] Thorson used his results to reason that there must be other sources fusion neutrons (specifically, deuterium implanted in the cathode) to make up the difference between experimental and computational results. In using many different assumptions; including the background pressure in the IEC device, the D_2^+ ion source location, and a metered current that is due to ions, the ACE model

accurately predicts neutron yield in the IEC A-device. However, further study is required to see if these assumptions are indeed valid. In addition, the ACE model needs to be applied to other IEC devices to determine its true effectiveness.

CONCLUSIONS

Based on some unusual assumptions, the ACE model of charge exchange collisions predicts the fusion neutron production in the IEC A-device. Both the magnitude of fusion production and the scaling of yield with respect to cathode grid diameter match experimental results. Further simulations of other spherical devices are needed to demonstrate the effectiveness of the ACE model. Furthermore, additional work is needed to improve the model so that it can automatically determine the chamber pressure based on applied voltage, current, and operating temperature.

Other areas of IEC research that warrant further study have been revealed. Experiments to determine the amount of ion current, the amount of charge exchange fast neutrals, and the location and nature of the ion source are underway. Continued computational studies, including the IONTRAC program, will be used to benchmark and enhance the understanding of these areas.

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