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Comparison of Spherical and Cylindrical Cathode Geometries in Inertial Electrostatic Confinement Devices

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Four different cathode geometries were investigated for an Inertial Electrostatic Confinement (IEC) fusion device. The relative performance of each geometry was compared experimentally and theoretically. Experimental data was generated at -30 to -150 kilovolts, 30 milliamps, and 0.3 Pascal of Deuterium (D) and/or Helium-3 (^3He). The best neutron rate achieved in a pure D environment was $2.7x10^7$ neutrons per sec at 145 kV and 35 mA. In an environment of a D-^{3}He mixture the best proton rate achieved was $2.0x10^7$ protons per second at 130 kV and 30 mA. Also in this study, 3D simulations of the electrical potentials were merged with the cross-sections for the $D(d,n)^3He$, and $^3He(d,p)^4He$ reactions to calculate a metric for comparing the relative performance of each geometry.

I. INTRODUCTION

A third Inertial Electrostatic Confinement (IEC) fusion device has recently been constructed at the University of Wisconsin-Madison (UW). This new device has been named Helium-3 Cylindrical Transmutation Reactor or ^{3}HeCTRE. The long term goal for ^{3}HeCTRE is to use 14.7 MeV protons from a D-^{3}He fusion reaction to produce radioisotopes of medical value, such as C^{11}, O^{15}, and N^{13}.

The ^{3}HeCTRE device will also be used to investigate effects of cathode and anode geometry on the operation and performance of IEC devices. Historically, the University of Wisconsin's IEC program has used spherical cathodes and anodes. [1] In this paper the experimental results from the UW's original device, taken with two different sizes of spherical anodes and cathodes, will be compared to the experimental results from ^{3}HeCTRE with a cylindrical anode and data from both a spherical and cylindrical cathode.

In the course of the design and construction of this new chamber a simple and fast modeling technique was developed to assist in the optimization of the design. This modeling technique provided qualitative results from which the relative performance of different designs could be compared. This helped to decrease the construction time by providing a basis for making design decisions before extensive time was spent building the experiment.

I.A. General IEC Operation

The general operating principle of an IEC device is to accelerate D and/or ^{3}He ions though a DC electric field to energies at which fusion reactions can occur. In the UW IEC experiments examined for this paper, D and/or ^{3}He gas is flowed into the vacuum chamber to a pressure of approximate 0.3 Pa (2 mtorr). Electrons emitted from heated negatively biased tungsten filaments ionize the gas forming the ion source plasma. The outer anode is held at electrical ground potential and the inner cathode is held at a negative potential. The ions from the source plasma are accelerated toward the center of the cathode by the electric field between the two electrodes. As the particles reach the energies required for fusion reactions to occur neutrons and/or protons are emitted via the following reactions.

D-D (~50%): $D + D \rightarrow {}^3He$ (0.82 MeV) + n (2.45 MeV)
D-D (~50%): $D + D \rightarrow T$ (1.01 MeV) + p (3.02 MeV)

D-^{3}He: $D + {}^3He \rightarrow {}^4He$ (3.7 MeV) + p (14.7 MeV)

II. EXPERIMENTAL DEVICES AND OPERATING CONDITIONS

In order to determine the level of performance of the newly constructed ^{3}HeCTRE, its experimental results were compared to the original UW IEC at equal operating conditions. All of the data presented from both chambers was taken with a pressure of 0.3 Pa (2 mtorr) of either D gas or a gaseous mixture of D and ^{3}He. The high voltage power supply meter current was held at a constant 30 mA. The cathode voltage was varied from -50 to -150 kV.

II.A. Features of ^{3}HeCTRE

The design and construction of ^{3}HeCTRE began in July of 2005 with the first fusion reactions occurring in April 2006. The main vacuum chamber is a single walled stainless steel cylinder vessel with an inside diameter of 46 cm and a height of 46 cm resulting in a volume of 75 liters as shown in figure 1. Equipped with a 250 liter per second turbo-molecular vacuum pumping system, the chamber achieves a base pressure in the range of $2x10^{-4}$ Pa ($1x10^{-6}$ Torr).

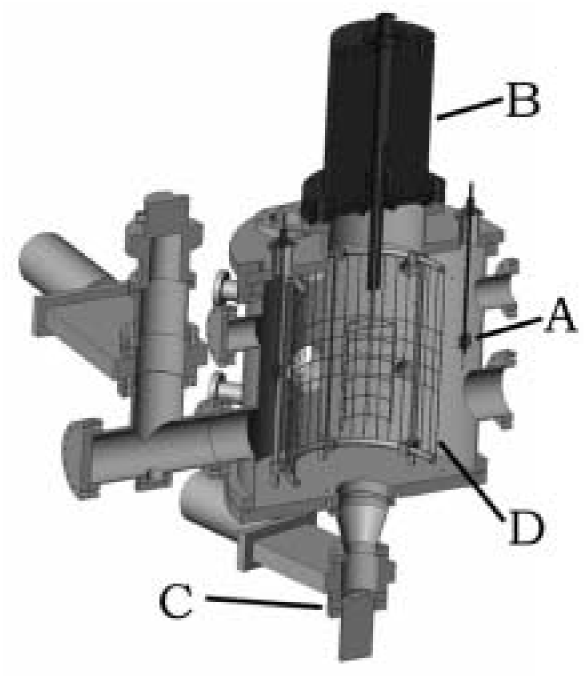

Figure 1: Cross-section view of ^{3}HeCTRE

The ion source plasma is created by four tungsten filaments labeled A in figure 1, with a capacity of up to six filaments for future work. The filaments are equally spaced 60 degrees apart and are placed between the outside chamber wall and the anode. The Z-axis position of the filaments is adjustable and was set at the center line of the cathode for these experiments.

Designing a -200 kV vacuum feed-through is a challenging design problem. The high voltage feed-through, label B in figure 1, must be able to withstand the high electrical field gradients and must provide a vacuum boundary. In addition, it must be able to withstand the plasma environment created by the IEC. The ^{3}HeCTRE device uses a unique, custom designed feed-through, which to date has been successfully tested up to -150 kV. Further testing of this design to higher voltages is planned.

An Ortec™ Ultra 1200 mm^2 700 µm thick silicon detector, labeled C in figure 1, was used to detect the protons produced by the D-^{3}He reactions. Lead foil with a thickness 400 µm was placed in front of the detector to reduce the X-ray noise. A permanent magnet of approximately 300 to 400 gauss was placed around the tube leading to the detector to prevent electrons from reaching the detector. Located 44.8 cm from the center of the chamber the detector was able to completely see the cathode.

The neutrons produced by the D-D reaction were counted using a ^{3}He neutron detector system. Both the neutron count data and the proton count data where recorded using two methods. The data was analyzed using multi-channel analyzer (MCA) software, monitored for excessive noise, and hand recorded. The detector signal was also fed into a single channel analyzer (SCA) set to match the MCA's region of interest (ROI). The digital output of the SCA was then digitally recorded using a custom LabView™ application which was also simultaneously recording the operating conditions of the experiment. This method of data collection allowed the post-analysis of the data to filter for variations in the cathode voltage and current, thus better controlling a source of error in the neutron and proton rate results.

II.B. UW's Original IEC Device as a Baseline of Comparison

The first UW IEC device [1] is a cylindrical vacuum chamber made of aluminum with a diameter of 95 cm and a height of 65 cm. It has a total volume of approximately 470 liters. Six tungsten filaments were used to produce the ion source plasma. These filaments are located every 120 degrees around the chamber and are not aligned with the equator of the cathode.

II.C. Anode and Cathode Geometries

A cylindrically shaped anode, labeled D in figure 1, was used for all of the experiments in ^{3}HeCTRE. The anode had a diameter of 27 cm and a height of 38 cm, and was constructed of stainless steel wire between two stainless steel rings on the top and bottom. A semi-opaque stainless steel mesh approximately 15 cm tall was wrapped around the midpoint of the anode to further shield the filaments from the cathode voltage.

Two cathode geometries were used in ^{3}HeCTRE: a 10 cm diameter spherical grid and a 10 cm diameter by 19 cm tall cylindrical grid. Both cathodes were constructed by spot welding 0.076 cm W-Re alloy wire to form the desired shape. The spherical grid, labeled 10S-27C in figure 2, consists of wire hoops welded together to form equally sized openings in the grid. The cylindrical grid, labeled 10C-27C in figure 2, consists of six vertical wires and six horizontal hoops.

Figure 2: Anode and cathode geometries in ^{3}HeCTRE

Historically, the majority of the experiments conducted in the first UW IEC device have used a stainless steel 50 cm diameter spherical anode and a 10 cm diameter W-Re spherical cathode. This configuration is labeled 10S-50C in figure 3. Previously collected best case data from this configuration was used as a baseline to compare the performance of the other anode / cathode configurations. As an additional point of comparison, recently collected data from the configuration labeled 20S-40S in figure 3 is also presented. This configuration used a 40 cm diameter stainless steel spherical anode and 20 cm diameter W-Re spherical cathode.

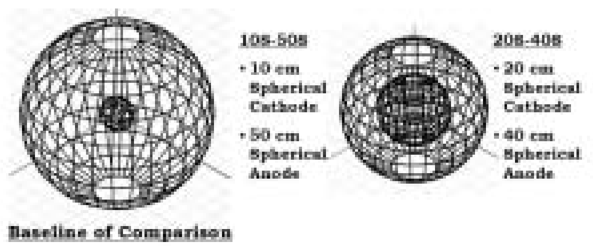

Figure 3: Anode and cathode geometries in the first UW IEC

III. EXPERIMENTAL RESULTS

III.A. D-D Neutron Rate Results

The first neutrons produced from a D-D reaction in ^{3}HeCTRE were observed in April 2006, approximately nine months after construction of the new chamber began. As of the writing of this paper, the best neutron rate achieved in ^{3}HeCTRE was 2.7×10^7 neutrons per second. This was achieved in the 10S-27C configuration at a cathode voltage of -145 kV, steady state meter current of 35 mA, and a total pressure of 0.3 Pa of D gas. Figure 4 shows the experimental results of the four configurations as a function of voltage at 30 mA of steady state meter current and 0.3 Pa of D gas.

In D gas, cathode voltages of -150 kV were achieved. At this level the 10S-27C system in ^{3}HeCTRE performed approximately 40% below the baseline in the original chamber with an identical cathode.

The cylindrical cathode configuration, 10C-27C, was conditioned to -110 kV. Higher cathode voltages are likely achievable with additional run time. At -100 kV, the cylinder cathode achieved a neutron rate 30% below the spherical cathode of equal diameter inside the same anode and chamber.

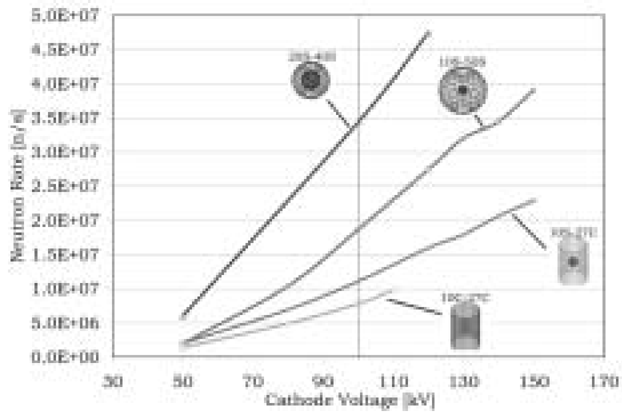

Figure 4: Experiment results of neutron rate versus cathode voltage at 0.3 Pa of D and 30 mA meter current steady state.

III.B. D-^{3}He Proton Rate Results

The first experiment in ^{3}HeCTRE with D-^{3}He reactions was conducted in October of 2006. The best proton rate observed to date in ^{3}HeCTRE is 2.0×10^7 protons per second. This rate was observed using the 10S-27C configuration at a cathode voltage of -130 kV, a steady state meter current of 30 mA, and a total pressure of 0.3 Pa of D and ^{3}He gas mixture. Figure 5 shows the experimental results of the 10S-50S, 10S-27C, 10C-27C configurations versus the cathode voltage.

Similar to the D-D neutron rate, the 10S-27C configuration in ^{3}HeCTRE performed approximately 40% below the baseline. The difference between the cylindrical and spherical systems in ^{3}HeCTRE was approximately 50%. In the case of the 10C-27C data, the experiment was not fully conditioned at the time of data collection. The experimental run reported here had a 25% improvement in proton rates versus the previous run. Additional run time on this system in a D-^{3}He environment will likely increase the proton rates further.

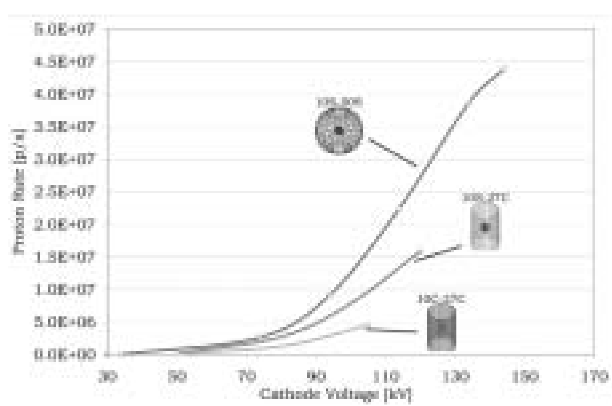

Figure 5: Experiment results of proton rate versus cathode voltage at 0.3 Pa of D – ^{3}He and 30 mA meter current steady state.

IV. MODELING TECHNIQUE

A simple modeling technique was developed to help in the IEC design process by providing a qualitative direction to various geometric design decisions. This technique is able to consider the 3-dimensional geometric details of the cathode, anode, and chamber. A user-friendly 3D parametric computer aided drafting (CAD) interface allowed for easy construction of the various models. The parametric feature allowed small changes in the geometry to be simulated sequentially with little effort.

Using the commercially available electrostatic finite element solver, Ansoft Maxwell® 3D [3], the vacuum electrical potentials were solved for each design iteration. Figure 6 shows a plot of the potential for the 10C-27C cathode-anode configuration. The potential as a function of radius along a line parallel to the X-axis was divided into small shells of width Δr. The estimated fusion cross-section, $\sigma(E)$, inside each shell for the D(d,n)^{3}He was calculated based on the formulas given by Bosch[2]. The energies used in the cross-section equation were the center-of-mass energy of a D particle with energy equal to the electrical potential of the shell striking a stationary D. The sum of the $\sigma[E(r)]^* \Delta r$ for each shell was then used as a metric to compare the various configurations.

Unfortunately, this model does not include much of the physics such as charge-exchange and ionization. Therefore, it is limited to being a qualitative tool for predicting the relative performance difference between small geometric changes while all other variables remain constant.

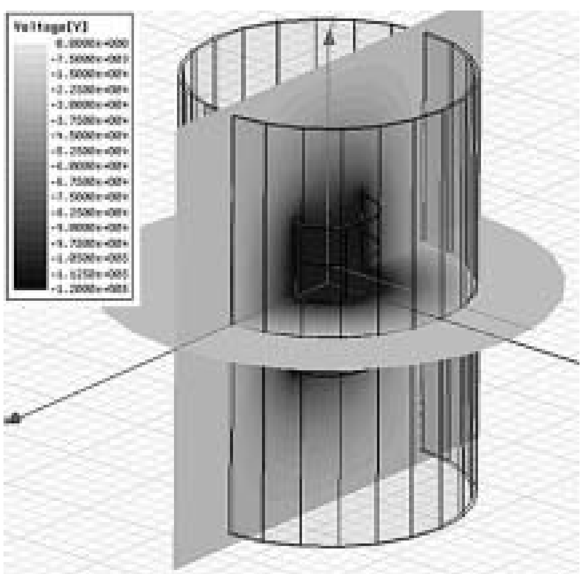

Figure 6: Plot of electrical potentials for the 10C-27C configuration created with Ansoft Maxwell® 3D.

IV.A. Model results and Comparisons to Experimental Data

Figure 7 shows the relative experimental performance and predicted performance of each cathode/anode configuration to the 10S-50S baseline at a cathode voltage of 100 kV and an experimental meter current of 30 mA. For the two purely spherical configurations, 10S-50S and 20S-40S, the experimental and modeled results are in general agreement at 88% and 77% respectively. A lessened, but still reasonable amount of agreement was observed when comparing the two cylindrical anode configurations, 10S-27C and 10C-27C, to each other. The experimental difference was -22% and the modeled difference was -5% for the cylindrical anode systems. A lesser level of agreement was seen when comparing the purely spherical 10S-50S to the purely cylindrical 10C-27C, at -57% experimental and -14% modeled.

The variation in the agreement between the model and experiment when comparing the various configurations to each other emphasizes the limitations of the modeling technique to small geometric changes. Changes in the cathode and anode sizes were in general agreement. Changes in the shape of the anode or cathode resulted in a lesser degree of agreement. It is interesting to note that in all four cases studied the direction of improvement or degradation in performance was predicted correctly.

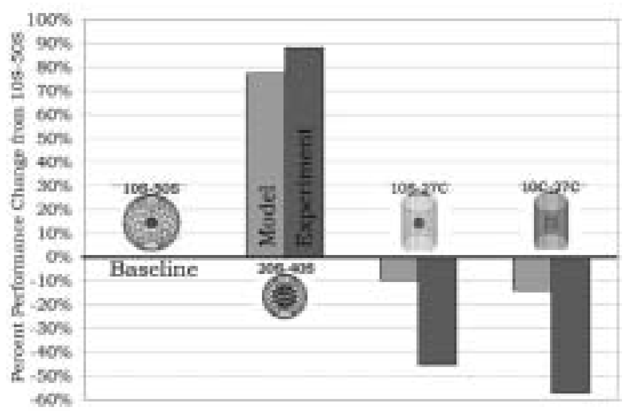

Figure 7: Comparison of the relative experimental and predicted difference in D(d,n)^{3}He performance for the four different configuration at 100 kV

V. Conclusions

Both D-D and D-^{3}He fusion reactions have been observed in the University of Wisconsin's newly constructed IEC device, ^{3}HeCTRE. With the best to date neutron rate of 2.7×10^7 neutrons per second and proton rate of 2.0×10^7 protons per second, the performance of ^{3}HeCTRE is in the range expected for an IEC device in the early stages of development. In order to provide a baseline from which to improve, the initial operating parameters for ^{3}HeCTRE were chosen to match those historically optimized for the original UW IEC device. Future work will be conducted to find the optimal parameters for ^{3}HeCTRE, after which the reaction rates are expected to improve

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REFERENCES

1. R.P. ASHLEY et al., “Recent Progress in Steady State Fusion using D-^{3}He,” *Fusion Science and Technology,* **44**(2), 564 (September, 2003).

2. H. S. Bosch and G. M. Hale, “Improved Formulas for Fusion Cross-Sections and Thermal Reactivities,” *Nuclear Fusion*, Vol. 32, Issue 4, pp. 611 (1992)

3. *Maxwell 3D version 11.0*, Ansoft Corporation, (Oct 2005).