Optimizing Neutron Production Rates from D-D Fusion in an Inertial Electrostatic Confinement Device

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OPTIMIZING NEUTRON PRODUCTION RATES FROM D-D FUSION IN AN INERTIAL ELECTROSTATIC CONFINEMENT DEVICE

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Detection of explosives has been identified as a near term commercial opportunity for using a fusion plasma. Typical explosive compositions contain low Z material (C, N, O) which are not easily detected using conventional x-rays or metal detectors. However, 2.45 MeV neutrons produced in a D-D fusion reaction can be used for detection of explosives or other clandestine materials in suitcases, packages, or shipping containers.

Steady-state D-D operation is possible using an Inertial Electrostatic Confinement (IEC) fusion device. The University of Wisconsin IEC device has produced D-D neutrons at 1.8 x 10^8 neutrons/second at a true cathode voltage of 166 kV and a meter current of 68 mA. These neutron production rates are approaching the levels required for the detection of explosives. In order to increase and optimize the neutron production rate in the IEC device, experiments were performed altering the cathode's size (diameter), geometry, and material composition. Preliminary results indicate that significant differences in neutron production rates are not achieved by altering the geometry or material composition of the cathode. However, the neutron production rate was found to increase approximately 20% by doubling the cathode's diameter from 10 cm to 20 cm. In addition, increasing the cathode voltage from 34 kV to 94 kV at a meter current of 30 mA increased the neutron production rate from 1.24 x 10^6 n/s to 2.83 x 10^7 n/s.

I. INTRODUCTION

The D-D fusion reaction can potentially be used for explosives detection using the University of Wisconsin (UW) IEC Device.[1] Figure 1 shows the D-D fusion reaction. The 2.45 MeV neutrons generated from this reaction can activate, for detection purposes, the low Z materials found in explosives. Specifically, the neutrons, once thermalized, will be captured by the ^{14}N nuclei, with a thermal capture cross section of 11.3 mb, resulting in a characteristic gamma ray of 10.829 MeV.[2]

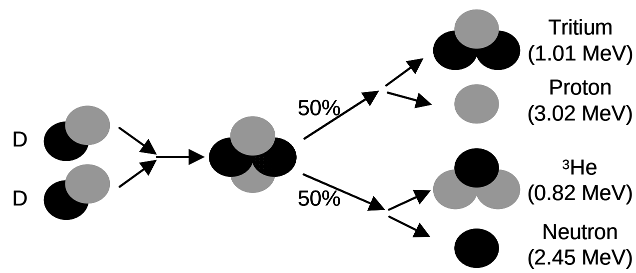

Figure 1: D-D Fusion Reaction.

A common technique for explosives detection utilizing thermal neutron activation analysis uses neutrons produced from the radioactive decay of ^{252}Cf. However, this method of explosives detection poses a significant health hazard and there is no way to stop the radioactive decay of ^{252}Cf and radiation protection is always a concern.[3] Furthermore, if an explosive device were detonated during inspection using a ^{252}Cf source, a significant health hazard would arise from the fragmentation of the ^{252}Cf source.

These health hazards are significantly reduced using an IEC device as the neutron source. Radiation protection is only a concern while the IEC device is operating. Once the IEC device is turned off, the health hazard essentially disappears. Additionally, if an explosive device were detonated during inspection of a container using the IEC device, the fusion of D-D immediately ceases and no health hazard would arise since deuterium alone is stable and there is very little induced radioactivity in the IEC device.

In order to make explosives detection utilizing an IEC device practical, the neutron production rates need to be 10^8 neutrons/second or greater.[4] The UW IEC device has produced D-D neutrons at 1.8 x 10^8 neutrons/second at a true cathode voltage of 166 kV and a meter current of 68 mA.[5] These neutron production rates are approaching the levels required for the practical detection of explosives. Multiple experiments were performed in this study in order to determine the effect on the neutron production rate by altering the cathode's size, geometry, and material composition. These variations were made in order to increase and maximize the neutron production rate in the UW IEC device.

II. EXPERIMENTAL OPERATION

The UW IEC device is an aluminum cylinder with an inner diameter of 91 cm and an inner height of 65 cm as shown in Figure 2.[6]

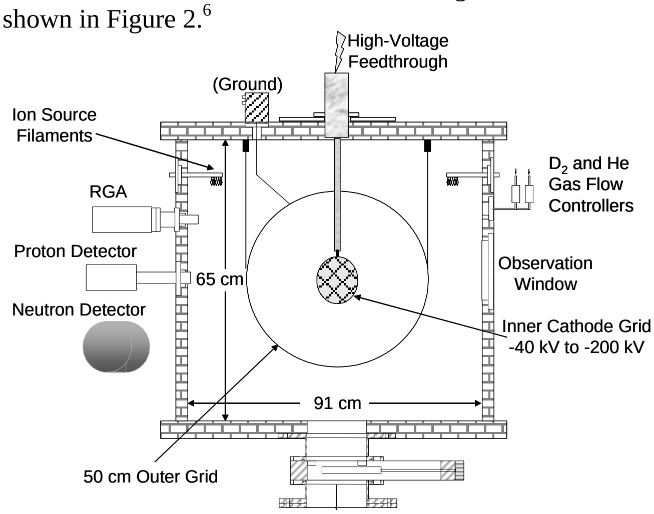

Figure 2: Schematic of the University of Wisconsin IEC Device.

This device is a vacuum chamber with a pumping system that allows for base pressures around 10^{-7} torr. A 50 cm, stainless steel, outer grid (anode) is kept at ground potential while a concentric, inner cathode grid of various dimensions and material is kept at a negative potential. A boron-nitride insulator is used around the high voltage feedthrough in order to allow for operation down to -200 $kV_{metered}$ on the inner cathode grid. The high voltage power supply runs through three sets of resistors, placed within a silicon oil bath, totaling 200 kΩ prior to reaching the inner cathode grid (ie. if the IEC device is operating at 60 $kV_{metered}$ and 30 mA, the true cathode voltage is 54 kV). During operation, the inner and outer grids form a potential well within the center of the IEC device. Deuterium ions can recirculate through this potential well leading to the D-D fusion reaction shown in Figure 1.

The UW IEC device is normally operated at a background gas pressure of 2 mtorr. The background deuterium gas is ionized outside of the 50 cm stainless steel anode by three 200 W light bulb filaments placed equidistant around the vacuum chamber. The deuterium ions, subject to the large potential well, are then accelerated towards the negatively charged inner cathode grid and subsequently are lost or create the D-D fusion reaction. A ^{3}He neutron detector, calibrated with a PuBe source, is used to measure the neutron production rate while a residual gas analyzer measures the gas and impurity levels within the vacuum chamber.[7]

In a desire to optimize the neutron production rates in the UW IEC device, three variables of the inner cathode grid were changed in order to determine the effect of each variable independently. These variables were cathode diameter, cathode geometry, and cathode material composition. In the first set of experiments, the inner cathode diameter was varied from 10 cm to 20 cm while maintaining a latitude/longitude geometry and WRe material composition as shown in Figure 3.

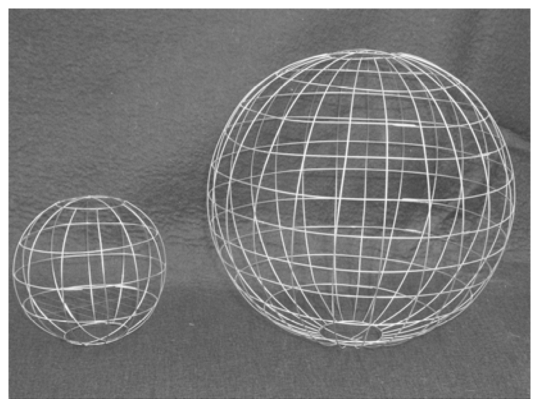

Figure 3: 10 cm and 20 cm, Latitude/Longitude, WRe Inner Grids.

In the second set of experiments, the cathode geometry was varied from latitude/longitude to symmetric while maintaining a 10 cm diameter and WRe material composition as shown in Figure 4.

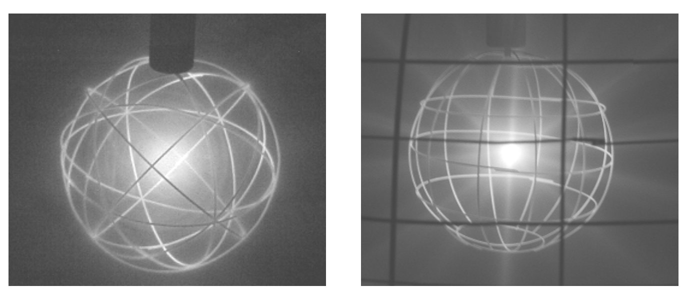

Figure 4: Symmetric and Latitude/Longitude Configurations, 10 cm, WRe Inner Grids.

Finally, the cathode material was varied from WRe to Re while maintaining a 10 cm diameter and a symmetric grid geometry.

III. RESULTS

III.A. Device Operation

Typically, the UW IEC device had been operated utilizing a 10 cm, WRe, inner cathode grid in a latitude/longitude geometry. Recently, a method was developed to manufacture the inner cathode grids utilized within the IEC device in a uniform manner.[8] Previously, the inner cathode grids had been made by hand and small variations existed between each of them. Currently, a wax mold is created in order to make each of the grids identical. This established consistency and uniformity in each of the grid designs as shown in Figure 5.

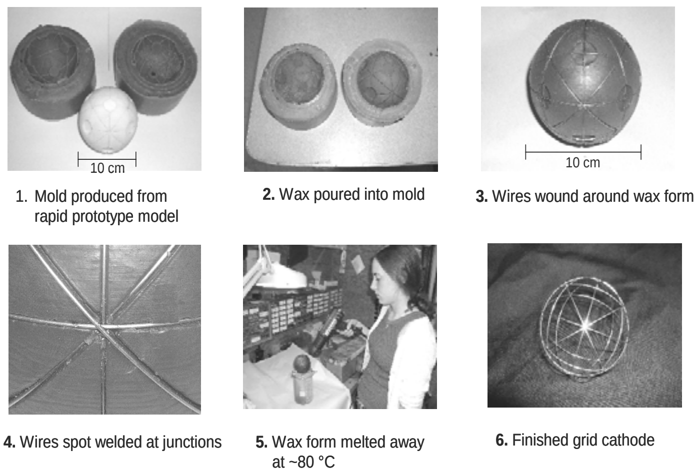

Figure 5: Fabrication of Standardized IEC Grid.[9]

In order to determine if the new symmetric grid geometry and mold for the inner cathode grids would significantly change the neutron production rate, experiments compared the previous 10 cm, WRe, latitude/longitude inner cathode grid to the new 10 cm, WRe, symmetric inner cathode grid.

For this set of experiments and each of the following experiments, the same methodology was used. After the IEC device was pumped down to a background pressure around 10^{-7} torr, two conditioning runs were performed and monitored utilizing a residual gas analyzer in order to ensure that each experiment began with similar gas and impurity levels within the vacuum chamber. Following the conditioning runs, two voltage scans were performed and then two current scans were performed as shown in Figures 6 and 7. Furthermore, each experiment was performed utilizing a constant background D-D gas pressure of 2 mtorr.

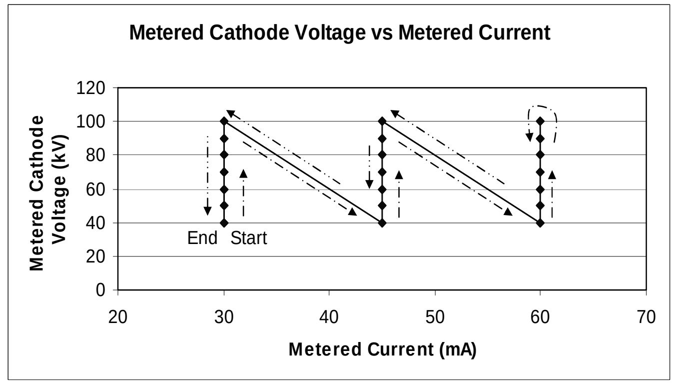

Figure 6: Voltage Scan Methodology Used for All Sets of Experiments.

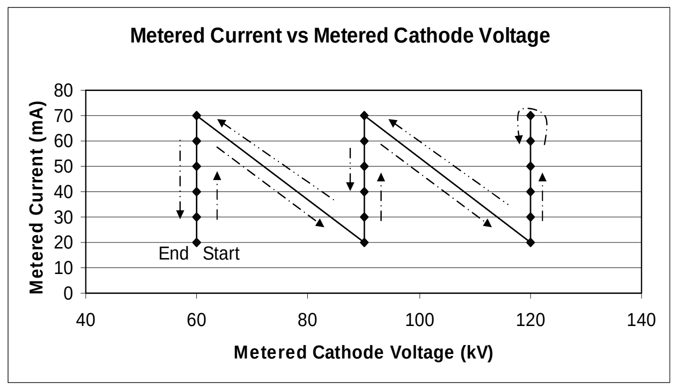

Figure 7: Current Scan Methodology Used for All Sets of Experiments.

III.B. Cathode Geometry

The early experiments compared two different inner cathode grids. The first grid consisted of a 10 cm, WRe, latitude/longitude design. The second grid consisted of a 10 cm, WRe, symmetric grid design. A comparison of the neutron production rates of the two inner grids as a function of current is shown in Figure 8.

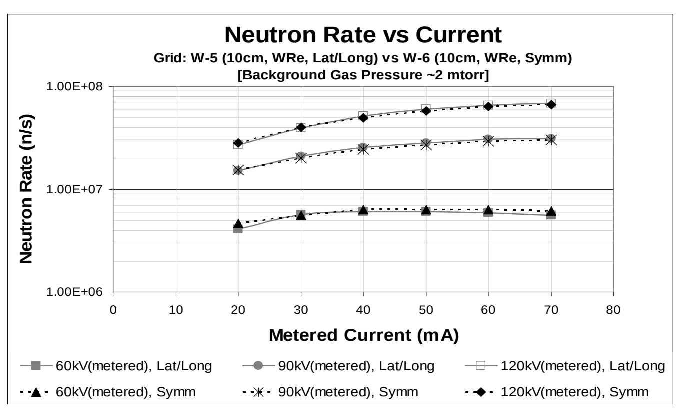

Figure 8: Cathode Geometry Neutron Rate vs Current.

III.C. Cathode Material

Once a comparison of the cathode geometry was completed, experiments to determine the variation in neutron production rate as a function of the grid material were performed. For these experiments, the first grid consisted of a 10 cm, WRe, symmetric grid design and the second grid consisted of a 10 cm, Re, symmetric grid design. A comparison of the neutron production rates of the two inner grids as a function of current is shown in Figure 9.

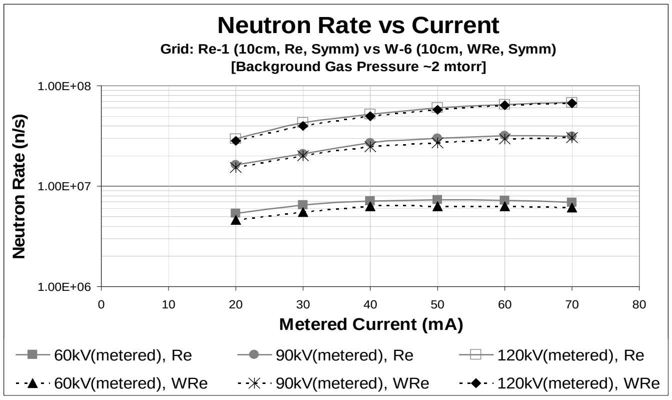

Figure 9. Cathode Material Neutron Rate vs Current

III.D. Cathode Size

Finally, once the comparison of the cathode geometry and material composition were complete, the question of a variation in neutron production rate as a function of the size of the inner cathode grid was investigated. For this experiment, the first grid consisted of a 10 cm, WRe, latitude/longitude design. The second grid consisted of a 20 cm, WRe, latitude/longitude design. A comparison of the neutron production rates from these two inner grids as a function of current is shown in Figure 10.

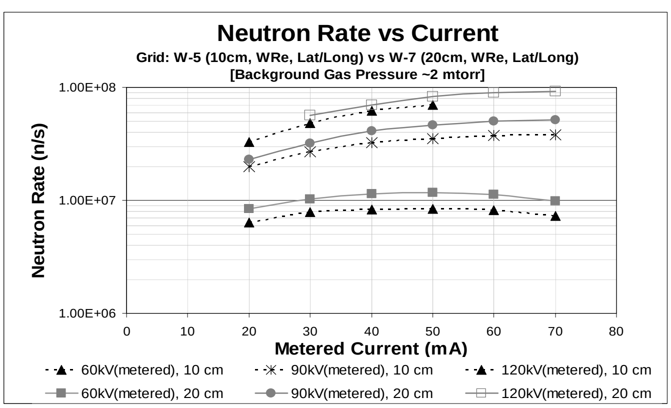

Figure 10. Cathode Size Neutron Rate vs. Current

III.E Cathode Voltage

Voltage scans were performed for each grid in addition to the current scans shown in Figures 8, 9, and 10. In Figures 8, 9, and 10, the neutron production rate appears to "rollover" or reach an asymptote as the current is increased instead of being proportional to the current. This "rollover" in the neutron production rate is due to the experiments being performed at a constant metered voltage (the true cathode voltage decreases with increasing current). Figure 11 shows the dependence of neutron production rate on true voltage at various currents. Although this voltage scan is for one run of a 10 cm diameter, WRe, latitude/longitude grid, it is representative of all of the runs that were performed with 10 cm grids regardless of geometry or material composition.

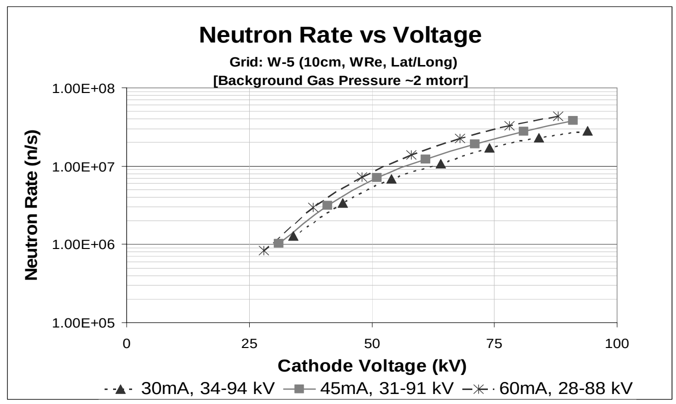

Figure 11. Representative Voltage Scan for 10 cm Diameter Inner Cathode Grids

IV. DISCUSSION

IV.A. Observations

IV.A.1. Cathode Geometry

No significant difference in neutron production rate was achieved by altering the geometry of the cathode for a constant voltage, background D-D gas pressure, size, and material.

IV.A.2. Cathode Material

No significant difference in neutron production rate was achieved by altering the material of the cathode from WRe to Re for a constant voltage, background D-D gas pressure, size, and geometry.

IV.A.3. Cathode Size

The neutron production rate was found to increase approximately 20% by doubling the cathode's diameter from 10 cm to 20 cm for a constant voltage, background D-D gas pressure, geometry, and material.

IV.A.4. Cathode Voltage

Increasing the true cathode voltage from 34 kV to 94 kV at a meter current of 30 mA increased the neutron production rate from 1.24 x 10^6 neutrons/second to 2.83 x 10^7 neutrons/second for a constant background D-D gas pressure and a constant cathode size.

IV.B. Discussion of Results

Increasing the cathode size does not significantly alter the number of beam-target and charge exchange reactions occurring within the IEC device. However, the higher neutron production rate can be attributed to an increase in the number of beam-background reactions occurring within the cathode due to the increased path length traveled by the energetic ions. The neutron production rate increase of approximately 20% can be explained by the dependence of the total D-D reaction rate on beam-background reactions. Previous experiments indicate that 22% of the D-D reactions occur from beam-beam and beam-background reactions while 78% of the D-D reactions occur from beam-target and charge exchange reactions.[10] Preliminary modeling indicates that beam-background reactions, not beam-beam reactions, are responsible for the majority of this 22% contribution. Therefore, doubling the path length or doubling the number of beam-background reactions would result in a neutron production rate increase of approximately 20% as observed experimentally.

V. CONCLUSION

During this study of D-D fusion rates, the only variables studied which significantly altered the neutron production rate were the cathode size, voltage, and current. Doubling the cathode's diameter resulted in a neutron production rate increase of 20%. The increased voltage takes advantage of the increasing fusion cross section with increased ion energy. The increase with increased current is due to the increased number of energetic ions passing through the plasma.

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