Effects of the Cathode Grid Wires on Fusion Proton Measurements in Inertial-Electrostatic Confinement Devices

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***Abstract*—Gridded inertial-electrostatic confinement (IEC) devices interest fusion researchers owing to their ability to burn advanced fusion fuels and have many near-term applications. In these devices, a high voltage (10–180 kV) accelerates ions radially between nearly transparent electrodes in spherical or cylindrical geometry. In this paper, we report experiments that study fusion reactions within the microchannels formed between the wires of the nearly transparent IEC cathode grid. Fusion proton counts were measured while sweeping the microchannels across a proton detector by rotating the central cathode grid with respect to the detector. The observed proton counts increased or decreased in correspondence with the grid wire orientation with respect to the proton detector. The fusion reactions were thus inferred to be nonuniform around the central grid and primarily occurring in channels formed by the grid wire gaps. We interpret this effect as an indication that most ions and charge-exchanged neutrals traverse radially along these microchannels. The grid wires will also shadow fusion reactions taking place at radii smaller than the cathode radius. Both the microchannels and the grid-wire shadowing causes the proton counts to vary, in measurements presented herein, by as much as 45%. We explore whether these effects could have played a role in previous research that reported potential-well structures.**

***Index Terms*—Grid rotation, inertial electrostatic confinement, neutrons, nuclear fusion, proton calibration.**

I. Introduction

THE CONCEPT of electrostatically confining the electrons was first conceived in 1959 by Elmore *et al.* [1]. In 1963, Lavrent'ev [2] from the former USSR independently came up with the idea of inertial-electrostatic confinement (IEC) fusion, and around the same time (1966), Farnsworth [3] invented the use of a plasma target to realize fusion while avoiding target deterioration. Hirsch [4] further investigated this device in 1967. Although initial efforts were directed toward power production, it was soon realized that gridded systems could not reach breakeven without melting the central grid [5]. Spin-off applications of IEC devices have also prompted further research [6], [7]. In addition, a gridded IEC device does not require magnetic coils for plasma confinement, allowing it to be relatively lightweight and hence, portable. A key feature of the gridded IEC devices is that they allow the steady-state burning of advanced fuels, such as D-^{3}He and, potentially, ^{3}He-^{3}He or p-^{11}B. Since IEC configurations are not restricted to D–T fusion, there can also be much less of a problem of neutron activation.

Ions of light nuclei produced through electron-impact ionization of the ambient gas inside the IEC chamber, shown in Fig. 1, are subsequently accelerated toward the negatively charged central grid. In the process, the ions not only gain fusion-relevant energy but also converge at the core of the central grid, forming a plasma target. This extends the life of the device as a neutron source. However, for the present operating conditions, the net gain (Q) is very small ($Q \sim 10^{-8}$ for D–D fuel, which extrapolates to 5×10^{-6} for D–T fuel, although the neutron production per kilowatt of power compares to the commonly used drive-in beam-target devices). Although not useful for power production, present IEC devices have many near-term applications, such as neutron sources for tritium production [8], neutron activation analysis [9], [10], tunable X-ray source [11], radioisotope production [12], boron neutron capture therapy, oil well logging, clandestine material detection, etc., hence the current interest in such low-efficiency devices. If high Q can be achieved, other possibilities open up, such as fusion materials testing, nuclear and chemical/biological waste management [13], and space propulsion [14]. The various fusion reactions (first- and second-generation fuels) currently realized in an IEC device are shown in Fig. 2.

II. Multiple Potential-Well (Poissor) Structure

The poissor structure of multiple electrostatic potential wells in the radial direction of an IEC device was first proposed by Farnsworth in a patent [3]. Theoretical work [4] has shown that a poissor [3] structure may be possible with these devices, although the analysis requires purely radial motion. Under the conditions of that analysis, potential structures are predicted to form within the cathode due to alternate positive and negative space charge buildup (see Fig. 3). With higher ion current at higher voltages, multiple potential wells are believed to form. The concerted interest in poissor structures is because the presence of such a potential structure could enhance the fusion rate, making the device more efficient.

Experimentally, several virtual anode measurements have been made in IEC devices by Nadler [15], Thorson *et al.* [16], [17], and Kachan [18]. The quantitative potential-well depth

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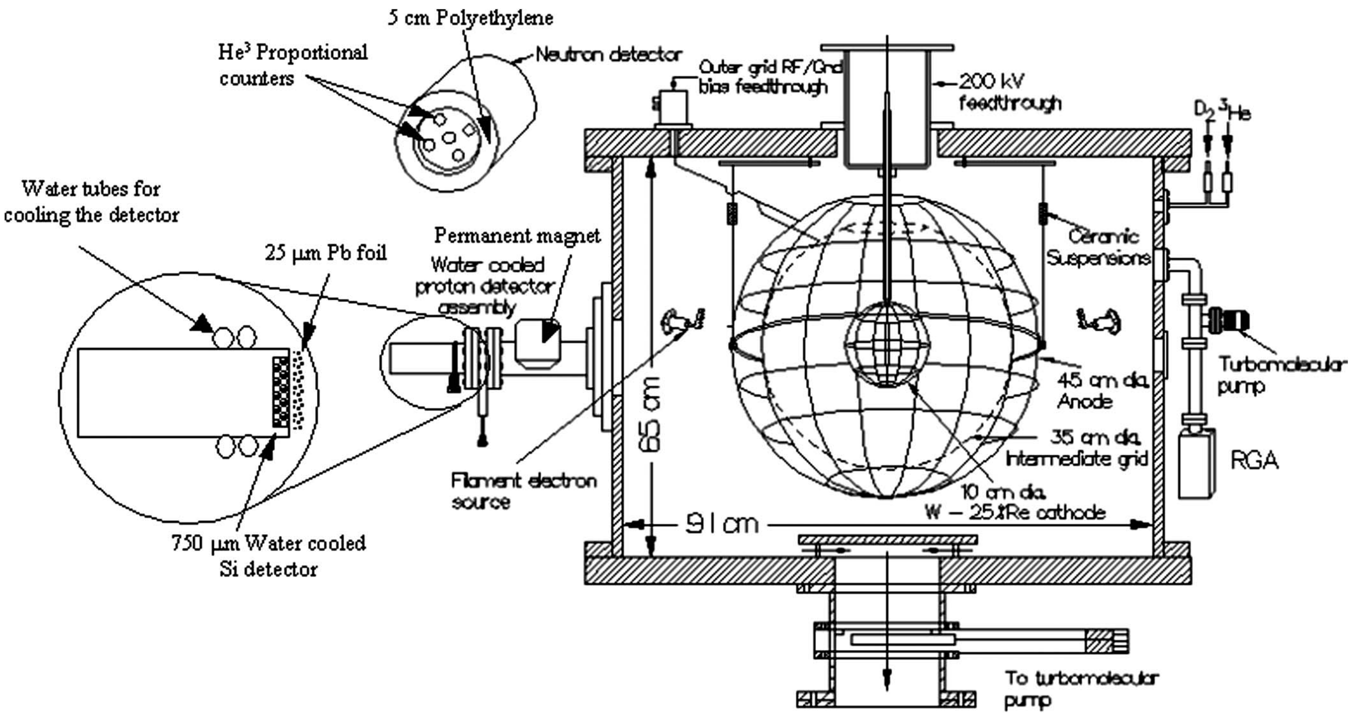

Fig. 1. Sectional view of the IEC device at the UW-Madison. An intermediate grid (35-cm diameter) with a fine mesh is not shown for clarity.

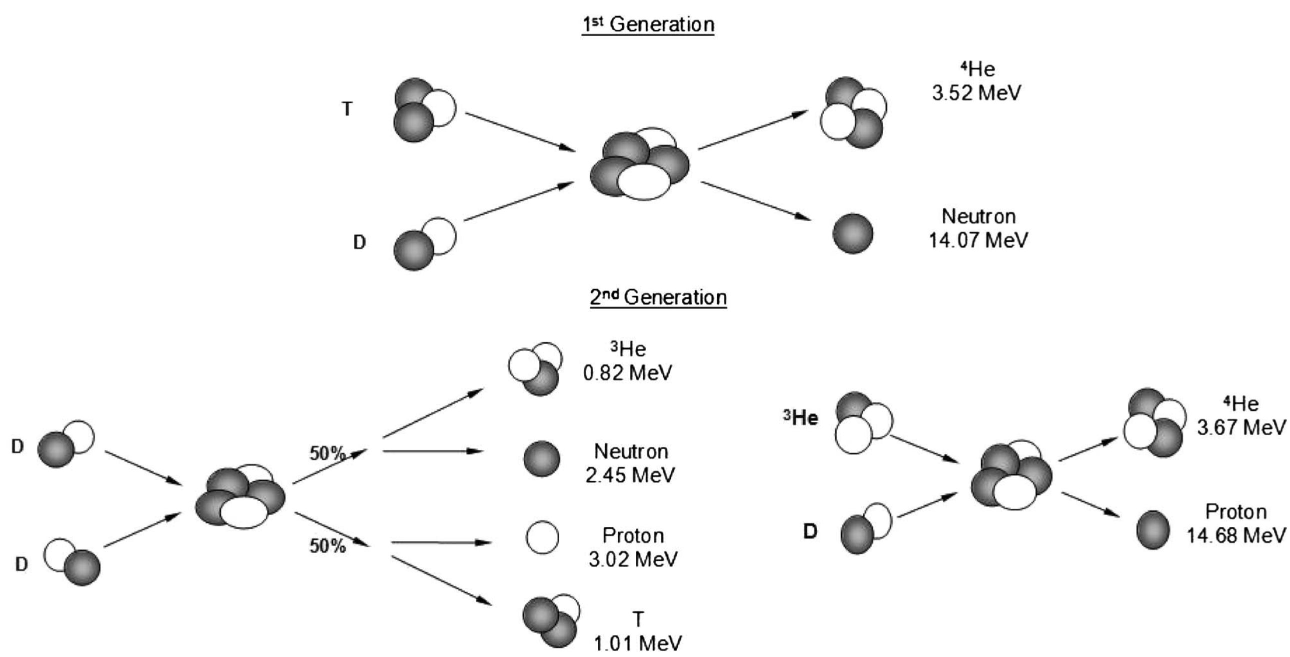

Fig. 2. Fusion reactions achieved in an IEC device.

estimates by Nadler are perhaps questionable due to their reliance on 1-D orbital model predictions and because they were performed with a relatively small potential. The detection of a virtual anode by Kachan [18], in essentially "star-mode" operation, differs from Thorson *et al.* [16], who observed a flat potential profile in "star mode"; however, Kachan's [18] cathode consisted of two parallel conducting rings separated by only 2 cm, so space charge could escape radially. Yoshikawa *et al.* [19] observed negligible electric fields within the core region of a "star-mode" device.

Several indications of double potential-well structures have been reported [4], [20]–[22]. Certain researchers have reported double potential wells of substantial depth (~30%) in star mode based on spatial variation in the radial fusion profile (see Fig. 4) [23], but an alternative mechanism for this variation in the spatial profile of the fusion output has been proposed—if it is assumed that fuel ions are confined keeping the total energy and angular momentum almost constant, the double radial peak in the neutron production rate could appear (numerically) without the creation of the deep double potential well [24]. Several other

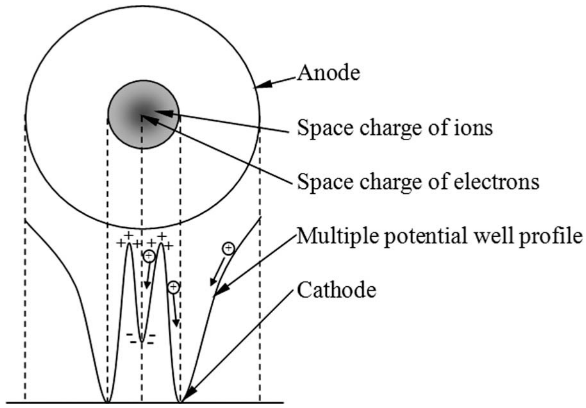

Fig. 3. Predicted multiple potential-well (poissor) structure within an IEC chamber.

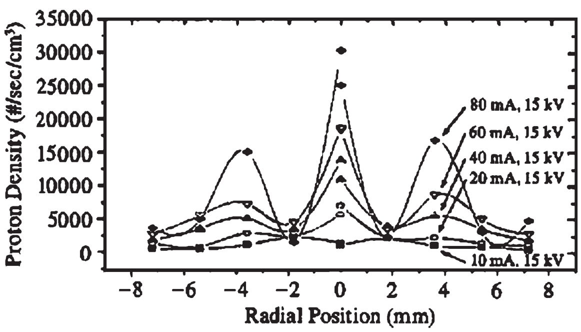

Fig. 4. Measurement of potential-well structure using a collimated D–D proton detector [23].

measurements consistently indicate the formation of double wells as potential increases [21], [25], [28], [29]. In some cases, the double wells are detected after a transition completely out of "star mode" in the direction of increasing pressure [21], [32]. One aspect that has been consistently neglected in these works is the effect of cathode grid wires on the fusion rate observed by the proton detector. In this paper, we explore the effects of the cathode grid wires (shadowing effect and production of most fusion reactions in discrete microchannels) on the measured fusion rate by the proton detector. Moreover, the understanding gained can be used to calibrate the device accurately [26]. A recommendation is also made on how to make the proton detector readings more consistent between experiments.

III. Experimental Facility

The University of Wisconsin-Madison (UW) IEC device used for the reported experiments is shown in Fig. 1 and consists of a cylindrical vacuum vessel made of aluminum with internal dimensions of 91 cm in diameter and 65 cm in height. The pumping system consists of a Leybold Trivac rotary vane roughing pump and a DynaTech turbo pump to allow base pressures $\sim 1{-}10 \times 10^{-7}$ torr. Although the base pressure is measured using an MKS ion gauge, higher pressures during chamber venting are measured using a capacitive manometer (Baratron gauge). The fuel gas is fed to the chamber through two MKS mass-flow controllers for both D_2 and ^{3}He gases. The electronic flow controllers allow fine adjustment of the gas flow up to 50 sccm into the chamber. During runs, the chamber pressure is monitored using an MKS Baratron pressure transducer. Typically, the device is run at 2 ± 0.5 mtorr. An SRS CIS 200 residual gas analyzer allows real-time gas composition measurement for monitoring the impurity levels. It also allows one to maintain a predetermined fuel ratio $D_2/^3$He if required by the experiment. The inner grid is typically 10 cm in diameter. Plasma is generated inside the chamber using a set of three electron emitters placed outside the outer grid. The temperature of the filaments and, hence, the number of electrons emitted by the filaments are controlled through a Variac. The efficiency of these filaments in ionizing the ambient gas in the chamber is improved by rectifying the ac power fed to the filaments, followed by the application of a controlled dc bias that aids better current control. The neutrons generated by the D–D reactions are detected using a ^{3}He-filled neutron detector enclosed by a paraffin shield that thermalizes all neutrons before detection [27]. This detector is calibrated using a standard Pu–Be source. For this purpose, this point source is placed in the center of the chamber, and the neutron detector is calibrated by approximating the chamber neutron source as a point source.

The protons are detected using an Ortec 1200 mm^2 silicon detector on a port facing the center of the chamber, along with accompanying MCA software (see Fig. 5). The detector is shielded from X-rays using thin Pb foil that keeps the background noise at tolerable levels and also allows simultaneous detection of D–D and D-^{3}He protons [28]. The proton detector is further protected from the electron beam coming from the cathode using a permanent magnet. A video camera is connected to a computer in the control room that allows visual monitoring of the operation through a view port. The view port is protected from the sputtered material using a transparent glass shield. A Raytek Marathon MR pyrometer can be pointed to different areas on the cathode to determine temperatures from 700 °C to 1800 °C with a temperature resolution of 1 °C. The whole IEC assembly and the related diagnostics are housed inside a radiation shielded room.

The (10-cm-diameter) cathode grid used in this paper has 5 latitudes and 12 longitudes. Fig. 6 shows a picture of the grid built using a wire of 0.08 cm in diameter. When this grid is rotated about the z-axis as shown in Fig. 7, the grid wire placed along the plane of latitude sweeps a constant volume in the azimuthal direction about the central axis and hence blocks a constant volume along the line of sight of the detector.

However, as the grid is rotated about the central axis, the longitudes sweep different volumes with respect to the line of sight of the detector because, unlike the latitude, the longitude rotates about the diameter, as shown in Fig. 8. The longitudes are spaced at equal intervals of 30°, and hence, with the rotation of every 30°, the grid returns to the initial orientation, assuming the grid is symmetric.

IV. Grid Rotation Experimental Setup

To study the eclipsing effect of grid wires on the proton rate from the converged core, it is important that the grid be rotated in small increments of angle. In the two sets of experiments

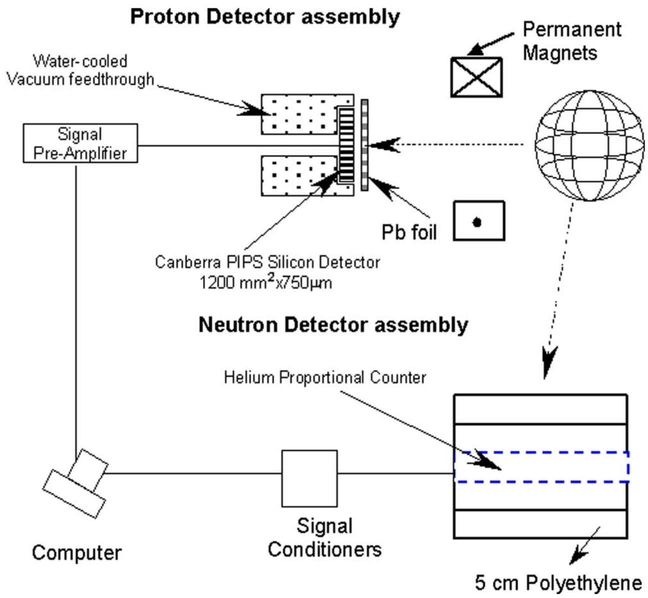

Fig. 5. Diagnostics used in an IEC device for detecting the fusion products.

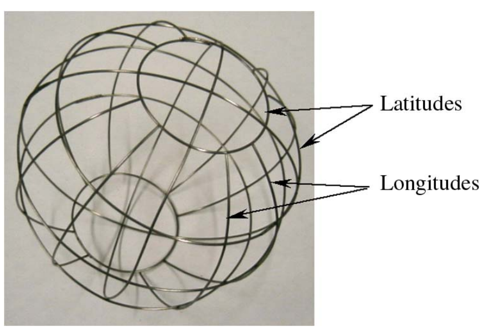

Fig. 6. Cathode grid with 12 longitudes and 5 latitudes.

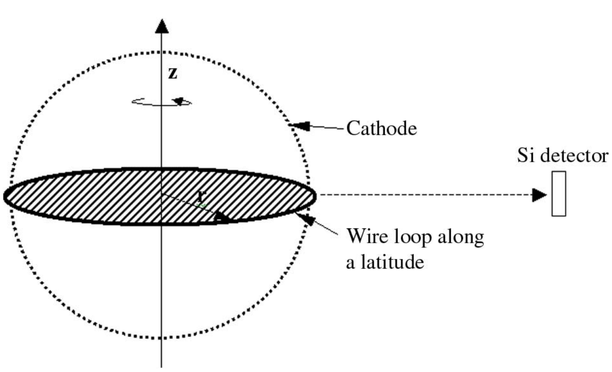

Fig. 7. Rotation of a longitudinal plane about the z-axis sweeps constant volume along the azimuthal direction toward the detector.

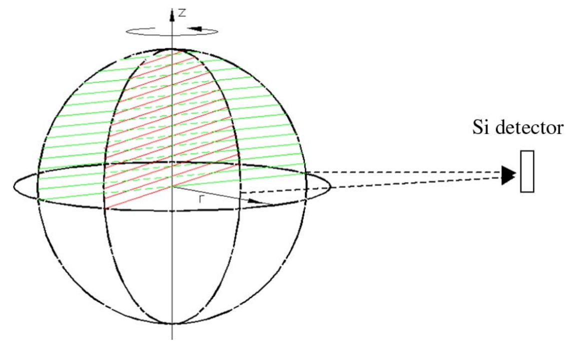

Fig. 8. Rotation of the longitude along the z-axis sweeps variable areas with respect to a stationary detector along the line of sight in the radial direction.

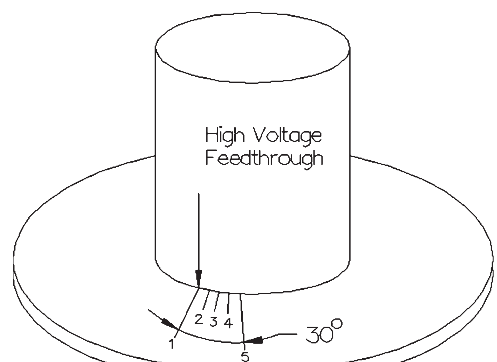

Fig. 9. High-voltage feedthrough was rotated in intervals of 7.5° from 0° to 30° (also, see Fig. 1).

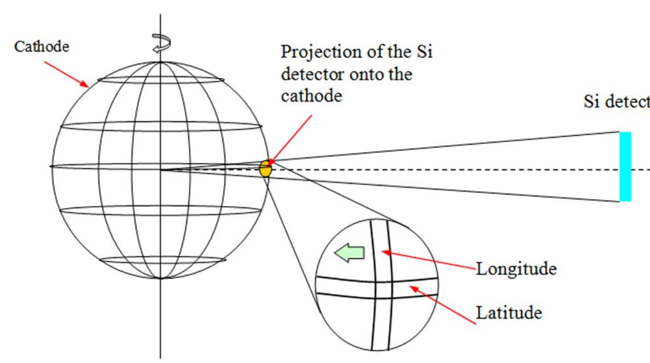

Fig. 10. Projection of the Si detector onto the cathode is approximately a circle. Assuming a perfect point source, the difference between the projected area and that blocked by the two wires is ~56%. Without the longitude in the view, the difference is ~28%.

conducted here, the angular step sizes adopted were $7.5° \pm 0.5°$ and $2.5 \pm 0.3°$, as shown in Fig. 9. Since the high-voltage feedthrough could be rotated under vacuum (without venting), the impurity levels in the chamber could be maintained constant during the entire experiment. All the other parameters, such as the chamber pressure, filament electron current, applied voltage, etc., were kept constant for the duration of the experiment.

If a very small (nearly a point source) converged core exists in the center of the IEC device and is the main region creating fusion products, the grid wires would play a major role in masking the counts from such a converged region. If this hypothesis was true, then the cross wires (one latitude and one longitude) would block approximately 56% (see Fig. 10), and since the latitude masks half (28%) of the counts constantly, the longitude alone should mask 28% of the counts when it falls in the line of sight of the proton detector. Hence, the maximum variation in the proton to neutron (P/N) ratio [29] should not exceed 28%. To verify this aspect, a set of experiments was performed, as explained in the next section, by rotating the grid in small increments of angle.

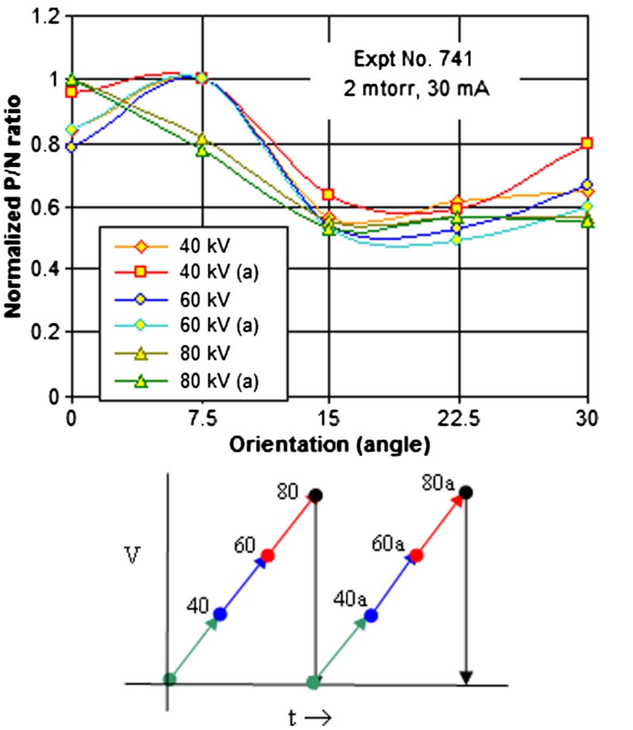

Fig. 11. (a) Variation of the P/N ratio with grid orientation. (b) Two voltage scans performed in a sequence (40–60–80 kV). The duration between each experiment varied, but the exact time between the ramp-up is not relevant to the experiment.

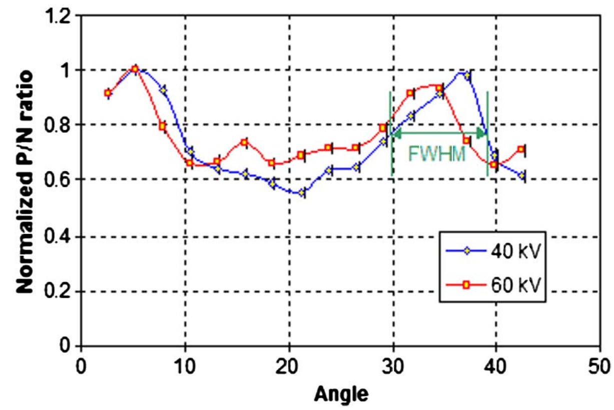

Fig. 12. Plot of the normalized P/N ratio scan with the angular orientation of the cathode grid being periodic every 30°.

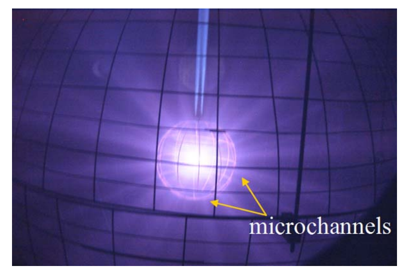

Fig. 13. Picture of the cathode grid at 25-kV 30-mA 7.59-mtorr pressure. The gas used is deuterium. The fusion reactions are minimal at this chamber pressure, low enough that pictures could be safely taken by the observer from the view port.

V. Results and Discussions

The high-voltage feedthrough was rotated in small increments of angle $(7.5^\circ \pm 0.5^\circ)$, as shown in Fig. 9, and the protons were recorded by a fixed proton detector simultaneously for each position at various voltages in a sequence shown in Fig. 11(a). Two voltage scans were performed at every orientation with varying voltages, as shown in Fig. 11(b).

The P/N ratio (normalized to the maximum value in a particular scan) measured at each position revealed an average of 40% variation between its maximum and minimum values. This is a source of error (if the proper calibration factor is not used), because the proton detector would detect fewer protons than the surface-averaged value if the grid was not properly oriented. This error would occur in addition to the statistical errors (square root of the counts) in the proton counts and would be significant. This implies that calibration must be done very carefully, taking the grid orientation into consideration [26].

To verify the aforementioned observation, another experiment was performed on a similar basis. The grid was rotated in steps of $2.5^\circ \pm 0.3^\circ$ through a total of 42°. The results of this experiment are shown in Fig. 12. It is observed that the P/N ratio value repeats itself at an interval of 30°. This is expected because, as mentioned earlier, the cathode grid has longitudes separated by 30°, and hence, a rotation by 30° would reproduce the original configuration. The value of the P/N ratio in Fig. 12 varies by about 35%–40%. The small variation in the data is caused by the small misalignments during rotation within the tolerable limits $(\pm 0.3^\circ)$. Hence, the grid orientation could affect the proton counts by as much as 45% if the appropriate calibration factor is not used.

Since the variation in the P/N ratio is greater than the expected 28% for a point converged core, it is unlikely that we have a source that is highly converged (point source). Hence, the microchannel that extends toward the proton detector from the cathode should be causing the P/N ratio to increase due to the $\sim 1/r^2$ falloff of the fusion rate in such microchannels. These results (see Fig. 12) suggest that, in the present design, the grid orientation has to be optimized every time the stalk is moved from its original position.

The conclusion of the aforementioned experiment that the microchannels formed between the longitudinal grid wires affect the D–D proton counts suggests that the calibration factors may be a function of the orientation of the grid/proton detector configuration. As shown in Fig. 13, the picture of the cathode at a high pressure reveals jet (microchannel) formation (star mode). Since the microchannels are principally constituted of recirculating ions, it would be reasonable to expect that fusion reactions also occur in the pathway of these recirculating ions. The charge-exchanged (CX) and dissociated neutral fusion reactions would also be enhanced along this path, since the fast neutrals would continue in straight-line paths along their initial trajectory and cause fusion along the trajectory.

Experiments to study the effects of vertical alignment of the grid were not performed because any misalignment from a concentric position affects the electric fields within the chamber drastically [30]. The only way to do this would be to mount the detector on a moveable port that could be used to scan the cathode grid in the vertical direction. Earlier work by Nadler [31] observed that the proton counts were inconsistent and would vary by as much as 40% from experiment to experiment. We believe that this was caused by the varying grid orientation between experiments.

In general, we expect microchannels to extend nearly to the origin of the IEC plasma. The proton detector used to generate the present results verified the discrete nature of the microchannels in the vicinity of the proton detector, but it does not have sufficient resolution to investigate the IEC device's core. Nevertheless, sufficiently focused microchannels could be misinterpreted as potential structures near the origin, and this possibility should carefully be eliminated from any experimental investigation of an IEC core.

VI. Conclusion

Grid rotation experiments have revealed that the fusion source is nonuniform inside an IEC device. Microchannels form at regular intervals corresponding to the spacing of the longitudes and, presumably, also the latitudes of the cathode grid. Most fusion reactions occur within these microchannels, with rates falling off as r^{-2}, and the CX and dissociation neutrals also cause fusion within these channels. Thus, consideration of the grid orientation with respect to the proton detector is essential for correct proton rate calibration and interpretation. The dip in the observed potential profile seems to be caused by the shadowing effect of the cathode grid wires. Observations of potential-well structures should be careful not to report artifacts of the experimental setup caused by grid wire shadowing or fusion-product creation in discrete microchannels.

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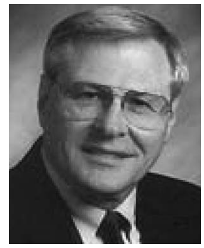
Prof. Santarius is a member of the American Physical Society and is a Senior Member of the American Institute of Aeronautics and Astronautics. He was a recipient of the Excellence in Fusion Engineering Award from Fusion Power Associates in 1991 and a Certificate of Appreciation from the Department of Energy in 1988.



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Prof. Kulcinski has been a Fellow in the American Nuclear Society since 1978. He currently serves on the NASA Advisory Council. He was elected to the National Academy of Engineering in 1993 and to Phi Kappa Phi in 1993. He was a recipient of the John Randle Grumman Achievement Award from the Grumman Aircraft Corporation in 1987, the Leadership Award in Fusion by Fusion Power Associates in 1992, the NASA Public Service Medal in 1993, the Distinguished Faculty Award by the Wisconsin Alumni Foundation in 1994, and the Wisconsin Big 10 Centennial Award in 1995.