Effect of Positive Polarity in an Inertial Electrostatic Confinement Fusion Device: Electron Confinement, X-Ray Production, and Radiography

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Abstract — The conventional inertial electrostatic confinement fusion (IECF) operation is based on the application of high negative voltage to the central grid, which results in the production of neutrons due to the fusion of lighter ions. The device can also be used as an X-ray source by altering the polarity of the central grid. In this work, electron dynamics during the positive polarity of the central grid are studied using the object-oriented particle-in-cell code XOOPIC. The simulated trapped electron density inside the anode is found to be on the order of 10¹⁹ m⁻³ when 10 kV is applied to the anode. The recirculatory characteristics of the electrons are also studied from the velocity distribution function. A scintillator-based photomultiplier tube is used to detect the produced X-ray. The X-ray-emitting zones of the device are investigated by pinhole imaging techniques. Last, the radiography of metallic as well as biological samples are reported in the later part of this paper. This study shows the utilization of the IECF device when the polarity of the central grid is reversed.

Keywords — X-ray radiography, pinhole camera, XOOPIC, fusion.

Note — Some figures may be in color only in the electronic version.

I. INTRODUCTION

The inertial electrostatic confinement fusion (IECF) device is a neutron/proton/X-ray source in which the confinement of plasma particles takes place due to the application of a purely electrostatic field between partially transparent gridded electrodes. The simple, less complex design and its compactness and portability make the IECF system a low-cost fusion reactor. The basic advantage of the device is its applicability in numerous fields, such as in the production of radioisotopes,1,2 in landmine detection,3–5 in the development of plasma jet for rocket propulsion,6 and in many other fields.7,8

In its simplest form, the IECF device consists of a transparent gridded assembly concentrically placed inside a spherical or cylindrical chamber. The central grid serves as the cathode in which high negative voltage is supplied. Breakdown of the fuel gas (deuterium, tritium, ³He, etc.) takes place between the grid and the chamber wall (grounded). The ions generated by the breakdown undergo a recirculating motion across the grid openings with a high acceleration depending on the applied voltage and current. The oscillating ions get

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trapped inside the potential well and form a high-density core region inside the cathode grid. Finally, the beam-beam or beam-background collisions initiate the fusion process, as a result of which neutrons are produced.\textsuperscript{7,9,10}

Since the inception of the very first IECF device,\textsuperscript{11,12} researchers have carried out geometrical and technical modifications of the device in order to enhance the neutron yield.\textsuperscript{13–18} Recently, our team of researchers at the Centre of Plasma Physics-Institute for Plasma Research carried out experiments in the cylindrical IECF device with some success in neutron production and its application in explosive detection.\textsuperscript{19–23}

The IECF device is also capable of producing X-rays that may find their application in the field of radiography. An X-ray emission experiment was carried out in the spherical IECF device by just altering the electrode polarities, i.e., the central grid is the anode and the outer grid is the cathode, and by adding electron emitters in the vessel ports.\textsuperscript{24} The electrons were made to focus on the center in this configuration so that X-rays could be produced due to electron collisions with the anode grids. The device was termed a tunable X-ray source due to the dependence of the X-ray photon energy on the applied anode potential.\textsuperscript{24,25}

Earlier, Hirsch\textsuperscript{11} experimentally observed that the spatial distribution of X-ray relative intensity peaks in the IECF system that appeared were due to bremsstrahlung radiation caused by the slowing down of the fast electrons in the regions of high ion density. He believed that the peaks in the intensity profile were caused by the presence of the virtual electrodes inside the cathode. In some other experiments,\textsuperscript{26} a pulsed X-ray from a tabletop cylindrical IECF device was produced in which the relative X-ray intensities were examined for three different gases. Recently, both neutron and X-ray production have been reported during the conventional negative polarity of the grid in which the neutrons were produced from the central region and the X-ray from the wall region of the chamber.\textsuperscript{16,23} However, due to the broad X-ray-emitting zone, the X-ray flux was less in such cases, and hence, it has limitations as far as X-ray applications are concerned.

This work studies the effect of positive biasing on the central grid in a cylindrical IECF device. Initially, the electron dynamics due to the positive biasing of the central grid in the device were studied computationally by using the open-source object-oriented particle-in-cell (PIC) code XOOPIC. The simulation results include the study of the recirculating nature of the electrons and their density profile inside the central grids (anode).

Second, we have demonstrated the production of continuous X-rays as a result of the continuous acceleration and deceleration of the electrons across the positively biased central grid during steady-state operation. Unlike the pulsed operation, the steady state allows the operator to regulate the voltage and current to customize the inspections of samples in accordance with needs. In other words, one can tune the voltage and current in the steady-state X-ray according to the nature of the sample through which it passes.

Third, in order to investigate the exact X-ray-emitting zone of the device, X-ray imaging experiments were performed using a pinhole camera. Two geometrically different anodes: a cylindrical rod and a cylindrical grid were used for this purpose. Finally, the emitted X-rays were utilized to record the radiography of metallic as well as biological samples.

The next section of this paper contains the numerical modeling of the device. \textbf{Section III} describes the experimental setup and procedure to perform this work. \textbf{Section IV} presents the obtained results, including the simulation, X-ray production, and imaging experiments along with the radiography of different specimens. Finally, the last section of the paper contains the concluding remarks of this work.

\section{II. MODELING}

An electrostatic PIC simulation was carried out using the XOOPIC code\textsuperscript{27,28} to characterize the kinetic properties inside the cylindrical IECF device. The code has the ability to operate in two-dimensional (2-D) physical space (Cartesian and cylindrical systems) and three-dimensional velocity space. In order to recreate the exact experimental conditions, the dimension of the simulation domain, including central grids and all other parameters, were considered as per the experimental setup. A horizontal 2-D cross section of the device, including the cross section of the anode grids (consisting of 12 grid wires) was considered as the simulation geometry (Fig. 1). Four electron emitters were also modeled near the four walls inside the simulation domain from which an equal flux of electrons was emitted continuously. These primary electrons interact with the neutral gas and produce positive ions through ionization collision.

A high positive potential was applied to the central anode grid, as a result of which the electrons accelerated toward the grid and the ions moved toward the wall region. The time step $\Delta t$ for the simulation was chosen such that it satisfies the Courant condition\textsuperscript{29} and it is
resolved from the fastest particles (electrons) present in the system.\textsuperscript{30} We also ensured that the chosen time step was smaller than the electron plasma period,

\[
\Delta t = 0.3 \times \frac{d}{v_{\text{drift}}}; d = \frac{\Delta h}{\sqrt{2}},
\]  

where \(v_{\text{drift}}\) is the drift velocity of the electrons, and \(\Delta h\) is the cell size for the numerical grid. Putting appropriate values into Eq. (1), \(\Delta t\) was found to be on the order of \(10^{-11}\) s. The size of the cell \(\Delta h\) was considered in such a way that \(\Delta h \leq \lambda_D\), where \(\lambda_D\) is the electron Debye length. XOOPIC also includes a Monte Carlo collision model that can incorporate elastic, ionization, excitation, and charge-exchange collisions.\textsuperscript{31}

A multigrid Poisson solver used to solve the Poisson’s equation also describes the boundary conditions of the simulation.\textsuperscript{27} The advantage of using the multigrid solver is that it speeds up the solution for a finer computational grid and reduces the total simulation time to converge to an accurate solution. Dirichlet boundary conditions are imposed by the solver on the computational grids of the domain boundaries. In order to get a good resolution of phase space, a large number of macroparticles (computational particles) with a relatively shorter domain length is appropriate. Since the trajectory of each macroparticle is computed kinetically in the PIC simulation, a longer domain length with a large number of macroparticles will require a much longer run time to solve the problem.

Therefore, a relatively shorter domain length and a large number of macroparticles were considered in this simulation, which also minimized the statistical noise associated with the simulation. A domain length of 21 cm was considered so that the distance between the electron emitters remained the same as that in the actual experimental setup (20 cm in both the simulation and experimental cases), and also, the resolution of the phase space remained intact. Again, considering the domain length and the size of each cell, the total simulation grid size was found to be 512 along each axis. The specific weight, i.e., the ratio of the number of real particles present in the system to that of the macroparticles considered in the simulation, was found to be of the order of \(10^8\). Considering all these parameters and conditions, the input file of the XOOPIC was developed to carry out the simulation. Some of the simulation parameters are presented in Table I. The diagnostics were saved as ASCII files after the simulation, and a few scripts were also developed in MATLAB to analyze the simulation data.

### III. EXPERIMENTAL SETUP AND PROCEDURE

The cylindrical IECF device was made of stainless steel with a diameter of 50 cm and a height of 30 cm. The central electrode consisted of a tungsten-gridded assembly having multiple numbers of grid wires. During conventional IECF operation, the central grid serves as the cathode in which high negative potential is applied in order to accelerate the ions to fusion-relevant energies.\textsuperscript{7} Confinement of the ions is the basic criterion to exhibit fusion and produce particles, such as neutrons, protons, etc. However, in this particular study, the central grid

| Parameter          | Value   |
|--------------------|---------|
| Simulation grid size | 512 × 512 |
| Length             | 0.21 m  |
| Width              | 0.21 m  |
| Time step, \(\Delta t\) | \(10^{-11}\) s |
| Specific weight    | \(10^8\) |
| Background gas     | Deuterium |
| Anode potential    | 10 kV   |
acted as the anode (positively biased) and the other electrode was the chamber wall itself, which was grounded. A ceramic feedthrough was accessed through the topmost port of the chamber in order to provide high voltage to the grid assembly. The side wall of the chamber consisted of multiple ports for gas inlet and outlet, viewing windows, filaments, pressure gauges, and to access diagnostic tools for plasma characterization, as shown in the schematic diagram in Fig. 2.

The chamber was evacuated using a rotary pump and a turbomolecular pump until a base pressure of $10^{-6}$ Torr was achieved. The pressure inside the chamber was monitored in a display control unit that was connected to a full-range pressure gauge attached to the chamber. The deuterium gas was supplied to the chamber, and a gas pressure on the order of $10^{-3}$ Torr was maintained during the experiments depending on the required operating voltage. It is worth mentioning that out of the different possible gases, deuterium was used in the present work to demonstrate that the same device, which had been previously used for neutron production, could also be used for X-ray generation. One can use the IECF device as a neutron source and also as an X-ray source just by altering the polarity of the central grid. The production of X-rays using different gases in a pulsed operation has already been reported elsewhere.

In order to detect X-rays, we positioned a NaI scintillator–based photomultiplier tube (SPMT) in close proximity to the chamber. It was connected to the PC interface to obtain the X-ray energy spectrum. The SPMT (procured from Osprey, Canberra) is an excellent gamma and X-ray detector that has NaI scintillator material to convert the incoming radiation into light in the visible range. The photons thus generated in the scintillator are subsequently detected by the photomultiplier tube (PMT) and converted into electrical signals. The pulse height spectra generated by the detector are analyzed using a PC interface (Maestro software). The peak wavelength of emissions from the scintillator is 4130 Å. It has a 10-stage PMT with an inbuilt multichannel analyzer of 2048 channels supported by a pre-amplifier, amplifier, and a high-voltage power supply. Initially, calibration of the SPMT was carried out with a known gamma-ray source of $^{137}$Cs before obtaining the X-ray spectrum.

Again, X-ray imaging was performed by constructing a pinhole camera having a 200-μm pinhole diameter. The pinhole camera was made up of a Cu assembly that is thick enough so that even very high-energy X-ray photons were unable to pass through it. Multiple imaging of the source was acquired by moving the X-ray photographic film (dental film with a dimension of $3.05 \times 4.05 \text{ cm}^2$) inside the pinhole assembly. The pinhole camera along with the film was placed before the glass window to obtain the inverted image of the X-ray source. In order to obtain X-ray radiography images, we kept the X-ray photographic film very close to the glass window from the outside. Contact radiography was basically performed in which the sample was attached to the film. After performing the experiments and being exposed to the X-ray, the film was processed in the developer and fixer solutions in order to obtain a permanent viewable image.

### IV. RESULTS AND DISCUSSION

As already mentioned, a lot of experimental and theoretical work on ion dynamics and neutron production in the IECF device has been carried out by many researchers. However, in the reverse polarity of the central grid (positively biased), the electron dynamics plays a vital role as far as the X-ray production and resolution of radiography images are concerned. First, we briefly discuss the electron dynamics through computer simulations in the next subsection.

#### IV.A. Electron Dynamics in the IECF Device

Electron dynamics is equally important as that of the ion in the fusion process inside the cathode during negative polarity of the central grid in the IECF device. In that case, the ions recirculate along certain channels across the...
cathode grids and the electrons move in the opposite direction toward the wall of the chamber. Confinement of secondary electrons also takes place inside the potential well along with the ions, which results in the formation of multiple virtual electrodes inside the cathode. However, if the polarity of the central grid is altered, i.e., the grid is biased with positive voltage, then the electrons are the ones oscillating across the grid and the ions move toward the wall region. The oscillating frequency of the electrons, in this case, is much higher than that of the ions in the previous case due to the higher mobility of the electrons.

In the simulation model, we applied a potential of 10 kV to the anode grids and ran it until the steady state was reached. The electrons from the emitters accelerated toward the anode grids and recirculated along the grid openings. The recirculation process of the electrons could be visualized during the run time of the simulation. Figure 3 shows the phase-space plot of the electrons after achieving the steady state. Apart from the straight-line path of the electron beams originating from the emitters, they also follow the curved paths along the anode openings during the recirculating motion.

The corresponding surface plot of electron density is shown in Fig. 4. It clearly shows that the electrons are confined at the central region inside the anode and that the peak density is found to be on the order of $10^{16} \text{ m}^{-3}$ at 10-kV operation. This electron cloud density was found to be increasing with the applied potential.

In order to have more insight into the electron motion across the positively biased grid, the electron velocity distribution function (EVDF) was measured. Three different locations were chosen inside the simulation domain at which the EVDFs were measured. One location was near the wall or emitter (first location), the second one was in between the emitter and the anode grids (second location), and the last one was inside the anode grids (third location), as shown in Fig. 5a. A function tool was used (in MATLAB) based on the normal kernel function, which is a nonparametric representation of the probability density function of the particle velocity. A similar approach was considered elsewhere.

Figures 5b, 5c, and 5d display the EVDFs at the prescribed locations. Near the wall region (Fig. 5b), the velocity distribution was observed to be Maxwellian. On the other hand, another distinct peak in the positive velocity axis was observed apart from the central peak in the second location, as shown in Fig. 5c. The population of the electrons in this peak was those high-energetic electrons that are moving in the forward direction toward the anode grids. Again, inside the anode region (third location) high-velocity peaks were observed on either side of the central peak (Fig. 5d). These peaks represent the electrons that have gained energy due to the high positive potential applied to the anode grids. The right peak in the positive velocity axis represents the population of the high-velocity electrons moving in the forward direction, while the peak on the left side of the central peak represents those electrons that are moving in the opposite direction. The velocity distribution of the electrons at different locations shows the recirculating characteristics of the energetic electrons across the anode grids. The high-energy peaks in the tail of the distribution functions suggest that the electrons acquire high energy during the course of their recirculating motion.
IV.B. X-Ray Production, Imaging, and Radiography

One of the primary objectives of operating the IECF device in positive biasing conditions is to generate X-rays from the device and to perform radiography of different specimens. As already mentioned, the fast-moving electrons interact with the anode grid, which is biased with high positive potential. In this interaction process, the electrons are rapidly decelerated by the target (anode grid) atoms. However, every electron does not decelerate in the same manner. Some of them are stopped in one impact and lose all of their kinetic energy, while others deviate from their original path due to the target atoms and successively lose some of their kinetic energy.

The electrons that are stopped in a single impact produce photons having maximum energy. The whole energy (electron-volts) of the electron is converted into maximum photon energy $h\nu_{\text{max}}$, where $\nu_{\text{max}}$ is the maximum frequency of the photon. If an electron undergoes a glancing impact or deviates from its original path and partially loses its velocity, then only a fraction of its energy is converted into radiation and the photon thus produced has an energy less than the maximum value $h\nu_{\text{max}}$.

In the simulated electron density profile shown in Fig. 4, the formation of a high-density electron cloud region is observed inside the anode grids. The process of deceleration of the electrons, and hence, the production of bremsstrahlung or continuous X-rays may also occur due to the presence of the high-density electron cloud inside the anode.\(^7\) The electron cloud takes part in the partial repulsion of the incoming high-velocity electrons and may produce a fraction of bremsstrahlung radiation. Figure 6 shows the conceptual picture of the generation of X-rays in the IECF device having a cylindrical anode grid at the center.

As discussed earlier in the experimental setup section, the SPMT detector was used to obtain the X-ray energy spectrum from the source. Initially, the detector was calibrated with a known gamma-ray source of \(^{137}\)Cs that gives a gamma-ray peak at 662 keV, as shown in Fig. 7a. After calibrating the detector, a high positive voltage was applied to the grids; the obtained spectrum at 70-kV voltage and 5-mA current is shown in Fig. 7b. The continuous X-ray spectrum mostly resembles the tungsten anode spectral model\(^ {34}\) that extends up to the applied voltage range.

IV.B.1. X-Ray Source Imaging

In order to observe the X-ray-emitting zone, we used the pinhole camera along with the X-ray film to record
The pinhole was fixed at the glass window from the outside, and the distance of the film from the pinhole was varied. At first, a solid cylindrical rod with a 1.5-cm diameter was used as the anode. While operating the device at 35-kV voltage and 5-mA current for ~1 min, the X-ray-emitting zone was captured on the photographic film. The image of the X-ray source region is shown in Fig. 8a when the film was at a distance of 0.1 cm from the pinhole.

The length of the X-ray source can be evaluated using the relation\(^{37}\)

\[
\beta = \frac{s'}{s} = \frac{L'}{L},
\]

where \(\beta\) is the magnification of the image, \(s\) and \(s'\) are the source and image distance from the pinhole, respectively, and \(L\) and \(L'\) are the length of the source and image, respectively. The \(s\) is fixed at a distance of 35 cm in all the cases. Now, if we increase the image distance, \(s'\) (or film distance), then the magnification of the image also increases. Figures 8c and 8e show the images of the source when the film was at 1.0 and 2.0 cm from the pinhole, respectively. The length of the source \(L\) was found to be \(\sim 18\) cm by measuring the length of the images and using Eq.(2) in both cases. Although, the total length of the cylindrical rod was 25 cm, and since the part of the X-ray emitting from the upper portion of the anode was obscured by the viewing window of the chamber, the film was not able to collect the radiation from that part. We observed only the remaining 18-cm part of the source in the film.

The corresponding grayscale intensity level of the images Figs. 8a, 8c, and 8e in the vertical direction are shown in Figs. 8b, 8d, and 8f, respectively. It was noticed that the intensity in the central part of the images decreased and became prominent with the increase in the magnification of the image. The primary reason behind this may be the formation of an asymmetric electric field in the middle part of the device due to the presence of multiple ports, diagnostic tools, gas inlet, outlet, etc. in that region. The motion of the electrons will be asymmetric in the midsection in comparison to the upper and lower sections of the device. As a result, variations in intensity were observed in all the images.

Second, the cylindrical grid was used as the anode, and a similar type of intensity variation of the images was noticed. Keeping the operating voltage and current the same as before, experiments were performed to capture the X-ray-emitting zone on the photographic film; the
inside the grid discards the contribution of the electron cloud in X-ray formation in this case. In fact, the six-gridded anode was unable to form a highly dense electron cloud inside it, which might be the reason for not getting X-rays from that region. The results suggest that the dominating zone of X-ray emission while using the gridded anode in the IECF device is the grid wires. The electron-grid interaction produces most of the emitted X-rays, while the high-density electron cloud formed inside the anode grid may also contribute to X-ray production, as observed in Fig. 9a, depending on the grid structure.

### IV.B.2. X-Ray Radiography

As far as X-ray radiography is concerned, we placed the sample on the glass window from the outside and also attached the X-ray film to it. The resolution and quality of the image depended on the anode structure apart from the applied voltage and current. Since we used a gridded structure as the anode, its transparency or the number of grid wires present in the anode plays an important factor on which the quality of the image depends. The image quality and intensity using a 12-gridded cylindrical anode was much better than that of a 6-gridded anode having the same diameter and applied voltage.

Again, the dependency of applied voltage on the radiography images is shown in Fig. 10. Here we used a universal serial bus (USB) plug as the object to show the variation of its radiography images by varying the applied voltage (constant current: 10 mA). As we increased the voltage, the interior parts of the sample gradually became more prominent. At 45-kV applied voltage, the outer part of the USB plug along with the connecting wires became invisible and only the hard metallic part of it remained in the image, as shown in Fig. 10d. Thus, the contrast of the radiography images can be easily varied by changing the applied voltage.

On the contrary, when we replaced the cylindrical grid with the solid extension rod we also observed a difference in the image quality. One such example is shown in Fig. 11, which shows the radiography image of a human little finger at 35-kV applied voltage. The bone structure of the finger can be visualized from the image using the cylindrical grid (Fig. 11a), while the image obtained using the solid cylindrical rod as the anode (Fig. 11b) displays some more detailed information, such as the knuckles of the finger which can be observed with a higher contrast level.

Optimization of the applied voltage is one of the key parameters when taking the radiography image of

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**Fig. 8.** Pinhole images of the X-ray source using an extension rod as the anode at an applied voltage of 35 kV. The distance of the film is at (a) 0.1 cm, (c) 1.0 cm, and (e) 2.0 cm from the pinhole. The corresponding grayscale intensity levels in the vertical direction of the images are shown in (b), (d), and (f), respectively.

obtained images are shown in Fig. 9. In this case, two grids having 12 and 6 grid wires were used separately. The hazy image of the grid wires of the anode with 12 grids can be noticed if carefully observed, as shown in Fig. 9a. Moreover, the image suggests that the X-rays are also emitted from the region close to the grid wires, including the region inside the grid.

The high-density electron cloud formed inside the anode grid, as suggested by the simulation results (Fig. 4), contribute to the partial deceleration of the recirculating electrons, and hence, has taken part in the X-ray production. The corresponding grayscale intensity level of the image in the vertical direction is shown in Fig. 9b. The figure shows a similar type of intensity variation with a slight decrease in intensity in the midsection, as obtained in previous cases.

In the case with the six-gridded cylindrical anode, the clear image of the grid wires can be noticed in Fig. 9c. The exact X-ray-emitting zone can be perfectly observed in this particular case. The absence of any dark region
If the voltage is too low (less than 25 kV), only the fleshy part of the finger appears without any visualization of the bone. Again, if it is too high (more than 50 kV) then the X-rays even pass through the bone and the structure looks to be darker. Moreover, the exposure time of the sample to the radiation is also equally important for getting a clear image. It has been observed that 50 to 60s is the appropriate exposure time to obtain images, as shown in Fig. 11.
The pinhole imaging technique was employed and revealed the exact X-ray-emitting zone of the device. The X-ray source also showed a slight decrease in image intensity in the middle portion. The asymmetric field distribution in the mid portion due to the presence of multiple ports might be the reason. Last, both metallic and biological samples showed good radiography images depending on the applied voltage, current, and the structure of the anode.

As far as future scopes are concerned, MCNP simulations can be performed to study both X-ray and neutron imaging, which will give a clear picture of the potential capability of the IECF device as an X-ray/neutron imaging source. A compact and portable version of the device that has the same or better capability as the present IECF device may be developed for X-ray photon and neutron imaging. Such devices may become an alternative when both neutron and X-ray scanning facilities are needed for greater accuracy in security systems. It may be useful in the signature-based radiation scanning technique in which both neutrons and X-rays can be used for better and accurate identification of any possible threat.

V. CONCLUSION

The present study showcased electron dynamics as well as X-ray emission and their application when the polarity of the central grid in the IECF device is reversed from the conventional negative biasing condition. The distinct features of this study include the computational observation of the electron characteristics through PIC simulation. It shows the recirculating nature of the electrons across the positively biased grid. The high-energy peaks in the EVDF signify the high-velocity electrons moving in the forward and backward direction through the grid. The high-density electron cloud formed inside the anode also contributes to continuous X-ray production apart from the contribution of the electron-anode interaction. The detected continuous or bremsstrahlung radiation shows an energy spectrum that extends up to the applied voltage range.

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Disclosure Statement

No potential conflict of interest was reported by the authors.
Data Availability Statement

The data that support the findings of this study are available within the paper.

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