Experimental Discharge Characterization of IEC Plasma Device

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Abstract

In this paper, Egyptian first inertial electrostatic confinement fusion (IECF) device, constructed at the Egyptian Atomic Energy Authority (EAEA-IEC), is introduced the characterization of IEC Plasma Device. It consists of 2.8 cm stainless steel cathode, 6.5 cm anode diameter with 10 cm diameter 30 cm height vacuum chamber. The discharge current and voltage of plasma discharge has been recorded using current probe and resistive voltage divider respectively. The X-ray emissions in IEC plasma device were investigated by employing time-resolved detector. The temporal distributions of detected x-rays emission are occurring during the initial 1 microsecond. The calculated rate of DD-neutron generation using the same electrode configuration about 10^6 – 10^8 neutrons/second.

1. INTRODUCTION

In IEC devices, fusion ions are electrostatically accelerated through a spherically symmetric central focus point. At the focus point they are at sufficiently high energy to overcome their mutual electrostatic repulsion that some small fraction of the ions will fuse and release energy in the form of high energy fusion products [1]. The IEC fusion device basically consists of a spherical-gridded cathode concentrically placed at the center of a spherical anode filled with a fuel gas. A glow discharge takes place between these electrodes. The produced ions are then accelerated toward the center through the transparent gridded cathode undergoing fusion reactions. Fusion reactions in spherical inertial electrostatic confinement (SIEC) devices were first realized by Hirsh [2, 3] using high energy ion guns as a source of ions. Miley et al. [4, 5] carried out experiments using a transparent grid as cathode and a spherical glow discharge as ion source. In their experiments, although the measured neutron production rate was a fraction [6] of that of Hirsh’s data, the dependence of the neutron production rate on the device parameters was similar to that of Hirsh.

For instance, an IEC neutron generator [7] of 20 cm in diameter demonstrated more than 6 kW discharge power to produce 10^7 neutrons/sec for D-D fusion. Both the input power and the neutron output are high in contrast with a typical commercial sealed neutron tube [8] with similar size, which generates ≈ 10^6 neutrons/sec for D-D with ≈ 9 W. The improvement of charged particle confinement in IEC systems is of paramount interest for higher intensity neutron sources and possible IEC fusion power plants. Sedwick and McGuire proposed a method of improving ion confinement times by electrostatically focusing ion beams to keep them away from cathode grid wires [9]. A Neutron/Gamma-ray combined inspection system for hidden special nuclear materials (SNMs) in cargo containers has been developed in Japan. The inertial electrostatic confinement fusion device has been adopted as neutron source have been developed to realize the fast screening system. The prototype system has been constructed and tested in the Reactor Research Institute, Kyoto university [10].

2. EXPERIMENTAL SET-UP

The IEC fusion device basically consists of a spherical-gridded cathode concentrically placed at the center of a spherical anode filled with a fuel gas. A glow discharge takes place between these electrodes. The produced ions are then accelerated toward the center through the transparent gridded cathode undergoing fusion reactions. An important advantage of IEC over accelerator-driven neutron generators employing solid targets comes from the use of “gas target” or “plasma target. The laboratory experimental set-up of the IEC plasma device is as shown in Figure 1. The IEC is a 10-cm of diameter Pyrex glass tube (and 30 cm height) vacuum vessel mounted on a laboratory table. A chamber base pressure of = 0.01Torr is achieved using differential pumping. The IEC cathode grid was constructed using stainless steel wire of 1 mm in diameter. High voltage insulation is provided using ceramic feedthrough system that is extended into the center of the chamber and attached to the cathode grid.
Different gases are injected into the quartz tube through the mass flow controller that regulates the mass flow rate of the propellant gas. The typical operating pressure is 0.08 – 1.0 Torr for different gases. If the vacuum vessel has been opened recently, there are surface contaminants, water vapor, grease and other impurities inside the vessel. It takes about 20-30 minutes after the initiation of the discharge during which chamber conditioning and surface cleaning takes place, and the impurities are pumped out of the system. To avoid vapor from back streaming, the vacuum chamber is washed by gas after evacuation by the rotary pump.

Instead of the traditionally used pure DC mode, a rectified AC approach was chosen. Preliminary data indicates that a more stable operational behavior is achieved with the potential to extend the operational range, and arcing was significantly reduced in this operational mode. The resulting output voltage was rectified through a custom built high voltage diode circuit to maintain the electrode bias with the inner electrode being the negative pole (cathode) and the outer electrode working as the anode at ground potential. The resulting output signal oscillating with 120 Hz as illustrated in Fig. 2 was supplied to the IEC. Quasi-stationary IEC plasma fluctuating with a frequency of 120 Hz was obtained for a wide variety of pressures and voltages.
3. RESULTS AND DISCUSSION

The applied voltage to and the discharge current through the discharge chamber were measured using a voltage divider (homemade), which was connected between the two electrodes, and a current monitor, which can be located upon returning to the ground. The signals from the voltage divider and the current monitor were recorded in a digitizing oscilloscope (Lecroy, USA) with 200 MHz bandwidth. Figures 3 and 4 indicate the current and voltage waveforms characterizing the pulsed IEC fusion device.

![FIG. 3. Discharge current signal from IEC plasma.](image1)

The light emitted by the plasma in the observation region was collected with an optical fiber and guided to a photomultiplier. A Hamamatsu photomultiplier tube (PMT) was used to detect coincident optical response. This PMT was mounted above and offset to the side of the plasma source, at a distance of 5 cm from the plasma source and the output signal was measured and recorded directly by a digitizing oscilloscope (Lecroy, USA) with a 200-MHz bandwidth (figure 5).

![FIG. 4. Discharge voltage signal from IEC plasma.](image2)
Typical photomultiplier signals correspond to plasma structures in the reactor for different gases can be observed. The photomultiplier voltage traces includes one pulse of interest is due to the primary discharge. Both intensity and duration of the pulses are different. This can be related to the different kinetics of elementary processes in the plasma structures. The intensity of emitted light, on the other hand, depends solely on the rate of recombination reaction within the plasma. The intensity of light, hence, can be deduced as an indicator of plasma density in the reactor.

Scintillation detectors were one of the first detectors developed to detect radiation, because these detectors could be used with simple photographic film acting as a light sensor. The light sensor can be a photodiode or photomultiplier, as well as photographic film. The choice of the detector depends on the response time desired, the kind of radiation, and its intensity. Scintillation detectors are of several types, classified according to their state—solid, liquid, or vapor—based on their chemical nature (organic or inorganic). The scintillation mechanism itself is dependent on the crystal lattice structure of the scintillator material. Such detectors have been used for the detection of X-ray and neutron radiation created in IEC devices [11].

The generation of x-ray has been investigated experimentally in the IEC fusion reactor using fast radiation detectors based on type of photomultiplier with high anode characteristics, nanosecond time resolution, shielded against electromagnetic interference in the assembly with fast scintillator. In the development of the detector housings special attention is paid to the screening of the pulsed electromagnetic interference occurring at the time of discharge.

The transmission of materials for X-rays up to 30 keV is readily obtained using the Center for X-Ray Optics (CXRO) web site [12]. Berillium is the most commonly used material for filters. It has good mechanical properties and provides a wide band-pass while also excluding visible light. Thin sheets of solid material absorb X-rays and the transmission of the sheets depends upon the X-ray energy, the material thickness, and the atomic number Z of the material. The transmission of Be foil that is 200 µm thick is shown as figure 6. The X-rays are absorbed in the Be until the X-ray energy gets above 3keV. The foil begins transmitting X-rays again when the X-ray energy rises above 3keV.
X-ray yield of hydrogen plasma have been registered by type of photomultiplier shown in figure 7. The temporal distributions of detected x-rays emission are occurring during the initial one microsecond.

According to the kinetic theory of gases, when gas pressure (or gas temperature) increases, the kinetic energy of gas increases, so it can reach to higher speeds. Therefore, more energetic particles emerge, as a result, more quanta of energy emerges in the form of bremsstrahlung radiations.

Hydrogen gas is substituted for deuterium or tritium because in this configuration the main function of gas ions is to provide electron Bremsstrahlung emission. Intense emission is concentrated in a small volume surrounding the central axis due to the high electron density formed there. A scintillator photomultiplier tube (SPMT) assembly was employed for the detection of hard X-ray, which was placed at a distance 5 cm away from the evacuated chamber. The scope graph below (Figure 8) is from the experiment of IEC plasma device when nitrogen is the working gas.
The accelerated electrons cause electron-electron collisions in central plasma core region, in other words the energetic electrons scatter in the center of the sphere. The scattering interactions create intense bremsstrahlung x-rays. The emitted x-ray energy is controlled by the grid bias. For mono-energetic electrons, related x-rays occur whenever electrons are rapidly accelerated across a high potential difference. The fraction of the energy in the electron beam that is converted into x-rays ($f_x$) is given by

$$f_x = 10^{-7} \times Z \times E$$

(1)

Where, $E$ is the electron energy in keV and $Z$ is the atomic number of the absorber.

According to relation (1), the anode of the IEC device should be made of Aluminum (lower atomic number) or other light materials for reducing Bremsstrahlung production. The electrons are hitting the anode produces many x-ray photons, these photons reaching the cathode grid. Furthermore, the x-ray photons could release multiple numbers of electrons from the cathode depending on their energy. This phenomenon could be especially significant in pulsed devices due to large currents during a pulse [13].

Deuterium makes a good fusion fuel because is easily obtained and because it has a cross section for fusion reactions that makes it obtainable within IEC fusion plasma. The production of neutrons in an IEC plasma device is based on two main mechanisms: the thermal mechanism and the beam target mechanism. The thermal mechanism of neutron production is based on the collision of energetic deuterium ions inside the bulk of the plasma. The beam target mechanism in IEC plasma devices is caused by the interaction of accelerated deuterons with the plasma or background gas. The greatest number of fusion reactions is occurring inside and around the cathode-grid; and in most devices operating today, the majority of reactions is beambackground in nature, that is, between the fast moving ions in the plasma and the neutral background gas.

For using deuterium gas, the rate of DD-neutron generation is given by [14]

$$\frac{dN}{dt} = \frac{1}{2} n^2 i \sigma(\epsilon_i) U_i \Omega$$

(2)

Where $\Omega$ is volume corresponding to maximum ion density, $\sigma$ is cross-section of fusion reaction, $n_i$ is the final density of deuterium ions and $U_i$ is the speed of deuterium ion.

The final density of deuterium ions is given by

$$n_i \approx 2.7 \times 10^5 f \varphi^{1.5} \nu^2 \text{ cm}^{-3}$$

(3)

Where $\varphi$ is the depth of potential well (the potential of the electric field in the axis of the system), $f \leq 1$ is the ratio of ion density to electron density and $\nu$ is the oscillation frequency is given by
\[ \nu \approx 8 \times 10^6 \frac{\sqrt{\varphi}}{r_g} \text{ Hz} \quad (4) \]

Where \( r_g \) is the initial radius of inner cathode in cm. For \( r_g = 1.4 \text{ cm}, \varphi = 20\text{kV} \) then the oscillation frequency equal 10MHz approximately and final density of deuterium ions equal \( 10^{16} - 10^{18} \text{ cm}^{-3} \) for \( \varphi = 20\text{kV} - 40\text{kV} \) respectively. Then the rate of DD-neutron generation \( (dN/dt) \) equal to \( 10^6 - 10^8 \text{ neutrons/second} \)

4. CONCLUSION

The IEC fusion device is a powerful source of x-ray radiations which may be suitable for different applications. The same device that produce x-ray yield can be used to generate neutrons yield. Also, the X-ray rate is dependent on the gas choice in the chamber of IEC device. The calculated rate of DD-neutron generation using the same electrode configuration about \( 10^4 - 10^6 \text{ neutrons/second} \).

REFERENCES