Plasma Diagnostics in the Optical and X-Ray Regions on the IEC Plasma Device

- ***ABSTRACT***
- The design and construction of first Egyptian inertial electrostatic confinement IEC fusion device has been studied [9]. It consists of 2.8 cm stainless steel cathode, 6.5 cm anode diameter with 10 cm diameter 20 cm height vacuum chamber. The operation of IEC experiments has concentrated on pulsed operation to achieve the high currents required to generate increased reactions rates. The discharge voltage waveform with peak voltage 12kV with a full width half maximum (FWHM) of 10 nanoseconds and current pulse waveform has been registered using pick-up coil with peak current about 170mA. Experiments are performed with nitrogen and hydrogen as operating gases at different pressures and voltages. Time resolved of x-ray radiation signals are obtained using fast radiation detector.

- ***BACKGROUND***
- The IEC concept dates back to the late 60's with the work of Farnsworth and Hirsch [1]. Farnsworth first patented the idea behind IEC [2], and Hirsch built on the work using a strong, negative, electrostatic potential well to promote fusion reactions. Research on IEC is being performed since the 1950's, but only limited in the studies for neutron source application, mainly exists in USA [3], [4] and Japan [5], [6]. Fusion reactions within an IEC device can occur in many different modes: beam-beam, beam-background, beam-target, and fast neutral-background. Beam-beam reactions are due to two accelerated ions fusing with one another. Beam-background reactions are due to an accelerated ion fusing with a background gas molecule. Beam-target reactions occur when ions implant into a solid component such as the cathode; further bombardment by ions can result in fusion reactions within the cathode material. Finally, fast neutral-background reactions occur when an ion charge-exchange with a background gas atom—the resulting fast neutral can then fuse with the background gas. It is important to understand how all of these modes influence the reaction rates both for a better understanding of the physics involved, and for any potential use of the fusion products [7].

• EXPERIMENTAL SET-UP

- A schematic of the IEC chamber is shown in Figure 2. A cylindrical glass vacuum vessel measuring 30 cm high and 10 cm in diameter houses the system. The pumping system consists of an Edward rotary vane roughing pump to allow base pressures in the low to mid 0.02 torr range. The base pressure is measured using digital thermocouple gauge. Table 1 shows some parameters of IEC fusion device. A typical grid is shown in Figure 2. The IEC cathode grid was constructed using stainless steel wire of 1 mm in diameter. High voltage insulation is provided using ceramic feed through system that is extended into the center of the chamber and attached to the cathode grid. The outer grid is remains grounded and a high voltage insulator carries the large negative potential to the inner grid. The high voltage power supply has maximum capability of 20 kV.

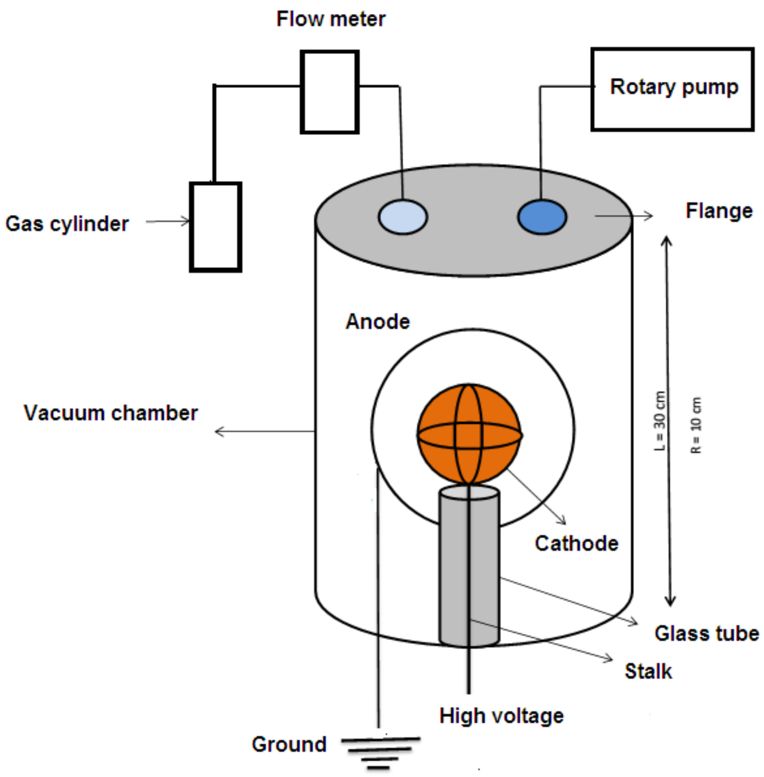
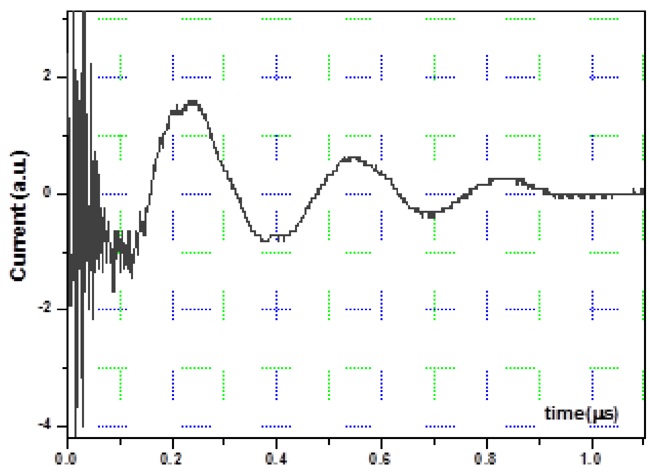


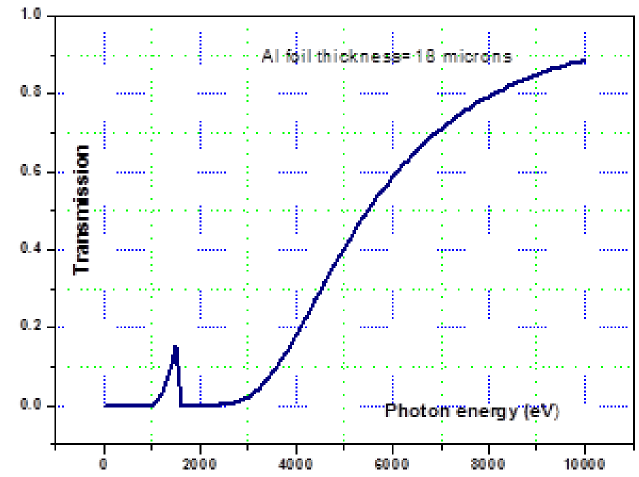
Table 1 Design and operational parameters of IEC fusion device

Parameter	Value
Vacuum chamber diameter	10 cm
Vacuum chamber height	20 cm
Anode grid diameter	6.5 cm
Cathode grid diameter	2.8 cm
High-voltage Stalk height	12 cm
Cathode voltage	20 kV (max.)
Gas pressure	0.001-1 Torr

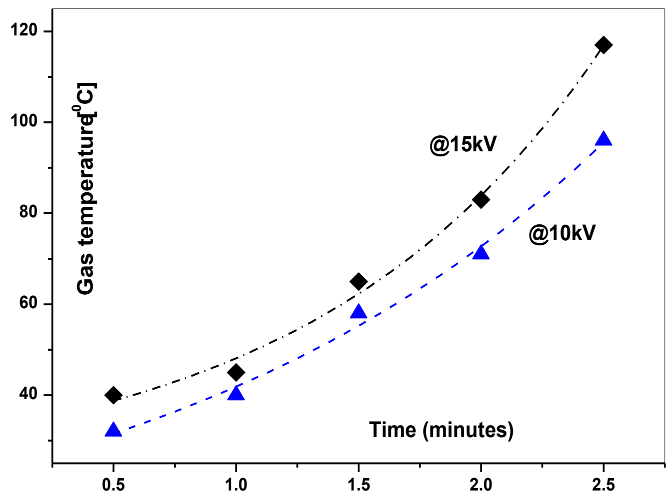
- ***EXPERIMENTAL RESULTS***
- The applied voltage to and the discharge current through the discharge chamber were measured using a voltage divider (homemade), which was connected between the two electrodes, and a current monitor, which can be located upon returning to the ground. The signals from the voltage divider and the current monitor were recorded in a digitizing oscilloscope (Lecroy, USA) with 200 MHz bandwidth. Figures 3 indicate the current waveform characterizing the pulsed IEC fusion device.
- Temperature was measured by exposing or attaching the thermocouple to the surface to be measured. The multi-meter displays the temperature directly in degrees Celsius. In this experiment, the thermocouple probe was placed inside of IEC reactor to monitor the gas temperature at 10kV and 15kV. This thermocouple probe picked up the maximum temperature in its focus as shown in figure 4.



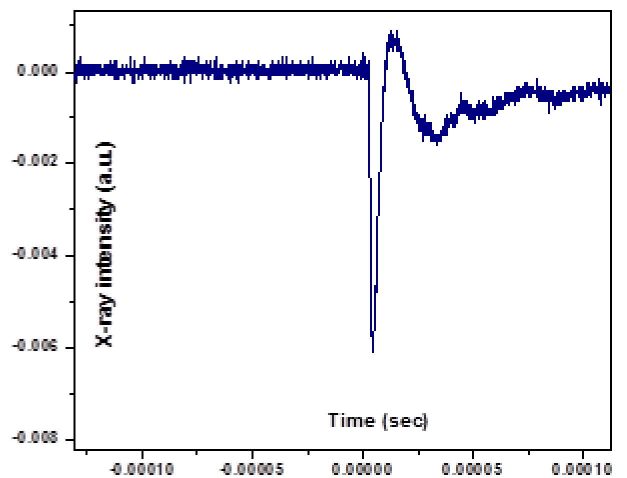
Current (a.u.)
time(µs)



Al foil thickness= 18 microns
Transmission
Photon energy (eV)



Gas temperature[^{0}C]
@15kV
@10kV
Time (minutes)



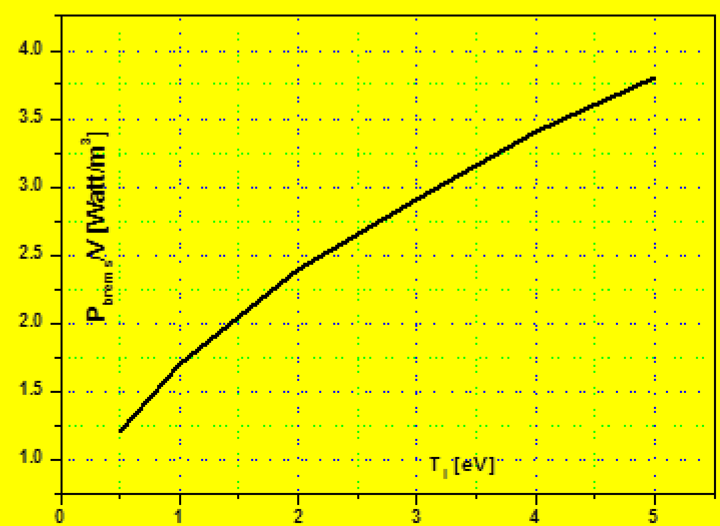
X-ray intensity (a.u.)
Time (sec)

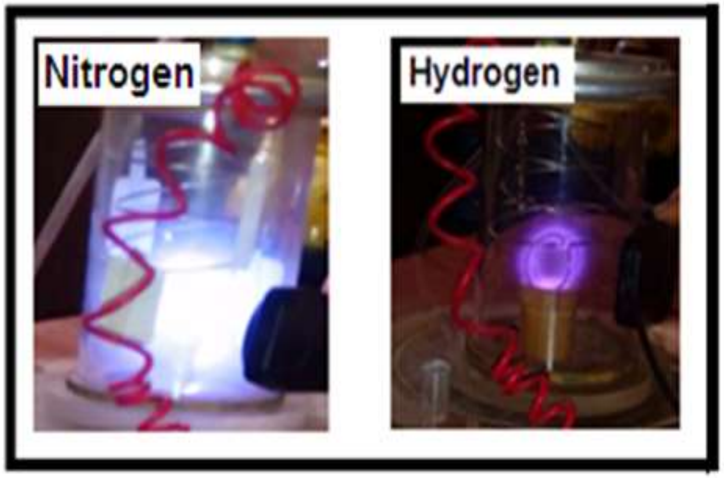
- Hydrogen gas is substituted for deuterium or tritium because in this configuration the main function of gas ions is to provide electron Bremsstrahlung emission. Intense emission is concentrated in a small volume surrounding the central axis due to the high electron density formed there. A scintillator photomultiplier tube (SPMT) assembly was employed for the detection of hard X-ray, which was placed at a distance 2 cm away from the evacuated chamber. The scope graph below (Figure 6) is from the experiment of IEC plasma device when argon is the working gas.
- Bremsstrahlung radiation occurs when a charged particle (typically an electron) is deflected by another charged particle (typically an ion). During this encounter the electron emits bremsstrahlung and loses some of its kinetic energy. The total bremsstrahlung power per volume [10], is

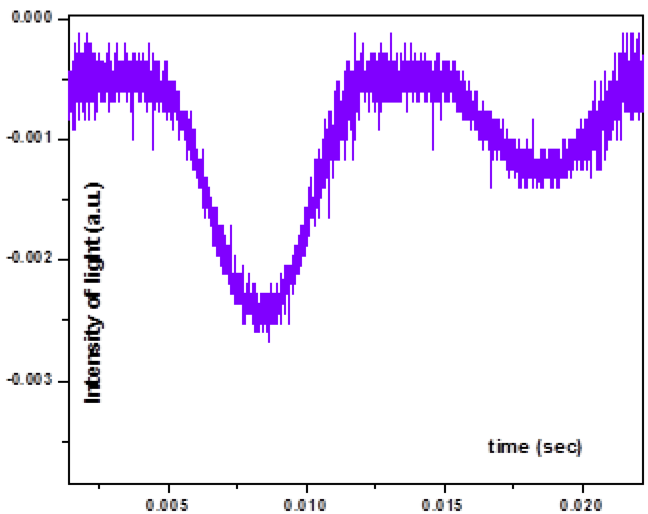
$$\frac{P_{br}}{V} = 1.69\cdot10^{-32} n_e^2 \sqrt{T_e}\left\{Z_{eff}\left[1+.7936\frac{T_e}{m_ec^2}+1.874\left(\frac{T_e}{m_ec^2}\right)^2\right]+\frac{3}{\sqrt{2}}\frac{T_e}{m_ec^2}\right\}\frac{\text{Watts}}{\text{cm}^3}.$$

- where, $Z_{eff} = \frac{\sum_i Z_i^2 n_i}{n_e}$, n_e is the electron density, k_B is the Boltzmann constant ,T_e is the electron temperature, Z is the charge number, e is the elementary charge, m_e is the electron mass and c is the speed of light in vacuum.

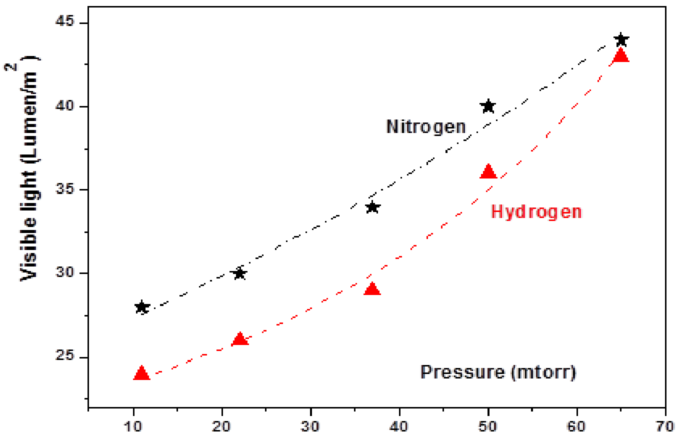
- Figure 7 shows the bremsstrahlung losses calculated from equation above, assumed ion temperatures ranging from 0.5-5 eV and hydrogen ion density about 10^{17} particles/m^3 the bremsstrahlung losses are in the order of magnitude of 10^{-4} W/m^3. Plasma ignition and observations for nitrogen plasma, the color of the plasma was bright blue outside and white inside inner grid. It was also observed that the color of hydrogen plasma was purple to pink inside and outside of inner grid (see figure 8).







- 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 9). Figure 10 show the effectiveness of IEC glow discharge, for visible flux density emitted from nitrogen and hydrogen plasmas at low pressures investigated. The luminance with the gas pressure increased exponential, due to the characteristics of IEC at the low pressures to produce more energetic excitation.



- **Conclusion**
- The flux density of visible light emitted from argon and helium plasmas different pressures was investigated. Since helium has a higher ionization voltage at lower pressures, visible flux density of helium glow plasma is greater than argon visible glow. X-ray has been detected using two PMT-scintillator systems.
- **References**

- [1] R.L. Hirsch, “Inertial-Electrostatic Confinement of Ionized Fusion Gases,” Journal of Applied Physics, 38, 4522 (1967).
- [9] G.M.EL-ARAGI, "Operation of Inertial Electrostatic Confinement Fusion (IECF) Device using different gases" Journal of Fusion Energy (2018)
- [10] Rider, T.H., A general critique of inertial-electrostatic confinement fusion systems, Physics of Plasmas, (1995) 1853-1872
- [11] G. M. El-ARAGI. Investigation of an Ion and Ultra High Frequency emissions in Inertial Electrostatic Confinement (IEC) plasma device Using Argon Gas. Science & Technology, 2018, 4, 71-79