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Scattered ionizing radiations from low-energy focus plasma and radiation dosimetery assessment

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Abstract. Scattered ionizing radiation emissions from a low-energy plasma focus (0.1 kJ Mather-type) device operating with different gases were studied. The plasma focus device was powered by a capacitor bank of 1 μF at 18 kV maximum charging voltage. The radiation emissions were investigated using time-integrated thermoluminescence TLD-500. These detectors were calibrated against standard X-ray machine as well as standard γ sources (^{60}Co and ^{137}Ca). Calibration of detectors showed linear relation over all the region of measurements. It was found that radiation levels would be minimum for different gases, when the gas pressure was between 0.5 and 0.8 Torr. Only helium deviated from this phenomenon as it gave maximum radiation level at 0.8 Torr pressure. It was also found that, for all the gases used, the radiation levels were maximum when the applied voltage was 15 keV.

Keywords. Plasma focus; radiation emission; detectors; thermoluminescence; X-ray.

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1. Introduction

The plasma focus (PF) was discovered independently by Mather (USA) [1] and Filippov (USSR) [2], although the devices used by these two pioneers had significantly different geometries.

The PF devices were developed and studied in the energy range from a few hundred Joules to mega-Joules, producing pulsed D-D neutrons in the range of 10^4 neutrons [3] to 10^{12} neutrons [4] per pulse. The principle of a dense plasma focus device operation lies in the conversion of energy collected in a capacitor bank into electromagnetic acceleration and compression of short-lived plasma which becomes a source of X-rays, charged particles and nuclear fusion neutrons, when operated in deuterium [5].

The thermoluminescent dosimeters (TLDs) are widely used in personnel monitoring (dosimetry) service for ionizing radiation, medical, industrial and research

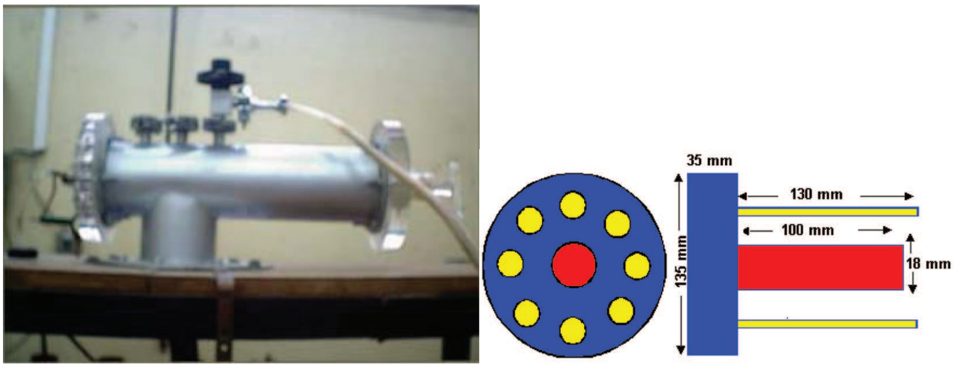

Figure 1. Schematic diagram of the construction details of plasma focus electrodes. (**a**) Shows the horizontal cross-section and (**b**) shows the vertical cross-section.

communities, and also for measurements of X-rays emitted from different laser-produced plasmas [6].

The detection of X-ray radiation by TLDs is affected neither by an electrical interference nor by a strong magnetic field. A large number of TLDs can be simultaneously used in an experiment, but only a single readout unit for the determination of their themoluminescent (TL) responses is needed. The application of TLDs makes possible only the time-integrated measurement of X-rays.

In this paper we show the results of an experimental study of X-ray emitted from a small plasma focus device (Mather-type) using time-integrated thermoluminescent detector crystals of Al_2O_3(C) (TLD-500). The thermoluminescent (TL) dosimeters have a series of advantages, such as its sensitivity to wide useful dose range, small physical size, no need for high voltage or cables, i.e., stand-alone character. TL detectors usually show a linear dose response in a wide range of photon energies ranging from keV to MeV, and can be easily calibrated by means of standard radionuclide sources in order to obtain an absolute measurement of the dose absorbed by the dosimeters. Detection of X-ray radiation by means of TLD is perturbed neither by electrical interference nor by strong magnetic fields.

2. Experimental set-up

Mather-type 112.5 J plasma focus device comprises of an outer electrode, which consists of eight copper rods, each of 130 mm length and 10 mm diameter as shown in figure 1.

The eight copper rods of the cathode are connected together by a copper ring behind the gun (breech).

The diameter of the outer electrode is 90 mm. The inner electrode is made of stainless steel of 18 mm diameter. There is a hole of 5 mm diameter in front of the inner electrode. The annular space gap between the inner and the outer electrodes is 36 mm. The cylindrical insulator ring is of 135 mm diameter and its thickness is

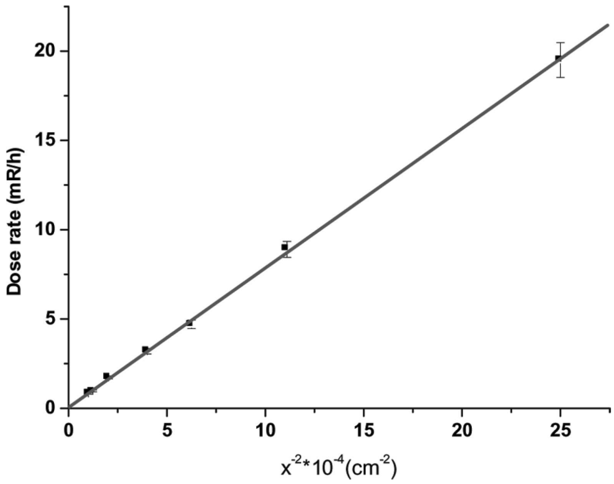

Figure 2. Calibration curve of the Co-60 source.

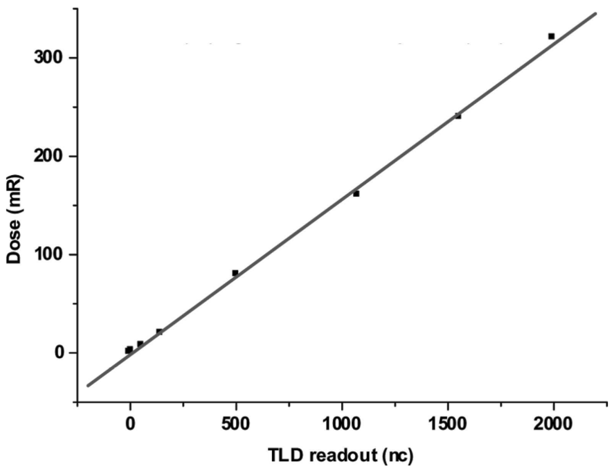

Figure 3. Linearity of Al_2O_3:C (TLD-500) chips readout (net count) against γ-ray dose (mR).

35 mm. A stainless steel tank (chamber) of 350 mm length and 100 mm diameter encloses the plasma focus. The condenser bank of the plasma focus device consists of a condenser of 25 kV and 1 μF low inductance condenser. The inner electrode is connected to the positive connection of high voltage supply via the thyratron tube (CX1159) switch, whereas the outer electrode is connected to Earth. The vacuum system consists of a rotary pump (Edwards single-stage model 1 Sc.-150B). To avoid vapour from backstreaming, the specimen was washed by gas after evacuation by rotary pump. The gas was fed into the system via a flow meter (OMEGA model). The pressure was measured using a thermocouple gauge (Edwards model).

Thermoluminescence dosimeter (TLD-500) (high sensitivity, simple re-use and minimum fading) chips are (5 mm in diameter with 1 mm thickness) pocketed in paper black box (to save it from plasma light) after the annealing. After 24 h of irradiation, TLD-500 is readout at TL-4000 reader with readout cycle. The TL-4000 system is in coaxial connection with a computer system which has a special software program for resolving TL-data and assorting the resolved data in classified files.

TLD-500 distributed inside the focus tube with distance 10 cm from the central electrode on disk with diameter 9 cm holding by copper rod. The TLD sample irradiated to 20 shots with constant pressure.

3. Experimental results and discussions

It is established from the series of the experiments carried out that the thermoluminescence phenomena using TLD-500 (aluminum oxide, $Al_2O_3(C)$) [7,8] is the best technique for dose assessment. Moreover, aluminum oxide is considered as a point detector as well as a stimulated tissue equivalent material. The results obtained using TLD readout are better than the film badge for the determination of the X-ray doses in the region of interest. Also the detection of X-ray radiation by TLDs is neither affected by the electrical interference nor by the strong magnetic field. The TLDs made the time-integrated measurement of X-rays possible.

Testing of the radiation detection tools was done by CO-60 source, which was standardized with the calibrated survey meter (figure 2). Diagnostic X-ray machine (type RayMax) was used to calibrate radiation detection tools, and these could be standardized using substandard ionization chamber (Victoreen model $4000M^+$).

Calibration of TLD-500

To determine the linearity of the new TL dosimeter, Al_2O_3:C(TLD-500) was irradiated with γ-ray from Co-60 standard sources with a dose rate of 80 mR/h at 10 cm for different times from 1 min to 4 h. The curve in figure 3 shows the linear dependence of the TLD readout and the exposure dose from γ-ray (Co-60 source). All the dosimeters are sensitve to the dose variation.

The calibration of TLD-500 with X-ray dose is more important than with the γ-ray sources. Victoreen ionization chamber (VIC model $4000M^+$) can standardize X-ray machine to identify the dose from X-rays delivered to the dosimeter [9]. The obtained result of the TLD readout (net count) is plotted against dose (mR) in figure 4.

The intensity of radiation dose as a function of the pressure of nitrogen gas inside the plasma tube and the time derivative of the discharge current are shown in figure 5. It was found that, the maximum dose decreased with pressure until it reached a minimum value at 0.5 Torr of nitrogen and then increased again in the range of operation. The X-ray output intensities vary from shot to shot even at identical experimental conditions.

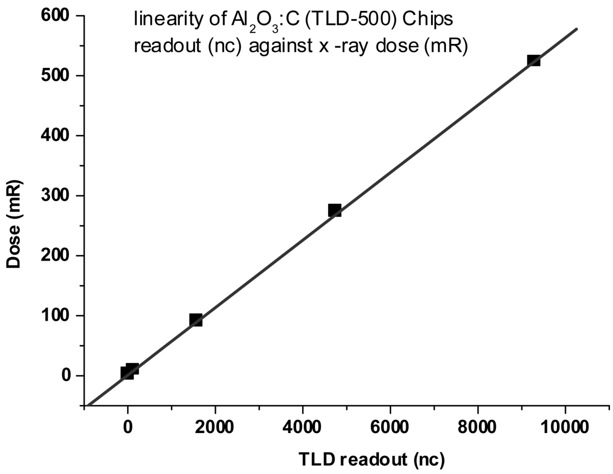

Figure 4. Calibration of TLD-500 with X-ray in the presence of the VIC.

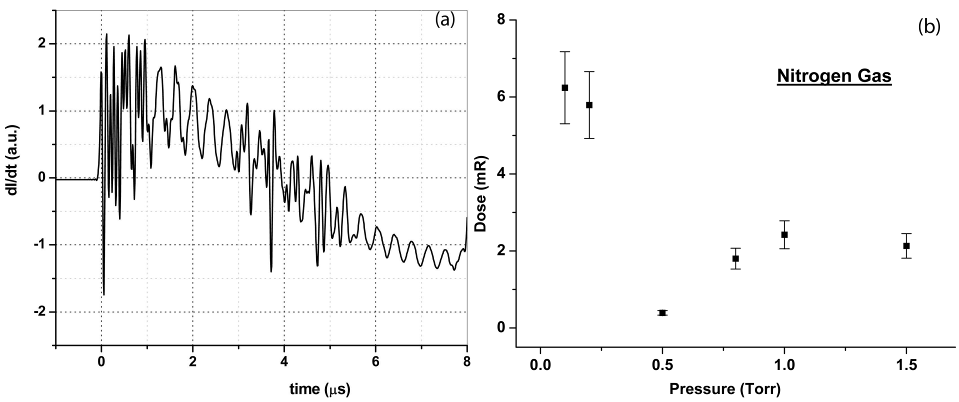

Figure 5. (**a**) Time derivative of the discharge current at a charging voltage of 15 kV for the nitrogen gas at pressure = 0.2 Torr and (**b**) X-ray dose as a function of the pressure of nitrogen in the plasma tube.

Figure 6 indicates the time derivative of the discharge current and intensity of radiation dose as a function of the pressure of argon gas. The maximum value of the dose is at a pressure of about 0.2 Torr and the minimum value is at 0.8 Torr.

Figure 7 gives the relation between the hydrogen gas pressure and the corresponding radiation dose after giving 20 shots and the time derivative of the discharge current at a charging voltage of 15 kV for hydrogen gas at 0.22 Torr (maximum dose). The variation of hydrogen gas pressure leads to change in the maximum exposure (dose), however, the maximum dose decreases when the pressure increases in the region of interest (range 0.1–1.5 Torr). As the gas operating pressure is lowered, the amount of hard X-rays emitted due to anode bombardment increases, which agrees with the work done by Krauz *et al* [10].

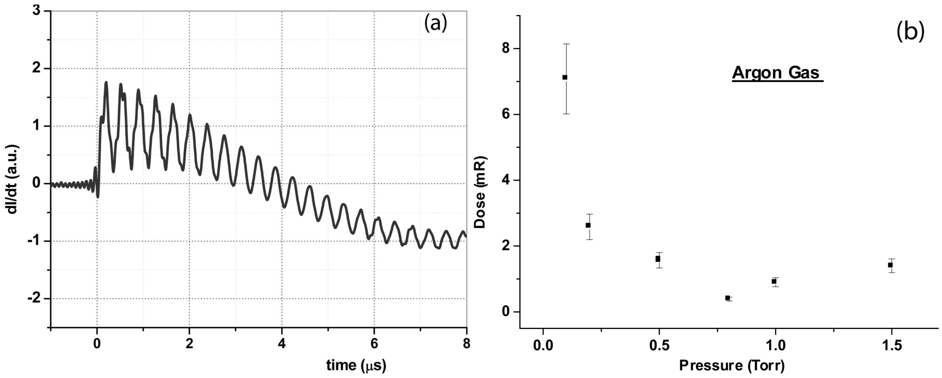

Figure 6. (**a**) Time derivative of the discharge current at a charging voltage of 15 kV for argon gas at pressure = 0.2 Torr and (**b**) X-ray dose as a function of the pressure of argon in the plasma tube.

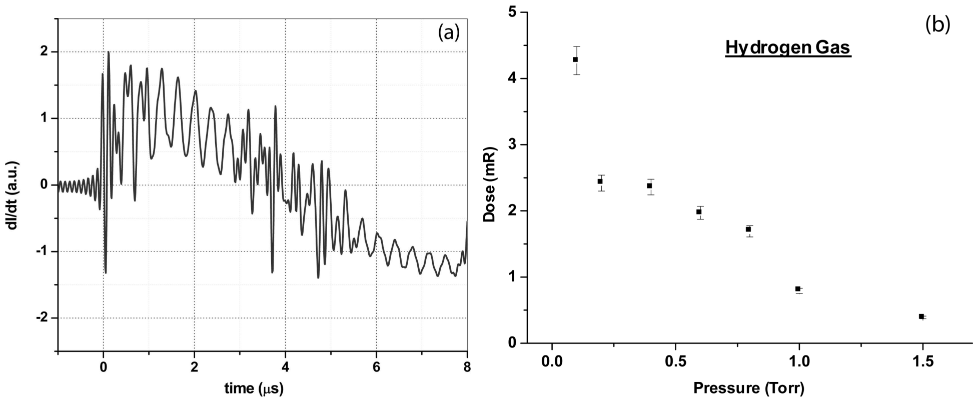

Figure 7. (**a**) Time derivative of the discharge current at a charging voltage of 15 kV for hydrogen gas at pressure = 0.22 Torr and (**b**) X-ray dose as a function of the pressure of hydrogen gas in the plasma tube.

Figure 8 gives the effect of the pressure of helium gas in the vacuum tube during plasma production and its corresponding radiation dose and time derivative of the discharge current at a charging voltage of 15 kV for helium gas at 0.8 Torr (maximum dose).

The change of the helium gas pressure leads to change in the maximum radiation exposure (dose). It is noticed that the maximum dose increases sharply to peak values in the range from 0.6 to 0.8 Torr then decreases again from 0.8 to 1.5 Torr until it reaches a minimum values at 1.5 Torr.

The effect when methane (organic gas) is used as a filling gas to plasma focus tube with constant applied voltage (V_{ch} = 15 kV) at different gas pressure, in the range 0.1–1 Torr is shown in figure 9. It is clear from figure 9 that minimum radiation dose can be obtained when the methane pressure is about 0.5 Torr and the maximum dose at 0.1 Torr gas pressure. Figure 9 also shows the time derivative

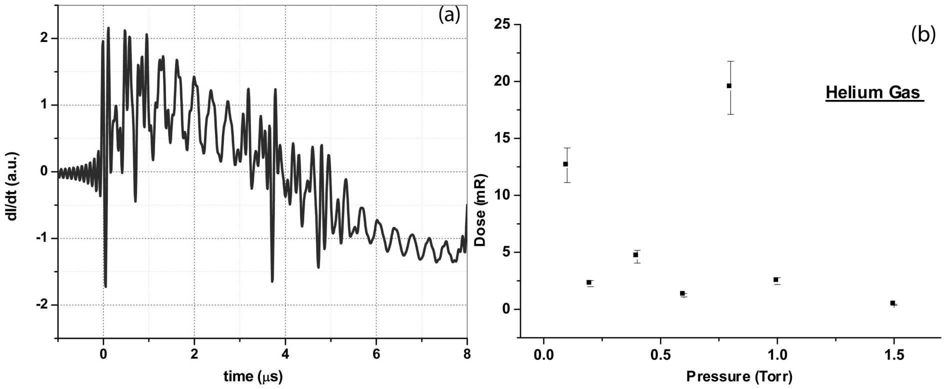

Figure 8. (**a**) Time derivative of the discharge current at a charging voltage of 15 kV for helium gas at pressure = 0.8 Torr and (**b**) X-ray dose as a function of the pressure of helium gas in the plasma tube.

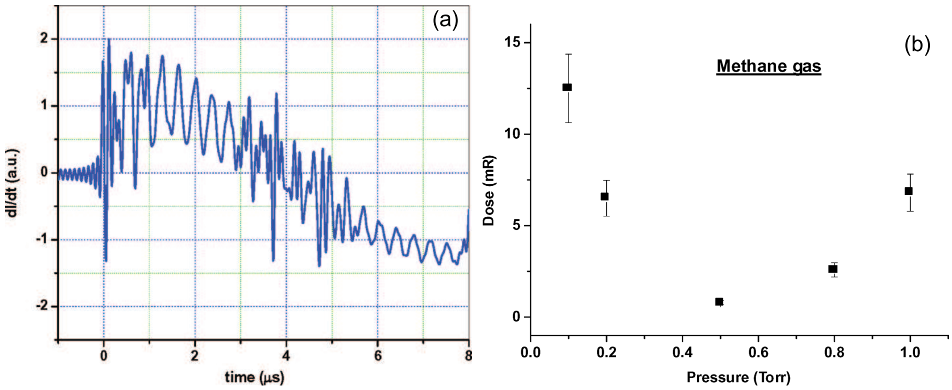

Figure 9. (**a**) Time derivative of the discharge current at a charging voltage of 15 kV for methane gas at pressure = 0.1 Torr and (**b**) X-ray dose as a function of the pressure of methane gas in the plasma tube.

of the discharge current at a charging voltage of 15 kV for methane gas at 0.1 Torr. The filling pressure affects the propagation velocity of the plasma sheath. Its structure above the anode influences the X-ray emission (the interaction of energetic electrons either in the current sheath or the electron beam generated in the focus region with the anode tip).

The pinched plasma gives high filling pressure, which leads to low or no X-ray emission. The emission of high-energy hard X-ray photon is indicative of the presence of a high accelerating field inside the pinch column.

Figure 10, which shows the X-ray dose as a function of discharge voltage of the helium gas, shows that maximum dose is registered at 15 kV charging voltage and 0.8 gas pressure for 20 shots.

Figure 11 indicates the relation between X-ray dose and the type of filling gas under operating conditions ($P = 0.1$ Torr, $V_{\rm ch} = 15$ kV) for 20 shots. It is found

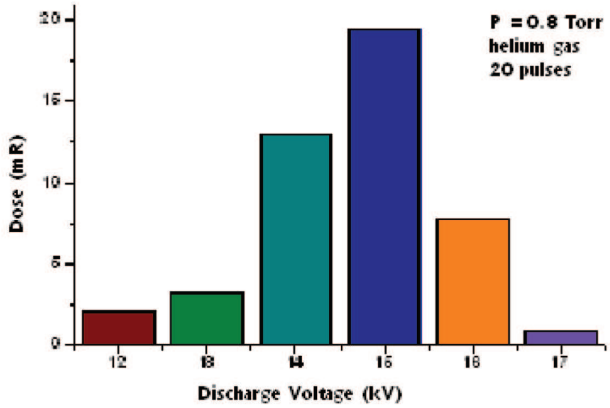

Figure 10. X-ray dose as a function of discharge voltage of the helium gas.

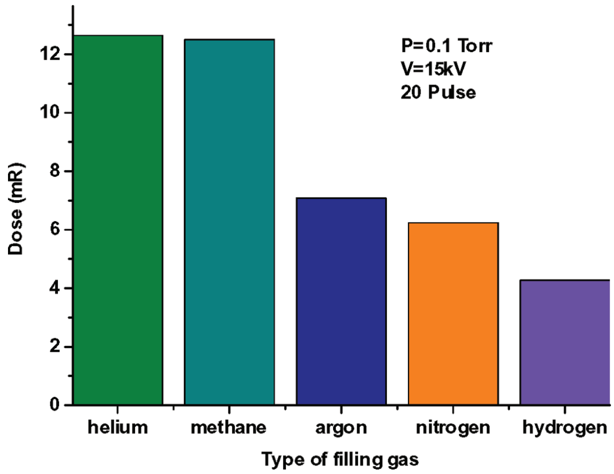

Figure 11. Relation between X-ray dose and the type of filling gas under the operating conditions ($P = 0.1$ Torr, $V_{\mathrm{ch}} = 15$ kV).

that maximum dose is registered for helium gas and organic gas (methane) when compared with other gases (argon, nitrogen and hydrogen).

The time correlation between X-ray and ion beam emission indicates that in plasma focus discharges, ion acceleration takes place at some time around the maximum radial compression phase. Therefore, it is reasonable to assume that ion acceleration takes place in the existing plasma, with a multi-charged ion composition. Under these conditions, all ions are accelerated by the same electric field and the energy gained in the acceleration process is proportional to the ion charge.

Bhuyan *et al* [11] investigated methane ion beams emitted from a low-energy (1.8 kJ) plasma focus device. Graphite collectors, operating in the bias ion collector (BIC) mode, were used to estimate the energy and flux of the ions along the anode axis of PF, using time of flight technique. The ion beam energy and flux correlation for methane discharge indicated that the dominant charge states of carbon ions were C^{4+} and C^{5+}. The maximum ion energies for H^+, C^{4+} and C^{5+} were in the range of 200–400 keV, 400–600 keV and 900–1100 keV, whereas their densities were maximum for the energy range 60–100 keV, 150–250 keV and 350–450 keV respectively.

Helium has an extremely low mass per nucleon and therefore is energetically favoured as a fusion product [12]. As with the other noble gases, helium has metastable energy levels that allow it to remain ionized in an electrical discharge with a voltage below its ionization potential. In a plasma, helium's electrons are not bound to its nucleus, resulting in very high electrical conductivity, even when the gas is only partially ionized. The charged particles are highly influenced by magnetic and electric fields.

From the series of the experiments carried out we can assume that the thermoluminescence phenomena using TLD-500 is the best technique for dose assessment. Moreover, aluminum oxide is considered as a point detector as well as a stimulated tissue equivalent material. The results obtained using TLDs readout are better than the film badge for the determination of the X-ray doses in the region of interest.

The integrated conversion efficiency η of the incident electron kinetic energy into continuum X-ray energy is [13]

$$\eta = 1.1 * 10^{-9} ZV,$$

where Z is the atomic number of the target material and V is the voltage by which the electrons are accelerated. For $V = 15$ kV, $\eta = 0.043\%$ at $Z = 26$ (Fe).

4. Conclusion

A bulk of radiation would be continuum emitted either from the hot plasma or from the anode tip through thick target bremsstrahlung radiation. The integrated conversion efficiency of the incident electron kinetic energy into continuum X-ray energy depends on the atomic number of the target material and the voltage through which the electrons are accelerated. For 15 kV charging voltage and 0.1 Torr helium gas pressure, the conversion efficiency is estimated to be about 0.043% with a photon energy limit of 12 keV.

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