Detection of X-ray from Micro-Focus Plasma (0.1kJ)

G.M.El-Aragi

Plasma Dept., Nuclear Research Center, EAEA, P.O. Box 13759 Cairo, Egypt

E-mail contact of main author: elaragi@gmail.com

Abstract. The X-ray emission was studied from low energy (112.5J) plasma focus device powered by a 1 μF single capacitor charged at 15 kV giving maximum discharge current of about 5 kA. The experiment was carried out on a conventional Mather-type plasma focus system and high density plasma was generated by an electrical discharge in helium gas between coaxial electrodes configuration. The X-ray emission was investigated using time-integrated and time-resolved detectors. Time- integrated X-ray pinhole images (side on) of the focus region at optimum pressure indicate a pinched volume roughly 8-10 mm in length. Time-resolved X-ray emission profile using pin-diode with suitable absorption filter has pulse width (FWHM) ~ 100 ns.

Introduction

The dense plasma focus device is a source of X-rays, neutrons, and beams of electrons and ions. Because of its high X-ray yield, plasma focus appears to be a promising device for X-ray generation with enhanced efficiency. When energetic particles interact with matter, electromagnetic radiations are emitted. In a dense plasma focus, the energetic electron and ions interact with each other as well as with the electrodes.

Hussain et al. [1] studied soft X-ray yield from plasma focus with 9 μF capacitor bank charged to 20 kV. With the hydrogen filling gas a total soft X-ray yield of 27.3 J per shot in 4π steradians was reported which corresponds to 1.52 % wall plug efficiency.

A large fraction of this X-ray emission is due to energetic electron bombarding the gun anode, as observed in previous work [2]. The physical process for such an interaction is known as thick-target bremsstrahlung, The radiation pattern from the interaction of electron with thick target is different from that due to thin –target interaction. A target is considered to be thin when it consists of only a few layers of atoms. The emission of these radiations from DPF depends upon many factors i.e. nature of the gas, pressure of the gas, operating voltage, capacitor bank energy and etc.

The intense x-ray pulses produced by focalized electron bremsstralung are excellent candidates for radiography of moving and soft objects [7-8] and for microelectronic lithography [3].

The aim from this work is to investigate X-rays emission in a low energy Mather type plasma focus (112.5 J) using X-ray detectors.

1. Experimental

Mather-type 112.5 J plasma focus device consists of an outer electrode, which is formed of eight copper rods, each of 130 mm length and 10 mm diameters as shown in figure 1. The outer diameter of center electrode is 18 mm and inner diameter of squirrel cage (outer electrode) is 55 mm.

A hole of 5 mm diameter and 8 mm depth was drilled in the front of the inner electrode in which different metals were filled. The cylindrical insulator ring is of 130 mm diameter and 35 mm thickness. The electrode system is enclosed in a vacuum chamber made of stainless steel tank of 350 mm length and 100 mm diameter which may evacuated up to 10^{-4} mbar. There are several ports in the vacuum chamber for diagnostic purposes. The condenser bank of plasma focus device consists of one condenser of 25 kV and 1 μF low inductance condenser. A capacitor bank charged at 15 kV (112.5 J), giving peak discharge current of about 5 kA, powered the focus device.

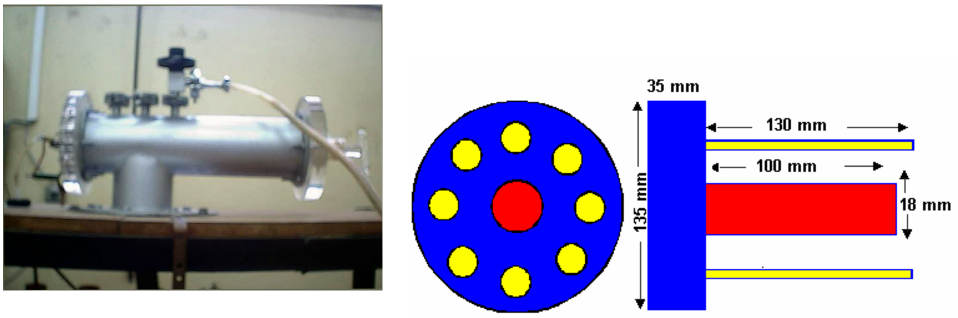

FIG. 1. Photograph of plasma focus head and schematic diagram of the construction details of plasma focus electrodes set-up. Right part shows the horizontal cross-section, while the left part shows the vertical cross-section.

The inner electrode is connected to the positive connection of high voltage supply via a triggertron-type vacuum tube (CX1159) served as a switch, whereas the outer electrode is grounded.
The vacuum chamber was evacuated up to 10^{-2} mbar pressure by a rotary pump (Edwards single stage model 1 Sc.-150B) before filling gas (helium). To avoid vapor from back streaming, the vacuum chamber is washed by gas after evacuation by rotary pump. The gas was fed into the system via flow meter (OMEGA model). The circuit diagram of trigger pulse for plasma discharge is shown in Fig. 2.

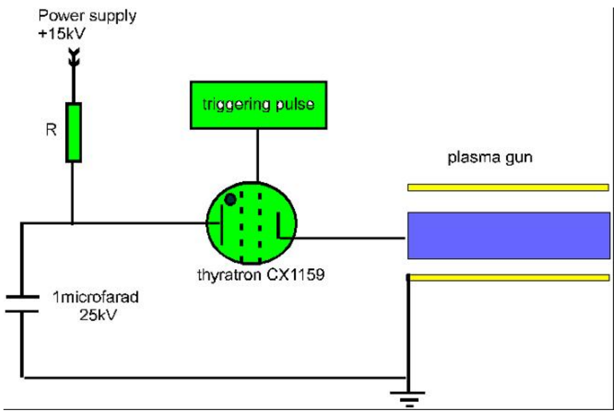

FIG. 2 The circuit diagram of trigger pulse

Time resolved X-ray emission was monitored by a pin-diode BPYP-44 with slight modification. The glass cover of the diode was removed and different thickness aluminum foils were used to screen the visible plasma light.
The pin-diodes were placed in the side on direction from the anode axis. For each measurement at different filling pressures several pulses (shots) were recorded using high voltage probe, Rogowski coil with pin diode masked with aluminum filter.
The applied voltage to and the discharge current through the discharge chamber were measured using a voltage divider (Home made), 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 a 200-MHz bandwidth.
The peak value of the discharge current was measured is approximately 5 kA during the pulse. Figure (3) shows the current, current derivative and voltage waveforms that characterized the pulsed low energy plasma focus device. Current, current derivative and voltage were measured as a function of time at an input energy of 112.5 J (maximum applied voltage 15kV) and helium pressure of 0.1 mbar.

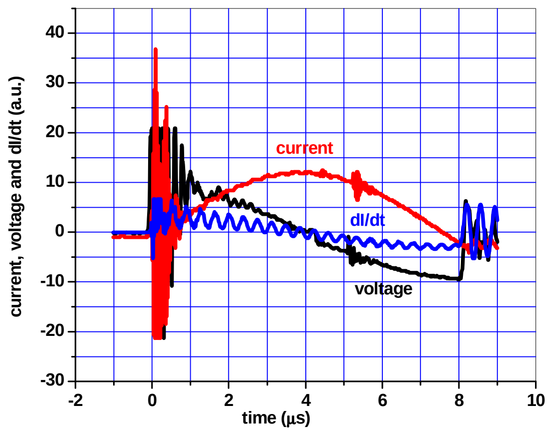

FIG. 3 Discharge current (red), voltage (black) and current dervative (blue) signals from the plasma device.

2. Results and Discussion

The diagnostic instrumentation employed in this work included a Rogowski coil, a voltage divider, time-resolved and time- integrated of x-ray
In order to measure the high-voltage pulses associated with the plasma discharges, a voltage divider was required to attenuate the magnitude of such pulses to a value safe enough for the oscilloscope on which the voltage waveforms are displayed. High-voltage resistive divider is commonly used because of their easy design and fabrication. A wide band voltage probe for work below 100 kV was reported by Keller [4]. In our application, the transient voltage across

the plasma was measured using a resistive voltage probe. This probe was connected at the lower end of the focus tube across the anode and cathode (input) flanges.
Various factors like voltage, pressure, inductance and capacitance affect the formation of a focus. These parameters were adjusted to obtain the focus while a Rogowski coil and resistive divider were used to measure the current and the voltage waveforms of the discharge, respectively. Figure (3) shows the current, voltage and current dervative waveforms of the plasma focus, operating at 0.1 Torr pressure (helium gas) and at 15 kV.
Photochemistry, in the form of photographic films, is one of the oldest and most common methods used in the detection of X-rays. It is essentially a two step process; the creation of a latent image by the x-ray photon and subsequent development of these activated sites. The common X-ray film uses a sliver halide emulsion embedded in gelatin on a substrate. It is sensitive medium for capturing and recording x-ray photons and possesses very high gain. The sensitivities vary between films from different manufacturers but lie in the range between 10^6 photons/cm^2 to 10^{10} photons/cm^2 for photons in the keV range for the common Kodak DEF film.
The side-on X-ray pinhole image of the pinched plasma in the case of solid anode had an appearance of a thin diffused column 8-10 mm long as shown in figure (4). The densitometric traces shown in the same figure gave a lineout of the side-on image obtained with 250 μm diameter aperture masked by Al (10 μm) filter at 0.1 torr helium filling.

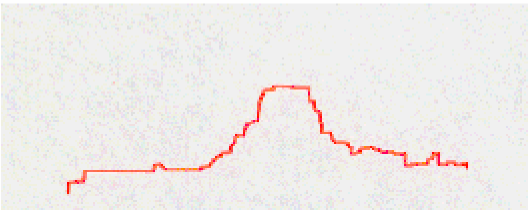
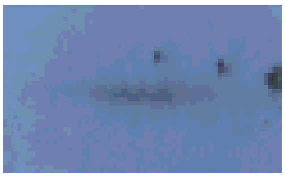

FIG. 4 X-ray pinhole image (side on) and lineout trace.

Solid state semiconductors have several advantages over other radiation detectors for X-rays. These advantages are [5, 6]:
Higher resolution because the photon energy required producing an ion-electron pair is much lower than that for other detectors, linear response over a larger energy range, faster pulse rise time, relative simplicity and convenient size, higher density which enables them to stop energies.
In the energy range between a few keV to 50 MeV, most of the interactions of X-rays with matter are due to one of the three processes: photoelectric effect, Compton effect and pair production. At energy below 50 keV, photoelectric effect predominates. In this process, a photon gives all its energy to a bound electron, which uses part of the energy to overcome it's binding to the atom and takes the rest as kinetic energy. The electron–hole pair generated is then collected by an applied electric field across the p-n junction of the semiconductor, and an electrical pulse is obtained proportional to the energy lost by the photon [7,8].

In plasma experiments the photodiodes must work in vacuum to avoid X-ray absorption by air. The photodiodes are also screened against light emitted from plasma. It can be work in time resolved and time integrated modes of operation. In the first mode it simply works on 50-ohm resistor, which is placed near the oscilloscope. Only part of incident X-ray penetrates through dead layer and is absorbed inside the active layer.
The energy conversion from absorbed X-ray into charge independent on energy of quanta. The total energy response function is a product of absorption and transmission functions. The

$$Q = 0.27 S\eta \int_0^\infty \int_{dt} F(E_x,t) R(E_x) dE_x dt$$

charge, which has been generated during x-ray pulse, is given by [9]

Where $F(E_x,t)$ is x-ray energy influence J/cm^2

E_x is x-ray quanta energy
$R(E_x)$ is x-ray response function
S is area of detection surface

η is efficiency of charge collection is function to be determined in measurements.
Soft X-ray emission from the focus plasma using different gases has been studied using pin-diode with differente filtering. The characteristic of the X-ray emission varies consideriably from shot to shot and depend crucially on the gas pressure. In general, there are two sources of soft X-rays. One source is the cylinderical pinch column located above the anode. The second source of soft X-rays arises from electron beam activity on the iron anode and the vaporized anode material above the anode surface. The relative contrbution from the two sources of X-rays depend crucially on the gas pressure.
The silicon detectors and the filters used in this experiment were not calibrated on an absolute scale. Therefore, only the relative magnitudes of the X-ray emissions were measured and compared. Because of the fast response of the semiconductors and oscilloscope used, the time-resolved X-ray pulses could be measured without the RC integrator. A typical Rogwski coil trace together with pin-diode signal (4 μm aluminum filter) is shown in Fig. 5. The oscillogram of diode X-ray signal indicates that the peak having a full width at half maximum around 100 ns.

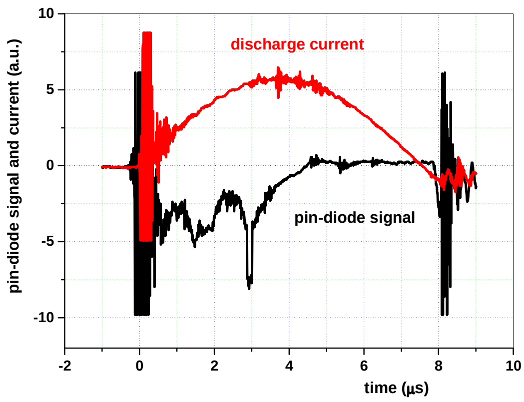

FIG. 5. Oscillogram of a typical x-ray signal using PIN detector (black) and Rogowski coil signal (red) at 0.1 torr of helium

The relative X-ray output from a dense plasma focus is plotted versus the voltage of the capacitor bank in Fig. 6. These data were taken with a silicon detector with a 4 μm aluminum window (see Fig. 7), the operating voltage was 15 kV and helium gas pressure was 0.1 torr.

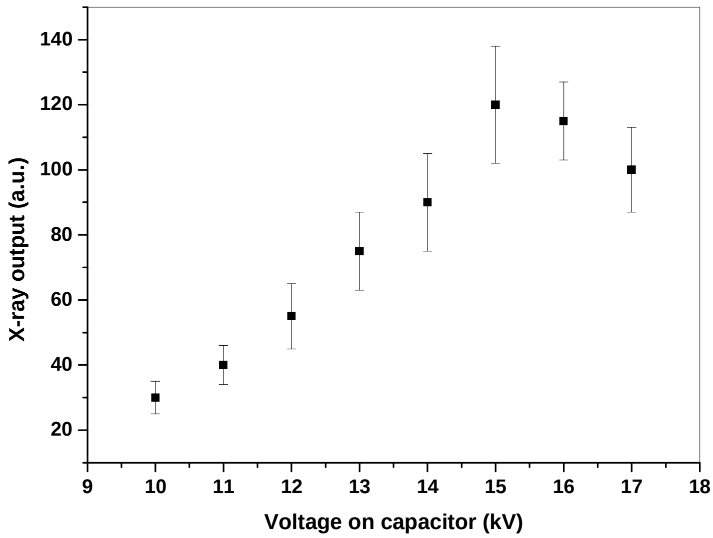

FIG. 6 The relative X-ray output from a dense plasma focus is plotted versus the voltage of the capacitor bank.

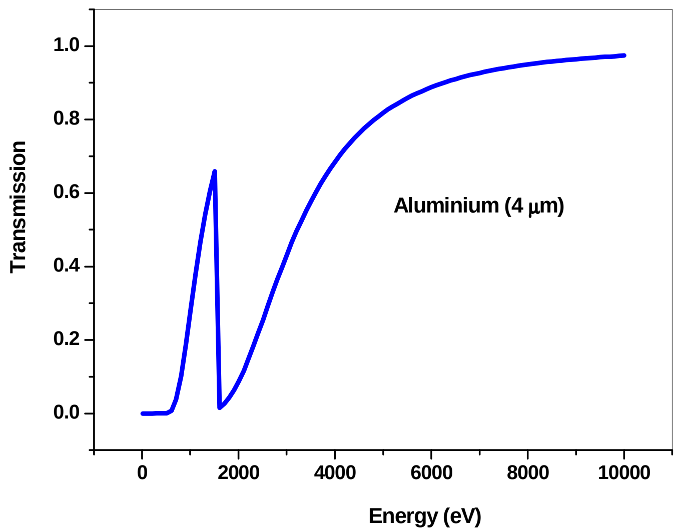

FIG. 7 Transmission curve of aluminum filters (4 μm) used.

The graph shows an increase of the total X-ray output with the voltage of the capacitor bank up to 15 kV and decrease again. The relative output magnitude increases from 30 units at 10 kV up to 120 units at 15 kV (the increase factor is 4). On the other hand, the relative output magnitude decreases from 120 units at 15 kV up to 100 units at 17 kV (the decrease factor is 0.83). This non-linear relation between the total X-ray output with the voltage of the capacitor bank may be indicate that the good focusing occur at specific conditions such as gas pressure, operating voltage and the dimensions of the system.

The integrated conversion efficiency η of the incident electron kinetic energy into continuum X-ray energy is [10].

$$\eta = 1.1 * 10^{-9} Z V$$

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

If the focus machine in this experiment converts 0.043 percent of the bank energy, then the total X-ray emissions at 10 kV and 15 kV are 0.02 J and 0.048 J respectively, and the increase factor will be 2.4 which are about half the measured value of 4. The discrepancy is due to two factors: the anisotropic distribution of the X-ray radiation and the variation of the X-ray spectrum with the operating voltage. The distribution of the X-ray emission from the focus device is anisotropic and the pattern varies with the operating voltage. The radiation distribution is a strong function of the acceleration of charged particles which is, in turn, affected by the electric field in the focus region. The X-ray spectrum also changes with the operating voltage. At higher voltages, more hard X-rays are produced because more charged particles are accelerated to higher energies. At lower voltages more X-rays are produced by thermal bremsstrhlung and result in the soft region.

The variation of the X-ray emission in certain energy window (4 μm aluminum filter) versus helium filling pressure within 0.05-3 torr pressure range is presented in Fig. 8. The error bars correspond to standard error. The highest X-ray emission is recorded at a filling pressure of 0.1 torr, for total discharge energy of 112.5 J.

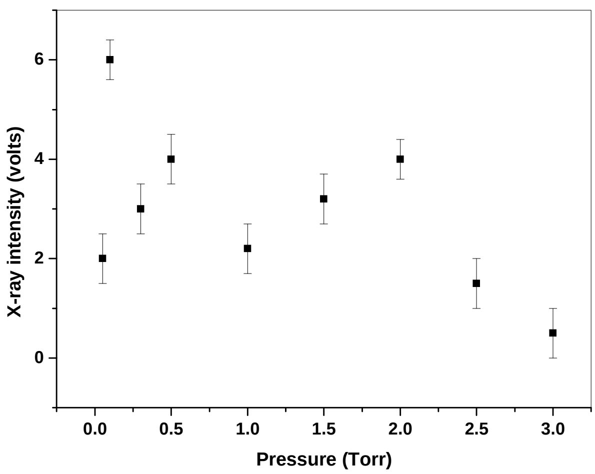

FIG. 8 The variation of the X-ray emission versus helium filling pressure within 0.05-3 torr pressure range

Conclusions

The X-ray emission in a low energy (112.5 J) Mather-type plasma focus was investigated by employing time-integrated pin-hole camera and time-resolved detector. The intense X-ray emission was observed within a narrow pressure range of 0.05-3 torr helium filling for total discharge energy of 112.5 J. This focus machine converts 0.043 percent of the bank energy, i.e. the total energy of X-ray emissions at 15 kV was 0.048 J.

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