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X-rays emission from a compact diode energized by capacitor discharge

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Abstract. X-ray emission from a compact diode consisting of a sharp edged cathode and flat anode of copper and lead, energized by simple capacitor discharge is reported. With a sewing machine needle cathode, and lead target, the generation efficiency upto 0.4% is obtained. The efficiency is expected to enhance further with the increase in discharge energy, charging voltage and reducing the parasitic inductance.

PACS. 52.70.La X-ray and gamma-ray measurements – 52.80.Vp Discharge in vacuum

1 Introduction

During the last few decades attention has been paid for the development of flash X-ray sources, due to their extensive potential applications. These sources play an important role in the investigation of high speed phenomenon, biomedical radiography, preionization of high pressure gas discharge laser, and more recently, in the photoexcitation of molecules and atomic systems for fluorescence studies and time resolved X-ray diffraction studies [1–3]. Presently available systems are large, complex and expensive so the challenge is to develop the systems at high repetition rates and also emitting a high dose of X-rays per shot, with energy range from a few keV to a few hundred keV, in order to minimize cost and maintenance. The generation of short X-ray pulses at high repetition rates seems to be very attractive, if obtained with a device of laboratory scale. A conventional X-ray diode operates in vacuum with closely spaced electrodes that are powered with a high voltage power discharge [4,5]. Short pulse interactions with solid target plasmas have been of great interest as these represent a unique, high brightness source of X-rays [6]. The bombardment of the electrons on the solid target is the most important practical method of generation of X-rays [7]. When suitable potential is applied, the thermionically emitted electrons are accelerated and then directed to some target. The X-ray emitting diode employing field emission instead of thermionic emission may also be attempted to operate. A Compact Electron Radiation Emission Source (CERES), operated by a Blumlein-type driver is the example of such a source.

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Zakaullah and Worley [8] studied the X-ray emitting diode having the impedance of 2.3 Ω with knife-edge cathode. The diode was energized by 90 kV, 30 J solid dielectric Blumlein driver having pulse length of 10 ns. Different materials such that titanium, copper, tin and lead were used as a target in the experiment. They concluded that it may be used as characteristics or continuum radiation source of choice, and may find applications in different disciplines like radiography, crystallography, X-ray contact microscopy and X-ray backlighting.

Khacef et al. [9] developed a compact and repetitive flash X-ray source based on cable transformer technology and that was powered by Blumlein type configuration. They found that the critical parameters, which limited the flash X-ray source performance, were mainly the pressure in the X-ray diode and the spacing between anode and cathode. The X-ray emission appeared below the threshold pressure about 0.4 mbar for most of electrode spacing. Below the characteristic pressure of about 0.05 mbar, the X-ray production efficiency was high and X-ray output remained constant. This device was able to produce the dose up to 1R per shot, measured at the output window, of X-rays between 5 and 100 keV. The pulse widths were about 20 ns and the maximum repetition rate was about 60 Hz.

Pouvesle et al. [10] drove X-ray diodes by repetitively pulsed Blumlein which were able to deliver high dose rates of X-rays in pulses of nanosecond duration. They showed that the dependence of X-ray dose per pulse and the duration of the out put pulse, are functions of the residual gas pressure in the X-ray diode. Of great significance was the pronounced threshold of the dose emitted as the pressure was reduced. It occurred near 0.06 mbar for most of the electrode spacing. However, it was seen that a base pressure of only one half of the threshold value was sufficient to stabilize the efficiency for the production of the X-rays at a value to which little significant improvement could be realized with even better pumping speed of the vacuum system. They also reported that an increase in duration of the out put pulse of X-rays by nearly a factor of 2 was realized with the improved evacuation of the diode. However, in this case the pulse duration continued to lengthen as residual pressure was reduced below the threshold, but at the expense of the peak intensity since the dose per pulse remained constant at the lower pressure. This was a consequence of the more subtle variations of the time dependence of the collapse of the diode impedance as conductive material was evaporated from anode into the inter-electrode gap.

Coogan et al. [11] developed various devices based around Blumlein technology. These devices were able to emit average powers of radiation nearly equal to 1 kR/min having photon energy 300 keV and charged up to 70 kV. These systems exhibited repetition rates up to 100 Hz and generated X-ray fluxes with pulse widths of the order of few tens of nanoseconds. The characteristics of these devices were very attractive but their size remained relatively large.

Bradley et al. [12] fabricated a flash X-ray source having 20 ns pulse width and 1.5 keV and 4.5 keV X-rays. This source was used to examine the plasma-driven shutter for the Nova Fusion Laser System. It was used to characterize plasma moving at 1–5 cm/μs with real densities down to 0.1 mg/cm^2 and a spatial resolution of 2.5 μm.

Johnson et al. [13] developed a flash X-ray tube and that was driven by Blumlein pulse generator to peak voltages 60–80 kV and peak anode currents 8–10 kA. The pulse width depended upon the anode-cathode spacing and was made $\sim$80 ns wide, and a small spot or line focus was possible. These features made this device useful for flash X-ray diffraction studies. Current in the anode region exceeded the space charge limited values, probably because neutralization of charge by plasma ejected from the cathode during the initial phase of discharge.

Collins et al. [14] developed a flash X-ray source capable of emitting 35 mW average power in 6 ns wide pulse of radiation near 8.28 keV. From this device a significant fraction of the output was represented by the K-line of copper, so that in less than one minute of experimental time a peak spectral density was radiated. For some applications this device was able to offer a laboratory alternate to laser plasma X-rays or synchrotron radiation.

Davanloo et al. [15] developed a repetitively pulsed, flash X-ray source to yield 140 mW average power in 15 ns wide pulse of radiation near 12.43 keV. Interchangeability of discharge anodes was provided for a significant fraction of the output to be extracted in the K-lines of Cu, Mo, Nb, and Ag. For some applications this device was able to offer a tabletop alternative to laser plasma X-rays and synchrotron radiation.

Zakaullah et al. [16] operated a low-energy (2.3 kJ) plasma focus in an enhanced Cu-K$_\alpha$ line emission mode. In the side-on direction, 0.4 J/sr line radiation is recorded. In 4π-geometry, 40 J of energy is found to be emitted as X-rays out of which 8 J is in the form of Cu-K$_\alpha$. The radiation yield represents a system efficiency of 1.7% for overall X-ray emission and 0.35% for the Cu-K$_\alpha$ line. The plasma focus may find application as a radiation source in X-ray diffraction experiments.

Shafiq et al. [17] investigated K-series line radiation emission of Mo and Cu from a low energy Mather-type plasma focus. The maximum Mo and Cu K-series line emission of about 0.05 J/sr and 0.17 J/sr are observed at hydrogen filling pressure of 2.0 mbar. Total X-ray emission and efficiency in 4π-geometry are also obtained with values 4.12 J and 0.18% at 2.0 mbar.

Shafiq et al. [18] investigated the X-ray emission from a low energy (2.3 kJ) plasma focus operated with hydrogen as the filling gas. Different high Z metallic discs are inserted at the anode tip. They studied the X-ray emission in the 5–9 keV and 13–25 keV energy range. The maximum value of the total X-ray emission in 4π-geometry is found to be 29.4 ± 0.2 J, 3.43 ± 0.05 J and 4.12 ± 0.02 J with Pb, W and Mo inserted anodes, respectively, and corresponding wall plug efficiencies for X-ray generation were found 1.28%, 0.15% and 0.18%.

In this paper X-ray emission from a compact diode system energized by a 0.5 μF capacitor charged upto 30 kV is investigated. The X-ray emission is studied with Pb and Cu targets. Section 1 reviews the X-ray emission from different compact diode systems, Section 2 describes that how the filters are selected, where as Section 3 contains the details of the experimental setup. Results are presented in Section 4 while discussions and conclusions are summarized in Section 5.

2 Selection of ross filters

X-rays emitted from the compact diode may be analyzed by using the dispersive techniques, which are based on delicate equipment. However, simple spectral analysis may be conducted by using a Ross filter pair of appropriate absorbers along with detectors like PIN-diodes. When X-rays pass through different material foils, intensity of radiation is attenuated according to the relation, $I = I_0 e^{-\mu(E)t}$, where I_0 is the intensity of incident radiation flux, I is the intensity of transmitted flux, and $\mu(E)$ is the absorption coefficient of the filter. The μ is a function of energy, as the high-energy photons observe less absorption, whereas low energy photons experience high absorption. Further, the transmission of photons observes a sudden jump, when the energy of incident photons equals the ionization energy from K, L, M, etc., energy levels of the filter material. Thus every element exhibits transmission windows. This property in different elements is exploited to select a pair of filters for detecting radiation in a narrow band, which is known in the literature as Ross filters [19]. By reviewing the transmission windows of different commercially available filters, the selected Ross filter pair is Co (20 μm) and Ni (17.5 μm) for the study of Cu-K$_\alpha$ emission. We have used Quantrad

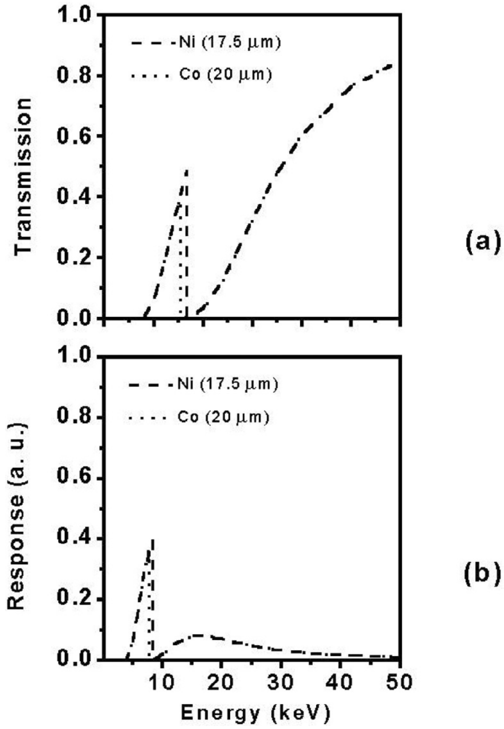

Fig. 1. (a) Transmission curves of Ni (17.5 μm) and Co (20 μm); (b) detector's (PIN-diode) response along with corresponding filters.

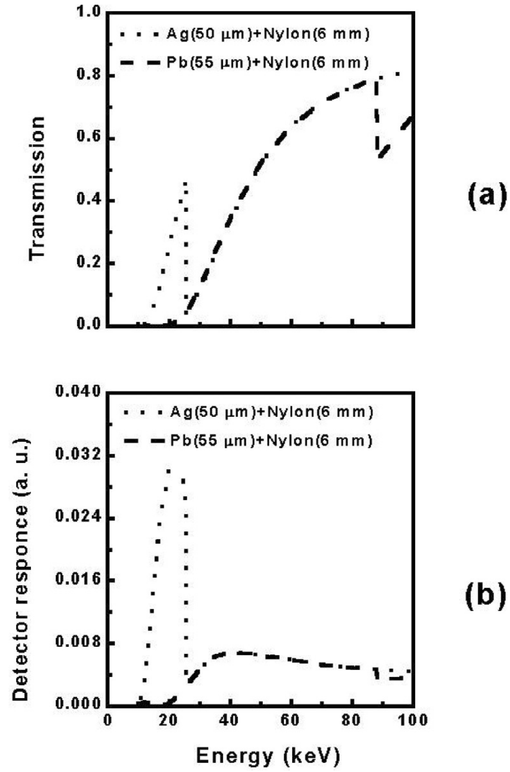

Fig. 2. (a) Transmission curves of Ag (50 μm) and Pb (55 μm); (b) detector's response along with the corresponding filters.

Si PIN-diodes of active layer thickness 125 μm. The detectors' response along with transmission characteristics of the filters is given in Figure 1. For the evaluation of curves presented in Figure 1, the data for absorption coefficients was taken from Handbook of Spectroscopy [20]. The Co filter has the absorption edge at 7.709 keV and allows transmission of X-rays in the 4–7.709 keV windows. The absorption edge of Ni lies at 8.333 keV and allows transmission of the Cu-K$_\alpha$ line of 8.047 keV. Thus the difference of transmission in the Ni and Co filters may be considered corresponding to the Cu-K$_\alpha$ line radiation. In order to study the X-rays in the energy range ~13–25 keV, for Pb inserted anode the selected pair of Ross filters is Ag (50 μm) and Pb (55 μm). The detector under Ag filter provides a window for X-rays in ~13–25 keV energy range, whereas the detector masked with Pb filter transmits X-rays whose energy exceeds from 20 keV, although the appreciable transmission is for photons of energy 25 keV. The difference between the signal intensities of the detectors masked with Ag and Pb filters provides estimate of the X-rays in the energy range ~13–25 keV. The detectors' response along with transmission characteristics of the filters is given in Figure 2.

3 Experimental setup

A schematic of the compact diode (CD) is given in Figure 3. It is comprised of a sharp edged cathode, which is a replaceable, either a piece of the razor blade or a sewing machine needle and a flat plate anode of copper having diameter of 30 mm and thickness of 10 mm. In the second experiment, the anode was engraved at the center and filled with lead. The sharp edged razor blade and sewing machine needle is replaced and surface of anode is cleaned after every five shots. The electrodes are enclosed in a cylindrical shaped nylon vacuum chamber of wall thickness 57 mm approximately. The energy storage system is a 0.5 μF, 100 kV capacitor that is charged at 30 kV. At the top of the discharge capacitor a field distortion type pressurized sparkgap, and then the compact diode is mounted. Six brass bolts tighten the cathode of the compact diode to the capacitor ground terminal coaxially, to reduce the parasitic inductance of the system. The capacitor was charged at positive polarity and the sparkgap transfers the energy directly to the anode of the compact diode. A rotary van pump was used to evacuate the system up to 10^{-2} mbar, which is found sufficient in this experiment.

As the voltage pulse is applied, high electric field between the anode and sharp edged cathode initiate the field emission. The emitted electrons are accelerated by the applied electric field and hit the anode, generating the X-rays. For the detection and measurement of the X-rays, two types of detectors are used. One is photomultiplier tube XP2020 coupled with 50 mm × 50 mm cylindrical plastic scintillator NE102A. To make the photomultiplier-scintillator light tight, it is shielded in 3 mm thick Al cylinder. This detector is positioned outside the compact

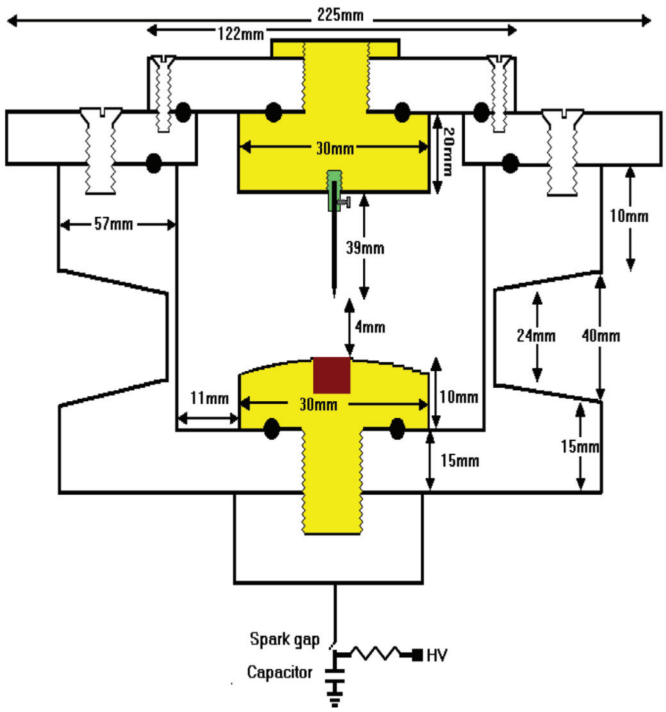

Fig. 3. The schematic diagram of the compact diode.

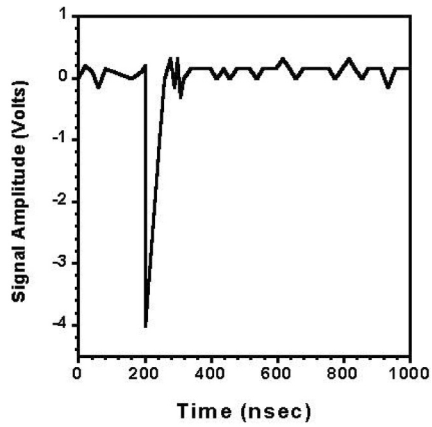

Fig. 4. A typical signal of photomultiplier tube coupled with plastic scintillators.

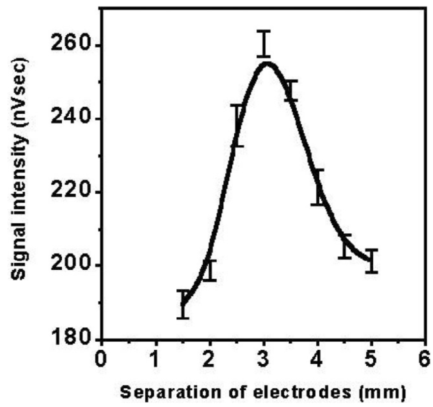

Fig. 5. Variation of signal intensity recorded by the photomultiplier tube coupled with plastic scintillator (razor cathode with Cu target) with separations of the electrodes.

diode at 170 mm from the X-ray emitting point. The X-rays have to pass about 6 mm thick nylon chamber body beside 3 mm thick Al shield before entering the plastic scintillator. It is estimated that the X-ray photons that succeed in arriving at the scintillator are of energy exceeding 20 keV. Two identical Quantrad PIN-diodes of 125 μm intrinsic silicon layer thickness covered with appropriate Ross filters are also used to study the X-ray emission in different energy windows. To record the different electrical signals, a four channel 200 MHz Gould 4074A digital storage oscilloscope was used and then the data was transferred to the computer through GPIB 488.2 port.

4 Experimental results

The peak discharge current calculated from the Rogowski coil signal is about 35 ± 2 kA and the total parasitic inductance of system (including capacitor, sparkgap, the compact diode and return current path) is 353 ± 15 nH.

4.1 Copper anode – razor cathode

The first experiment was conducted with the razor blade piece, as the cathode. Different widths of the razor blade as knife-edge cathode were tried and 2 mm was found most appropriate in this experiment. A typical PMT signal is presented in Figure 4, which shows that the X-ray pulse width (FWHM) is 35 ± 2 ns. The pulse is recorded 200 ± 10 ns after the application of high voltage. The internal transit time of the PMT is 28 ns. Therefore, one concludes that the X-ray emission is about 170 ns after the application of high voltage. There is a small dip in the current waveform of the Rogowski coil, which synchronizes with the PMT signal. This observation reveals that the discharge in the compact diode undergoes Z-pinch type compression. Figure 5 represents the variation of average signal intensity with the separation of electrodes. It is found that the average signal intensity recorded by PMT attains its maximum value at 3 mm inter-electrode separation.

The variation of X-rays signal intensity recorded by PIN-diodes masked with Ni (17.5 μm) and Co (20 μm) with inter-electrode separation is depicted in Figure 6. Each data point in these curves corresponds to an average of five shots. The average X-ray signal intensity increases with increasing separation of electrodes and becomes highest at separation of 3 mm. When the separation of electrodes is increased beyond 3 mm, the X-ray signal intensity drops.

The method to estimate X-ray emission in a certain energy window has been described elsewhere in detail [21]. The variation of Cu-K$_\alpha$ emission as a function of separation of the electrodes is described in Figure 7. The highest Cu-K$_\alpha$ yield in 4π-geometry, which is recorded at a separation of 3 mm, is 8.4 ± 0.4 mJ and the

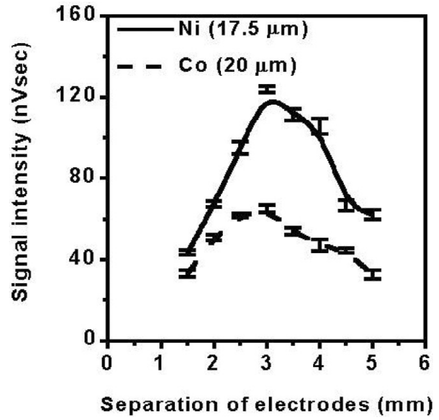

Fig. 6. Signal intensity recorded by PIN-diodes masked with Ni (17.5 μm) and Co (20 μm) for various separations of the electrodes.

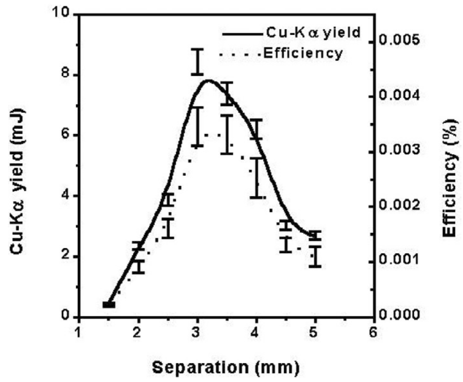

Fig. 7. Variation of Cu-K$_\alpha$ emission and efficiency versus separation of the electrodes (razor cathode with Cu target).

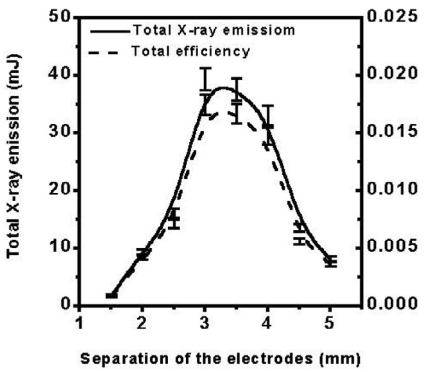

Fig. 8. Total X-ray emission and total efficiency versus Separations of the electrodes (razor cathode with Cu target).

corresponding efficiency is 0.004%. Figure 8 shows the variation of total X-ray emission and efficiency against the separation of electrodes. Maximum X-ray emission and wall plug efficiency in 4π-geometry for inter-electrode separation of 3 mm and for 2 mm wide razor blade (cathode) is 39 ± 2 mJ and 0.02%. This small yield is speculated due to the high parasitic inductance of the system.

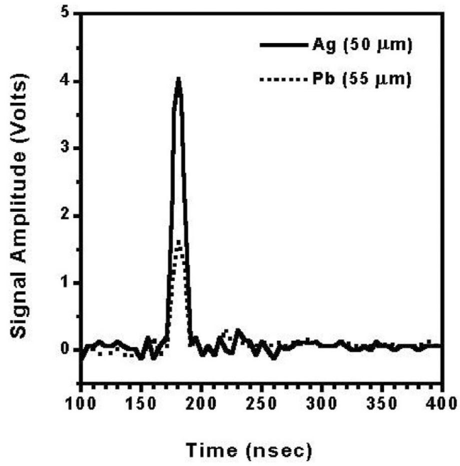

Fig. 9. Typical oscillogram of PIN-diode signals with Ag (50 μm) and Pb (55 μm) filters (needle cathode with lead target).

4.2 Lead anode – needle cathode

The second experiment was conducted with lead anode. A sewing machine needle was used as a cathode. Typical signals recorded by the PIN diodes masked with Ag (50 μm) and Pb (55 μm) filter pair are shown in Figure 9. The PIN-diodes were mounted at the 6 mm thick nylon window. The transmission curves of the filters plus 6 mm thick nylon window and response of the detectors is presented in Figure 2. The variation of average signal intensity recorded by PIN-diodes and PMT with separation of electrodes is shown in Figure 10. For both detector systems the average signal intensity is maximum at 4 mm inter-electrode spacing.

The X-ray emission in 13–25 keV window is presented in Figure 11. The maximum X-ray emission in the above stated energy window is found to be 535 ± 26 mJ at the separation of 4 mm and the corresponding system efficiency is about 0.24%. Figure 12 shows the total X-ray emission in the 4π-geometry and total efficiency for various separations of the electrodes. At 4 mm inter-electrodes separation, the total estimated yield is about 940 ± 46 mJ and the total X-ray generation efficiency is about 0.4%.

5 Discussions and conclusion

A simple configuration of compact diode energized by capacitor discharge is studied for X-ray generation. The cathode is made sharp edged to facilitate the electron emission due to strong electric field. In different experiments, pieces of razor blade and sewing machine needles are used. When separation of electrodes is reduced, the X-ray emission increases, and an optimum separation is obtained. When the separation is reduced further, the radiation emission decreases. The decrease in the X-ray emission for separation of the electrodes other than optimum value may be due to following reasons. When the separation of electrodes is reduced, the electrons may

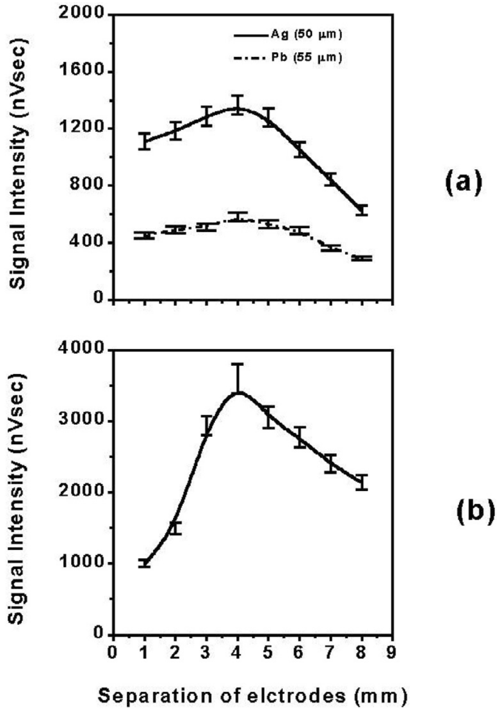

Fig. 10. Signal intensity versus separation of the electrodes (needle cathode with lead target) recorded by (a) PIN-diodes masked with Ag (50 μm) and Pb (55 μm); (b) photomultiplier tube coupled with plastic scintillator.

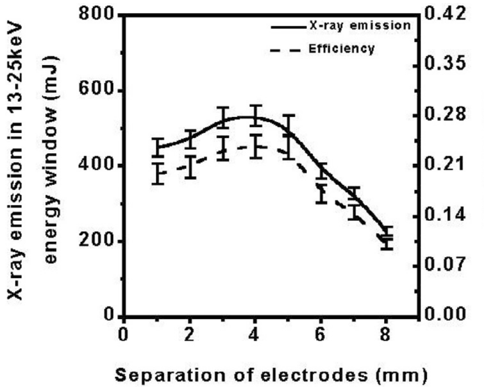

Fig. 11. The X-ray emission and efficiency in 13–25 keV energy window versus separation of the electrodes (needle cathode with lead target).

penetrate deeper into the target, which may cause enhanced self-absorption of X-rays and hence reduced emission. When the separation of electrodes is increased, that offers the reduced electric field for the field emission and hence lowers X-ray emission.

The X-ray generation efficiency with razor cathode and copper anode is 0.02%. It increases by an order of magnitude to 0.4% when needle cathode – lead anode is used. If one compare the radiation emission for Cu target with the case of lead target, the radiation emission is much higher for lead. Same behavior is observed in entirely different systems, [8,22] a compact diode operated by a 30 J

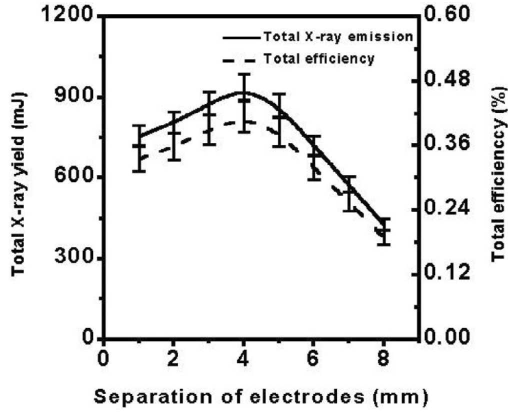

Fig. 12. Total X-ray emission and efficiency versus separations of the electrodes (needle cathode with lead target).

Blumlein driver, [8] and a plasma focus with lead insert at the anode tip [22]. That is, the X-ray generation from lead target is much higher and more reproducible than other targets.

In conclusion, X-ray emission from a simple configuration of compact diode consisting of a sharp edged cathode and flat plate anode is investigated. The generation efficiency of about 0.4% is obtained for needle cathode – lead anode, which is expected to increase further with the increase in working voltage.

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