Pramana – J. Phys. (2016) 87: 6
DOI 10.1007/s12043-016-1224-8

Experimental study of soft X-ray intensity with different anode tips in Amirkabir plasma focus device

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MS received 1 July 2015; revised 12 August 2015; accepted 1 October 2015; published online 15 June 2016

Abstract. To study the effect of different anode tip geometries on the intensity of soft X-rays emitted from a 4 kJ plasma focus device (PFD), we considered five different anode tips which were cylindrical-flat, cylindrical-hollow, spherical-convex, cone-flat and cone-hollow tips. BPX-65 PIN diodes covered by four different filters are used to register the intensity of soft X-rays. The use of cone-flat anode tip has augmented the emitted X-ray three times compared to the conventional cylindrical-flat anode.

Keywords. Plasma focus; soft X-ray; PIN diode; anode tip.

PACS No. 52.58.Lq

1. Introduction

In a plasma focus device (PFD), the electrical energy of the capacitor bank (of order 1 kJ–1 MJ) is converted to the magnetic energy behind the current layer. This current layer is focussed at the tip of the anode by the Lorentz force and forms a short-lived (10–100 ns), high-temperature (0.1–2.0 keV) and high-density (10^{18}–10^{20} cm^{-3}) plasma column [1,2]. As shown in figure 1, due to the Lorentz force, while the current sheath reaches the anode's end, it slips off and is rapidly compressed to create a focussed plasma column. The device operated with different gases has been used as X-ray source for a variety of applications such as X-ray microscopy [3], imaging of thin biological samples [4], X-ray backlighting [5] and X-ray lithography [6]. Besides making this device useful for many applications, the X-ray emitted also can be used for investigating fundamental process in the plasma. It is well known that electron–ion interaction processes such as bremsstrahlung radiation, recombination emission and line emission are responsible for the emission of X-rays from the hot and dense plasma column [7].

The radiation spectrum of X-rays by a PFD covers a range of 1 keV–0.5 MeV, in a time span of a few to a few hundred nanoseconds [6]. Three main sources of X-ray emission are present during focus evolution [8]. The first is a soft X-ray emission in the focussed plasma column where X-rays are emitted by electron bremsstrahlung. This emission is characterized by a low-energy spectrum (a few keV) and is associated with thermal processes. The second, a hard X-ray emission, results from the electron collisions of the centre electrode by electron beams axially emitted from the focus. The spectra of these electrons cover a wide range of energy (several hundred keV) and due to such high energies, these emissions are considered to be originated from non-thermal processes. A third source of X-ray generation is related to line emission of K series in elements of high atomic numbers. This is observed in both the plasma column and in the anode region, where the electron beams collide with the surface of the anode tips.

Zakaullah *et al* [9] studied X-ray intensities from a 2.3 kJ PFD with three different anode tips which were cone-shaped, tapered and cylindrical flat ends. They found that the appropriate tapering of anode end causes a three-fold enhancement of emission of X-rays. Hussain *et al* [10] reported X-ray emission from a 5.3 kJ energy PFD with different inserts (Cu, Mo, W and Pb) at the anode tip. At optimum conditions, the maximum X-ray yield was found with Cu, Mo, W and Pb inserted anodes, respectively. Mohammadi *et al* [11] studied the X-ray emission from a 3.3 kJ PFD by using three different anode tips – flat, spherical and tapered. The maximum soft X-ray yield for the flat anode was about 0.4 J, whereas for hemispherical and tapered anodes it was almost halved. In this paper, the effect of five different anode tips on the intensity of soft X-ray emitted from a 4 kJ PFD is studied by using four filtered PIN diodes.

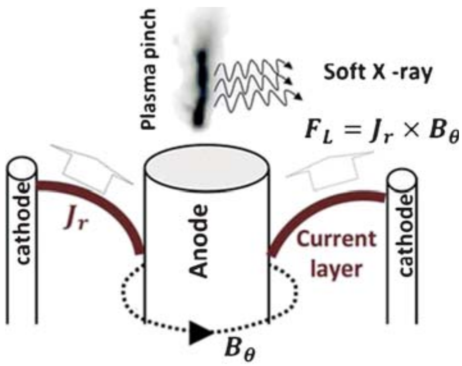


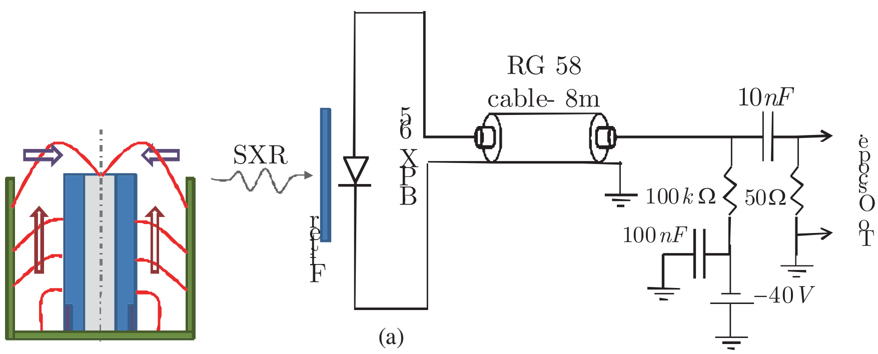
Figure 1. Plasma pinch formation and soft X-ray emission from a PFD.

Table 1. An array of four PIN diodes masked with Al−Mylar 12-24-150 μm and Cu 10 μm.

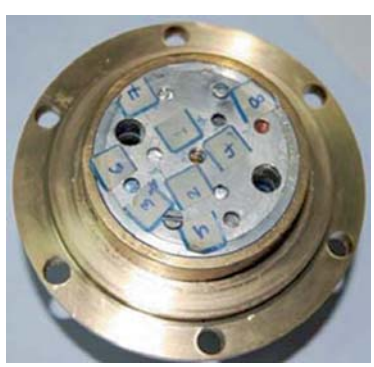
PIN Diode	Filter	Thickness (μm)
1	Al+Mylar	12
2	Al+Mylar	24
3	Al+Mylar	150
4	Cu	10

2. The PFD device and filtered PIN diodes

The experiments are performed in a 4 kJ Mather-type PFD (APF device), which is powered by a 40 μf capacitor, operating at 13 kV. The APF device consists of a central solid copper anode of 148 mm length and 20 mm diameter, and a cathode consisting of six 9 mm copper rods arranged in a circle of 44 mm diameter [12,13]. To reduce the impurity effect, after every five shots, the previous gas is purged and fresh nitrogen gas is filled. We used an array of 4-channel BPX-65 PIN diodes along with suitable absorption filters to obtain information about the soft X-ray intensity [14]. The attenuating filters used in five channels were Al + Mylar and Cu, with the thickness of each of them given in table 1. The PIN diodes are arranged in radial position at a distance of 22 cm from the anode axis. The bias circuit of the diodes is depicted in figure 2 and as can be seen, the PIN diodes are reverse biased at −40 V. The PIN diode sensitivity curves along with these eight filters are plotted in figure 3. The PIN diodes which are covered with Al−Mylar 150 and Cu 10 μm filters have a maximum sensitivity of 4.8 keV and 6.3 keV, respectively. The maximum sensitivity



(a)



(b)

Figure 2. BPX-65 PIN diodes: (**a**) Biasing circuit and (**b**) four-channel filtered PIN diodes array.

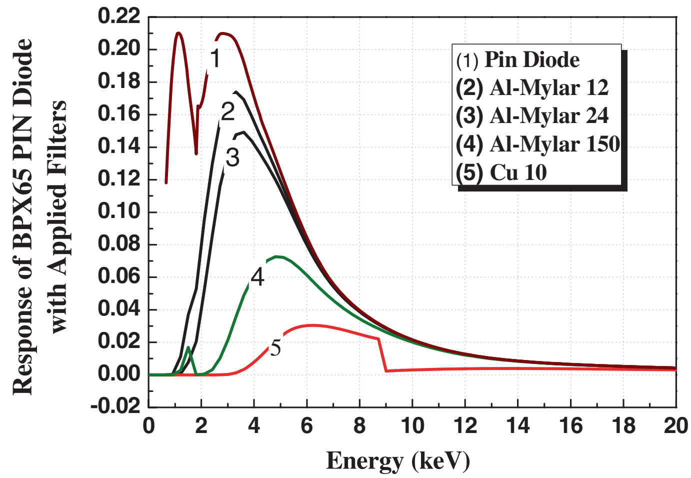


Figure 3. BPX-65 PIN photodiode response using different filters.

Figure 4. Different types of anode inserts in this study (right to left): cylindrical with flat top, cylindrical with hollow top, spherical with convex top, cone with flat top, and cone with hollow top.

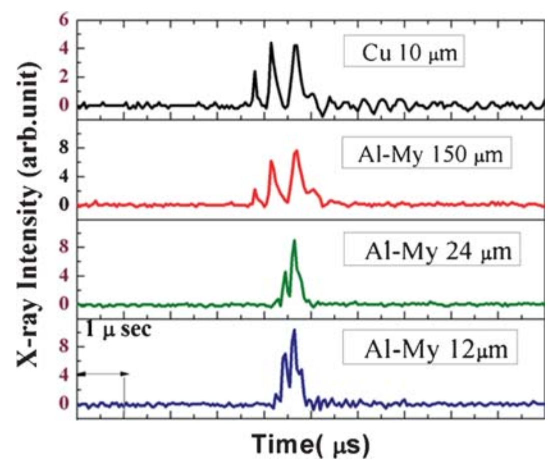


Figure 5. Typical signals of PIN diodes with different filters for cone-flat anode tip under 13 kV discharge and 4 mbar pressure.

of a detector folded in Al + Mylar 12 and 24 μm are 3.3 and 3.6 keV respectively. The sensitivity curves of figure 3 show that the signals from all channels must be almost the same for Cu-kα line radiation.

To study the effect of anode tips on X-ray intensity, as shown in figure 4, five different geometries, i.e., cylindrical with flat top, cylindrical with hollow top, spherical with convex top, cone with flat top and cone with hollow top are chosen. It should also be mentioned that while the total length of the anode is 14.8 cm, the effective length of all these tips is 3.3 cm.

A four-channel 200 MHz TDS 2024 oscilloscope is used to record the soft X-ray signals. The peak detection and integration of the data was performed by using the SAP-ALCOR 9.20 software which has been developed in the Amirkabir Fusion Laboratory [8].

3. Experimental results

The experiments were performed in the APF device filled with nitrogen gas in a pressure range of 2–7.5 mbar at a voltage of 13 kV. The nitrogen filling pressure range was scanned and five shots were recorded for each selected pressure value. The typical recorded

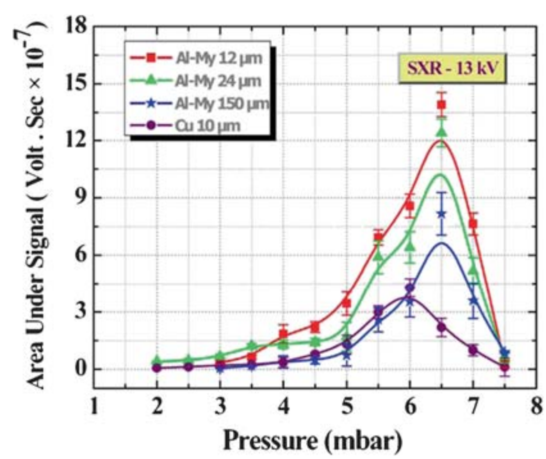


Figure 6. Soft X-ray intensity vs. pressure for different filtered PIN diodes vs. pressure at 13 kV voltage for cylindrical-flat anode tip.

PIN diode signals for cone-flat anode are shown in figure 5. For the conventional cylindrical flat-end anode, the variation of X-ray intensity vs. pressure is shown in figure 6 in which each point of the curves is the representative of averaged areas under recorded signals. The change in soft X-ray intensity resulted from different anode tips with respect to pressure is plotted in figure 7. As can be seen in the graphs of figure 7, the SXR intensity shows similar trend of increasing to a maximum at the optimum pressure followed by a decrease, and optimum pressures are different for different anode tips.

They obviously show that the optimum pressure, in which the highest intensity is obtained, depends on the inserted anode tip. The value of these highest intensities at the exemplary discharge voltage of 13 kV is presented in table 2 to give more quantitative aspect. The values are also normalized to the cylindrical-flat anode which is commonly used in most PFDs.

On the basis of results, conical or spherical anode tips exhibit a considerable increase in emitted X-ray compared with conventional cylindrical anodes. The X-ray intensities are seen to be maximum for the cone-flat anode, while it is the lowest in the

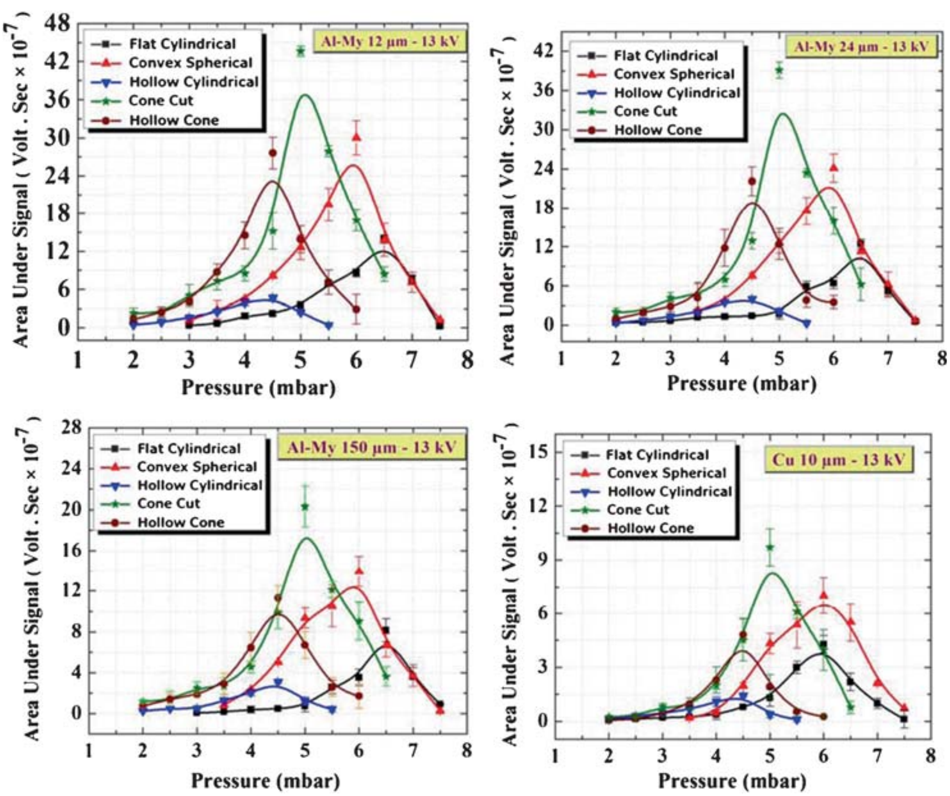


Figure 7. SXR intensity vs. pressure at a constant 13 kV working voltage for different anode tips.

Table 2. Comparison of different filtered PIN diode signal areas for different anode tips at optimum pressure at 13 kV.

Anode tip geometry	Optimum Pressure (mbar)	Signal intensity (a.u.) Al–My 12 μm	Al–My 24 μm	Al–My 150 μm	Cu 10 μm	Normalized intensity to cylindrical flat Al–My 12 μm	Al–My 24 μm	Al–My 150 μm	Cu 10 μm
Cylindrical-flat	6.5	13.9	12.4	8.17	4.28	1	1	1	1
Cylindrical-hollow	4.5	5.68	4.03	3.12	1.43	0.4	0.3	0.4	0.3
Spherical-convex	6	30	24.1	13.9	7.01	2.2	2	1.7	1.5
Cone-flat	5	43.6	39.1	20.3	9.7	3.1	3.1	2.5	2.2
Cone-hollow	4.5	27.6	22.1	11.3	4.81	1.9	1.8	1.4	1.1

cylindrical-hollow one. This may be due to the fact that in conical or spherical anodes, the diameter of the anode reduces towards the anode tip. Therefore, a larger transition radius at the edge of the anode helps to avoid rapid changes in the motion of the plasma current sheath from the axial acceleration phase to the radial implosion phase which helps to form a better dense plasma pinch. Gradual transition will increase symmetry and thereafter pinch lifetime of the plasma to radiate soft X-rays. Moreover, in the axial phase, the current sheath sweeps all the mass it encounters and the accumulated mass at position z along the anode bar is $\rho_0[\pi(b^2 - a(z)^2)z]$, where ρ_0, $a(z)$ and b are the filled gas density, the anode radius and the cathode radius, respectively. Decrease of $a(z)$ along the anode bar for non-cylindrical anodes result in increasing swept mass which enhances plasma density and thermal radiation of dense plasma columns. It should be reminded that when the shock front in the radial phase goes on the axis of the device, a reflected shock is expected to emerge from the axis, while the magnetic piston is moving in. Collision of the reflected shock and imploding piston causes an intense decrease in the plasma cross-section leading to induced electric field and sausage instabilities. Decreasing diameter in the case of conical or hemispherical anodes can decrease the time interval of the radial phase, consequently increasing the induced electrical field. Therefore, the electron beam will be more accelerated toward the anode surface, gaining more intensive emissions. In this study, applied filters were 12, 24, 150 μm Al–My and 10 μm Cu, which have transition edges at 0.8, 1.2, 2, 2.5 keV, and maximum sensitivity at 2.7, 2.9, 4.4, 6.1 keV, respectively. Consider the rising trend; the energy range of photons passed through the mentioned filters will increase. On the other hand, normalized data in table 1 show the falling trend in X-ray enhancement. For instance, spherical-convex anode has increased SXR intensity of about 2.2, 2, 1.7 and 1.5 times through the mentioned filters.

4. Conclusion

The effect of cylindrical-flat, cylindrical-hollow, spherical-convex, cone-flat and cone-hollow anode tips on the intensity of soft X-ray emitted from a 4kJ PFD is investigated. Analysed data have shown that cone-flat, spherical-convex and cone-hollow tips significantly increase X-ray intensity respectively in comparison with conventional cylindrical-flat anode tips, while the cylindrical-hollow tip decreases the intensity. Reduction of anode radius at its end, in conical or spherical anodes, enhances X-ray emission through significant increase in radiation time, resulted from consistent transition phase of current sheath from axial acceleration to radial implosion phase. Moreover, the modified configurations enhance the mechanisms which accelerate electron beams toward the anode end. As a result of this study, the cone-flat anode is introduced in cases where the plasma focus device is used as an intense X-ray source due to its highest intensity of X-ray emissions.

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