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Enhancement of X-ray emission in the side on direction in a Mather-type plasma focus

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Abstract. A 1.8 kJ Mather-type plasma focus (PF) for argon and hydrogen filling is examined. Two anode configurations are used. One is tapered towards the anode face, and the other is cylindrical but the face is cut at different angles. At optimum conditions, the system is found to emit Cu–Kα X-rays of about 1.6 ± 0.1 J/sr in the side-on direction for argon filling, which is about 32% of the total X-ray emission. In 4π-geometry, maximum total X-ray yield and wall plug efficiency found are 26.4 ± 1.3 J and 1.5 ± 0.1% respectively. The modified geometry may help to use the PF as a radiation source for X-ray diffraction.

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1 Introduction

Soft X-rays have been demonstrated to be useful in applications such as micro machining, radiography, X-ray microscopy, lithography and X-ray backlighting [1–8]. For this purpose different types of pinch devices like Z-pinch, X-pinch and plasma focus (PF) are under investigation [9–11]. The latter is the simplest in construction and yet provides the highest X-ray emission [6,12–15]. Bhuyan et al. [16] investigated the soft X-ray emission from a low energy plasma focus by employing different anode shapes with hydrogen/nitrogen filling gas. Their results indicate that X-ray yield can be enhanced more than ten fold with an appropriate design of the anode. Plasma focus is an intense and pulsed X-ray source, which make it attractive for X-ray diffraction. Azarkh et al. [17] used a Mather type plasma focus charged at 10 kV, with stored energy of about 7.2 kJ and 650 kA discharge current for X-ray diffraction experiments. X-ray beam from xenon plasma was transmitted through 0.5 mm thick polythene. The PT-1 X-ray film of sensitivity 70 std R was employed for radiograph of copper and tungsten samples placed at 45° to the X-ray pulses of about 20–30 ns duration. Sample was placed at a distance of about 53 mm from the anode and X-ray film.

In this paper, emission of soft X-rays ($\leq$10 keV) and specifically Cu–Kα line (1.54 Å) from a Mather-type PF operated with argon and hydrogen filling and energized with a 9 μF capacitor bank charged at 20 kV are studied, by shaping the anode tip at various angles with reference to the focus axis, to tailor higher X-ray emission in the side-on direction. The modified geometry may be helpful in designing PF for X-ray diffraction experiments.

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2 Experimental set-up and diagnostics

The experiment is carried out with a Mather-type PF system powered with a 9 μF capacitor bank whose detail is given elsewhere [18], charging it at 20 kV (1.8 kJ) and giving peak discharge current of about 175 kA. A triggertron-type pressurized sparkgap [19] is used as a switch for transfer of stored energy in the capacitor bank to the system. The electrode system is comprised of a copper rod of 96 mm in length and 20 mm in diameter as an anode, which is slightly tapered towards open end [20]. The experiment is also performed for two cylindrical anodes with a face-cut at $\theta = 45°$ and 76° with anode axis as shown in Figure 1. When the electron beam hit the solid target normally, maximum X-ray emission is along the beam axis, which decreases gradually towards the direction perpendicular to the beam [21]. That is why, in X-ray tubes, the target face is cut at a suitable angle for obtaining higher emission in the side on direction. This modification in the target enhances the X-ray flux in the preferred direction, but not the total radiation emission. A similar technique in this experiment with PF is employed for enhancing the X-ray emission in the side-on direction. It is estimated that the total X-ray yield from the device remains the same. A good focus and high X-ray emission

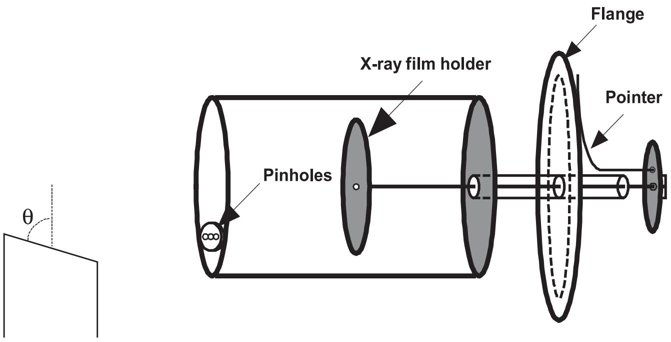

Fig. 1. The schematic of modified cylindrical anode tip with face-cut and a pinhole camera.

was observed with anode having cut at 76°. The anode with a cut at 45° did not provide appreciable X-ray emission and the focus as observed by the HV probe was weak. Therefore detailed experimental work with this anode was not conducted. Six copper rods each of 9 mm in diameter surround it such that the ratio of cathode to anode radii is 3.2. The PF chamber is evacuated up to 10^{-2} mbar using a rotary vane pump. The experiment is conducted with argon and hydrogen as filling gases and ten shots are recorded for each filling pressure. After recording ten shots, the old gas is purged out and fresh gas is filled to minimize the effects of impurities.

For monitoring the X-ray emission in different shots, the Quantrad Si PIN-diodes of 125 μm active layer thickness along with suitable absorption filters are used. These detectors were placed in the side on direction at 14.5 ± 0.2 cm from the anode axis, and elevated at 1.5 ± 0.1 cm from the anode tip. A set of absorbers and PIN diode detectors is used for estimating of Cu–Kα line emission. By reviewing the transmission windows of different commercially available filters, the selected filters are 17.5 μm thick Ni and 20 μm thick Co. The absorption edge of the Co filter lies at the 7.71 keV, which stops Cu–Kα line radiation of energy 8.05 keV. The Ni filter with absorption edge at 8.33 keV allows the transmission of Cu–Kα line radiation. The thickness of the two filters is adjusted to achieve almost equal transmission curves for the two filters over the entire photon energy range, except within the narrow spectral region between the filters' absorption edges. The transmission curves and the detectors' response along with corresponding filters are presented in Figure 2. By subtracting the signal (area under the curve of voltage trace) of the detector masked with Co filter from that of Ni filter, we might estimate the Cu–Kα line emission. For the evaluation of these curves, the data for the absorption coefficients is taken from Handbook of Spectroscopy [22]. The face of each diode is protected from intense X-ray emission by 1.6 mm thick brass disc with a hole of 2 mm diameter at the center. The holes were covered with the balanced filters. The intensity of X-rays from the focus region is found measurable for argon and hydrogen within the pressure ranges of 0.25–2.5 mbar and 0.25–5.0 mbar respectively; below and above these pressure ranges it attains very small values.

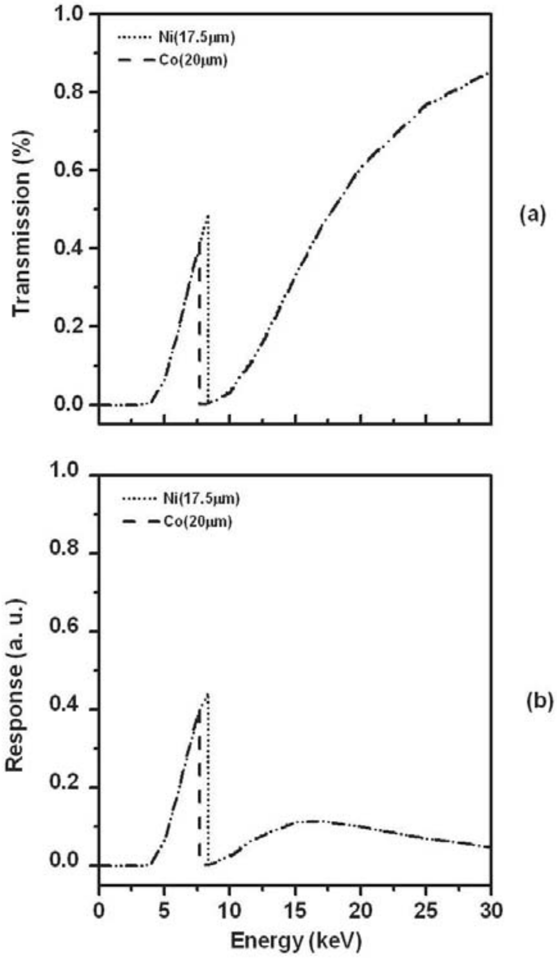

Fig. 2. (a) Transmission curves of Ni (17.5 μm) and Co (20 μm) filters and, (b) response of PIN-diode detectors along with respective filters.

For time-integrated X-ray measurement a pinhole camera [23] with three pinholes each of 200 μm in diameter are employed. The pinholes are masked separately with Cu 10 μm, Ni 12.5 μm and Co 10 μm thick filters for tapered anode whereas for cylindrical face-cut anode the pinholes are covered with Ni 5 μm, Co 10 μm and Al 5 μm thick filters.

The electrical signals from the two PIN-diodes, high voltage (HV) probe and Rogowski coil were recorded by a four channel 200 MHz Gould 4074A digital storage oscilloscope and the data was transferred to a computer through a general purpose interface bus (GPIB) 488.2.

3 Experimental results and discussions

Figure 3a depicts variation of Cu–Kα emission versus pressure of argon filling for the tapered and cylindrical face-cut anodes. The technique to estimate the X-ray emission from a point source is reported elsewhere [24]. A maximum Cu–Kα emission of about 0.7 ± 0.1 J/sr and 1.6 ± 0.1 J/sr per shot is recorded for the aforesaid anodes

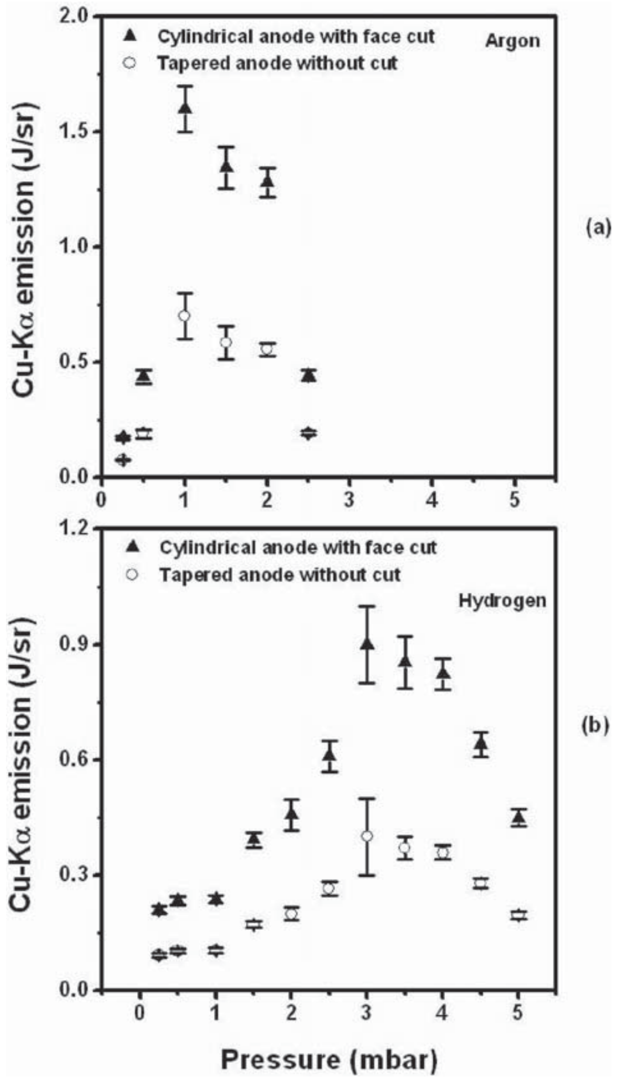

Fig. 3. The variation of Cu–Kα emission for tapered and cylindrical face-cut anode versus filling pressure for: (a) argon, (b) hydrogen filling.

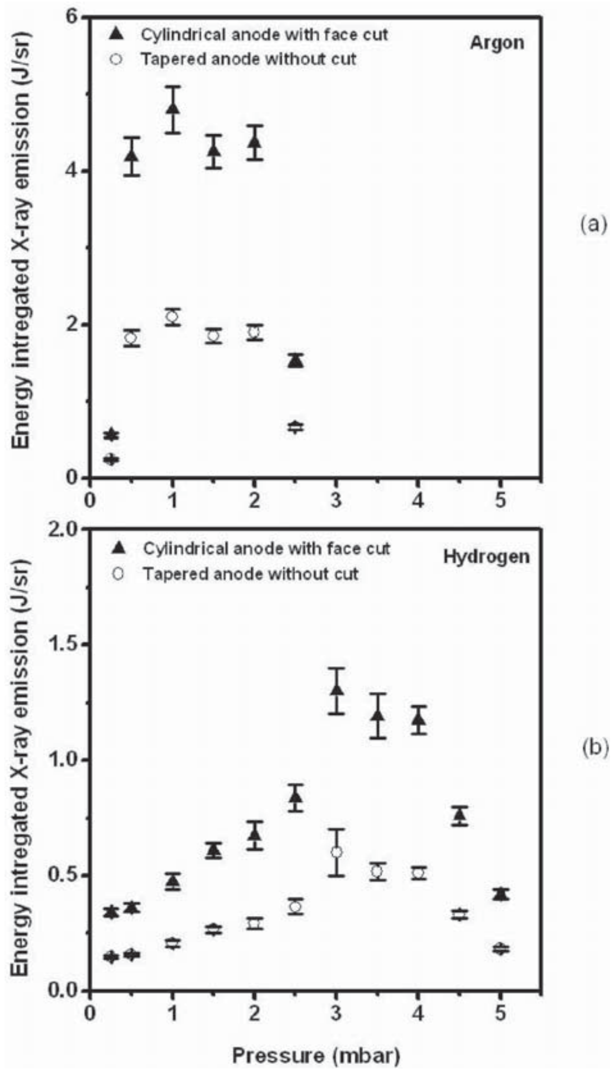

Fig. 4. The variation of energy integrated X-ray emission for tapered and cylindrical face-cut anode versus filling pressure for: (a) argon, (b) hydrogen filling.

respectively at 20 kV charging voltage and 175 ± 5 kA discharge current. It is estimated that for the cylindrical face-cut anode, the observed emission corresponds to 1.2×10^{15} Cu–Kα photons/sr per shot, when the PF is operated at 20 kV charging voltage. Figure 3b is a representation of the variation of Cu–Kα emission for hydrogen filling. At optimum pressure, maximum Cu–Kα emission of about 0.4 ± 0.1 J/sr and 0.9 ± 0.1 J/sr per shot is recorded for the tapered and cylindrical face-cut anodes at the identical charging conditions. Comparison of graphs given in Figure 3 shows that the optimum pressure for argon and hydrogen are 1 mbar and 3 mbar respectively. It is observed that [25] the X-ray emission with argon filling, when the anode tip is engraved, is not significant. When the anode tip is flat (in this experiment), the Cu–Kα as well as the energy integrated X-ray emission is much enhanced. It reveals that the Cu–Kα emission is not from plasma, but due to interaction of the energetic electrons' with the anode tip. Energetic electrons in the current sheath as well as the electron beam generated during the pinch will hit the anode and generate X-rays through thick target bremsstrahlung mechanism. From the PIN-diode signals (in correlation with the current and voltage waveforms), it may not be simple obtaining information that the dominant X-ray emission from the anode tip is due to electrons' in the current sheath, or the energetic electron beam generated in the focus region. The emission is much higher for argon filling compared with that of hydrogen. It is evident that the Cu–Kα emission for argon is about 50% higher than that of hydrogen for both anode shapes.

Figure 4a presents variation of energy integrated X-ray emission versus pressure of argon filling for both the anodes. A maximum X-ray emission of about 2.1 ± 0.1 J/sr and 4.8 ± 0.3 J/sr per shot is recorded for tapered and cylindrical face-cut anodes respectively. Figure 4b is a representation of the variation of energy integrated X-ray emission for hydrogen filling. At optimum pressure, the

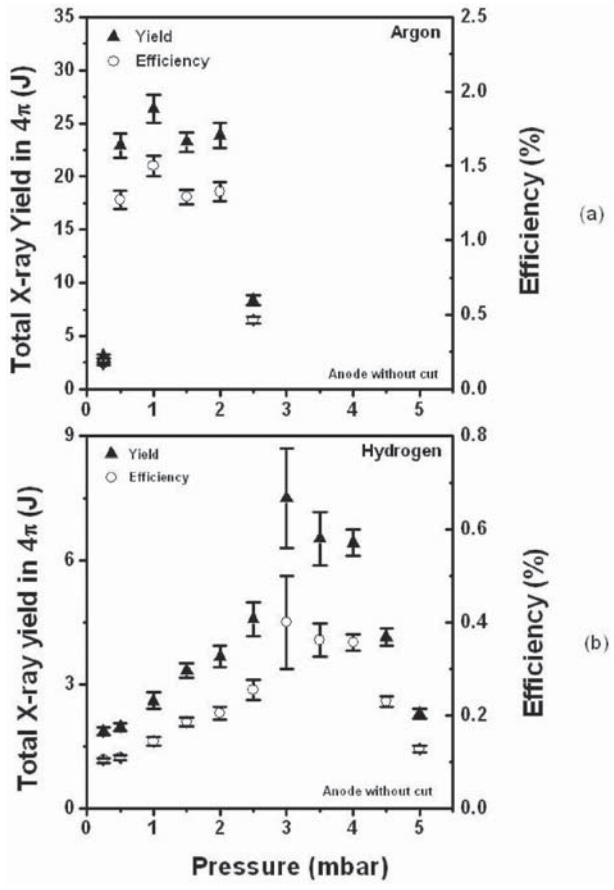

Fig. 5. The variation of total X-ray yield and efficiency versus filling pressure for: (a) argon, (b) hydrogen filling.

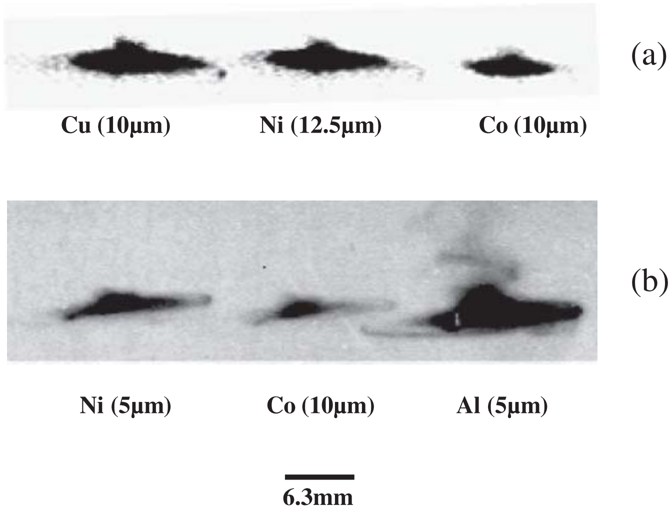

Fig. 6. X-ray images with pinhole apertures of 200 μm for: (a) tapered anode without cut, (b) cylindrical anode with face-cut. For each image, the transmission filter is described.

highest energy integrated X-ray emission of about 0.6 ± 0.1 J/sr and 1.3 ± 0.1 J/sr per shot is recorded for the aforesaid anodes. These graphs show that the energy integrated X-ray emission for argon is about 2 times higher than that of hydrogen for both the anodes. Figures 3 and 4 show that the X-ray emission (J/sr) for the face-cut anode in the side-on direction is increased about 100%.

Figure 5a demonstrates the variation of total X-ray emission and corresponding efficiency for argon filling with tapered anode. In 4π-geometry, a maximum soft X-ray yield of about 26.4 ± 1.3 J is recorded at 1 mbar and the corresponding efficiency is about 1.5 ± 0.1%. Figure 5b represents the total X-ray emission and corresponding efficiency versus hydrogen filling pressure for tapered anode. In 4π-geometry, a maximum soft X-ray yield of about 7.5 ± 1.2 J is recorded at 3 mbar and the corresponding efficiency is about 0.4 ± 0.1%.

Photographs of plasma region obtained by a pinhole camera mounted in the side-on direction for tapered (without face-cut) and cylindrical (with face-cut) anodes with argon filling are shown in Figure 6. The X-rays from the focus region and anode tip after passing through the three pinholes covered with different filters fall on the photographic film, which is fixed in a holder. From these images, one can see that the X-rays are dominantly emitted from the anode tip. Most of the filters do not transmit the soft X-rays emitted from the plasma column and this region is not visible. The Ni filter allows the transmission of Cu–Kα line radiation, whereas Co filter stops it. The images behind Ni filter are larger in size and much dark than the images behind the Co filter, which demonstrate that a substantial X-ray emission from the anode tip is Cu–Kα. In the pinhole image with Al(5 μm) filter, a part of pinch filament is also visible, because the Al filter is transparent for photons of energy $\geq$1.5 keV.

It is observed that after about one thousand five hundred shots, electron beam produced a hemispherical cavity of about 2.2 mm depth and 7 mm diameter at the anode tip. Further, the damage at the anode face by impact of the energetic electron beam is not at the center. Due to the face-cut, current sheath travels unequal distances in the radial direction in the compression phase. As a result the plasma is not compressed at the anode axis and the electron beam generated from the PF region does not hit the axial point of the anode.

Preliminary experimental results of an X-ray diffractometer, using PF as the radiation source and Fuji X-ray film as the detector, in the Debye-Scherrer camera arrangement are presented. The spectrum of X-rays from a PF is almost similar to a typical X-ray tube, but the wall plug efficiency is higher. That advantage may make the PF attractive as a source for X-ray diffraction. Due to high ion beam flux in the end-on direction, the emitted X-rays may not be used to this end. A brass barrel of 1.5 mm inner diameter and 22 mm in length along with a pinhole aperture of 300 μm diameter is used as a collimator. Pinhole and point source of X-rays are aligned with the help of He–Ne laser. The Cu–Kα radiation was passed through the collimator and a 300 μm aperture masked with 6 μm Ni foil, at a distance of 18.5 cm from the focus point. In front of the pinhole, the single crystal Cu powder was mounted in polythene cover. For recording the diffracted beam, the X-ray film was placed in a circle of radius 27.3 mm. This whole arrangement forms the typical Debye-Scherrer camera system. However, a very weak diffraction pattern was recorded, due to the following reasons. Although, the X-ray emission from the focus point is estimated 1.2×10^{15} photons/sr, just about 3.1×10^{9} photons pass the pinhole aperture, and further half through the Ni foil. Low sensitivity of the X-ray film and lack of arrangement for differential pumping hindered from obtaining good contrast diffraction pattern. Work to improve the Debye-Scherrer camera system efficiency is in progress and will be reported later, in detail.

4 Conclusions

In conclusion, X-ray emission from a 1.8 kJ Mather-type PF operated with argon and hydrogen as the filling gases is studied by employing time-resolved and time-integrated detectors. For 20 kV charging voltage, the highest X-ray emission is recorded at filling pressures of 1 mbar and 3 mbar of argon and hydrogen respectively. With a cut anode at 76° the maximum Cu–Kα emission and energy integrated X-ray emission found for argon filling are 1.6 ± 0.1 J/sr and 4.8 ± 0.3 J/sr respectively. Whereas for hydrogen the corresponding values are 0.9 ± 0.1 J/sr and 1.3 ± 0.1 J/sr respectively. The total X-ray emission in 4π-geometry at optimum pressure of argon is about 26.4 ± 1.3 J. For optimum hydrogen filling, the highest total soft X-ray emission in 4π-geometry is about 7.5 ± 1.2 J.

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