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Optimization of neon soft X-ray emission from 200 J plasma focus device for application in soft X-ray lithography

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The Fast Miniature Plasma Focus (FMPF) device is basically made up of coaxial electrodes with centrally placed anode and six cathode rods surrounding them concentrically. They are enclosed in a vacuum chamber, filled with low pressure operating gas. However, in our experiments, these cathode rods were removed to investigate the influence of them on neon soft X-ray (SXR) and hard X-ray (HXR) emission from the device. On removal of cathode rods, the cathode base plate serves as cathode and the plasma sheath is formed between the anode and the base plate of cathode. Neon was used as the operating gas for our experiments and the FMPF device used is of 235 J energy capacities. The experimental results showed that the FMPF device was able to focus better and the SXR emission efficiency was five times higher without cathode rods than with cathode rods. On the contrary, HXR emission did not vary with and without cathode rods. This observed phenomenon was further cross-checked through imaging of plasma dynamics, with and without cathode rods. FMPF device consists of 4 Pseudo Spark Gap (PSG) switches, which need to operate synchronously to deliver high voltage from capacitors to the anode. It was also seen that, the presence or absence of cathode rods also influence the synchronous operation of PSG switches. It also implies that this is one definite way to optimize the SXR emission from the FMPF device. This study reveals an important finding that, cathode rods play a vital role in the formation of plasma sheath with consequential influence on the radiation emission from plasma focus devices. Enhancement of the X-ray emission from this device is definitely a stepping stone in the realization of this device for industrial applications such as X-ray lithography for semiconductor industries.

Keywords: Plasma focus device; Soft X-ray (SXR); Cathode rods.

1. Introduction

Plasma focus devices are basically Z-pinch devices which emits radiations of wide spectral range given the suitable operating gas and device parameters. For instance, with neon as operating gas plasma focus device radiates effectively in 0.9 - 1.5 keV range[1] while with argon as operating gas it radiates (though with much less efficiency) predominantly at higher photon energies.[2] Similarly, with Xenon as operating gas, they emit pre-dominantly in the EUV range.[3] It is especially advantageous to use plasma focus device for Neon Soft X-ray emission, as the plasma temperature is in the range of energy required for emission of dominant spectral lines of Neon, such as 922 eV and 1022 eV.[4] FMPF devices,[5] have various advantages owing to applications as a X-ray source,[6-8] as they are compact, portable, cost effective, pulsed source and comparatively easier to build and maintain than other existing X-ray sources.

This is therefore, one of the actively pursued fields. There are a number of ways through which SXR emission from FMPF can be enhanced such as optimization of bank energy,[9] discharge current, electrode configuration (shape and material),[10, 11] insulator material and dimensions,[10] gas composition and filling gas pressure.[12] Some numerical studies have been conducted in the past to investigate the operation of plasma focus devices without cathode rods.[13, 14] Some limited experimental works have also been carried out in the past without the outer electrodes.[15-17] Although experiments and simulations were done on operation of plasma focus device, without cathode rods no comparison has been made in the past, to compare the operation of FMPF with and without cathode rods while keeping all the other parameters constant. The plasma focus dynamics are sub divided into three distinct phases: the breakdown phase (or reverse pinch phase), the axial acceleration phase (or axial rundown phase) and the radial phase (or radial collapse phase). It is the breakdown phase, during when the plasma sheath is formed between anode and cathode and it is lifted up during the axial acceleration phase and finally compressed during the radial phase. It is during the final compression phase, during when the intense radiations and high energy particles are emitted from the hot, dense and short lived plasma. The initial plasma sheath that is formed between anode and cathode is the base for final compression. The good quality plasma sheath that is formed during breakdown phase is dependent on the distance between the anode and cathode, as the curvature of the plasma sheath formed is dependent on the position of the cathode rods. Hence we decided to conduct some study on the influence of position of cathode rods on SXR emission in order to determine if it can be one possible way to enhance SXR emission. The time period of the discharge current is given by, ($T = 2\pi\sqrt{LC_0}$) where, L is the overall inductance of the system, including the static inductance of the device (L_o) and dynamic plasma inductance (L_p), and C_0 is the capacitance of the capacitor bank. The magnetic compression and Joule (resistive) heating of the focused (pinch) plasma column is efficient, if the radial compression phase takes place at or near the maximum discharge current i.e. at about quarter time period, ~T/4. Hence, the length of the central electrode (anode) should be based on the quarter time period of the discharge current and the typical current sheath speed, say 5 cm/μs, in axial acceleration phase. For the same anode, the operating gas pressure was varied from 1 to 10 mbar in steps of 1 mbar and experiments were conducted with and without cathode rods. It was seen that without cathode rods the plasma sheath formation was better and the SXR emission efficiency was higher. Time integrated imaging of the plasma focus dynamics was done using laser shadowgraphy technique to analyze the plasma sheath formation and final compression, with and without cathode rods. It was done to further investigate, whether, the experimentally observed phenomena is reflected on the plasma dynamics, especially at axial acceleration phase and radial compression phase.

FMPF-3 device was optimized in the past for enhanced SXR emission through optimization of anode dimensions, gas pressure [18] and through doping of operating gas.[19] Although there was remarkable improvement in the SXR emission efficiency based on the above mentioned methods,[18] we decided to explore further on the possibilities of enhancement of SXR emission. One of the ultimate goals for the FMPF-3 device is to make it a miniature SXR source for X-ray lithography for which, higher the SXR emission efficiency, higher is the feasibility to make it an efficient X-ray source for lithographic applications.

2. Experimental Setup

The plasma focus device basically has co-axial electrodes and an insulator sleeve which is enclosed in a vacuum chamber filled with low pressure operating gas to generate plasma. The central electrode is anode, which is either hollow cylindrical or hollow tapered, and is surrounded concentrically by 6 cylindrical cathode rods placed equidistant from each other. The anodes are generally made hollow at the centre, to subdue material ablation at the anode tip and the resultant material debris contamination of the operating gas especially during the pinch phase. The anode use for our experiment is made up of copper and 2 cm long, tapered head with 1 cm long insulator sleeve. The 235 J, FMPF-3 device used for our investigation is powered by a four module capacitor bank (with total bank capacitance of 2.4 μF) and each module consists of a pair of 0.3 μF capacitors connected in parallel. The power from the capacitors banks are discharged into the anode through four in-line pseudo spark gap (PSG) switches [model TDI1-150 k/25] which are connected in parallel to reduce the system inductance (34 nH). This also helps to increase the life time of the switches as the total coulomb transfer is shared among the switches. The schematic of the FMPF electrode assembly with and without cathode rods are shown in Fig. 1. Position of the diagnostic devices and other associated components are maintained the same throughout the experiment for fair comparison. They are mounted on the end-on port of vacuum chamber, aligned at zero degrees to anode.

X-ray spectrometer (DXS), built with BPX65 silicon PIN photo detectors shielded with suitable filter pairs for measurement of exclusive energy range of X-rays, serves as the diagnostic component. The X-ray signals and the current derivative signals are acquired using Rogowski coil are collected using the Yokogawa digital storage oscilloscopes (model – DL9140) with a fast sampling speed of 5 GS/s and a high-bandwidth of 1 GHz. Such a high end data acquisition system is required because of the low quarter time period for FMPF-3 device, which is about 0.5 μs and the pinch lifetime or dynamics is about tens of ns[20] which is faster when compared to other mid- and high-energy plasma focus devices in larger extent. For the time integrated imaging of the plasma focus dynamics using laser Shadowgraphy, a 532 nm, Q-switch LOTIS TII laser was used as the source, a CCD camera was used to record the images and a micro-controller was used for the sequential operation of the different components of the laser shadowgraphy setup.

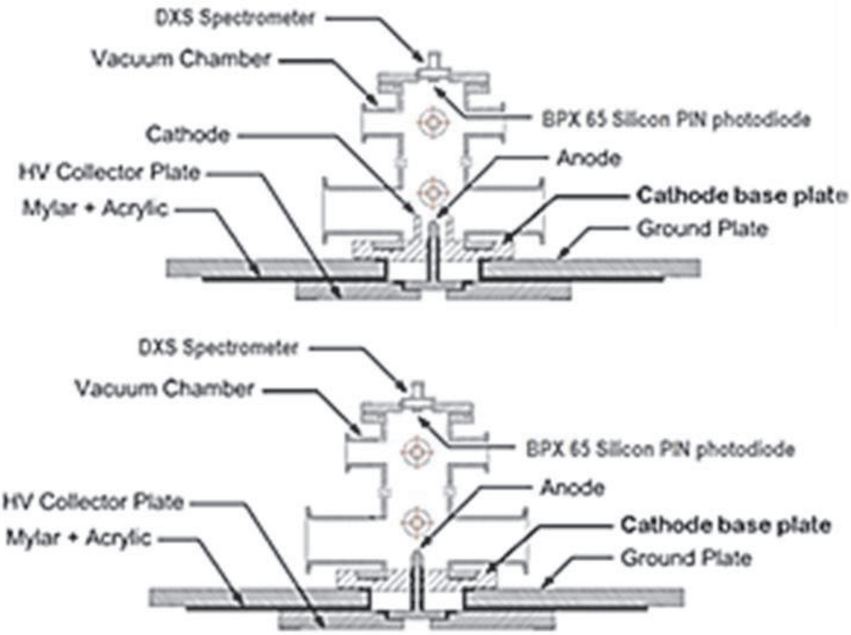

Fig 1. The electrode assembly of fast miniature plasma focus device with cathode rods (Top) and without cathode rods (Bottom).

3. Experimental Results

FMPF-3 is a pulsed source of SXR, hence with good efficiency, lesser would be the number of shots needed to deposit a certain dosage on the sample. With lesser number of shots fired, lesser would be the probability of debris formation, puncturing of X-ray filter, heating of the electrodes, contamination of operating gas etc., Hence we thought that it would be worthwhile to investigate on the much less explored field of enhancement of SXR emission, which is to study the influence of the position of cathode rods on SXR emission. As the variation of distance between anode and cathode or variation of radius of cathode (b) would be a very tedious procedure with demand for large physical modifications of existing experimental setup, first trial was done by overall removal of the cathode rods itself. This is in turn lead to the substitution of the cathode wall plate as the cathode, which is an indirect way of increasing the cathode radius b. In our case, the wall of the vacuum chamber did not act as the cathode, as they were farther away in comparison to the cathode wall plate. Hence, the plasma sheath was forming between the anode and the cathode base plate as it was closer in comparison to the wall of the vacuum chamber. The major influence of the position of cathode rods lies on the curvature of the plasma sheath formed during the breakdown phase of the plasma focus dynamics. Another impact is that, the radius of the cathode rods plays a major role in determining the plasma inductance, which in turn will affect the magnetic flux density as per Eq. (1):[21]

$$L_p = \frac{\mu}{2\pi} ln\left(\frac{b}{a}\right)z \quad (1)$$

where
L_p – Plasma inductance in nH
μ – Magnetic permeability in Hm^{-1}
b – Radius of cathode in cm
a – Radius of anode in cm
z – Length of anode in cm

The obtained experimental results were further cross checked through time resolved imaging of plasma dynamics using laser shadowgraphy technique. The obtained results are discussed in detail in the following sections.

As can be seen from Fig 2, with removal of cathode rods, the SXR emission efficiency was enhanced by about 5 times together with slight increase in the peak operating pressure. There could be few possible reasons, for enhancement of SXR emission without cathode rods.

With increase in b, the inductance should increase, as it is directly proportional to b, as shown in equation 1, however, this increase may be very meagre such that only quarter time period (*T/4*) increases (where $T = 2\pi\sqrt{L_0 C_0}$)) resulting in increase of peak operating pressure.

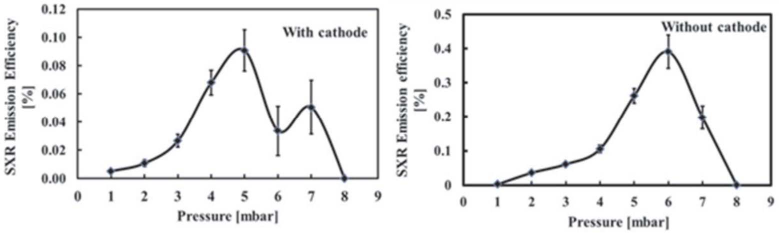

Fig 2. SXR emission efficiency as a function of operating gas pressure for 2 cm long, tapered Cu anode.

The increase in overall impedance of the device may be matching with device impedance which might have resulted in higher power transmission as per maximum power transmission theorem [22]. Although b increases, the curvature of plasma sheath also increases, which results in the angular variation of the plasma sheath. The increase in inductance is not only dependent on area of flux and flux density but also on the angle of the current field as shown in Eq.(2), which might also be contributing to increase or decrease of the overall inductance:

$$\varphi = B.A.cos\theta \quad (2)$$

where
ϕ – Magnetic flux passing through the field in wb
B – Flux density in T
A – Area of surface in m^2
θ – Angle between normal to the surface and the current field.

It was seen that without cathode rods, the PSG switches were operating more synchronously which definitely leads to efficient power transfer to the anode. The curvature of the current sheath formation at the breakdown phase is very much decisive of the final current pinch compression and subsequent SXR emission and this curvature is dependent on the position of the cathode rods.

However, for HXR emission, with removal of cathode rods, did not improve the HXR emission, as shown in Fig. 3. HXR emission is mostly due to Bremsstrahlung, which is dependent on the electron acceleration. For SXRs, the absolute emission yield and efficiency were calculated, whereas, the HXR component was estimated, only on relative basis, by estimating the area under the signal received through absorption filters, which transmits only X-ray energies above 1600 eV. As Ne dominantly emits in 900-1600 eV range and the relative spectral emission in this range are known[1], whereas, the nature of spectrum in >1600 eV range is not known. Hence, the relative HXR emission yield is given in arbitrary units.

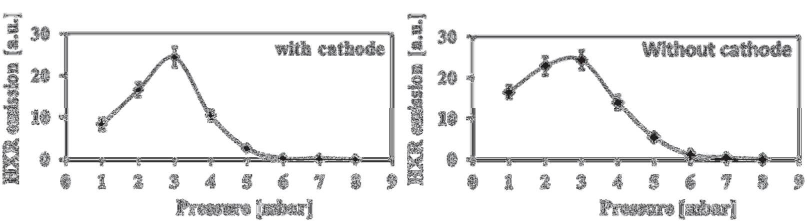

Fig 3. HXR emission as a function of operating gas pressure for 2 cm long, tapered Cu anode.

Laser shadowgraphy technique was used to obtain the time integrated imaging of the plasma focus dynamics to better understand the reason behind better SXR emission without cathode. The images obtained using a Q-switched laser as the source and CCD camera as the detector was very well supporting the experimental results. According to the experimental results, the SXR emission obtained without cathode rods were 5 times higher than that achieved using with cathode rods.

The reason behind this can be very clearly seen in the obtained images shown in Fig. 4 where, without cathode rods the plasma sheath formation is denser and more symmetrical. As we were focused on general investigation of the behavior of plasma dynamics we did not pay attention on the exact time instant when these frames were taken.

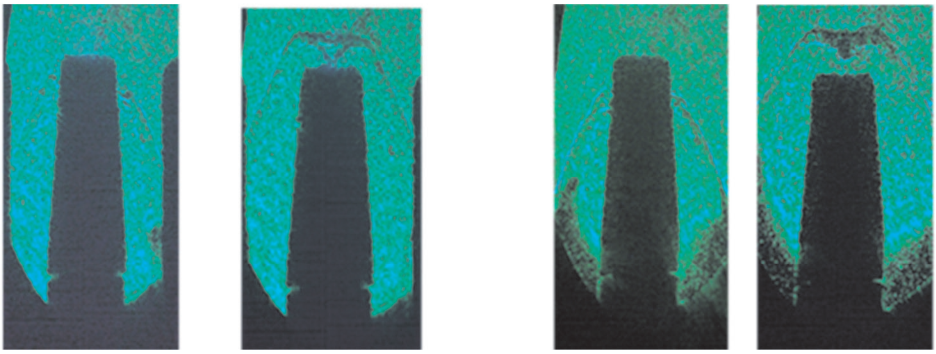

Fig 4. Laser shadowgraph images showing axial and radial phase of plasma dynamics, with cathode (Left) and without cathode (Right).

4. Conclusions

Experiments were to done to investigate the prospect of enhancement of SXR emission from FMPF-3 device through the analysis of less explored field of influence of position of cathode rods on SXR emission. Because of the removal of cathode rods and due to the formation of plasma sheath between anode and cathode wall plate, the curvature of the formed plasma sheath was higher as well as the the plasma sheath looked denser, symmetric and more uniform. The operating gas pressure was scanned from 1 mbar to 10 mbar in steps of 1 mbar, with cathode rods and without cathode rods. Although, the inductance of the device is expected to increase due to increase in cathode radius b, thereby reducing the peak discharge current with a consequential reduction in SXR emission, it was seen that the SXR emission was five times higher without cathode rods at peak operating gas pressure. Although the inductance of the device is higher, the overall impedance of the device may now be better matching with the device impedance which might have caused maximum power transmission to the device with consequential improvement in the SXR emission. And also the increase in flux density and variation of the current field due to variation of curvature of plasma sheath could also have contributed to higher peak discharge and SXR emission. However, there was almost no improvement seen in the HXR emission at peak operating pressure due to removal of cathode rods. The obtained results were very well supported by the time integrated images of the plasma dynamics obtained using laser shadowgraphy technique. It was seen that without cathode rods the plasma sheath was looking denser, more uniform and symmetrical. This study reveals the significant influence of the cathode radius b on the SXR emission from the plasma focus device and demonstrates one less explored approach of enhancing the SXR emission from plasma focus device. The obtained results have yielded a very important outcome for exploitation of this device for industrial applications such as X-ray lithography where the enhanced SXR emission increases the feasibility of utilizing this device for such applications.

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