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Effect of anode shape on pinch structure and X-ray emission of plasma focus device

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ABSTRACT

The effect of anode shapes on pinch structure and X-ray emission of plasma focus device operated with cylindrical, diverging, oval and converging anode tips is reported. The pinch structure in the radial compression phase has been investigated by employing a triple pinhole camera. It has been observed that pinch structure as well as the X-ray emission of PF device strongly depends upon anode tip designs. For the first time the studies were carried out in two new shapes of anode tips that is the oval and the divergent one. It has been observed that the oval and diverging anode tips are more conducive for the formation of instabilities and hotspot generation. The studies of X-ray emission were also carried out by employing three channels of a *p-i-n* diode X-ray spectrometer in entire anode designs to corroborate the results of a triple pinhole camera. Additionally, the effective hard X-ray photon energy was also estimated by the radiography method for all the anode tip designs, which indirectly provide a qualitative idea of the generation of induced accelerating field in the pinched column during compression.

1. Introduction

The plasma focus (PF) device produces highly dense transient pinch plasma by making use of self-generated magnetic field for compression of current sheath. The pinch plasma of PF device exhibits various interesting plasma phenomena such as formation of sausage and kink instabilities [1], Raleigh tailor Instabilities [2], hotspots [3] and so on. Besides, it is a rich source of various electromagnetic radiations starting from IR to X-ray [4–8], charged particles [8] and neutrons [9]. Due to the profuse radiation emission, PF device has found applications for X-ray lithography [10], electron beam lithography [11], material processing [12], ion implantation [13], pulse neutron activation analysis [14] etc. On the other hand, Lee et al. [15] termed PF as an excellent device to teach plasma dynamics, thermodynamics, plasma phenomena and plasma nuclear fusion with its added features of simplicity and cost-effectiveness. Thus, the PF device has proved itself as a unique device in terms of innumerable aspects of basic physical phenomena and several prospects for technological applications. As a result, the PF device has still been able to draw attention to researchers for basic research as well as for improving its performance as a source of various emissions. In this line, researchers studied various physical phenomena such as current sheath dynamics, optimized working pressure, instability growth, etc. along with the emissions of various radiations by changing different experimental conditions and parameters such as bank energy, circuit inductance, gas types, anode design, etc. [16–20].

It is observed that the pinching of plasma column greatly depends on the dimension and shape of its electrode assembly as a whole or in parts. Recently, Mohammadi et al. [20] studied the pinch dynamics and X-ray emission using three different anode shapes and observed some interesting structures of the pinch column. They also found that the pinch plasma length decreases as anode radius decreases, resulting in a reduction of total soft X-ray yield. Similarly, Kubes et al. [21] found that the presence of the anti-anode influences the distribution of the plasma density in front of the anode and decreases the neutron yield. A reduction of neutron generation was observed without a conventional outer cathode than with it in PF device as reported by Bruzzone et al. [22] Zhang et al. [23] reported that the change in insulator sleeve length modifies the current sheath curvature angle and thus the length of the pinched plasma column that affects the neon soft-X-ray emission. Beg et al. [19] observed that the structure and the dimensions of the X-ray-emitting plasma are different for low- and high-Z gases. They also found that the X-ray emission maximizes at a pressure, which depends on the constituent gas and the anode length. Zakaullah et al. [7] studied the effect of anode shape on PF operation with argon as operating gas and reported that an appropriate shaping of the anode tip could enhance the emission of both ion beam and X-ray. Rawat et al. [24] optimized their

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3.3 kJ neon-filled PF device for maximum X-ray yield by varying the insulator sleeve lengths. They concluded that the insulator sleeve could severely affect the X-ray yield. Similarly, Bhuyan et al. [25] observed a ten-fold enhancement of X-ray emission in an appropriate shape of the anode. In the same configuration of Ref. [25] Mohanty et al. [26] also observed an enhancement of ion beam emission in the same shape of the anode.

Inspired from the earlier reports on the effect of the anode dimension on the pinch structure and emission of various radiations, an effort has been made to study the pinching phenomena, generation of instabilities and hotspots of PF device by using four different anodes. In this experiment, we have introduced two new shapes of anodes i.e., diverging and oval along with the earlier explored shapes e.g., cylindrical and converging. The lengths of anodes are kept same with the cylindrical one keeping the radius same with cylindrical anode up to a certain height. Beyond that height, in case of diverging one, the radius increases gradually over the last few centimeters of its length, while in case of oval one, a bulging out portion is introduced over the last few centimeters of its length toward the open end. Therefore, it can be mentioned that the radius of cylindrical anode (1.05 cm throughout its length) is the basis of all the other anodes. These two new shapes of anodes may provide us information on the structure of plasma column and X-ray emission, which may be somewhat different from the other anode shapes. In this way introduction of these two anode shapes can be considered as novel in PF research. Thus four anode tips of different shapes have been used and a triple X-ray pinhole camera captures the images of pinching region. Three channels of a *p-i-n* diode X-ray spectrometer [25] were employed simultaneously to study the X-ray emission from PF device in entire anode designs to corroborate the results of a triple pinhole camera. Furthermore, the strength of the induced accelerating field depends on the structures, dimension and compression of the plasma column. Again, the dimensions and other structures of the plasma column depend on the electrode structures and dimensions [7,20,25]. Therefore, the information on the accelerating field induced in the different anode designs may be important along with the pinch structures. The qualitative idea of induced accelerating field in different anode shapes is brought from the measurement of hard X-ray energies.

2. Experimental set up

2.1. Plasma focus device

The experiment was carried out in a 2.2 kJ Mather type PF device, which consists of a coaxial electrode assembly. The schematic of the experimental system is shown in Fig. 1. The system was energized by a high voltage energy storage capacitor (7.1 μF, 40 kV), which can deliver a peak current of around 110 kA. The detailed electrical and mechanical parameters are reported elsewhere in. [27]. The whole electrode assembly is housed inside a stainless steel evacuation chamber having an approximate volume of 6 L. The chamber is filled with hydrogen gas and evacuated up to a desired pressure level. A Mcleod gauge monitors the pressure of the chamber. In the present experiment, we have operated the PF device with four different shaped anodes namely diverging tip, oval tip and converging tip in addition to the conventional cylindrical tip anode as shown in Fig. 2. It is worth mentioning that any change in electrode dimension in PF device alters the current sheath traversal time t_a as suggested by the Lee model Eq. (1) [28].

$$t_a = \left[\frac{4\pi^2\rho_o(b^2 - a^2)z_o^2}{\mu I_0^2 \ln\left(\frac{b}{a}\right)}\right]^{1/2} \tag{1}$$

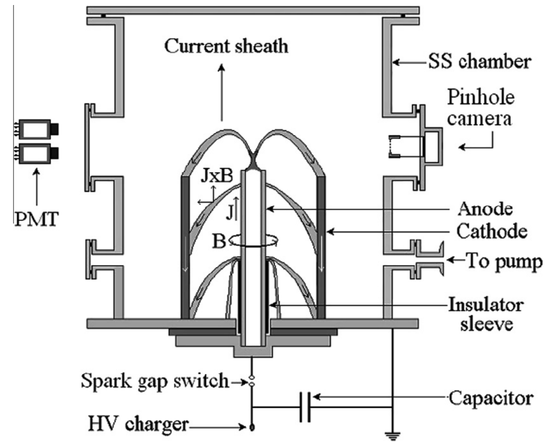

Fig. 1. Sketch of the PF device with triple pinhole camera and PMT.

where '*a*' and '*b*' are the anode and cathode radius, ρ_o is the ambient gas density, Z_o is the length of the anode and I_0 is the peak discharge current. Any change in dimension of '*a*' or '*b*', leads to a change in the optimum operating pressure so that the value of t_a is maintained to synchronize with the time of peak discharge current. Accordingly, in case of diverging and oval anode, the operating pressure should decrease. On the contrary, the optimum operating pressure should increase in case of converging anode.

Therefore, we have made a pressure scan of each anode in PF device and observed the optimum operating pressure according to the Lee model. The optimum operating pressure for cylindrical, diverging, oval and converging anodes is 0.6–0.7, 0.1–0.2, 0.7–0.8 and 1.0–1.2 Torr of hydrogen gas, respectively. It is notable that the accurate measurement of pressure by a McLeod gauge is difficult by observing with the naked eye, as the physical gap between two consecutive readings is very small. Thus the measured pressures might be little bit undervalue or overvalue, because of the limitation of human eye resolution. In our measurement, we could not adjust the pressure to a single point and therefore, we have given the pressure in the range of 0.6–0.7 or 0.7–0.8 Torr. Further the experimentations were carried out at an optimum pressure of each anode design.

2.2. The triple-pinhole camera

The pinhole based X-ray imaging camera [25] is an efficient and cost effective as well as simple device to study space resolved X-ray emitting zone of dense hot pinched plasma of PF device. It gives an overall idea of the location of the X-ray emitting zone as well as approximate size and qualitative idea of radiation density of the X-ray emitting plasma column. The introduction of multiple pinholes in the pinhole camera will help to capture the image of pinched plasma column of PF device in a single shot with multiple filters of different thickness.

Thus, an X-ray pinhole camera (Fig. 3) that is capable of capturing three images simultaneously of the same object was fabricated and employed to capture X-ray emitting zone of PF device. The three pinholes were made by drilling on a 1 mm thick Aluminum circular disk of diameter of 35 mm having 9 mm distance apart from each other's on a straight-line. The size of each pinhole is 300 μm and the resolution of each pinhole is around 600 μm. We used three pinholes in the camera due to the limitation of the port size of our device. However, one may incorporate more numbers of pinholes in a camera with a larger sized viewing port. The circular disk along with the pinholes was fixed light tightly on one side of a