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Effect of inserted metal at anode tip on formation of pulsed X-ray emitting zone of plasma focus device

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ABSTRACT

The effect of the anode's insert material of a plasma focus device on the properties of X-ray emission zone was studied. Inserts were fabricated out of six different materials including aluminum, copper, zinc, tin, tungsten, and lead to cover a wide range of atomic numbers. For each anode's insert material at different gas pressures and different voltages, the shape of X-ray emission zone was recorded by three pinhole cameras, which were installed on sidewall and roof of the chamber of plasma focus device. The results indicated that by changing the gas pressure and the charge voltage of capacitor, the X-ray source of plasma focus emerges with different forms as a concentrated column or conical shape with sharp or cloudy edges. These structures are in the form of a combination of plasma emission and anode-tip emission with different intensities. These observations indicate that the material of the anode-tip especially affects the structure of X-ray emission zone.

1. Introduction

The plasma focus device produces a dense (10^{19} cm^{-3}), unstable (with lifetime of 50–200 ns) and thin filament of plasma by using of self-generated magnetic field. Dynamic behavior of plasma focus includes electrical breakdown, axial and radial acceleration phases. The pinch of PF device exhibits various plasma phenomena such as formation of sausage, kink and Raleigh tailor instabilities (Haines, 1981) and hotspots (Silva and Favre, 2002). Besides, it is a rich source of various electromagnetic radiations starting from IR to X-ray, charged particles and neutrons (if deuterium gas is used) (Zakaullah et al., 1998). Due to the various radiation emissions, PF device has proved itself as a unique device for technological applications (Gribkov et al., 2002; Hussain et al., 2005; Kato et al., 1988; Venere et al., 2001). In the other hand, the PF device still attracts attention from researchers that studies various physical phenomena such as pinch dynamics and optimized working conditions. One of the main outputs of plasma focus devices is pulsed X-ray emission. Very short X-ray pulses (~ 100 ns) emitted from this device made some challenges in the measurements. For this reason, the measurement tool in this situation is limited to some special methods. X-ray radiation emitted from the plasma focus devices has high intensity as well as wide energy range and can be controlled using different parameters such as type of gas injection, gas pressure and operating voltage and anode's insert materials. Therefore, the optimum characteristics of X-ray in these devices are determined only by experimental studies.

There have been many studies on X-ray emission of PF devices. Beg et al. 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 (Beg et al., 2000). Shafiq et al. also studied X-ray emission in different energy windows by filtered pinhole camera and PIN diode detector together with Ross filters. They used a high atomic number metal (lead, tungsten, and molybdenum) for the anode's tip. They concluded that the maximum energy at the 4π geometry was obtained for the three inserts of Pb, W, and Mo was 29.4 ± 0.2, 3.43 ± 0.05, and 4 ± 0.02 J respectively (Shafiq et al., 2003). Hussain et al. placed lead insert inside copper anode of the 1.8 kJ plasma focus device, which was filled with hydrogen gas. They measured the X-ray radiation intensity across different energy windows. They performed spectral analysis by PIN diode detectors with Ross filters. The maximum intensity at 4π geometry was obtained as large as 27.3 ± 1.1 J. They also obtained the images of X-ray emission zone by pinhole camera at the optimal pressure of 0.5 mbar. For this purpose, they placed a filter on the aperture of pinhole camera, then separated soft and hard X-ray emission zones from each other and observed these zones on Fuji films (Hussain et al., 2003). Hussain et al. also investigated the total X-ray yield of plasma focus with different inserts (Cu, Mo, W and Pb) at the anode tip. They also investigated the X-ray emitting zone with tungsten at the anode tip. They found that the energy of X-rays emitted from plasma region is less than 5 keV and hard X-rays are emitted only from the central portion of anode tip. Their

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experiments indicated that the X-ray emission with energy > 5 keV is spread out over the tip of the anode and the harder X-rays are concentrated towards the center of the tip of the anode (Hussain et al., 2006). Mohammadi et al. studied the 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 (Mohammadi et al., 2009).

Today, various studies have been performed to use plasma focus device in medical and industrial imaging. Raspa et al. prepared the images of rapid rotating aluminum blades using high-energy and pulsed X-ray generated by plasma focus device 4.7 kJ, which operated with a mixture of deuterium-argon gas (Raspa et al., 2004). Further, several years later, they used the same device as pulsed X-ray generator with repeatable energy spectra within the range of 40–150 keV and obtained the radiographic image in a discharge with a favorable contrast (Raspa and Moreno, 2009). Baijan et al. (2010) performed some experiments with radiographic films and found that the penetration of X-rays changes with the energy stored in the capacitive bank and with pressure of argon gas. Da et al. (2001) studied the feasibility of the new technology of plasma focus regarding the rapid radiography of objects. Kanani et al. (2014) determined the parameters of the image quality of X-ray radiography imaging using a small plasma focus device.

The X-ray emitting zone in PF device is one of the important characteristics to better understand and use this device in industrial and medical imaging. The geometry and dimensions of the X-ray emitting zone provides useful information about the source used in the imaging applications. In this research, attempts were made to examine the effect of the material of anode insert on X-ray emission zone. For this purpose, six metal insert fabricated out of aluminum, copper, zinc, tin, tungsten and lead were used. For each of the inserts, under various conditions at different pressures and voltages, pinhole cameras captured the X-ray emission zone and further analysis was performed based on the images.

2. Laboratory layout

In this research, plasma focus device of Mather-type in the energy range of 2–3 kJ was employed. This device is supplied by a 11.4 μF capacitor as energy storage. The central anode is made of copper, its diameter is 2.5 cm and its effective length is 13 cm. Anode's tip has a cylindrical hole with a diameter of 1 cm and depth of 2 cm so that the insert materials could be embedded into this site. The insulator between the anode and cathode is made of quartz with a length of 6.2 cm. For the plasma focus device, six insert materials in a cylindrical form with a diameter of 1 cm were fabricated out of aluminum, copper, zinc, tin, tungsten, and lead. These inserted materials were placed in the hole of the anode such that their tip was at the same level with the central anode and there was no protrusion or dent on tip of anode.

To record the image of pulsed X-ray emission zone from the plasma focus device, three pinhole cameras were installed around the chamber, according to Fig. 1, Pinhole camera is an effective instrument for studying the X-ray emission zone. This instrument can offer some characteristics including an overview of the spatial position of X-ray emission zone, its approximate size, and a qualitative view of the radiation density of the X-ray source.

In a pinhole camera, whatever the aperture is smaller in comparison with the object, spatial resolution of the image will be improved. If the aperture diameter is not much smaller than the object size, the details of the object cannot be recognized in the image, however, it is possible to realize general information about size of the source. The experiments were carried out using the 500 μm aperture and magnification of the cameras was adjusted unity.

Placing a filter between the aperture of pinhole camera and the radiographic film can affect the radiation from the X-ray source and complicate analysis of the formation of X-ray emitting zone because the filter has different attenuation coefficients for different energies.

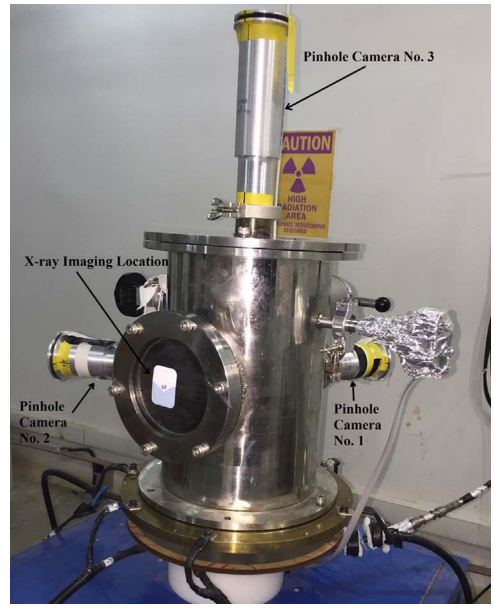

Fig. 1. Plasma focus device and pinhole cameras.

Accordingly, we did not use any filter in this study. The images were recorded on Kodak E-speed dental radiographic films. The darkness of the points on the film is proportional to the exposed X-ray dose; therefore, level of the darkness denotes intensity and energy of radiation emitted from different parts of the source. Images of the X-ray source were scanned at 1200 dpi resolution.

By placing different inserts in the hole of the anode tip, the images of pinhole cameras were recorded under different conditions. For every insert, at voltage of 21 kV, the images of every pinhole camera were recorded at four different pressures of injected air (as working gas) including 0.3, 0.6, 0.9, and 1.2 mbar. Then at pressure 0.9 mbar, the images of pinhole cameras were recorded at 19, 21 and 23 kV respectively.

X-ray emission from plasma focus device shows shot-to-shot variation. From the application point of view, single shot is probably not proper choice. Average or integration of an output over higher number of shots (in the same conditions) will be more predictable than output of single shot. On the other hand, higher number of shots in each experiment, result to increase in darkness of the films. We conducted experiments with three and five shots, and we observed that in five-shots experiments, the films were saturated in most of the experiments. Number of three shots was optimum for our experimental setup. In each experiment, the film was exposed to three consecutive successful shots of the plasma focus device in the same operating conditions (i.e. gas, pressure, charge voltage, and anode insert). Therefore, the X-ray emission zone that is reported in this paper is integrated zone over three successful shots under similar conditions. The evidence that confirm the occurrence of a successful shot (Pinch) is a sharp spike in the current derivative signal, as well as observation of X-ray pulse by a scintillator detector. Unsuccessful shots were rarely happened.

The current derivative signal was measured using a Rogowski coil. The intensity of the pulse x-ray transmitted from the Plexiglas window of the vacuum chamber was measured using a scintillator detector (BC-400) placed 1.5 m in front of the Plexiglas window.

3. Results and discussion

Formation of X-ray source at different operational pressures for the six insert materials are shown in Fig. 2. In this figure, the images are recorded by the lateral pinhole camera. These images were obtained at the constant voltage of 21 kV. It can be concluded that in low pressures