Study of Plasma Sheath Formation in a Low Energy Plasma Focus

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The effects of gas pressure and insulator length on uniform formation of current sheath in a low energy (1.4 kJ) Mather type plasma focus are investigated. The PF device is powered by a 11 μF single capacitor bank, charged at 15 kV giving peak discharge current of 130 kA. The formation of the current sheath is monitored using a magnetic probe. The magnetic probe was radially inserted between the anode and the cathode at the middle of the insulator length to explore the evolution of the plasma sheath during the initial phase. The radial component of the sheath velocity during the formation of plasma column is measured at various locations. All of the measurements were performed using argon and nitrogen as the filling gas. The magnetic probe measurements show a rather symmetric profile for the current sheath near the insulator. Results of velocity variation as a function of the sheath position from the insulator, for different insulator lengths and filling gas pressures, are presented and the sheath uniformity is analyzed.

Keywords: current sheath, Plasma Focus devices, insulator length, Mather type plasma focus, filling gas pressure, Nitrogen filling gas, magnetic probe, sheath velocity.

1. Introduction

Plasma Focus devices are versatile sources of high intensity x-ray pulses [1], fast neutrons [2], energetic electron [3], and ion beams [4]. These devices have found variety of applications such as x-ray lithography, x-ray spectroscopy, material coating through ion sputtering, pulsed activation analysis, and material research. The operation mechanism of a Plasma Focus is commonly divided into three phases; the initial break-down phase, the run-down phase, and the compression phase. The initial break-down starts by application of a large voltage across the anode-cathode electrodes and formation of a current sheath. During the run-down phase, the $J \times B$ force due to the coupling of the current density and the self-generated magnetic field guides the current sheath axially upwards along the anode. The compression phase starts when the current sheath reaches the top of the anode. At this stage, the $J \times B$ force and the inertial force compress the plasma column inward. This leads to the focusing phase of the plasma column where a hot and dense column of plasma is formed.

The characteristics of the initial formation of the current sheath in Plasma Focus devices can be important for the optimized operation of the device. In this paper, we present the results of experiments conducted on a low energy (1.4 kJ) Mather type Plasma Focus, using a magnetic probe to study the dynamics of current sheath formation. The effects of gas pressure and insulator length on uniform formation of current sheath in the PF device are investigated

2. Experimental setup

The experiments were carried out on a 1.4 kJ Mather type Plasma Focus device. The PF device was driven by a 11 μF single capacitor bank, charged up to 15 kV giving peak discharge current of 130 kA. The stored energy of the capacitor bank was transferred to the anode-cathode assembly through an atmospheric pressure spark gap. The anode electrode was a 120 mm long, 20 mm in diameter copper rod. Six 130 mm long and 9 mm in diameter copper rods, equally spaced from the anode, formed a 30 mm radius cathode. All six electrodes were screwed to a copper cathode base plate. The position of cathode electrodes around the anode was completely symmetrical and provided a cathode to anode radius ratio of 3. A 2.5 mm thick Pyrex insulator sleeve shielded the anode electrode from the cathode base plate. The insulator radius was 12.5 mm. The insulator length was adjustable and was varied from 20 to 40 mm throughout the experiments. The anode-cathode assembly was placed inside a stainless steel vacuum chamber and a rotary vane vacuum pump evacuated the chamber. A schematic diagram of the chamber along with the electrodes is shown in Figure 1.

To study the plasma evolution during the initial phase, a magnetic probe was radially inserted between the anode-cathode electrodes. The magnetic probe consisted of a four turn, 2 mm in diameter coil connected to a 50 Ω micro-coaxial cable. A brass sleeve of 4 mm diameter covered the coaxial cable to provide the electromagnetic shield to the probe. The vacuum seal of the probe assembly was accomplished by enclosing the entire structure in a 6 mm diameter closed end Pyrex tube. This also provides further electrical shielding to the probe. The center of the probe coil was located at the middle of the insulator length, oriented in such a way to monitor the azimuthal component of the magnetic field. At each probe location five shots were recorded to assure the reproducibility of the signals.

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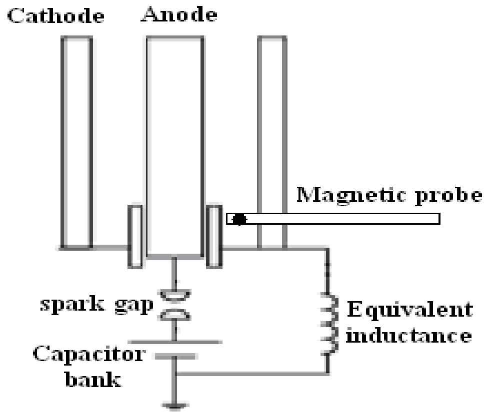

Fig.1: A schematic of the plasma focus electrodes and the magnetic probe.

A high voltage probe with a response time of 2 ns was connected across the anode-cathode electrodes to register the transient high voltages. A typical high voltage probe signal is shown in Figure 2. A calibrated Rogowski coil was used to measure the transient discharge currents. The signals from the HV probe and the Rogowski coil were recorded on a four-channel 250 Mega-sample per second digital oscilloscope.

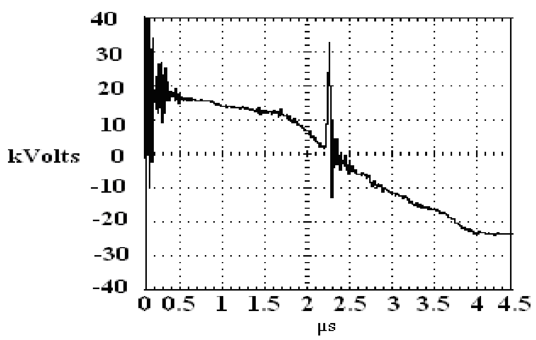

Fig.2: Typical high voltage probe signals showing the plasma focus effect.

3. Experimental results

The PF vacuum chamber was evacuated up to 10^{-2} mbar and then filled with nitrogen gas at different filling pressure. In order to characterize the radial velocity of the current sheath, three sets of experiments were conducted. In the first set, the charging voltage as well as the insulator length was kept constant while varying the vessel pressure. The second series were performed under constant charging voltage and operating pressure while insulator length was changed. In the last set, the charging voltage varied while the gas pressure and the insulator length were constant. In this article, we are only reporting the results of the former two series of experiments

In the first series of experiments, the magnetic probe signals were recorded by operating the system at filling pressures of 0.5, 1.0, and 4.0 mbar. At each operating pressure, the probe tip was set at five different radial locations, starting from the insulator position out towards the cathode electrode in steps of 2.5 mm. Figures 3(a)-(c) show the magnetic probe signals taken at radial positions $r = 20, 25,$ and 30 mm from the symmetric axis of the anode for various pressures. The probe signals show rapid rise-times at lower filling pressure regardless of the radial position of the magnetic probe. Moreover, for the entire pressure range and different location of the magnetic probe tip, the probe signal is broad.

In order to characterize the effect of the insulator length on current sheath formation and its radial velocity, the second series of experiments were performed at constant charging voltage and pressure while changing the insulator length.

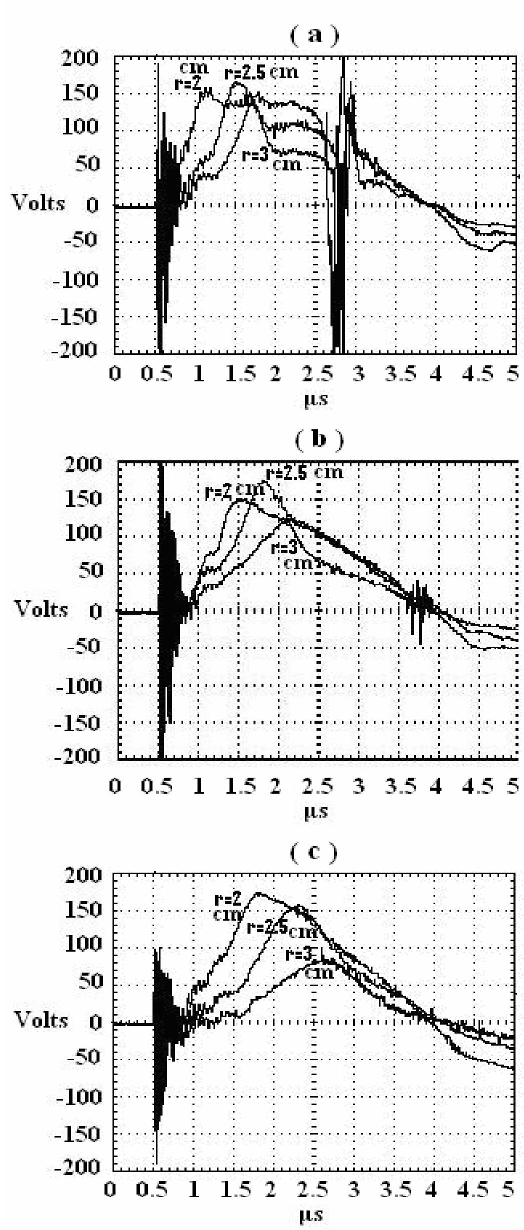

Fig.3: Magnetic probe signals taken at three different radial positions for operating pressures: (a) $p = 0.5$ mbar, (b) $p = 1.0$ mbar (c) $p = 4.0$ mbar .

In Figures 4(a)-(c), the signals of the magnetic probe registered at previous radial positions for insulator lengths of $L_{ins} = 25, 30$, and 35 mm are shown. The gas filling pressure was kept constant at 1 mbar and the charging voltage was 15 kV. Once again, a point worth noticing is the broad peak nature of the magnetic probe signal for various insulator lengths. This indicates the passage of the current sheath through the tip of the probe. It is clear from Fig. 4(b), that a strong pinch effect takes place when the anode-cathode insulator shield is 30 mm long.

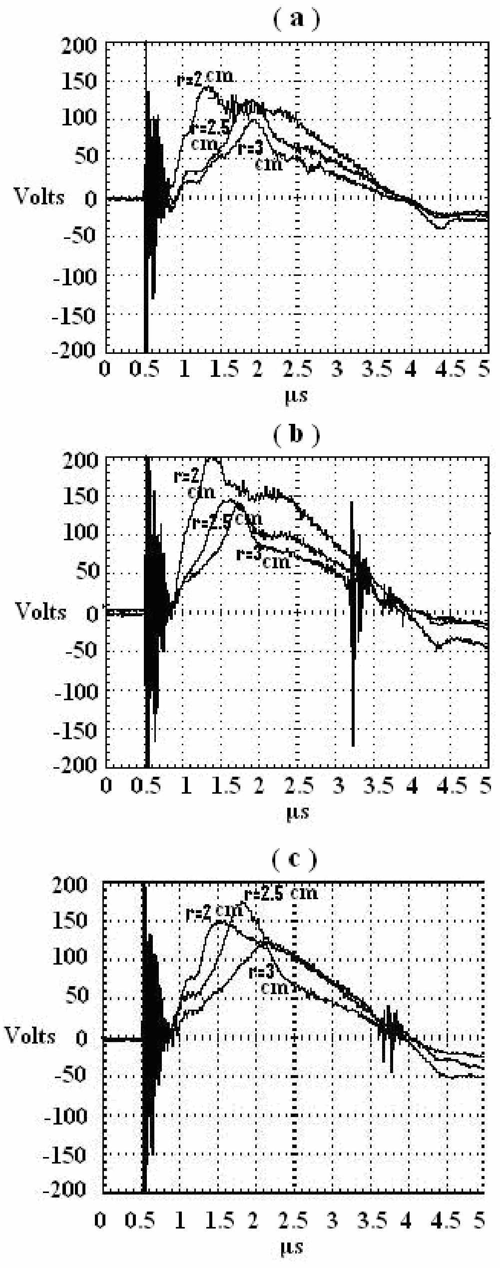

Fig.4: Magnetic probe signals taken at three different radial positions for insulator lengths: (a) $l = 25$ mm, (b) $l = 30$ mm, and (c) $l = 35$ mm.

4. Discussion and conclusion

The measured magnetic probe signals provide valuable information on how discharge plasma evolves during the initial phase of operation in a Plasma Focus device. Inspection of the first series of experiments (Fig. 2(a)-2(c)) indicates that an enhanced pinch effect occurs at low filling pressure of 0.5 mbar. By increasing the gas pressure, the pinching trend weakens and no pinch effect can be realized at gas pressure of 4.0 mbar. It is obvious from these figures that at lower gas pressures, pinch-effect happens at earlier times.

The data gathered for various insulator lengths at constant pressure as well as different filling gas pressure at fixed insulator length indicates that the amplitude of the magnetic probe signal decreases by moving towards the cathode. Another point of notice is the symmetrical behavior of the signal near the insulator. During the run-down phase of the PF device and under the assumption of constant current, the voltage signal of the magnetic probe is proportional to the current density distribution of the current sheath [5]. The assumption of constant current is not valid for the initial breakdown phase. Bruzzone and Grondona have demonstrated that the probe voltage is proportional to the current density of the current sheath during the initial phase (at which the current is not constant), if the current density profile and its velocity do not change during the transit time [6].

The collected data from the magnetic probe measurements show that the velocity of the radial movement of the current sheath at different filling gas pressure is almost constant. The least variation in current sheath velocity is observed for the operating gas pressure of 1 mbar. In Table 1, values of radial velocity at different probe location for various gas pressure is tabulated. In the second column of the Table, the estimated take off times obtained from the probe measurements are listed. The take off time is the initial acceleration time after which the current sheath travels at constant velocity. The velocity of the current sheath listed in column 4 of the Table was determined by measuring the time delay for the change of the distance between the probe tip and the anode electrode (the take off time is included in calculation). It is clear that at gas pressures of 0.5 and 4.0 mbar, the variation in the current sheath velocity is more significant than the desired operating pressure of 1.0 mbar.

In conclusion, the dynamics of the current sheath during the initial break down phase in a Mather type PF device is investigated. The radial motion of the current sheath was monitored with a magnetic probe. Our results show that, for an optimized filling gas pressure of 1 mbar, the current sheath moves at a constant velocity. Change in the insulator length has almost no effect on the velocity and only leads to an improved break down and pinch condition. In addition, a good focusing strongly depends on the sheath velocity in the break down phase. This fact is substantiated from the data listed in the Table 1 and also from the magnetic probe signals shown in Figures 3(a)-4(b).

Table 1. Values of τ_{off}, v_r, and v_{rav} for a typical insulator length.

P (mbar)	τ_{off} (ns)	r (cm)	V_r (cm / µs)	v_{rav} (cm / µs)
0.5	170	r = 2	v_r =4.65	3.52
		r = 2.5	v_r =3.01	
		r = 3	v_r =2.91	
1	200	r = 2	v_r =2.22	2.21
		r = 2.5	v_r =2.27	
		r = 3	v_r =2.14	
4	270	r = 2	v_r =1.94	1.67
		r = 2.5	v_r =1.44	
		r = 3	v_r =1.63	

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