

Research Article

Study of Magnetic Field Behavior at Lower Pressure of Neon in the Axial Phase of INTI Plasma Focus

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Abstract: The magnetic field distribution substantially affects mechanisms for the generation of radiation in Z-pinches. Investigation of the axial component of the magnetic field is one of the important problems in plasma focus studies. The designed magnetic probe is intended to use for the study of current sheet in INTI plasma focus device with energy of about 3.3 kJ. The measurements of the azimuthal component of the magnetic field on the INTI Plasma Focus operated at neon pressures below 1 Torr was carried out using a custom built calibrated magnetic probe. The probe was tested for neon gas under the various lower pressures (i.e., 0.1, 0.3, 0.5 and 0.7, 1, 2, 3, 5 torr etc.). It is observed that the time response of the designed probe is sufficient for the rise time of the magnetic field associated with the current in the axial phase. We also note that the small size of the designed probe is well suited to sense the magnetic field without perturbing the plasma unduly. The probe designed and constructed is also suitable to carryout measurements to obtain axial distributions of trajectory, average axial velocity and magnetic field of the current sheath at a certain radial distances along the axis of the tube.

Keywords: Axial velocity, current sheath, plasma focus, pulsed plasma, radial distance, tiny structure

INTRODUCTION

A plasma focus produces plasma of high energy density with emission of intense beams of charged particles and radiation and neutrons when operated in deuterium. Thus, it becomes a laboratory for fundamental and applied research related to fusion, neutron production, hard and high brightness soft x-ray production and astrophysical phenomena (Bernard *et al.*, 1998; Soto, 2005; Lee, 2011). The use of neon in a plasma focus is important because of the intense radiation achievable, particularly in Soft X-Ray (SXR) regime, which has several applications (Lee *et al.*, 1988a; Wong *et al.*, 2004; Kato *et al.*, 1988; Beg *et al.*, 2000; Rawat *et al.*, 2004; Gribkov *et al.*, 2002). The development process of current sheath in the Mather type plasma focus devices can be divided into three main phases as Initial breakdown, Axial acceleration and Radial collapse. In Initial breakdown phase, the capacitor charged by a high voltage source switched on to the inner electrode and discharge occurs across the surface of the insulator between the electrodes. The initial gas break down between the inner electrode (anode) and the back plate of the focus tube forms weak

current filaments. The current filaments at the inner surface of the outer electrode blend to form a uniform, homogeneous and azimuthally symmetric current sheath which is lifted off the insulator surface by the $J \times B$ force. The plasma dynamics enter into the axial acceleration phase with the uniform current sheath formation. The features of the formed current sheath are essential for final focusing of plasma with maximum energy density. The current that flows outwards between the electrodes in axially symmetric sheath now has a strong radial component. This provides a strong axial component of $J \times B$ resulting in the acceleration of the current in the forward z-direction towards the open end of the coaxial electrode assembly. As the current sheath experiences stronger magnetic field influence nearer the anode, the radial component of the $J \times B$ force also decreases accordingly, causing the sheath to curve. At the end of the axial acceleration phase, begins the Radial collapse phase. In this phase the inner end of the current sheath that is attached to the central electrode sweeps around the end of the central electrode (anode) and finally collapses at the centre of the anode due to radially inward $J \times B$ force resulting in hot dense plasma column. The other end of the current sheath that has

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been sliding along the outer electrode continues in its motion. The focused plasma column has a lifetime of typically 10 ns (for a kJ device) and then it becomes unstable and finally breaks away with emission of x-rays, electrons and ions.

Behbahani *et al.* (2010) studied the dynamics of the current sheath in a low energy (4.9 kJ) PF device at various conditions of gas pressure, charging voltage and anode shape. Aghamir and Behbahani (2009), 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. Reported results showed that, for an optimized filling gas pressure of 1 mbar, the current sheath moves at a constant velocity. Hawat (2004) used a magnetic probe in analyzing the current sheath in plasma focus device with energy of about 2.8 kJ. Two magnetic probes are used in these studies for 1 mbar filling of argon. The axial distributions of trajectory, average axial velocity and magnetic field of the current sheath at a certain radial distance along the axis of the tube were obtained experimentally and compared with numerical analysis from the snow plow model for the axial phase. The arrival time of the current sheath at the end of anode (16 cm) is similar for both of the magnetic probes and gives an average velocity of the current sheath equal to 1.52 cm/ μ s. Lee *et al.* (1986) used magnetic probes and detected toroidal loops and multiple current sheaths in an electromagnetic shock tube. Gurey *et al.* (2009), studied current sheath by magnetic probes on PF-400 and detected toroidal vortexes and repeated current sheaths, indicating a complicated picture of current flow in plasma focus discharge. Other works studied the current sheath dynamics in plasma focus devices using magnetic probe technique with different designs (Bilbao *et al.*, 1985; Favre *et al.*, 1998, Bruzzone and Grondona, 1997; Bhuyan *et al.*, 2003; Soliman and Masoud, 1994; Heo *et al.*, 2003). Most of the studies using magnetic probes have been made in hydrogen, deuterium or argon. In this study we study current sheath dynamics on the INTI plasma focus device (Saw *et al.*, 2010, 2012; Lee *et al.*, 2011) using magnetic probe technique for various gas pressures of neon.

Design of magnetic probe: A multiple magnetic probe assembly with high frequency response has been specifically designed and fabricated. The probe contains three magnetic coils spaced at 4, 8 and 12 cm, respectively from its tip. The coils are closely wound from SWG 44 enameled copper wire on a Mylar former. The 3 coils are firmly fixed on a thin Mylar former and is jacketed into a 3-mm-diameter glass tube. The axes of all coils are aligned in the same direction (to measure azimuthal magnetic field). The leads from the 3 coils are brought out as a tightly twisted pair and

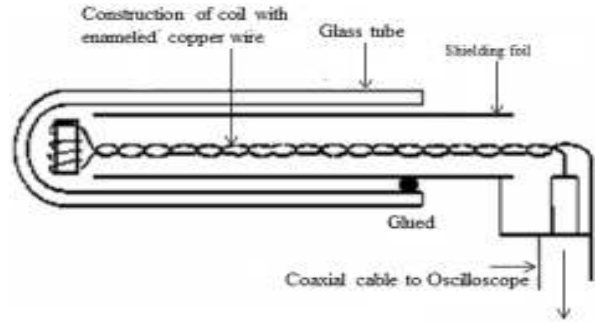


Fig. 1: Geometry of magnetic probe (only one coil is shown in this schematic)

outside the jacket they are connected to a coaxial transmission line which carries the signal to the oscilloscope directly or through an integrator circuit to display result of measurement. The geometry of magnetic probe is shown in Fig. 1 (Saw *et al.*, 2012).

METHODOLOGY

The schematic diagram of plasma focus system for the INTI PF is shown in Fig. 2 (Saw *et al.*, 2012). The system is energized by a single capacitor (30 μ F, 15 kV), with a maximum storage energy of 3 kJ. The short-circuit (static) inductance of the system is 110 nH and stray resistance is 12 m Ω . The electrodes system consists of a tubular copper anode of 16 cm length and 1.9 cm diameter and a cathode of six copper rods arranged in a circle of 6.4 cm diameter concentric with the anode. The diameter of each cathode rod is 8 mm. The anode is insulated from the cathode at the back wall by a Pyrex glass tube of 5 cm length and 2.4 cm diameter (Lee *et al.*, 1988b). The plasma focus is operated with neon. The device was evacuated to a vacuum (10^{-3} Torr) by a vacuum pump and filled to a particular pressure (0.1-15 Torr) before operation. To reduce the impurity effect, after every 2-3 shots, the previous gas is purged and fresh neon is filled. We have recorded 1-3 shots for each pressure. The derivative of the current in the discharge circuit and the voltage across the INTI PF versus time during the plasma focus process, were monitored by a 3-turn Rogowski coil and a voltage probe, respectively. Current sheath velocities were determined by using the magnetic probes. The magnetic probe was inserted vertically between the anode and cathode in the PF tube, at a radial position 1.7 cm from the center of anode. The signal from the probe allowed us to determine the arrival time and the velocity of the current sheath in the axial phase of plasma focus. All diagnostic outputs were connected to a 4-channel 300 MHz TDS3034C DSO set at a sampling rate of 1 Gsa/s. An EXCEL template was designed to facilitate faster handling of the many sets of experimental results. The details on template are as follows:

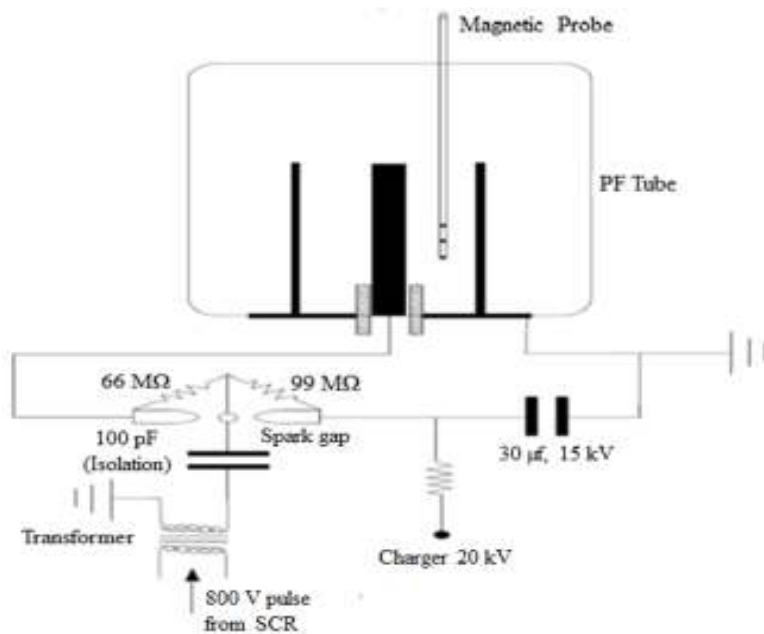


Fig. 2: Outline diagram of plasma focus device

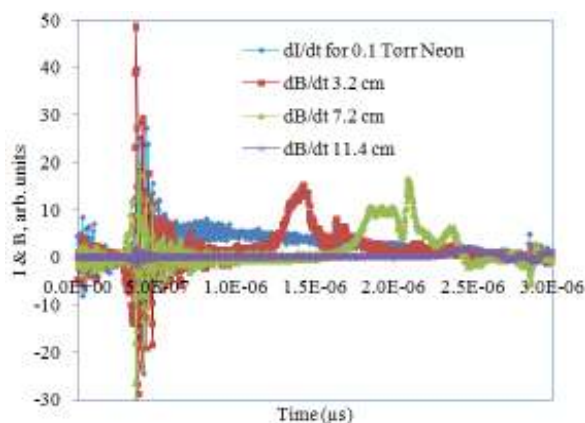


Fig. 3: dI/dt and dB/dt directly measured signals by rogowski coil and magnetic probe

Table 1: Corrected arrival times of current sheath at different positions for 0.1 torr neon

Z (cm)	t_a (μ s)	t_s (μ s)	t_{ac} (μ s)
3.2	0.92	0.11	0.81
7.2	1.44	0.11	1.33
11.4	2.03	0.11	1.92

- The digital data was placed in four columns (dI/dt, dB/dt for probes 1, 2 and 3).
- The data is numerical integrated to get the current trace I and the B traces.
- The integrated signals typically show significant baseline shifts.

The baseline shifts are evident from the traces before the start of signal e.g., for the current trace in the

0.5 μ s that signal acquisition was started before the start of discharge. It was found that each baseline shift could be fitted with a linear function which could then be extrapolated into the region of the signal. The values generated from the fitted baseline functions were then subtracted from the corresponding signals. In this way the I and B signals are corrected.

RESULTS AND DISCUSSION

Magnetic probe measurements have been investigated on INTI PF with neon at different pressures: 0.1, 0.3 and 0.7 Torr, respectively. In order to optimize the results, conditioning of PF has been done by firing several shots before collecting the data. Three sets of data with different pressure condition have been collected from magnetic probe. The results are then compared with a set of data collected at 3 Torr Neon gas, with a similar magnetic probe effectively placed at many positions above the cathode plate. This comparison enables more accurately measured arrival times especially near the starting position. Figure 3 shows dI/dt and dB/dt directly measured signals by Rogowski coil and magnetic probe at 0.1 Torr Neon. The dB/dt pulse peaks at 1.41 μ s for 3.2 cm, peaks at 2.09 μ s for 7.2 cm and peaks just past 2.42 μ s for 11.4 cm.

Figure 4 shows the magnetic field of the current sheath for 0.1 Torr Neon gas after numerical integration by EXCEL template. The start time of the current, t_s and arrival time of current sheath, t_a are recorded in Table 1 in order to calculate the corrected arrive time of

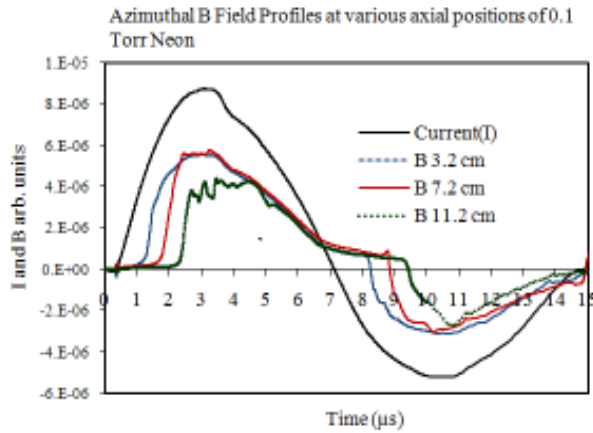


Fig. 4: Arrival time of current sheath under a pressure of 0.1 Torr neon gas

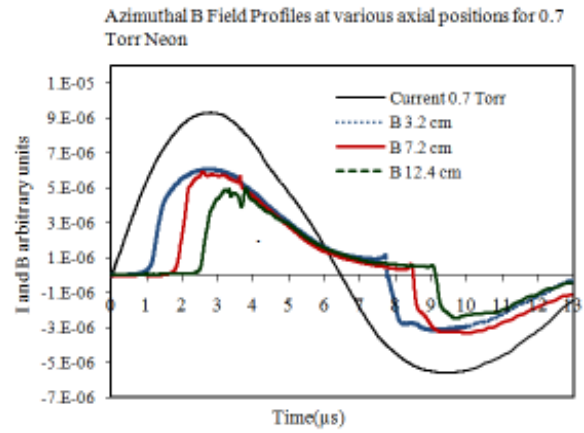


Fig. 6: Arrival time of current sheath under a pressure of 0.7 Torr neon gas

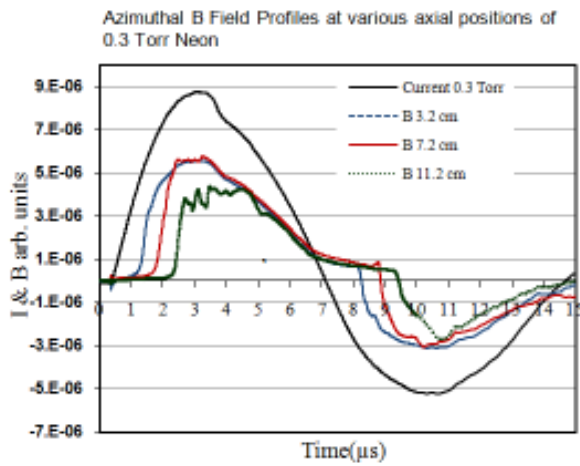


Fig. 5: Arrival time of current sheath under a pressure of 0.3 Torr neon gas

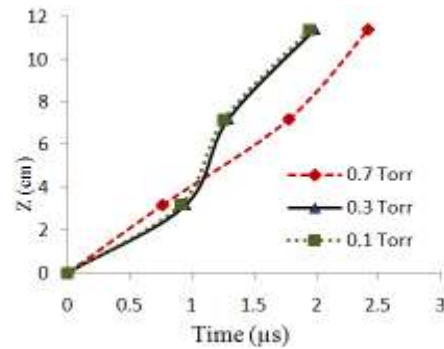


Fig. 7: Variation of the current sheath's velocity at 0.1, 0.3 and 0.7 Torr neon

current sheath, t_{ac} . The current profile of the PF tube is determined by numerically integrating the current derivative measured by the 3-turn Rogowski coil. The data of t_a , t_s and t_{ac} for three different positions, Z are shown in the Table 1. The corrected arrive time, t_{ac} is the time taken from the start of current to the time the current sheath arrives at a probe. Current sheath arrives at 3.2 cm in $0.81 \mu s$ once after the start of current, then at 7.2 cm in $1.33 \mu s$ and at 11.4 cm in $1.92 \mu s$. It is observed that there is a current dip at $3.5 \mu s$ in the current trace corresponding to a radial compression. The measurement was also carried out for 0.3 Torr neon using the same magnetic probe. Figure 5 shows the arrival times of the current sheath for 0.3 Torr neon. The corrected arrive times of current sheath, t_{ac} have been determined in Table 2. Current sheath arrives to the first coil at 3.2 cm at $1.0 \mu s$ after the current sheath is formed, arrives at 7.2 cm at $1.38 \mu s$ and at 11.4 cm at $1.99 \mu s$. It is observed that there is a current dip at 3.6

Table 2: Corrected arrival times of current sheath at different positions for 0.3 Torr neon

Z (cm)	t_a (μs)	t_s (μs)	t_{ac} (μs)
3.2	1.11	0.11	1.00
7.2	1.49	0.11	1.38
11.4	2.10	0.11	1.99

Table 3: Corrected arrival times of current sheath at different positions for 0.7 Torr neon

Z (cm)	t_a (μs)	t_s (μs)	t_{ac} (μs)
3.2	0.88	0.02	0.86
7.2	1.69	0.02	1.67
11.4	2.36	0.02	2.34

μs in the current trace corresponding to a radial compression. The measurement using the same magnetic probe was also carried out at 0.7 Torr neon. Figure 6 shows the arrival times of the current sheath for 0.7 Torr Neon gas. There is a just noticeable current dip at past $4 \mu s$.

The corrected arrival times of current sheath, t_{ac} have been determined in Table 3. Current sheath arrives to the first coil at 3.2 cm at $0.86 \mu s$ after the current sheath is formed, arrives at 7.2 cm at $1.67 \mu s$ and at 11.4 cm at $2.34 \mu s$. The axial transit time for the current sheath is longer at the higher gas pressure.

The variation of the current sheath's velocity for 0.1, 0.3 and 0.7 Torr, respectively neon were obtained by plotting the position versus time graph for each case and fitting with a second order polynomial is shown in Fig. 7. For each curve the slope of the line is gradually increasing indicating increasing current sheath velocity throughout the coil positions. At 0.7 Torr of filling pressure, the current sheath velocity is lower than at 0.1 and 0.3 Torr. This is to be expected because the load being driven by the electromagnetic force is greater the higher the pressure. In fact it was found in earlier measurements that the average speed of the current sheath scales with pressure^{-0.51} (Saw *et al.*, 2012).

CONCLUSION

Experiments are carried out on the 3.3 kJ INTI PF device with neon filling gas. A new design with a 3-turn Rogowski coil was used to measure the current derivative. New 3-position magnetic probes have been made and used to study current sheath dynamics generated in INTI plasma focus device. The current sheath arrival time, current profile and its velocity variation in the axial phase were experimentally measured for 0.1, 0.3 and 0.7 Torr neon, respectively. The average speed of the current sheath is found to scale with pressure^{-0.51} agreeing with theoretical scaling according to speed factor variation (Saw *et al.*, 2012). It is clear that the probe does affect the plasma flow and causes the axial speeds to be lower than when the probe were not there. However the disturbance caused by the probe does not seem to affect the conclusion that the speed of the current sheath scales as the inverse of square root of pressure and that over the pressures 0.1, 0.3 and 0.7 Torr neon, respectively the INTI PF axial phase is observed to be electromagnetically driven.

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