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# AXIAL DISTRIBUTION PROFILE OF MAGNETIC FIELD AND PLASMA SHEATH VELOCITY IN ARGON PLASMA FOCUS DEVICE

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## ABSTRACT

The main aim of this work is to study dynamics of plasma current sheath, PCS during the axial acceleration phase in term of its axial velocity, $V_z$ and the induced azimuthal magnetic field induction, $B_\theta$ in 2.2 KJ plasma focus, PF device of Mather type. It powered by a capacitor bank of 30 µf capacity with charging voltage of 12 KV. In the present paper all the experimental work are performed for Argon gas pressure in the range of 0.2 – 1.8 Torr. The length of the inner electrode, IE has been changed to 9.5, 10.5 and 11.5 cm respectively. To detect, $B_\theta$ and $V_z$ three identical magnetic probes are located at radial distance $r_1$ = 2.75 cm, $r_2$ = 3.5 cm and $r_3$ = 4.25 cm from the IE axis and at axial distance $z$ = 8.15 cm from coaxial electrodes breech.

The dependence of $V_z$ and $B_\theta$ on gas pressures are measured and the results of them clear that, $V_z$ is decayed with increasing of gas pressures and it has a maximum value for IE length of 10.5 cm, $P$ = 0.2 Torr and at $r_1$, while $B_\theta$ has a maximum value for IE length = 11.5 cm, 1.2 Torr at $r_1$ . Also distribution of $V_z$ with $p$ in linear fitting shows that efficient a snow-plough action is obtained approximately for IE length = 10.5 cm. Results of $V_z$ versus radial distance demonstrated that the PCS has a parabolic shape especially at lower Argon gas pressures. Results of modification factor, $F$ as a function of gas pressures show that at IE = 10.5 cm, $r_1$ and for most Argon gas pressures $F$ has a higher values than any others IE lengths and radial distances. Also the decay of $dF/dp$ along radial distances has a smaller values at IE length = 11.5 cm than any other lengths (9.5 and 10.5 cm).



## Keywords

Plasma focus; Magnetic field induction; Plasma current sheath; Modification factor.

## 1. INTRODUCTION

A dense plasma focus (DPF) device is a pulsed coaxial accelerator that produces a high-density, high temperature plasma along with particle beams and electromagnetic radiation [1, 2]. The research efforts on plasma focus devices have recently been intensified with the emergence of many new research groups across the globe [3- 6] and also due to construction of many new plasma focus facilities, particularly at lower energies, by established research groups [7- 9]. The increasing popularity of plasma focus devices is attributed to the fact that it is relatively simple and economical to construct, is an excellent platform for studying complex high energy density dense magnetized plasmas and also provides a multiple radiation source with diverse applications[10]. The overall dynamics of the plasma sheet in the coaxial annulus of the DPF device is mainly a result of three basic processes[11]:

(i) formation of an axisymmetric current sheet at insulator end of the device,

(ii) subsequent acceleration of the current sheet by the $J \times B$ force towards the open end of the electrode assembly and

(iii) rapid collapse of the current sheet at the end of the electrode assembly resulting in the formation of a thin filament of extremely hot, dense plasma.

Decker et al [12], investigated the current sheet structure (using image converter camera) in the initial breakdown phase. They observed that a luminous plasma sheet is formed near the insulator surface and it accelerated axially and radially. Magnetic probe measurements of the initial phase revealed that the thick current sheet traverses radially outward at a constant speed between 2.5 and 3.4 cm $\mu s^{-1}$ [13].

Behbahani et al. [14] 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. Two magnetic probes are radially and axially inserted in the PF tube to observe the propagation of the plasma sheath and to evaluate the range of its velocity during the breakdown and axial phases. The radial magnetic probe measurements showed a rather constant current sheath velocity near the insulator, which was more sensitive to the variations of the gas pressure than the charging voltage, and the current sheath did not lose its uniformity by expanding away from the insulator during the break-down phase.

This paper will throw some light onto the effect of varying the inner electrode length on the plasma current sheath, PCS behavior and its associated azimuthal magnetic field induction along a radial and axial direction between the coaxial electrodes system by using magnetic probe technique for various Argon gas pressures.

## 2. EXPERIMENTAL SETUP

The experimental set-up with the equivalent circuit for our study is shown in figure (1a, b). It consists of a plasma focus tube, power supply, storage capacitor bank, spark gap, triggering unit, storage oscilloscope and a set of three magnetic probes.

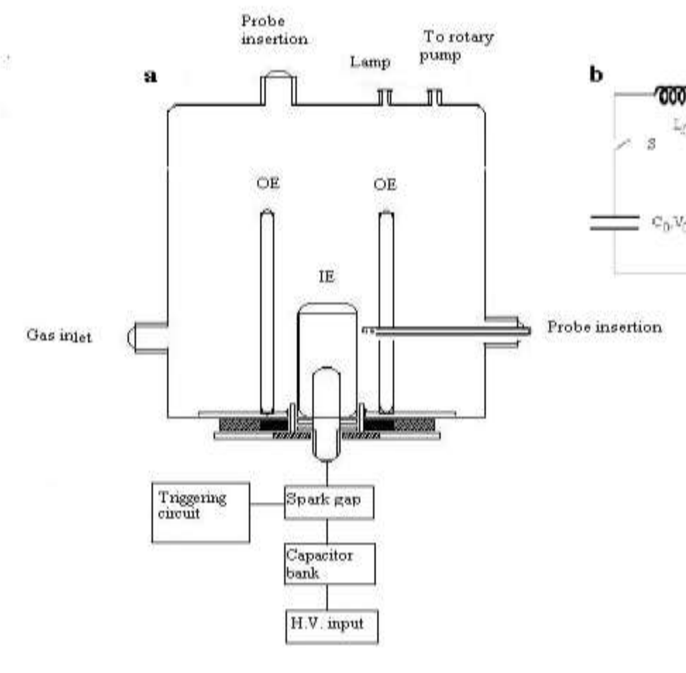


**Fig. (1) The experimental setup (a) and its equivalent circuit (b)**

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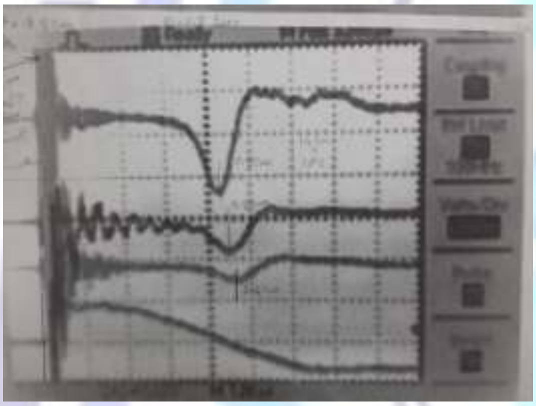
The plasma focus, PF device used consists of a brass plate carrying the inner and outer electrodes, IE and OE. Each of them is made from brass. The IE used has a diameter of 4.5 cm with lengths 9.5, 10.5 and 11.5 cm. The OE consisted of eight brass rods each of them has a length of 18 cm and thickness 1 cm fixed around the inner electrode in the form of a squirrel cage, on a diameter of 9 cm. A Pyrex glass insulator of 2.1 cm length is inserted between the coaxial electrodes and held in position by a thick rubber. This rubber acted as a vacuum seal and insulator between the two electrodes.

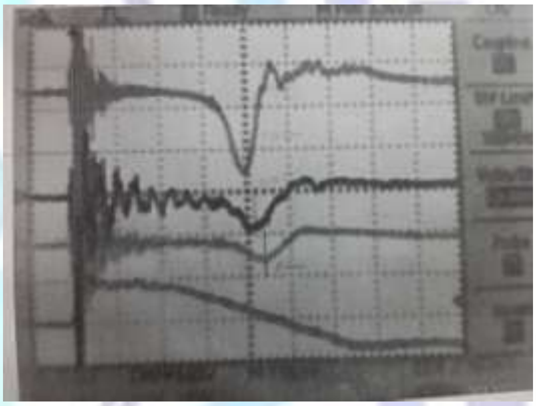
The plasma focus chamber is made of stainless steal. It is 35 cm long and 41.7 cm in diameter. The chamber is evacuated to a proper vacuum and then filled with Argon gas at pressure ranging from 0.2 to 1.8 Torr where an Edwards High Vacuum Gauge is used to measure the gas pressure. A capacitor bank of 30 μF capacity is charged up to 12 kV and discharged through an open air spark gap to give a total energy of 2.2 kJ. A set of three identical magnetic probes are inserted in the radial direction within the annular space between the coaxial electrodes, at axial position z = 8.15 cm (z = 0 at the back plate) to measure the rate of change of the induced azimuthal magnetic field induction, ($dB_\theta/dt$). Each probe consists of 7 turns of thin Copper wire 0.28 mm in diameter wound around a spool of 1 mm in diameter and this coil has 1 mm length. The three probes are located within a glass tube. Measurements are made as a function of radial distances $r_1$, $r_2$, and $r_3$ where $r_1$ (distance between the first probe and the axis of inner electrode) = 2.75 cm, $r_2$ = 3.5 cm and $r_3$ = 4.25 cm.

## 3. RESULTS AND DISCUSSION

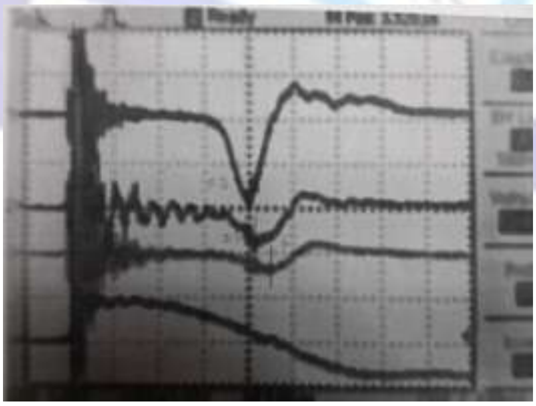
Magnetic probe measurements have been investigated on PF with Argon gas at different pressures ranging from 0.2 to 1.8 Torr. As the current sheath traverses through the magnetic probe coil, a voltage is developed at the out put of it due to the change in magnetic flux in the coil; the output signal from magnetic probe describes $dB_\theta/dt$. This signal is transmitted to the oscilloscope through coaxial cables. Some oscillograms of magnetic probe signals $dB_\theta/dt$ (at axial distance = 8.15 cm) at different IE lengths, different gas pressures and at time base of 1 μs are shown in figure (2). The magnetic field signal rises sharply because of the large current at the plasma sheath, and decreases in its amplitude as the later moves down the location of magnetic probe.



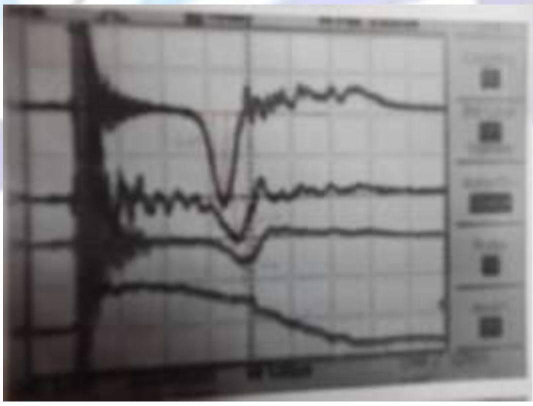
IE= 9.5 cm, p= 1.8 Torr



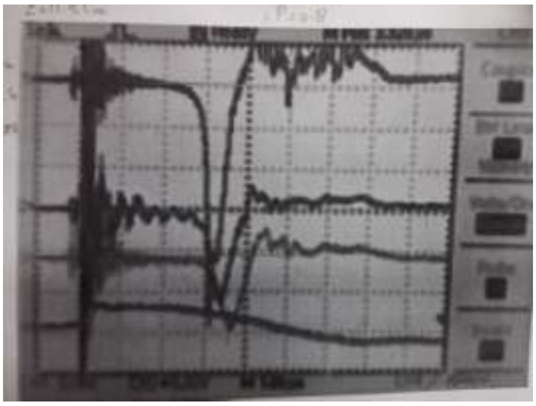
IE= 9.5 cm , p=1.6 Torr



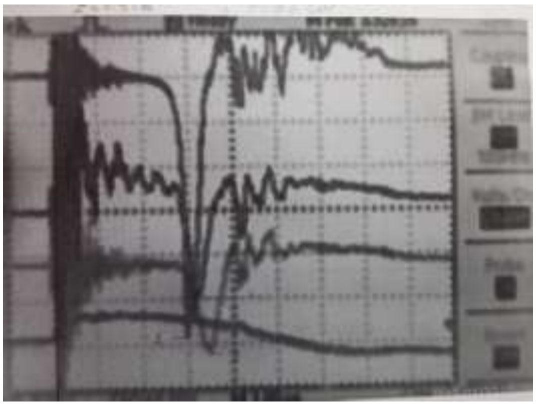
IE= 10.5 cm, p= 1.2 Torr



IE= 10.5 cm, p=1 Torr



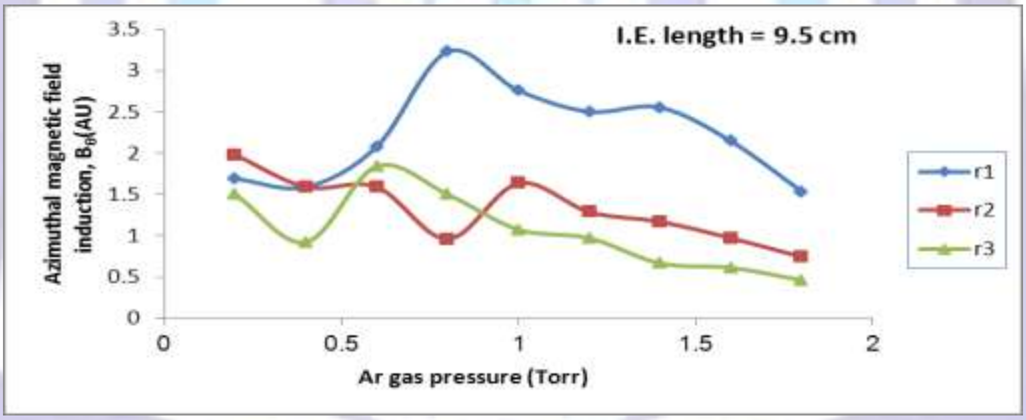
IE= 11.5 cm, p= 0.6 Torr



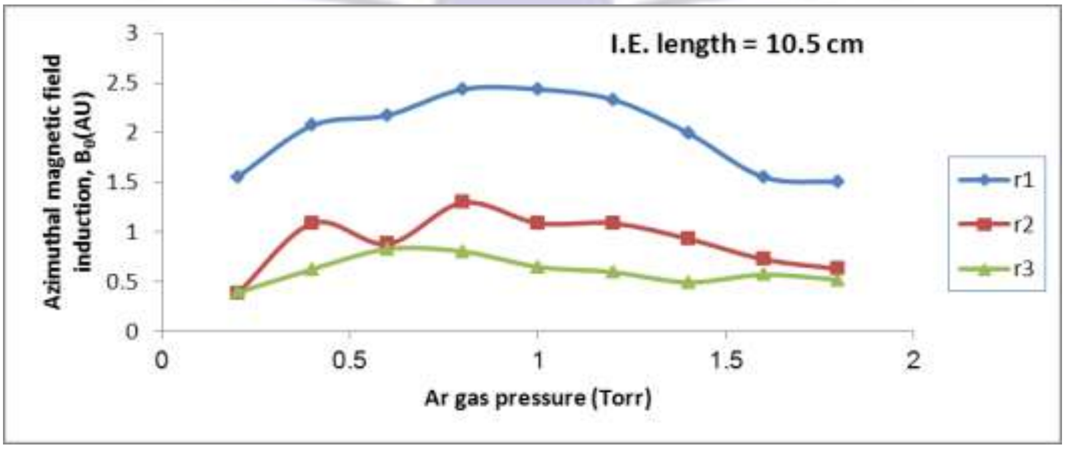
IE= 11.5 cm, p= 0.8 Torr

**Fig. (2): Magnetic probe signals (at axial distance = 8.15 cm) at different IE lengths, different Ar gas pressures and at time base 1 μs (traces upper, middle, lower). The discharge voltage signal (last trace)**

The variation of maximum azimuthal magnetic field induction $B_{\theta(max)}$, obtained by integrating ($dB_{\theta}/dt$) signals in figure (2), at $z$ = 8.15 cm with Argon gas pressure at different radial locations of the probe and for the different electrode lengths is obtained and plotted as shown in figure (3a, b, c). The figure shows that the magnitude of $B_{\theta(max)}$ decreases as the probe radial location distance from the inner electrode increases. This is because the magnitude of the field has a ($1/r$) fall-off as expected from the relation ($B = \mu I / 2\pi r$). It can be seen also that $B_{\theta(max)}$ is greater at IE length of 11.5 cm, $r_1$ and $p$ = 1.2 Torr. For IE length = 10.5 cm and at $r_1$ the plot clears that the $B_{\theta(max)}$ amplitude is almost constant in range of Argon gas pressure from 0.8 to1.2 Torr.




(a)




(b)

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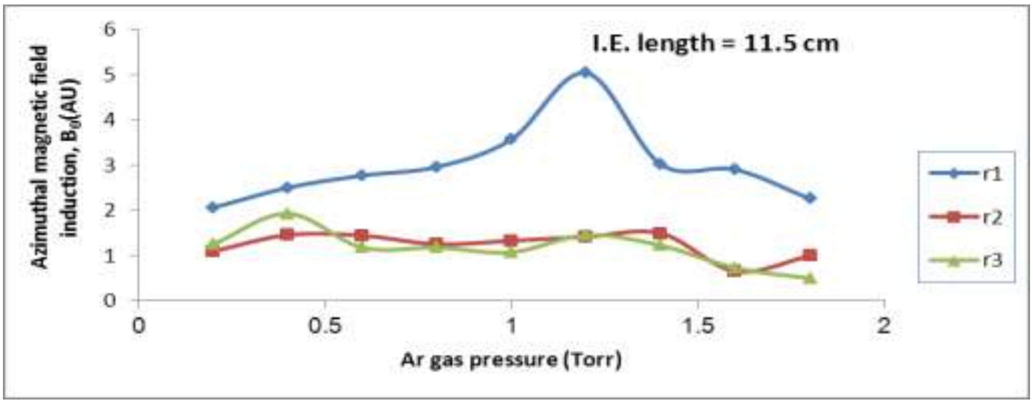
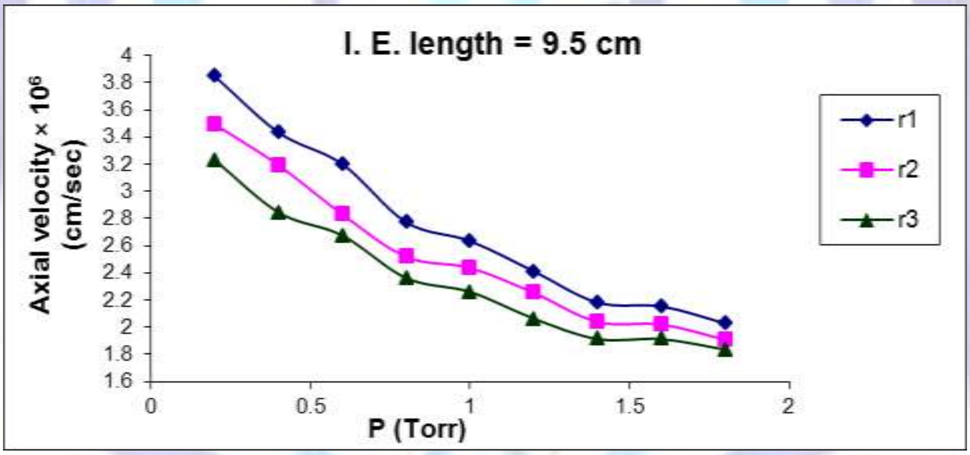



(c)

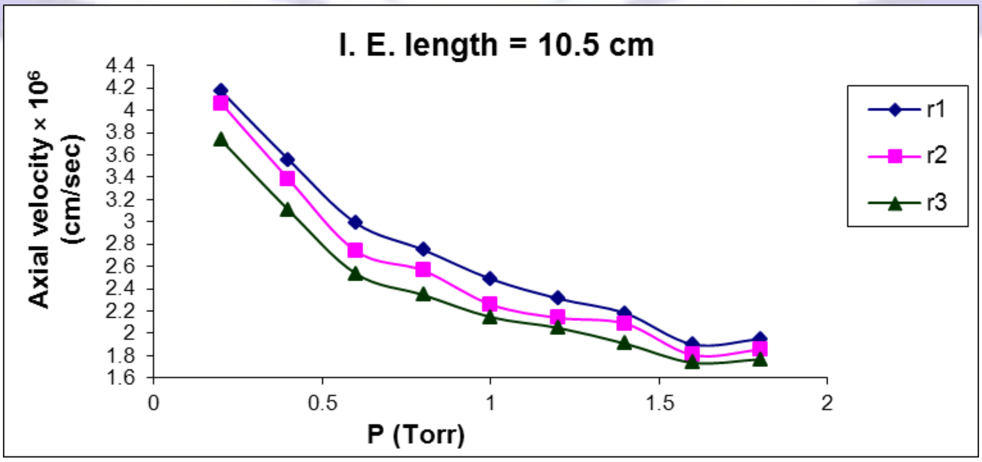
**Fig. (3 a, b, c) Variation of maximum azimuthal magnetic field induction $B_\theta$ with gas pressure at different IE lengths and different probe positions**

Magnetic probe signals mentioned above were used to estimate the axial PCS velocity, $V_z$ as a function of Argon gas pressures, radial distance as well as different IE lengths. $V_z$ is estimated from knowledge of the arrival time, $t$, of maximum $dB_\theta/dt$ signal at axial distance $z$ = 8.15 cm, then $V_z = z / t$.

The variation of the current sheath's velocity versus gas pressure for the range of pressure under investigation is shown in figure (4 a, b, c). From this figure it can be noticed that the PCS velocity decreases as the gas pressure increases. This is agreed with the fact that the current sheath moves slower in a higher gas pressure condition due to a decrease of the mean free path of gas. Maximum velocity is found to be $4.17\times10^6$ cm/s at IE length of 10.5 cm and $p$ = 0.2 Torr.




(a)

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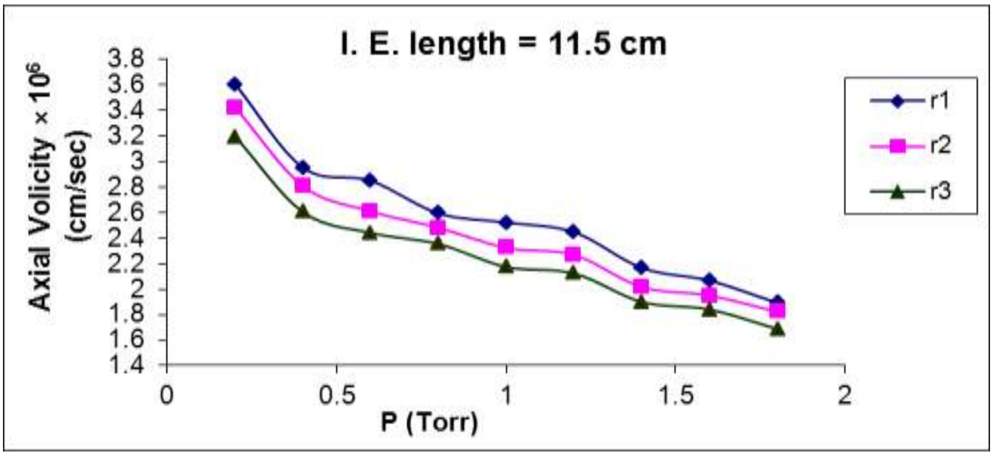



(c)

**Fig. (4 a, b, c) Variation of axial plasma sheath velocity vs gas pressure at different IE lengths and different probe positions**

Figure (5 a, b, c) shows the variation of the axial plasma sheath velocity with the radial positions at different gas pressures and for different IE lengths. The plot indicates that the portion of the plasma current sheath near the outer electrode (cathode) lags behind the portion near the inner electrode (anode). These results verify that the current sheath across the electrode assembly is not planer; it is canted back words from the anode to the cathode. This indicates that the profile of the current sheath is in general has a clear parabolic shape especially for lower values of gas pressures.

A linear fitting of the axial plasma sheath velocity and gas pressure for different IE lengths and different radial positions is shown in figure (6 a, b, c). This figure indicates that $V_z \alpha P^{-0.3}$, $V_z \alpha P^{-0.4}$ and $V_z \alpha P^{-0.3}$ for inner electrode length of 9.5, 10.5 and 11.5 cm respectively. These results verify that, the PCS dynamics for IE length of 10.5 cm obeys approximately a snow plough action [15] and inefficient snow plough action by PCS is detected for IE lengths of 9.5 and 11.5 cm respectively.

A modification factor $F = f_c / \sqrt{f_m}$ [16], (where $f_m$ is some percent of mass was sweeping by PCS, and $f_c$ is some percent of bank current was driving the PCS), is estimated from the following equation of plasma sheath motion [15, 17, 18].

$$Z = \frac{\left(\mu_0^{\frac{1}{2}} I_0 f_c \left(\ln {}^{b}/_{a}\right)\right)^{1/2}}{2\pi \left(b^2 - a^2\right)^{1/2} \rho^{\frac{1}{2}} \sqrt{f_m}} \left(t^2 - \frac{1}{w^2} sin^2 wt\right)^{1/2}$$

Assuming sinusoidal variation of discharge current, $I = I_o \sin wt$, where $I_o$ is the maximum discharge current, $w$ is the angular frequency of time varying current, $t$ is the PCS arrival time, $\rho$ is the gas density, $\mu_o$ is the permeability of free space, $a$ and $b$ are radii of the inner and outer electrodes respectively and $z$ is the axial distance traveled by PCS, in our experiment we take $z$ = 8.15 cm, $w$ and $I$ are detected previously in reference [19].

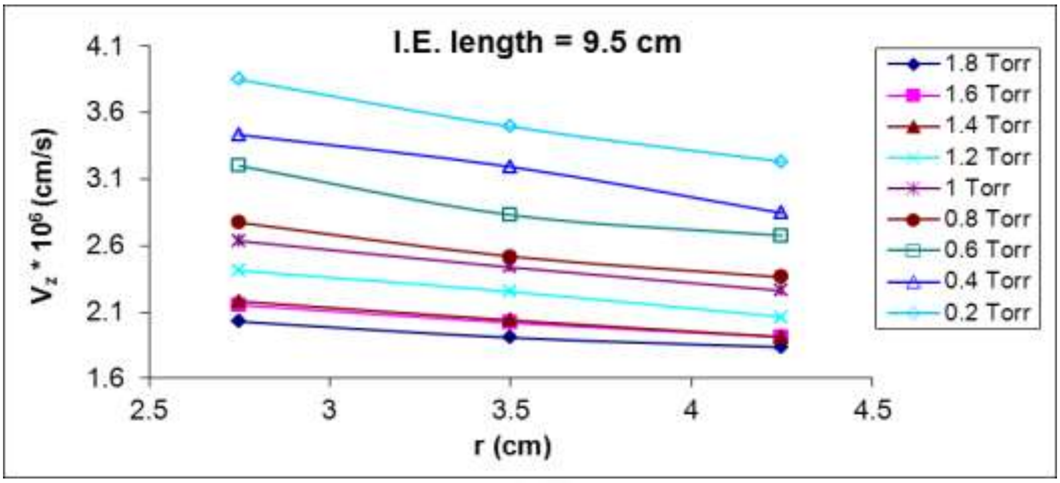
Dependence of modification factor, $F$ on Argon gas pressures is plotted in figure (7 a, b, c) for different radial distances for each IE length of 9.5, 10.5 and 11.5 cm. The curves in these figures show that, distribution of $F$ with gas pressures, for $r_1$, $r_2$ and $r_3$ has approximately the same behavior for each IE length, also at IE = 10.5 cm, $r_1$ and for most Argon pressures, $F$ has higher values than any others IE lengths and radial distances. From a linear fitting shown in the same figures mentioned above we noticed that the modification factor is decayed with increasing of gas pressure. The rate of change of F with gas pressure *dF/dp* data are listed in table 1 for different radial distances and different IE lengths.

It is seen from the data of table 1 that *dF/dp* is decreased with increasing the radial distances for all IE lengths and for all operation conditions under consideration. Also *dF/dp* at IE = 11.5 cm and for all radial distances ($r_1$, $r_2$ and $r_3$) has smaller decayed values than any other IE lengths (9.5 and 10.5 cm).

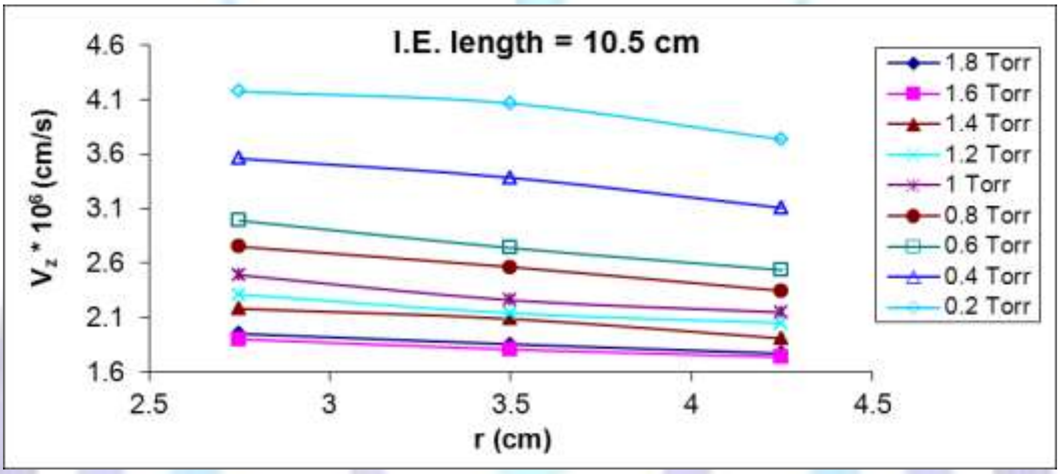
| IE length | *(dF/dp)* at $r_1$ | *(dF/dp)* at $r_2$ | *(dF/dp)* at $r_3$ |
|---|---|---|---|
| 9.5 cm | - 0.4 | - 0.25 | - 0.094 |
| 10.5 cm | - 0.71 | - 0.63 | - 0.42 |
| 11.5 cm | - 0.187 | - 0.14 | - 0.086 |

**Table 1 *dF/dp* data for various values of radial distance and IE lengths**

All the above results are taken as an average of three or more data for each discharge conditions.




(a)

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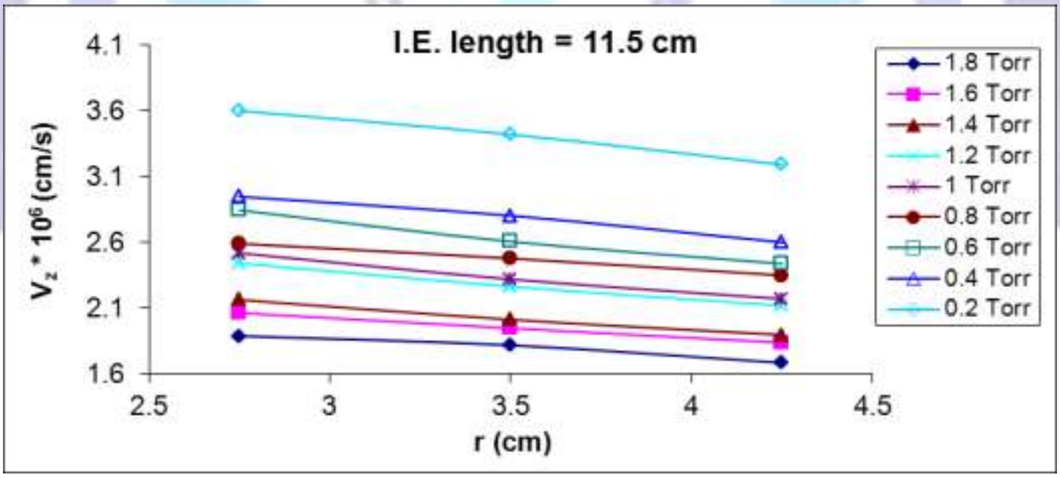
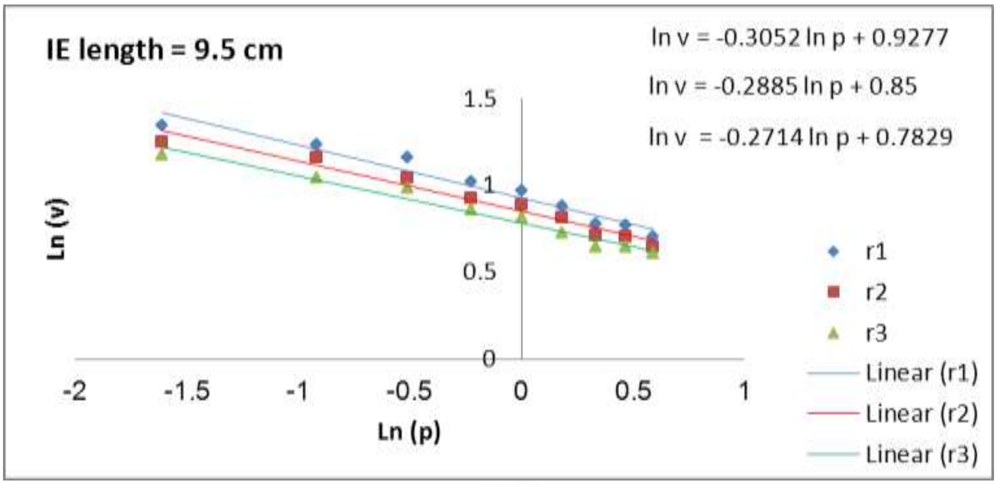
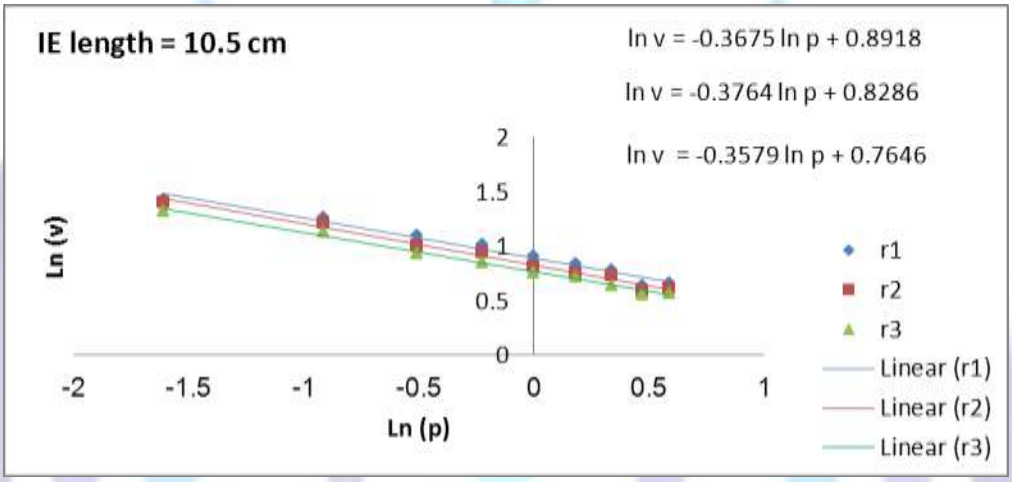



(c)

**Fig. (5 a, b, c) Variation of axial plasma sheath velocity with radial position at different IE lengths and different Ar gas pressures**




(a)

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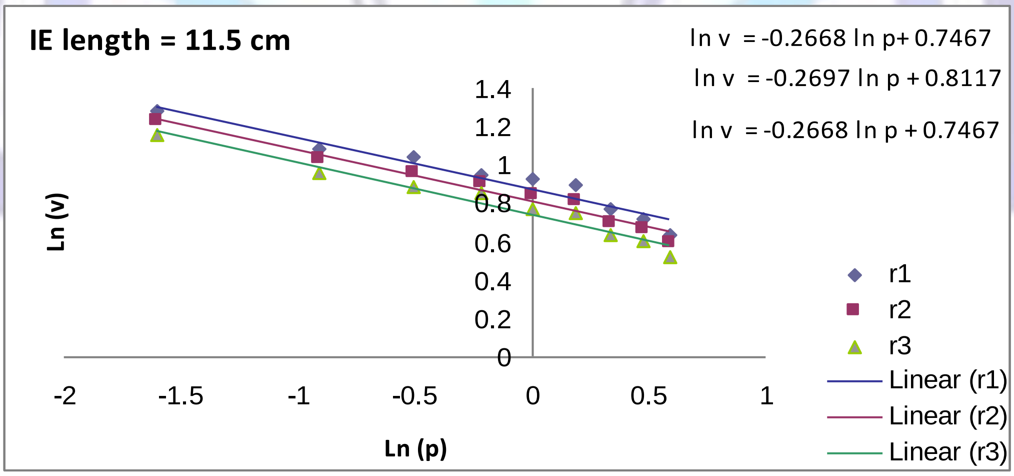


(c)

**Fig. (6 a, b, c) Ln V versus Ln p for different radial positions and IE lengths**

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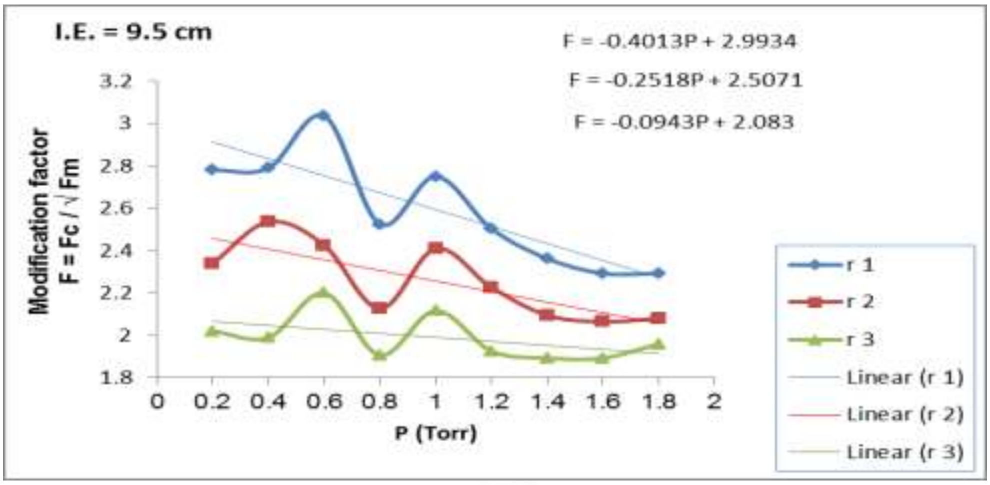
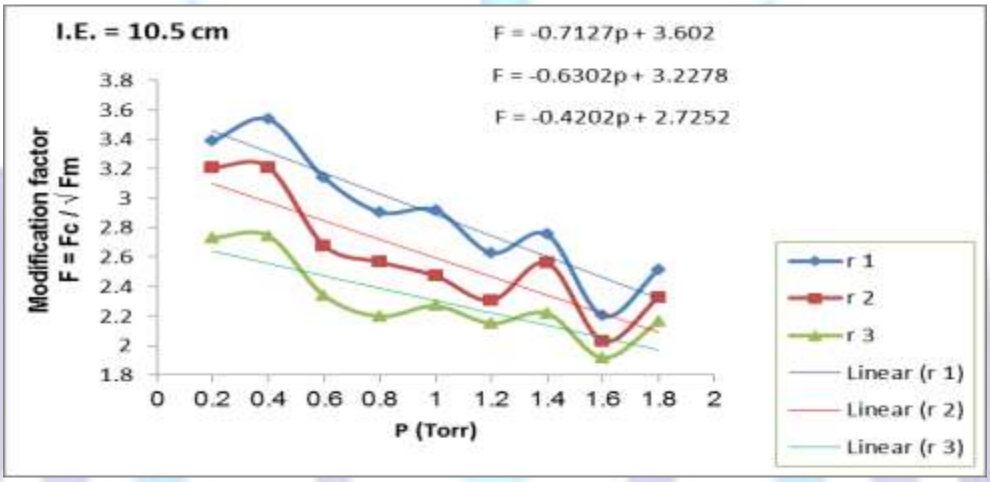



(a)

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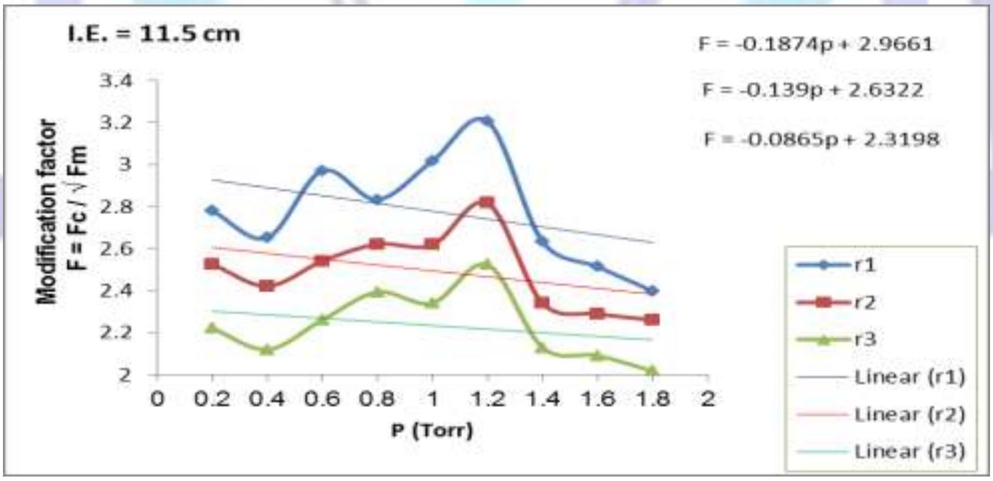


(c)

**Fig. (7 a, b,c) Plot showing modification factor as a function of Argon gas pressures, for different radial distances and different IE lengths**

## 4. CONCLUSION

Plasma current sheath dynamics and the induced azimuthal magnetic field induction during the axial acceleration phase of 2.2 KJ plasma focus device were measured. Experiments were carried out with three identical magnetic probes assembly at axial distance 8.15 cm and at radial distances 2.75, 3.5 and 4.75 cm within the annular space between coaxial electrodes with IE length of 9.5, 10.5 and 11.5 cm. The PF device was operated in Argon gas with pressure of 0.2 – 1.8 Torr.

Results of axial plasma current sheath velocity, $V_z$ as a function of gas pressures demonstrated that $V_z$ has highest value for IE length of 10.5 cm (at different radial distances) in comparison with the other electrode lengths (9.5 and 11.5 cm) under a gas pressures of 0.2 and 0.4 Torr. In general, we noticed that, PCS velocity decreased with the increase in gas pressures; this may be attributed to the PCS scoops up more gas resulting in a drop in $V_z$ and also due to a mass shedding effect. Approximately an efficient snow plough model was detected at IE length of 10.5 cm and for all radial distances where $V_z \alpha\, P^{-0.4}$. Results of $V_z$ versus radial distances cleared that the PCS has a parabolic shape; it is canted back words from the anode to the cathode at low values of gas pressures than higher ones.

Variation of $B_\theta$ with $P$ verified that the maximum value of $B_\theta$ is obtained at $r_1$, IE length = 11.5 cm and at $P$ = 1.2 Torr. Profiles of these distributions were related to the discharge and plasma currents as well as the current shedding factor.

Results of distribution of $F$ versus $P$ illustrated that, the maximum value of $F$ is detected at $P$ = 0.2 and 0.4 Torr, IE length of 10.5 cm and $r_1$, these results were compatible with $V_z$ results. Also a maximum decay of $dF/dP$ was detected at IE length = 10.5 cm and along the radial distances, these results confirmed the results of $dV_z/dP$.

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