Dynamics of the expansion discharge originated by a dense plasma focus

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Abstract. The expansion phase of the discharge in Dense Plasma Focus devices might be used in order to simulate the interaction between edge plasmas and wall facing materials in fusion devices. Preliminary results of the study of this phase with the use of a triple a Langmuir probe are presented. A review of the use of triple Langmuir probes for the study of flowing plasmas is made.

1. Introduction

Dense plasma focus devices have been and will continue to be extensively studied, in their first three stages, namely, the breakdown, rundown, and focusing of the plasma column. However, one of its features has been neglected; namely, the expansion of its discharge along the vacuum chamber, after the compression of the plasma column, which is akin to those in plasma guns. This work is motivated by the possibility of using this stage as a source of energetic plasma, which might simulate the effect of high density plasmas colliding on walls in magnetic confinement devices. This may be important from the materials study standpoint. For this purpose, it is necessary to be able to determine the dynamics of the discharge, for which measurements of density, temperature and speed are needed. We show preliminary results obtained using a triple Langmuir probe (TLP). As part of the work, a review of such probes is made. A study of the convenience of using the probe in voltage [1] and current modes [2, 3], which is reported to be best suited for a high electromagnetic noise environment, is made. The present work is done along the axis of the FN-II dense plasma focus, which is a 4.8 kJ device.

2. Langmuir probes

The Langmuir probe is the most familiar of the electrical diagnostic techniques, consisting on one or more conductors immersed in the plasma. The main variants are single, double and triple. The single probe consists on a conductor (usually cylindrical or spherical) immersed in the plasma. When there is a plasma flow, it is usually placed parallel to its direction. In the case of the single probe, there is an external voltage applied between the probe and one electrode. From sweeps of an applied voltage, the floating potential can be obtained, and consequently the electron temperature ($T_e$) and electron density...
(n_e) [1,4,5]. However, there are cases when the use of a single probe is difficult. For example, when there is no convenient ground or reference plane to use as a counter-electrode. In these instances the use of a double probe is indicated. In that case, the return current source comes from a second probe immersed in the plasma, and the external voltage is applied between the probes. Both single and double probes are suitable for flowing and steady plasmas, in the collisionless regime.

In the triple probe a third electrode is added in close proximity to a double probe, and is used in order to measure the floating potential independently. Triple probes offer an advantage over single and double Langmuir probes, allowing simultaneous measurement of plasma parameters without the need for voltage sweeps that can be limiting in pulsed plasma environments, specially if the discharges are not reproducible from shot to shot [1,2,4,6].

![Figure 1(a). Diagram of voltage-mode triple Langmuir probe.](image1)

![Figure 1(b). Electric circuit for a triple Langmuir probe operating in voltage-mode.](image2)

Triple probes can be operated in either voltage or current modes. In voltage mode operation there is an external potential applied only between two probes while the third one is floating (figure 1). Temperature $T_e$ and density $n_e$ are obtained from

\[
\frac{1}{2} = \frac{1 - \exp\left(-\frac{eV_{13}}{kT_e}\right)}{1 - \exp\left(-\frac{eV_{12}}{kT_e}\right)} \quad (1)
\]

\[
n_e = \frac{J_i}{\exp\left(-\frac{1}{2}e\sqrt{\frac{kT_e}{m_i}}\right)} \quad (2)
\]
where $J_i$ is the ion current density, given by

$$J_i = \frac{1}{A_p} \frac{I_{13}}{\exp \left[ -\frac{e(V_{12} - V_{13})}{kT_e} \right] - 1}$$  \hspace{1cm} (3)

where $A_p$ is the parallel area of the cylindrical probe, and $I_{13}$ is the current between probes 1 and 3, measured over the resistance $r$.

**Figure 2(a).** Diagram of a current-mode triple Langmuir probe.

**Figure 2(b).** Electric circuit for a triple Langmuir probe operating in current-mode.

In current mode there are external potentials applied between the three probes, as shown in figure 2. The potential $V_{ls}$, and $T_e$ and $n_e$ are obtained by $J_{e0}$ is the random electron current equation (7). The triple probe, referred operated in current mode, is suitable for flowing, steady, and unsteady plasmas in the collisionless regime. The implementation of current mode originates from the fact that the voltage needed in the voltage mode operation (voltage that comes from the probe which is floating) is a high impedance measurement that can be susceptible to electromagnetic noise in pulsed plasmas [1-6].

$$I_1 = A_p J_{e0} \exp \left[ -\frac{eV_{x1}}{kT_e} \right] - A_p e n_e \sqrt{\frac{kT_e}{m_i}} \exp \left[ -\frac{1}{2} \right]$$  \hspace{1cm} (4)

$$I_2 = A_p J_{e0} \exp \left[ -\frac{e(V_{x1} + V_{12})}{kT_e} \right] - A_p e n_e \sqrt{\frac{kT_e}{m_i}} \exp \left[ -\frac{1}{2} \right]$$  \hspace{1cm} (5)
\[ I_s = A_p J_{e0} \exp \left[ -\frac{e(V_{s1} + V_{13})}{kT_e} \right] - A_p e_n e \sqrt{\frac{kT_e}{m_i}} \exp \left[ -\frac{1}{2} \right] \]  

(6)

where

\[ J_{e0} = e_n e \sqrt{\frac{kT_e}{2\pi m_e}} \]  

(7)

In the TLP theory for plasma, consisting of electrons and a single species of ions, it is assumed that the electrodes are immersed in a plasma with different temperatures for each species, \( s = e, i \), with distribution function for species is Maxwellian distribution functions:

\[ f_s(r, v, t) = n_s(r, t) \left( \frac{m_s}{2\pi kT_s} \right)^{\frac{3}{2}} \exp \left[ -\frac{m_s(v - U_s)^2}{2kT_s} \right] \]

where \( m_s \) is the mass, \( v_s \) is the velocity, \( n_s(r, t) \) is the number density, \( U_s(r, t) = \langle v_s \rangle \) is the average velocity (brackets represent an average over the distribution function) and \( T_s \) is the temperature. Furthermore, we assume that the angle between the plasma flow velocity and the axis of the probe (a cylindrical probe is considered) is given by an angle \( \theta \) (figure 3).

Figure 3. Probe and its sheath. Where \( W \) is the velocity of the plasma.
Theory [1,2,4-6] requires that the cylindrical probe is working in collisionless plasma, so the Knudsen number for a probe of radius \( r_p \) must satisfy

\[
Kn_{sl} = \frac{\lambda_{sl}}{r_p} >> 1
\]

where \( \lambda_{sl} = \lambda_{ei}, \lambda_{ee}, \lambda_{en}, \lambda_{in}, \lambda_{ii} \) are the mean free paths for collisions of species s and l. Therefore, it must meet:

\[
r_p << \lambda_{ei}, \lambda_{ee}, \lambda_{en}, \lambda_{in}, \lambda_{ii}
\]

It also requires that the sheath of the plasma has to be collisionless (where \( a_p \) is the width of the sheath of the plasma):

\[
a_p << \lambda_{ei}, \lambda_{ee}, \lambda_{en}, \lambda_{in}, \lambda_{ii}
\]

The Debye length \( \lambda_D \) (assuming a quasi-neutral plasma \( n_e = n_i \) ) given by:

\[
\lambda_D = \frac{\varepsilon_0 k T_e}{e^2 n_i}
\]

should also be smaller than both \( r_p \) and \( a_p \). It is also required that the width of the sheath is smaller than the space (\( d_p \)) between probes, i.e. there is no interaction between the sheaths of the probes.

3. Plasma Focus FN-II
The device on which this work was done is the Fuego Nuevo-II dense plasma focus, which operates at the Instituto de Ciencias Nucleares, UNAM, and has been described in [7]. Both inner and outer electrodes are made of oxygen-free copper, and the latter is a squirrel cage made out of 12 bars. Their length is 40 mm, and the diameters of the inner and outer electrodes are 50 and 100 mm respectively. The insulator is a 19 mm Pyrex® tube, whose outer diameter matches the 50 mm of the inner electrode. The usual operating voltage is 38 kV, with a stored energy in the capacitor bank of 4.8 kJ. The current has been measured to be 350 kA. The pressure range in which these experiments were made is 2.5-2.6 Torr.

4. Experimental set-up and results
A voltage-mode TLP was placed inside the vacuum chamber, along the axis of the plasma focus, at three different distances from the inner electrode (\( \Delta x = 16 \) cm, 21 cm, 26 cm) (figure 4). The device was operated with pure deuterium at \( \sim 2.6 \) Torr, and the data were collected with Tektronix TDS3034 oscilloscopes.

![Figure 4. Sketch of a plasma focus. The expansion of the discharge, and the location of the TPL.](image-url)
Figures 6 and 7 show the behavior of the signals of $V_{12}$ (as defined in figure 1) and the potential measured in the resistance $r$, respectively, when $r$ was varied with values of 1MΩ, 100 kΩ, 10 kΩ, 1 kΩ, 100 Ω, 10 Ω and 1 Ω (always with $V_{13} = 100$ V).

Figure 5(a). Sketch of triple Langmuir probe.

Figure 5(b). Photograph of TLP inside the vacuum chamber.

Figure 6. Signal of $V_{12}$ for different values of $r$. The first curve is the signal of the Rogowski coil which measures the derivative of the current. The two peaks mentioned in the text are encased in the blue box. The peaks inside the blue square show the moment when the discharge passes across the probe.

Figure 7. Signal of the potential measured in the resistance $r$, when $r$ has different values. The first curve is the signal of the Rogowski coil. The two peaks mentioned in the text are encased in the blue box. The peaks inside the blue square show the moment when the discharge passes across the probe.
The purpose of varying the value of $r$ is to find out how electromagnetic noise may be reduced. Although it decreases, it is possible to see in the curves that there are two peaks after the pinch, that do not vanish with the different values of $r$. These are encased in figures 6 and 7 in blue boxes. We interpret them as a sign of the discharge front passing across the TLP.

Figure 8 shows that there is a phase difference ($\Delta t$) between the three curves (at the start of the first peak of the discharge that passes across the TLP), this allows the determination of the value of the average velocity (between curves) of the expansion:

$\Delta v_{16\text{ cm} - 21\text{ cm}} = (5.7 \pm 3.6) \times 10^5 \text{ m/s}$

$\Delta v_{21\text{ cm} - 26\text{ cm}} = (5.3 \pm 3.5) \times 10^5 \text{ m/s}$

Using the Voltage-Mode [3-9] allows measuring the electron temperature and the density of electrons in the zone when the discharge passes across the TLP (figure 9).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{The upper signal comes from the Rogowski coil. Signals below show probe signals at different distances ($\Delta x = 26 \text{ cm}, 21 \text{ cm}, 16 \text{ cm}$). The red square is the zone where the discharge passes across the TLP. The blue line is at $\Delta x = 16 \text{ cm}$, the red line is at $\Delta x = 21 \text{ cm}$, and the black line is at $\Delta x = 26 \text{ cm}$. (Right) Zoom in the zone where discharge passes across the TLP.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{(Left) Curves of electron density and (right) electron temperature. Both curves were calculated in the zone when the discharge passes across the TLP (red square, see figure 8).}
\end{figure}

5. Conclusions and future work
The dense plasma focus device has been extensively studied in the breakdown, rundown and pinch phases. The first two are of paramount importance for a good pinch performance, when most of the interesting phenomena occur; soft and hard x-ray emission, collimated ion and electron beams, and
fusion reactions, when deuterium is used as a filling gas. However, the there is a fourth phase beyond the pinch formation, which is usually neglected, and which we have called here the expansion discharge phase. While it may not be of relevance for the usual research of plasma foci, this is a very energetic plasma which may be of interest in order to simulate the interaction between the plasma and wall-facing materials.

Although it has not been reported in the literature to our knowledge, there are at least two groups (The PACO team at Tandil, Argentina, and the CCHEN group at Santiago, Chile) that have recently followed the evolution of the discharge at this phase with Schlieren photography, and have found the formation of a plasma dome, which evolves like a shock wave, out of which a bubble emerges on the axial direction. This was also reported in pictures in the early days of plasma focus research by Bernard et al. [10], although no attention was paid to the bubble, since the interest was focused in the neutron production. It is probably produced by a plasma jet, which emerges from the focus region, although it is preceded by an ion beam, as has been established in previous studies by Lepone et al. [11]. Since the speed of this bubble is larger than that of the dome, which roughly has the same speed as the plasma sheath before the pinch, this may help to explain the high speed reported in this paper. On the other hand, it is important to notice that the speeds obtained using two different distances are consistent.

Several improvements need to be performed in our experiment. In order to get good signals, reliable enough to make temperature and density measurements, it will be necessary to operate the probe in current mode, rather than in voltage mode, which implies the use of two, rather than one power supply. We have also found that it will be necessary to use higher current power sources. A further improvement would be to use a fourth crossed probe in the flowing plasma. This adaptation of a quadruple Langmuir probe (QLP) should allow the determination of the ratio \( S \) between ion speed \( U_s \) and the most probable ion velocity \( C_n \) [12-16] (figure 10). This would be accomplished by solving

\[
U_s(r,t) = \langle v_s \rangle
\]  

(8)
\[ c_s = \frac{2kT_s}{m_s} \]  
(9)

\[ S_s = \left( \frac{U_s}{c_s} \right) \]  
(10)

\[ I_A = A_p J e_0 \exp \left[ -\frac{e(V_{sl} + V_{ls})}{kT_e} \right] - A_\perp e_n e \sqrt{\frac{kT_e}{2\pi m_e}} \frac{2}{\sqrt{\pi}} \exp \left[ -\frac{S_i^2}{2} \sum_{n=0}^{\infty} \frac{S_i^2}{n!} \Gamma \left( n + \frac{3}{2} \right) \right] \]  
(11)

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