# CHARACTERIZATION OF ARGON PLASMA IN A VARIABLE MULTI-PLOE CUSP MAGNETIC FIELD: TOWARDS A FAVORABLE SOURCE FOR NBI SYSTEM

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**Abstract**

This paper demonstrates experimental results on confinement of argon plasma in a variable multi-pole line cusp magnetic field (VMMF). The VMMF has been produced by placing six electromagnets (with embedded profiled vacoflux-50 core) over a large cylindrical volume (1 m axial length and 40 cm diameter). The magnetic field have been measured by hall probe method and compared with simulated magnetic field by performing simulation using FEMM tools. From the experimental results, it has been observed that in this field configuration the confinement of the primary electrons increases and leak width of plasma decreases with increasing the magnetic field. Thus the mean density, particle confinement time of the plasma increase with increasing magnetic field.

## 1. INTRODUCTION

The utilization of multi-pole cusp magnetic field (MMF) has found a wide application in the development of ion sources due to its ability to confine a large volume of high-density uniform and quiescent plasma [1]. In fact the principle of plasma confinement by using MMF is mainly originated with fusion research [2-3], but it has been demonstrated that MMF based negative ion sources are capable for producing high current low emittance and stable ion beams which are essential for the new generation particle acceleration experiments. Also in NBI system of tokomak, to heat the core region of Tokomaks plasma up to the ignition temperatures, high power neutral beams having energy of the order of hundreds of keV (up to1MeV for $D^0$ or up to 870keV for $H^0$) are required [4]. For this application, the plasma source should be capable of producing quiescent, uniform and dense plasmas in order to produce a well-collimated high current density beam. As for example, the noise level and spatial density should be less than 10% over a several hundreds of square centimetres at a plasma density of a few times $10^{12}cm^{-3}$. It is found that MMF can confine large volume quiescent plasma at a density in the order of $10^{12}cm^{-3}$ [5].Thus MMF based plasma sources have achieved a great deal of attention to NBI (Neutral Beam Injection) systems. In addition to the above plasma (ion) sources confined by MMF are widely employed in a number of systems which include particle sources, etching [6], implantation [7], deposition [8-9] and fusion devices [4, 10]. Because of above mention crucial application study of plasma confined in a different geometry of cusp magnetic field pay a grate attention in plasma physics.

The bulk plasma confined at the null region diffused across the magnetic field and stream out along the magnetic field and maximum loss at the cusp region. The width of plasma escape through the cusp region is known as the leak width of plasma [11-14]. The leak with of plasma is controlled by the magnetic field as well background gas pressure [11-12]. Since, in our device the pole magnetic field is controllable [15] thus leak width of plasma is also controllable. In this present article, we have demonstrated the effect of the leak width of plasma on mean plasma parameter at confined plasma region (null region). The rest of the paper is arranged as follows: Sec. II describes the brief description of the experimental setup and plasma diagnostic. Sec. III describes the experimental observation of plasma confined in a cusp magnetic field will be discussed and conclude in the last section.

## 2. EXPRIMENTAL SETUP AND PLASMA DIAGNOSTICS

### 2.1. *EXPERIMENTAL SETUP*

Figure 1, (a) shows a Schematic diagram of experimental setup and (b) shows end cross sectional view of experimental set up of the variable multi cusp magnetic field plasma device (MPD). The experimental setup consists of vacuum chamber (diameter = 40 cm and length = 1.5 m) with wall thickness 0.6 cm. This chamber is pumped out by a combination of Rotary-TMP (430 liter/Sec) pump capable of $10^{-6}$ mBar of base pressure. The cusp magnetic field has been produced by six rectangular electromagnets and magnetic field is profile using vacoflux-50 core material [7]. Figure 2 shows the 2-D contour plot of the magnetic field, simulated using Finite Element Method Magnetics (FEMM) [29] on the centre $(r, \theta)$ plane of the chamber in vacuum condition. The radial variation of the measured magnetic field $(B_M)$ along the cusp region (θ =0º) and the non-cusp region ($\theta$ = 30º) are shown in figure 3 for two different currents ($I_{magnet}$ = 100 A, and 150 A) passes through the electromagnets. Figure 3 (a) shows the comparison of magnetic field between measured ($B_M$), simulated ($B_S$) shows good match and (b) shows the variation pole magnetic field (at R=20cm near the pole) with magnet current. The filamentary argon discharge plasma was produced using hot filament based cathode source. The plasma source (cathode) is two dimensional (8cm x 8cm) vertical array of five tungsten filaments; each filament has 0.5 mm diameter and 8 cm length. It is fitted from the conical reducer such that the filaments are inside the main chamber itself where the magnetic field is low. Also it has been taken care to push the source well inside the main chamber to avoid the edge effects of the magnets. These filaments are powered by a 500 A, 15 V floating power supply $(V_f)$ while it is normally operated at around 16 - 19 A per filament. The chamber was filled with argon gas through a needle valve to a pressure 2 x $10^{-4}$ mBar. The source is biased with a voltage of -76 V with respect to the grounded chamber walls using discharge power supply $(V_d)$. The primary electrons emitted from the filaments travel in the electrical field directions, while they are confined by the cusp magnetic field lines. Because of mirror effects due to cusp configuration, electrons move back and forth between the poles ionized the background gas atoms. The confinement of plasma is provided by a multi-cusp magnetic field produced by a six electromagnets accommodated on chamber surface. It also enhances the confinement of primary electrons and subsequently helps in density enhancement. All experimental measurements as well as the radial profile of plasma parameters are measured along the non-cusp region are carried out at mid *(r, θ)* plane of the device which is z = 65 cm away from the filaments at 2 × $10^{-4}$ mbar until and unless specified

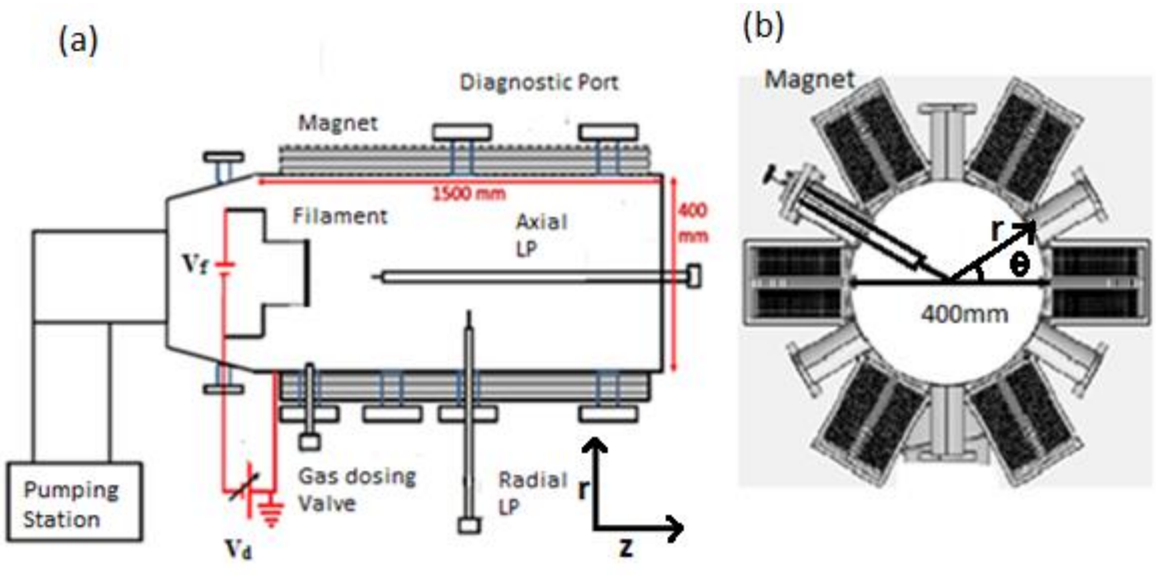


Figure 1. Schematic diagram of (a) Experimental setup and (b) Chamber end cross sectional view of the multi-line cusp magnetic field plasma device, where LP-Langmuir Probe, $V_f$- floating Power supply for filament heating, $V_d$- discharge power supply.

*2.2. PLASMA DIAGNOSTICS*

For measuring the variation of mean value of plasma density ($n$), electron temperature ($T_e$), and floating potential ($V_f$) from *I-V* characteristic of plasma obtained using simple Langmuir probe a sweeping circuit of frequency 1 Hz and a voltage sweep from -80 V to +30 V has been used. An analysis code has been developed in MATLAB for quick processing of the data. For calculation of mean electron temperature ($T_e$) and plasma density ($n$) following equations is used throughout the manuscript.

In general, bi-Maxwellian plasmas consist of two types of electrons with hot electron temperature component ($T_h$) and cold electron temperature component ($T_{ec}$) [16-17]. Kinetic definition of Effective temperature ($T_e$) can be expressed as:

$T_e = \frac{1}{3} m_e \int_{-\infty}^{\infty} v^2 f(v) dv$……………................... (1).

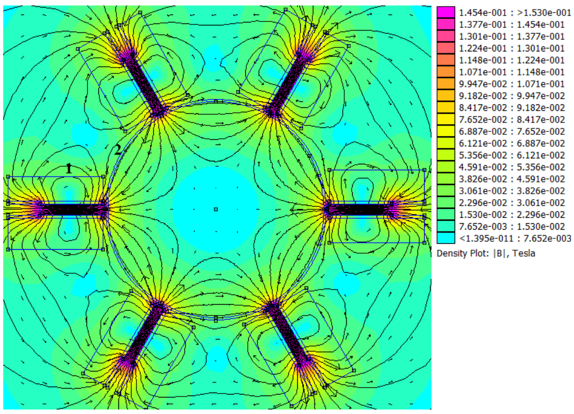


Figure 2. Contour plot of the vacuum field lines on $(r, \theta)$ plane of device using FEMM simulation when magnets are energized with 150A current. 1 is electromagnet, 2 is chamber cross section.

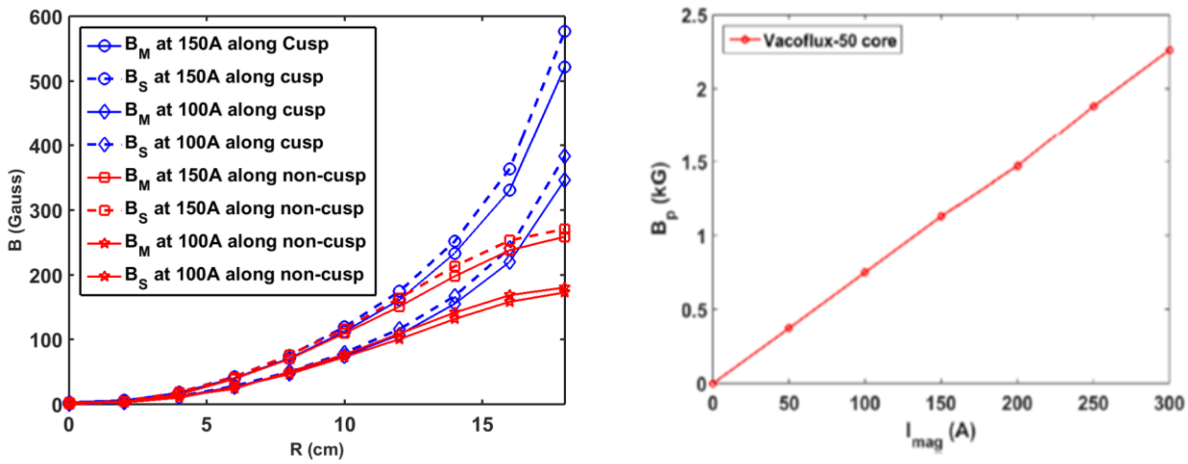


Figure 3. (a) Radial variation of magnetic field (both simulated ($B_s$) and measured ($B_m$)) along the cusp and non-cusp regions when magnets are energized with two different currents ($I_{mag}$) 100 A and 150 A. (b) Variation of pole magnetic field with different magnet current.

An effective temperature can be derived by assuming electron energy distribution function (EEDF) as bi-Maxwellian, $f(v) = \alpha f_h(v) + (1-\alpha) f_c(v)$ , Where $f_h(v)$ is the hot electron distribution function and $f_c(v)$ is the cold electron distribution function. $\alpha$ is the ratio of hot electron current to electron current at plasma potential [29-30]. Hence, for bi-Maxwellian plasma, the effective temperature can be derived as [16]:

$$T_e = (1-\alpha)T_{ec} + \alpha T_h \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3).$$

A detailed analysis of electron temperature ($T_e$) has been reported in an earlier publication by the same authors [15]. In our experiments, the Debye number (ratio of the probe radius to the Debye length) varies from 3 to 10. The plasma density ($n$) is determined from the ion saturation current by assuming the plasma to be quasi-neutral ($n_e \approx n_i = n$). The details of density ($n$) determination are given in Ref. 15 and 18.

## 3. EXPRIMENTAL RESULTS AND DISCUSSION

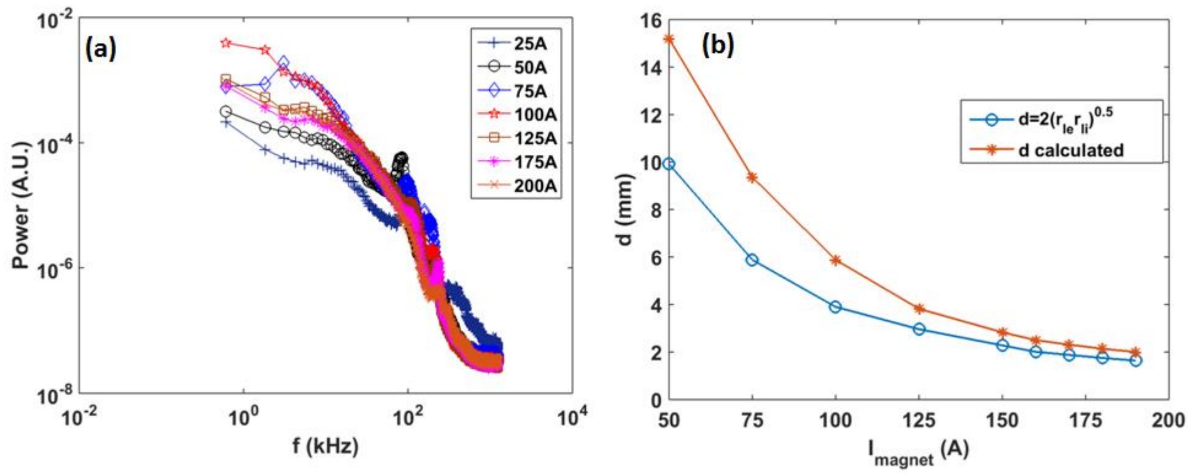


Figure 4.(a) Density auto power spectra at R=16cm in cusp region near the pole and (b) comparison of leak width between calculated from equation (4) and calculated from hybrid gyro radius at R=16 cm in cusp region when core is magnetized with different current and 2.0 × $10^{-4}$ mbar argon gas background pressure.

The leak width ($d$) of quasi-neutral plasma flowing out of a cusp and cross field diffusion is dominated by Bohm diffusion is given by [11-12]

$$d = \left(\frac{D_\perp L}{C_s}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (3)$$

where, $D_\perp$ is diffusion coefficient across the magnetic field near the pole of magnet, $L$ is scale length of magnetic field ($B$) and $c_s$ is the ion acoustic speed.

In low background gas pressure, R. Jones (1981) relates the leak width ($d$) to plasma turbulence [13-14]. Micro-instabilities which are unstable in a cusp sheath (e.g. drift wave, ion cyclotron waves) give rise to Bohm like diffusion [13-14]. The relationship between the relative electron density fluctuation level ${dn_e}/{n_e}$ and the leak width ($d$) for turbulent line cusp [13],

$$d \geq \frac{dn_e}{n_e}\frac{T_e}{T_i} r_{Li} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (4)$$

Where $n_e$ the electron density is $r_{Li}$ is ion Larmor radius, $T_e$ and $T_i$ are electron and ion temperature respectively.

The density fluctuation have been measured at R=16cm near the pole in cusp region. The power spectra of density fluctuation at different magnet current are shown in figure 4 (a). The observed turbulence have broad band spectra with significant power. Hence considering turbulant line cusp, we use equation (4) for leak width calculation. In equation 4, we consider $\frac{dn_e}{n_e} \approx \frac{\delta I_{esat}}{I_{esat}}$ where $I_{esat}$, the electron saturation current is observed in the cusp region at R=16cm and it is also considered that the ion temperature ($T_i$) is 10 times less than the electron temperature ($T_e$). The electron temperatures ($T_e$) and electron saturation currents ($I_{esat}$) are measured from same single Langmuir probe at R=16cm near the pole of magnet. The leak width ($d$) from equation (4) at different magnet currents are calculated and compared with leak width calculated from hybrid gyro-radius $d=2(r_i r_e)^{0.5}$ [2].The leak widths are good match at high magnetic field values but not for low magnetic field as shown in figure 4 (b) and these results are consistent with results obtained by Bosh *et al.* [11-12]. The leak width of plasma is decreased with increasing magnet current and hence decreasing the loss rate of bulk plasma. Thus it effect the plasma parameters i.e. plasma density, and particle confinement time.

Figure 5 (a) shows the variation floating potential at R = 0 cm with magnets current ($I_{mag}$).The floating potential is very high and negative at R = 0 cm because cusp magnetic field confined the primary electron. The leak width of plasma is decreased with increasing magnet current as shown in figure 4 (b) because of that leak rate of plasma decreased hence confinement of primary electron increased. Thus, the floating potential becomes more and more negative with increasing the magnet current as shown in figure 5 (a).These confined primary electrons move back and forth between two poles of magnets and makes more collision with neutral background argon gas atoms and enhance the plasma density as well as plasma leak rate of plasma also decreased with increasing magnet current (magnetic field) thus the plasma density in confined region (R = 0 cm) is increased with increasing magnet current as shown in figure 5 (b).

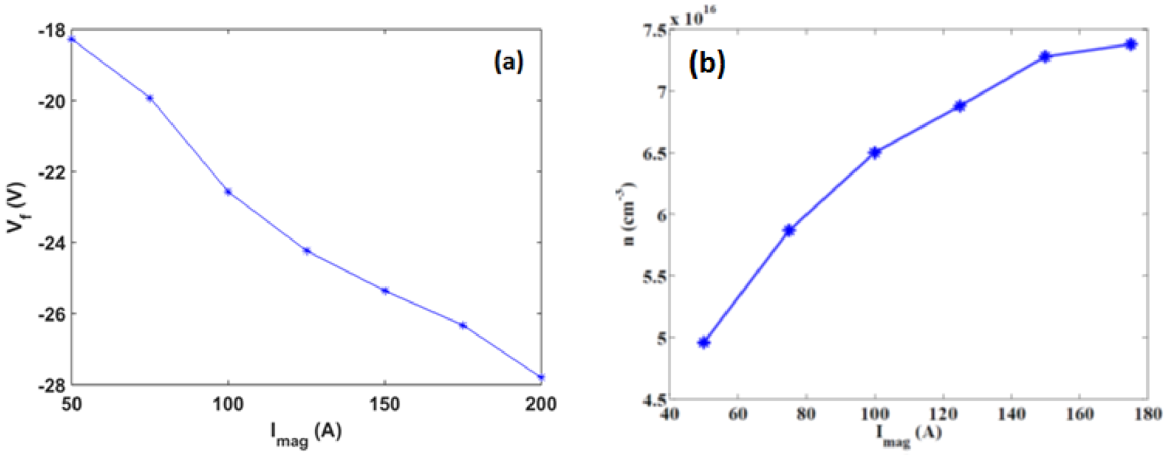


Figure 5: Variation of (a) floating potential ($V_f$) and (b) plasma density ($n$) at R = 0 cm with different magnet ($I_{mag}$) current.

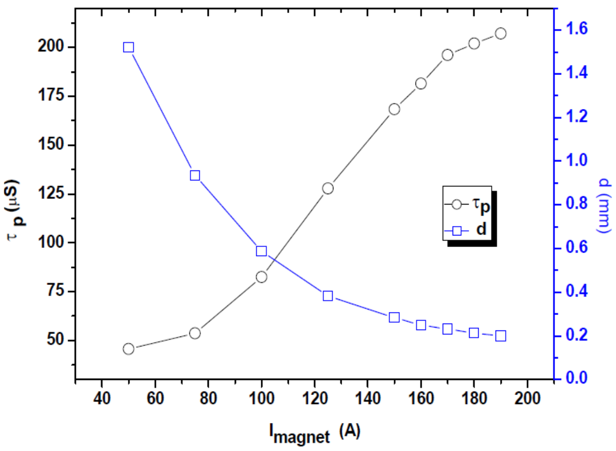


Figure 6. Variation of particle confinment time ($\tau_p$) with magnet current ($I_{mag}$) when core is magnetized with differet magnet current ($I_{mag}$).

Now, we describe the effect of leak width on particle confinement time with changing magnet current. The particle confinement time is measured from time profile of ion saturation current in afterglow plasma. The afterglow plasmas can be produced by switching off the biasing voltage of the multi-filamentary discharge. The discharge power supply is switched oFF and ON for 500 ms and simultaneously measure the ion saturation current across the 10 kΩ resistance using simple Langmuir probe and applied voltage at probe tip is -100 V. The time profile of ion saturation current using at R = 0 cm in afterglow plasma at different magnet current. The time is taken for ion saturation current to reduce 1/e of its initial value is called the particle confinement time. Figure 6 shows the variation of particle confinement time when the core is magnetized with a different current. As we discussed earlier that the leak width of plasma decreased with increasing magnet current (or magnetic field), because of that plasma density at confined region is increased and leak rate of plasma decreased, thus particle confinement time is increased with increasing magnet current (or magnetic field).

## 4. CONLCUSION

The Argon plasma is characterized by a variable multi-pole line cusp magnetic field. The leak width of plasma is calculated using existence formula at different magnetic field and results are consistent with earlier results. The experimental results shows multi-pole cusp magnetic field confined the primary electrons and confinement of primary electron also increased with increasing magnetic field values. The measured density and particle confinement time is increased with decreasing leak widths of plasma hence the stability of plasma also increased. The control over the plasma density without increasing collision with background neutral atoms my useful for new generation of particle accelerator, plasma sources as well as NBI system of tokomak.

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