Experimental determination of radial spread of residual fast electrons in a hot filament toroidal magnetized plasma discharge

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Abstract. Plasma production and confinement using a simple toroidal magnetic field in the experiment described here results in a spread of residual fast electrons in bulk plasma. Often a prior knowledge of this spread is essential before making interpretations about bulk plasma measurements using various diagnostics, for example, Langmuir probes. Retarding field energy analyzer is used to obtain radial spread of relative population of these fast electrons with different energies. The experimental results show that the width of radial spread of fast electrons is small. Effects of magnitude of the toroidal field and direction of filament current on this spread are also discussed.

1. Introduction

Production and confinement of plasma are the most important topics of plasma physics today. Tokamaks are believed to be promising devices in achieving improved confinement and hence fusion [1]. However the complexity involved in the design and physics issues in tokamaks give rise to a need for simple devices where experiments can be conducted in a controlled manner to study various physics aspects. BETA (Basic Experiments in Toroidal Assembly) is such a device which uses, in general, a hot biased filament and toroidal magnetic field to produce and confine the plasma. The thermionically emitted electrons from hot pure tungsten filament help in breakdown of filled gas. A residual population of these fast electrons still remain present in a region around the filament and spread toroidally through magnetic field lines.

Measuring floating potential of a simple Langmuir probe gives the indication of presence of a fast electron (or primary electron) species in a given plasma [2]. However, to make quantitative measurement of radial spread of this species, a retarding field energy analyzer (RFEA) has been designed and used in BETA. RFEAs have been extensively used in the past to determine the properties of charged particle beams [3, 4, 5, 6]. Simple parallel plate analyzers have been used in plasma confinement devices to measure axial energy distributions of either ions or electrons [7, 8]. In many cases these analyzers have been used as alternative diagnostics to Langmuir Probes (LPs), which are still widely used to diagnose the electron distributions in modern plasma confinement devices.

In this report, radial spread of fast electron species and its behavior are described. The necessary experimental setup and typical plasma parameters are described briefly in Sec.2.
Profiles of energetic spread is discussed in Sec.3. With a given negative bias to the hot filament, the effect of the magnetic field and the direction of filament current on this spread are also observed as shown in Sec.4. For the results presented here, the toroidal magnetic field used is around 200 G and 800 G with a filament current of 150 A. For these values, the effect of self magnetic field of the filament is known to be unimportant [9].

2. Experimental setup and Diagnostics

2.1. Setup

BETA is a torus with major radius 45 cm and minor radius 15 cm enclosed in a toroid formed by 16 coils of square cross section, each with 3 turns in it. Magnetic fields of order of 0.1 T can be produced. Base pressure of the order of $3 \times 10^{-6}$ torr is achieved by two diffusion pumps. Argon plasma is produced at a filled neutral pressure of $10^{-5} - 10^{-4}$ torr by striking a discharge between a hot tungsten filament, located on minor axis of the toroid, acting as a cathode and a conducting limiter, with open aperture of 18 cm diameter, grounded along with the vessel acting as anode. Typical densities of $10^{11} \text{ cm}^{-3}$ and electron temperature ($T_e$) of 5 eV are achieved. Ions are expected to be cold. A thermalized species of electrons emitted from hot cathode [10], initiate the discharge and a residual population of these is left in the bulk plasma around the minor axis. Contribution to the net electron flux by these fast electrons can lead to a modified electron distribution. Thus it is of paramount importance to clearly identify the qualitative and quantitative nature of this fast electron species. To this end we have designed analyzer and measured fast electron profiles. A view of cross section of BETA and diagnostics is shown in Fig. 1.

![Figure 1. Schematic view of the experimental setup and diagnostics](image)

2.2. Diagnostics

2.2.1. Langmuir probes: LPs are extensively used on this device to measure plasma density and electron temperature. In the past, fluctuation studies are conducted using array of probes [11, 12, 13]. At present cylindrical probes of 0.7 mm dia. and 3 mm length are used. Densities are obtained from ion saturation current measurements at a sufficient negative bias, typically -50 V. A ramp voltage in a range -80 V to 0 V is swept on LP and the probe current is measured using a current transformer (CT). The transition region which is predominantly due to change in electron current is fitted with an exponential function to derive local electron temperature. Typical data of I-V characteristics and an exponential fit are shown in Fig. 2.

2.2.2. Retarding Field Energy Analyzer: A schematic picture of analyzer used here is shown in Fig. 3. The RFEA design to probe electron distribution consists of a stack of a slit, two grids and a collector plate. Stainless steel (SS) mesh with open aperture (w) 130 $\mu$m and grid
bar thickness (t) 70 µm is used. The grid aperture is comparable to the Debye length which is typically 50-100 µm. The entrance slit is made of a SS plate with a circular hole of diameter 0.8 mm. Since slit aperture is much larger than Debye length, slit plate does not have a control on the potential of entire aperture. Instead this will be useful in controlling incident current. The next grid, called grid-1 (G1), is to repel all positive ions. The grid next to this, called grid-2 (G2), is the electron repeller to selectively transmit the electrons. The collector plate is placed next to this. The successive components are separated by ceramic washers. Collector is made of a SS plate of diameter 8.5 mm. The inter spacing between the grids is 10 mm. The entire stack is mounted in a ceramic housing. The axis of the RFEA gridded stack is aligned along the toroidal magnetic field. The entrance grid is grounded. Working in the electron mode of operation, grid-1 is given a sufficient positive bias to repel all the ions. The grid-2 is biased to high negative voltage which is varied from shot to shot during the pulsed operation of plasma discharge. The selectively transmitted electrons are collected at the collector plate and the collector current is measured across a resistance (R) of typically 1-10 kΩ which connects from collector to ground. The voltage drop across R is measured using an oscilloscope.

**Figure 3.** A cross sectional view of retarding field energy analyzer. S, G1, G2, C are slit, grid-1, grid-2 and collector respectively.

3. **Fast electron spread**

With a repelling voltage \( V_{g2} \) of -70 V on grid-2, collector current \( I_c \) at some location close to minor axis is measured by RFEA. I-V characteristics using LP is also obtained at same radial location as shown in Sec.2.2.1. On a suitable fit to the electron current in the bulk transition region obtained from LP, a small electron current is expected at -70 V. However measured electron current by RFEA is significantly large confirming the presence of fast electron species over the
bulk plasma. A plot of radial profile of $I_c$ for various repelling $V_{g2}$ on grid-2 is shown in Fig. 4. The bias (discharge voltage) applied to the filament is -80 V. However finite $I_c$ is measured even for repelling voltages more negative than -100 V. This is suspected to be contribution from tail end of thermalized fast electron species [10]. The negligible increase in magnitude of $I_c$ when $V_{g2}$ is less negative than -80 V is due to the space charge limited currents [14, 15, 16]. However large current densities incident on stainless steel collector is found to modify the surface. Hence working at low repelling voltages on grid-2 is avoided. Furthermore the effect of correcting for space charge limited current would be in a direction to further sharpen the peak especially at low repelling voltages.

![Figure 4. Radial profile of electron current corresponding to the fast electrons using different repelling voltages on grid-2 for toroidal magnetic field = 860 G](image)

Considering the $I_c$ profile for $V_{g2}$ equal to -70 V, and assuming all the electrons move with a speed equivalent to 70 eV, and using transmission coefficient equal to 0.16 (for two grids each with geometrical transmission of 0.4) number density of these fast electrons is calculated. This number $n$ is given by $I = neAv \times T$ where $e$ - electron charge, $A$ - area of entrance slit, $v$ - velocity of electrons and $T$ - net transmission coefficient. From this plot the peak value of fast electron density is of the order of $10^{14} m^{-3}$ where as the bulk plasma density is of the order of $10^{17} m^{-3}$. Hence the fast electron population close to the minor axis has a peak of less than 1% of the bulk plasma density. A rough estimate of this density profile of these electrons and a comparison with bulk plasma is shown in Fig. 5. The plot shows errorbars which are determined from 4 shots at each location.

4. Effect of $B_T$ and $I_f$

At low toroidal magnetic field ($B_T$) it is suspected that fast electron spread can be much larger than high $B_T$. However Fig. 6 shows profiles of $I_c$ for two values of toroidal fields 215 G and 860 G, with not much difference in spread, also for two directions of filament current ($I_f$). The peaks of these profiles are consistent the way filament is seen to bend away from minor axis. Also the voltage drop across the filament causes the effective bias on it to be slightly less in reversed filament current direction experiment and hence reduces the peak value of the fast electron species.
5. Conclusions
Measurements by a Langmuir probe and retarding field analyzer close to the minor axis in BETA plasma have shown the presence of residual fast electrons. The profiles of fast electron current to collector are obtained by choosing high repelling voltages on electron repelling grid of the analyzer. From such profile a rough estimate of the number density of the residual fast electrons and its spread are calculated. Also the effects of magnitude of toroidal field and also direction of filament currents are observed. The peak of the fast electron profile is observed to shift accordingly with the bending of filament away from minor axis which is due to the force acting in the external magnetic field.

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