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Effect of radio frequency field on toroidal plasma parameters

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Abstract. Low temperature plasma parameters in a toroidal magnetic field are measured. The effect of an externally applied perpendicular electric field on the plasma parameters is studied. The lifetime of the plasma is measured in the presence and absence of the RF electric field. Decrease in the plasma lifetime in the presence of RF field is attributed to detrapping of the primary electrons to a larger volume. Plasma lifetime increases when a small vertical magnetic field is added to the toroidal magnetic field.

Keywords. Toroidal plasma; radio frequency electric field; major radius; minor radius; toroidal magnetic field; vertical magnetic field; antenna.

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1. Introduction

Toroidal experimental systems (Wong *et al* 1982; Kojima *et al* 1984) are being used for basic experimental plasma physics research. Some of the limitations of linear machines are overcome in these systems. For example, they are more useful for producing high density plasmas. Toroidal systems have no ends and, as such particles do not come in contact with material walls and it is thus possible to obtain higher electron temperatures in comparison to linear devices. Ion temperature is also higher than in linear machines. Additional complexities arise due to curved radially inhomogeneous magnetic field in toroidal systems which, however, have topological affinity towards the high temperature magnetically confined toroidal systems.

Toroidal assembly (BETA 1984) is one such system, which has been installed to investigate various problems of current interest in plasma physics. Experiments on interaction of plasmas with radio frequency fields are in progress. Here, we describe the effect of RF electric field on plasma parameters applied perpendicular to the toroidal magnetic field over a small section of the plasma in toroidal direction. During the experiment, DC as well as pulsed toroidal magnetic fields have been used. Plasma lifetime is measured under different conditions. The experimental system along with instrumentation related to RF experiments is briefly described in §2. Section 3 is devoted to experimental observations, discussions and conclusion.

2.1 *Experimental system*

The experimental set-up consists of the following sub-systems. The top view of the set-up is shown in figure 1; (a) vacuum system; (b) magnetic field systems; (c) capacitor banks for magnetic field coils; (d) supporting structure; (e) plasma source and (f)

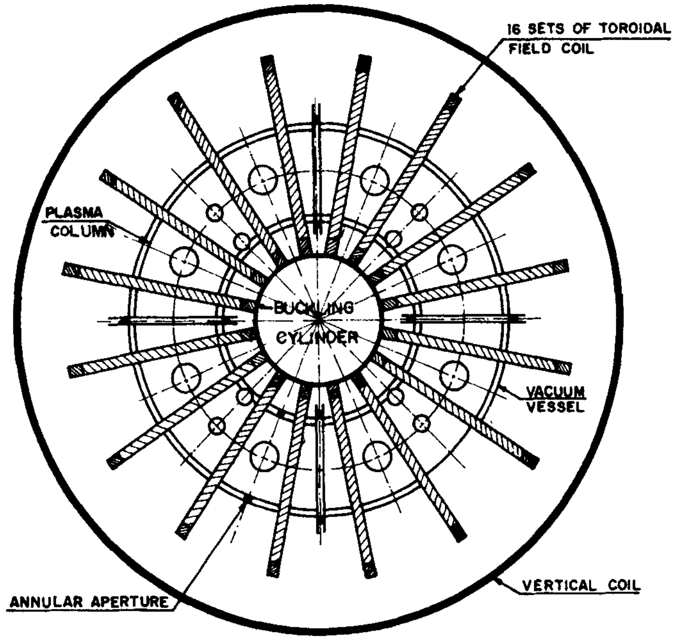

Figure 1. Schematic of the top view of BETA.

diagnostics. The vacuum vessel in the shape of a torus is constructed out of four quadrants of stainless steel. The major and the minor radii are 45 cm and 15 cm respectively. Each quadrant has 10 ports to enable us to deploy diagnostics and other necessary instruments during experimentation. The system is evacuated to a base pressure of 10^{-7} torr. However, the normal operating pressure range is 10^{-4}–10^{-6} torr.

A set of 16 toroidal field (TF) coils are placed around the vacuum vessel. TF coils are of picture frame shape with a square aperture of 50 cm^2. Each coil consists of three turns. The major radius of the coil is 50 cm. A maximum of 25 kA is passed through the coils which produces a pulsed toroidal magnetic field (B_T) of 5 kG at plasma minor radius. The magnetic field values as a function of minor radius are plotted in figure 2. Toroidal field ripple as a function of minor radius is shown in figure 3. To reduce the field ripple, the vacuum vessel major radius is shifted 5 cm inside with respect to that of TF coils.

The toroidal coils are supported by a supporting structure to take care of in-plane and out-of-plane forces acting on them.

Two coils are placed at a distance of ± 60 cm from the equatorial plane to produce a maximum vertical magnetic field (B_v) of 500 G in the plasma region.

TF and vertical field coils are energized using two capacitor banks. Total energy required for TF coil bank is 150 kJ. A maximum of 28 kJ is used for the vertical field coils. The crowbarred toroidal magnetic field upto 750 G is of 35 msec duration. Higher toroidal magnetic field values are of 8 msec duration with a half sinusoidal shape in time. The vertical field bank is initiated with a desired delay with respect to the toroidal field bank. A longer duration pulse of 100 msec is provided for toroidal field. A 90 kW DC power supply can be used to produce a maximum of 60 G toroidal magnetic field. The same power supply can be used to produce a maximum vertical field of 20 G.

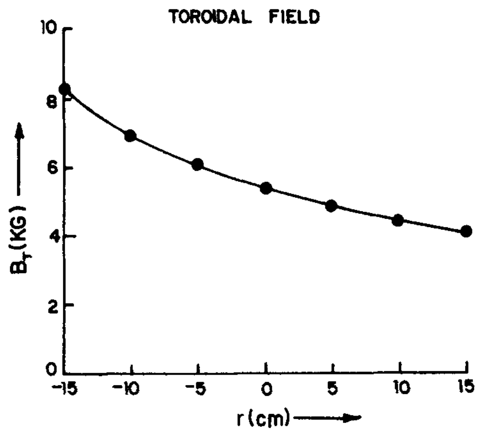

Figure 2. Toroidal magnetic field as a function of minor radius.

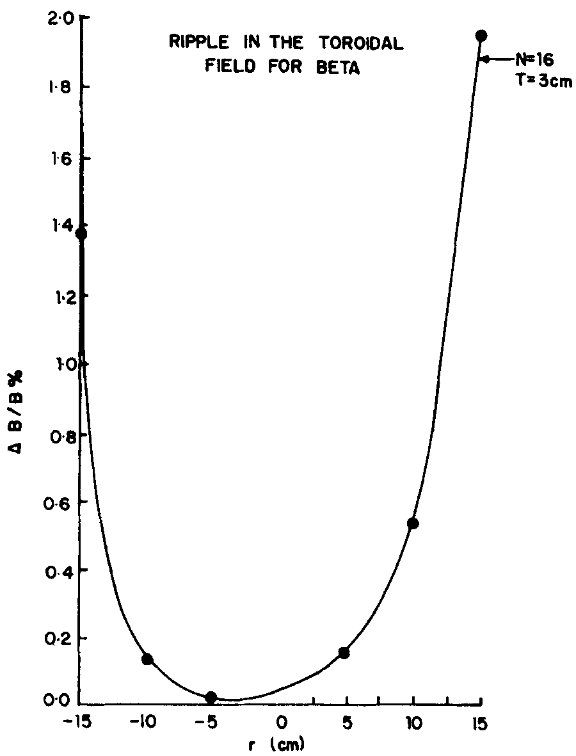

Figure 3. Toroidal field ripple as a function of minor radius.

Hot cathode discharge is one of the methods used to produce plasma in BETA machine. A tungsten filament of 2 mm diameter and 7 cm length is used as the cathode. It is placed vertically at a major radius of 39 cm. System wall is used as the anode. Discharge voltage is applied between the two in the presence of toroidal magnetic field.

An annular ring of 5 cm width is placed concentric with the vacuum vessel minor axis toroidally opposite to the cathode. Typical discharge voltage applied is varied between 75 V and 150 V. Detailed discharge characteristic of such a source is described elsewhere (Mattoo and Venkataramani 1985). During the toroidal magnetic field pulse, the discharge current increases and a high density plasma is formed. As the toroidal field rises, the thermionically emitted electrons travel along the field lines till they are lost due to curvature and ∇B drifts and ionizes the residual gas, thus forming plasma. The path electrons travel greater as compared to linear machine and hence ionization efficiency increases. Plasma density of $n_e \simeq 10^{12}$/cc is easily obtained at a gas pressure of 5×10^{-4} torr. Hydrogen and argon gases have been used for plasma production.

2.2 *Instrumentation*

RF instrumentation in the BETA machine is deployed according to requirements. Figure 4 schematically shows the relative placement of the diagnostics along with the antennae placed during the experiment.

RF power of $P_{max} = 100$ watts is used at the frequency of 10 MHz during the experiment. Availability of RF power at 10 MHz enabled us to select the other parameters for the experiment. One of the main considerations is to design the antennae to localize the transverse field well within one side of the shallow mirror as shown in figure 5 which plays a crucial role in another RF experiment. The same electric field is applied during this experiment as well. An evanescent extraordinary mode is used to avoid excitation of natural mode in the plasma and feed maximum power to the centre. The plasma radial density and radial variation of the toroidal magnetic field together determine the power level penetrated into the system.

A pair of capacitive antennae are used to reduce the spread of the RF electric field in the toroidal direction. However, the power coupled to the antennae is distributed among the capacitors formed between the antennae and the antennae separately with the wall. Antennae are made in the form of plates (5 cm × 5 cm) of SS 304. They are covered completely with teflon sheet to avoid direct contact with plasma or breakdown

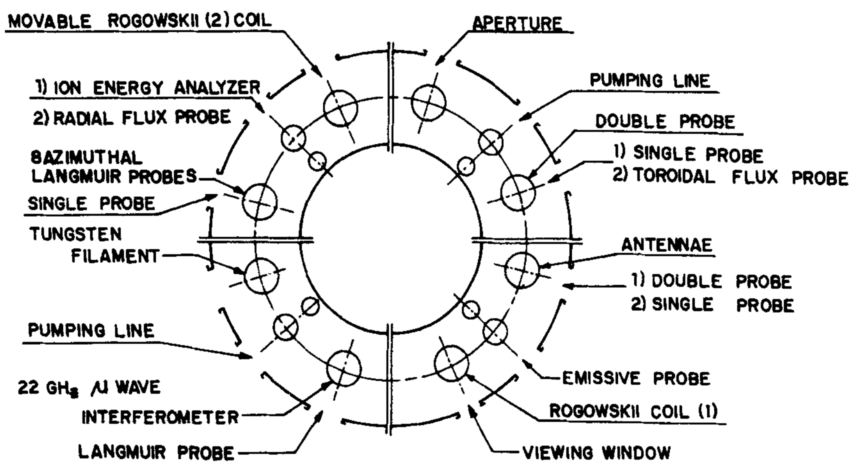

Figure 4. Schematic of the relative positions of the diagnostics w.r.t. filament and antennae.

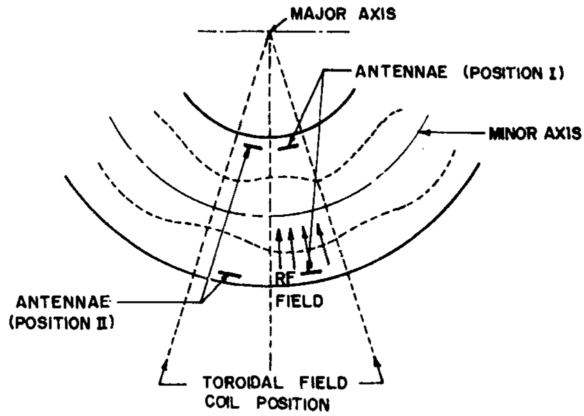

Figure 5. Schematic of the localized RF electric field with respect to the position of TF coils.

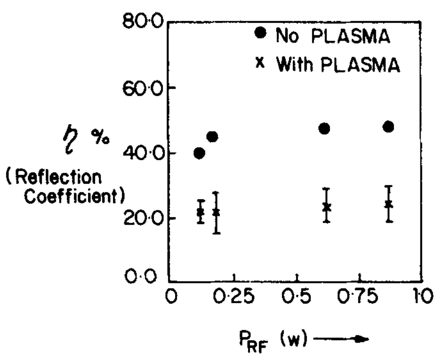

Figure 6. Reflection coefficient in the presence and in the absence of plasma as a function of RF power.

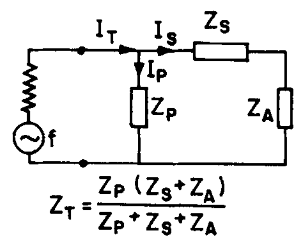

Figure 7. Schematic of the matching circuit.

between wall and antennae. RF power is fed to the antennae through coaxial cables. To reduce reflection due to mismatch in the circuit, a matching circuit is used to improve the transmission coefficient. Figure 6 shows the improved transmission coefficient in the presence/absence of plasma. A schematic of the matching circuit is shown in figure 7. A π network was used for this purpose (Valanju 1985). Z_A represents the antennae (load) impedance; Z_s and Z_p are respectively the series and parallel impedances used. Total impedance can be written as

$$Z_T = \frac{Z_p(Z_s + Z_A)}{Z_p + Z_s + Z_A}. \tag{1}$$

Total current I_T can be written as a sum of current I_p and I_s;

$$I_T = I_p + I_s, \tag{2}$$

and

$$\frac{I_p}{I_T} = \left(\frac{Z_s + Z_A}{Z_s + Z_A + Z_p}\right) = (I_p/I_T)\exp(i\phi_{PT}) = R_{PT}.$$

Hence

$$Z_A = \{Z_p/[(I_T/I_p) - 1]\} - Z_s. \tag{3}$$

Knowing the antennae impedance, the parallel and series impedances are calculated. We preferred the use of inductances as series and parallel impedances. Resonance condition is met when I_s and I_p are equal.

RF probes are used to measure the high frequency oscillations. Conventional electrostatic probes, emissive probe and directional probes are used to measure the plasma parameters. Chord-averaged plasma density is also measured with the help of 22 GHz microwave interferometer.

3. Experimental observations, discussions and conclusion

3.1 *Measurement of plasma parameters*

Argon is used as the working gas during the RF experiments. Some of the experiments are conducted with hydrogen as well. Extraordinary evanescent mode is used to introduce the transverse RF electric field. Antennae are placed at minor radii of ± 12 cm. Hence it is necessary to apply RF field which would penetrate to a distance of at least 12 cm and the frequency consideration was such that no natural mode was excited in the plasma. Figure 8 shows penetration depth dependence as a function of plasma density. Toroidal magnetic field strength is kept constant at 1 kG at the minor axis unless otherwise mentioned.

Radial and vertical density profiles are plotted in figures 9a and 9b, in the absence as well as presence of RF field applied locally at one toroidal location. The measurements are made using Langmuir probes biased to a negative potential to collect ion saturation current. Knowing the temperature from separate measurement, density is calculated from ion saturation current. Figure 9a shows a marked reduction of plasma density at the centre with a slight increase in number density away from the centre. Density measurements are conducted near the antennae to check undesired local ionization, if any. However the number density is not found to increase locally in the presence of RF power. Antennae are placed 2 cm away from the plasma edge and gap between the vacuum vessel wall and each antenna is 3 cm. During the presence of RF voltage on the antennae, it was thought that they could collect plasma current as collectors. Therefore, antennae are totally covered with teflon and the measurements are repeated and found to be the same.

Floating potential (figure 10) and space potential profiles are measured using high impedance and emissive probes respectively. Measurements are conducted in the presence of RF field as well. A Langmuir probe is directly used for floating potential measurement. The probe output is directly connected to a high impedance Tektronix vertical amplifier module whose input resistance is 1 megaohm and input capacitance is 22 pf. Space potential measurements under similar conditions are shown in figure 11. Tungsten wire (0.22 mm) is used as emissive probe. This filament is glown to incandescence and the probe characteristic is recorded. Probe characteristic is

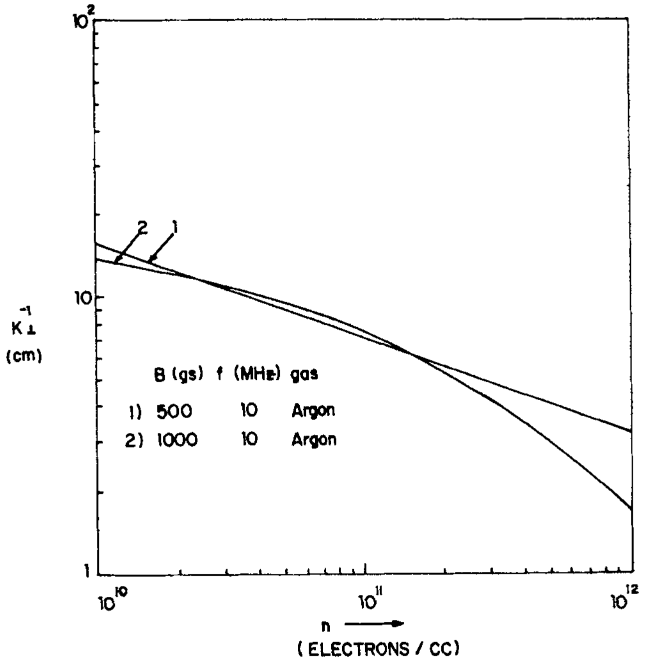

Figure 8. RF penetration depth (K^{-1}) as a function of plasma density for different working gas and toroidal field.

measured once again in cold condition. The intersection near the electron saturation current yields the space potential. A marked difference in the profile of floating potential and space potential is seen for the two cases. Primary electron population also contributes to the potential measurements. The I-V characteristic does not show ion saturation current even at very high negative voltage due to the presence of high energy electrons near the filament. In the presence of RF field, space potential peak broadened and spread towards the centre of the vessel. This is because the primary electrons interact with the RF field and are scattered over a larger volume. The existence of high energy electrons in a larger volume is reflected in the broadened peak. As a consequence, the plasma density profile also changed marginally which is also depicted in figure 9a.

An interferometer (22 GHz) is used to measure the central chord average plasma density. Figure 12 shows the interferometer fringes. Cut-off density of $n_e = 4 \times 10^{12}$/cc is reached within 5 msec. The top curve represents the ion saturation current picked up by a Langmuir probe in the vicinity of the interferometer. Thus one can calibrate the fringes in terms of density. For this case each fringe corresponds to $n_e \simeq 5 \times 10^{11}$ electrons/cc.

Plasma formation and confinement in a low DC toroidal magnetic field of 20 G are also studied. In a weak toroidal field, the primary electrons occupy a larger cross-section of the vessel and the plasma volume increases. Radial plasma density profiles in the presence and absence of RF field are shown in figure 13. It is observed that the radial profile is broader in this case in comparison to the high pulsed toroidal magnetic field case. Similar floating potential and space potential profiles are shown in figures 14a, b. Broadening of the negative peak in floating potential as well as the trough in space potential is seen in the presence of RF fields.

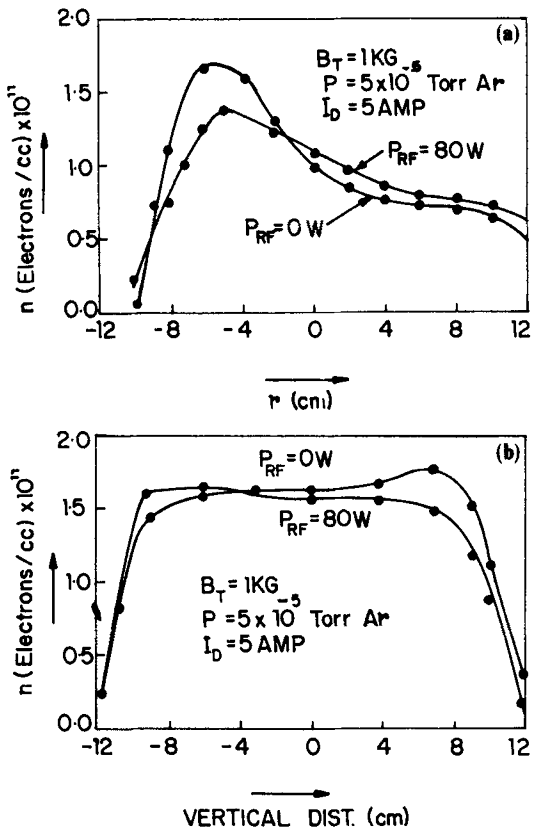

Figure 9a, b. Radial density profile in the presence and in the absence of RF electric field.

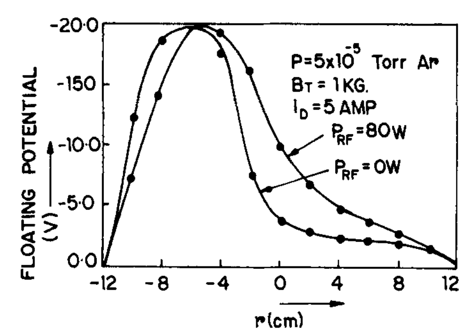

Figure 10. Radial floating potential profile with and without RF electric field.

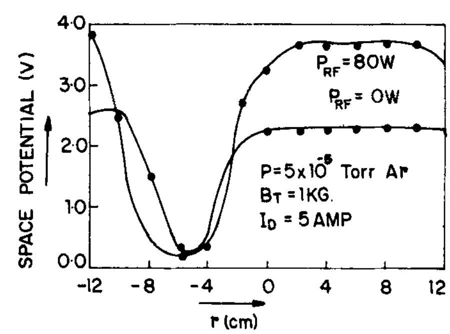

Figure 11. Radial space potential profile in the absence and in the presence of RF electric field.

Langmuir probe is used to measure electron temperature and its radial variation. A sawtooth voltage from -60 V to $+20$ V is applied with a sweep rate of 1 msec. From the slope of the plot of $\ln I_e$ vs voltage applied on the probe, the electron temperature is calculated. The density does not change during the measurement time. Synchronizing the sweep voltage pulse with the toroidal magnetic field pulse, electron temperature (T_e)

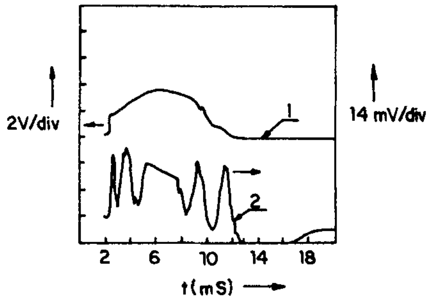

Figure 12. 1. Ion saturation current of Langmuir probe 2.22 GHz microwave interferometer output.

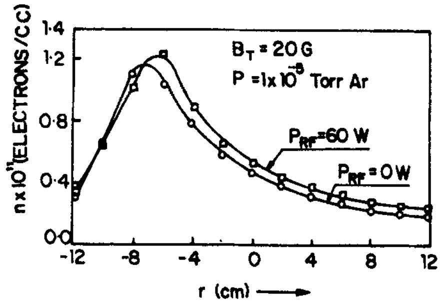

Figure 13. Radial plasma density profile in the presence and in the absence of RF field.

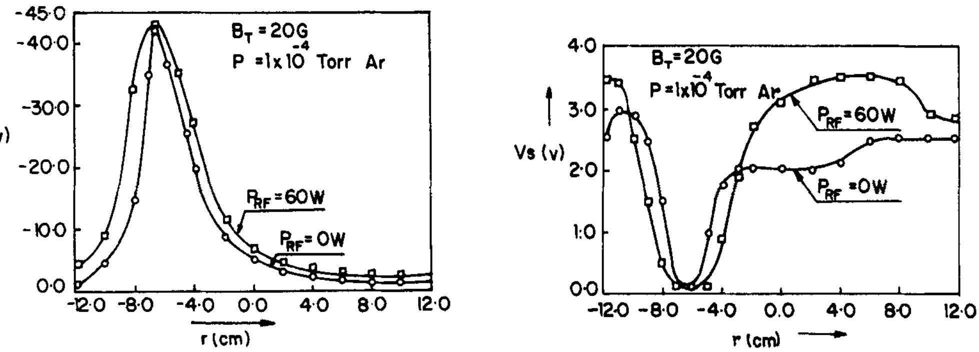

Figure 14. a. Radial dependence of floating potential in the presence and in the absence of RF field. **b.** Radial space potential profile in the presence and in the absence of RF field.

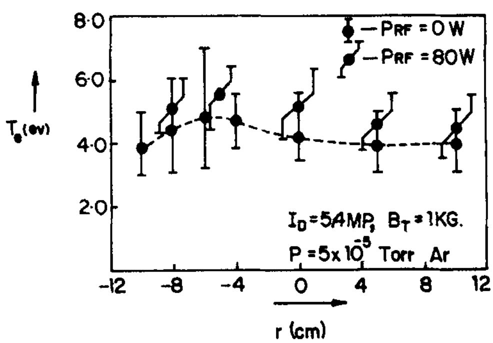

Figure 15. Radial electron temperature profile.

is measured after every msec. Radial T_e profile is measured and shown in figure 15. Temperature measurement becomes difficult in the radial positions near the filament. Temperature in the presence of RF field is also measured. The change in temperature falls within experimental errors. However, an important observation seen in the presence of RF field is that the ion saturation current is not attained with -60 V on the probe during the measurements even at $r = 0$ position and beyond the outer edge. This is because of the contribution of the high energy electrons to the probe current. In the absence of RF field, a similar observation is made near the radial location of the filament.

It must be mentioned that care and precaution are to be exercised while using Langmuir probe in the presence of strong magnetic and RF fields. Use of such a probe in the presence of magnetic field is described in many places and appropriate corrections are used. To avoid the effect of RF fields, one can use a two-probe method (Chen 1985). One measures the floating potential while the other measures the probe current. Methods described in the above paper are used for measurements in strong B_T and RF fields.

Ion temperature is measured with the help of a directional probe (Motley and Kawabe 1971). Ion temperature T_i is found to be $(0{\cdot}7 \pm 0{\cdot}2)$ eV during our measurement.

BETA has only a toroidal magnetic field. In principle, the field lines should close on themselves. However, due to small errors in fabrication and positioning of the coils, field lines, in reality, form a spiral and intersect the wall. From experimental evidences, it is concluded that in our machine, the toroidal field lines encircle the vacuum vessel at least 50 times before they intersect the wall.

A small vertical magnetic field is added to the existing field configuration. Depending on the direction of the field lines, the existing spiral could become tighter or looser. Plasma density and potential profiles are measured and shown in figures 16 and 17. Figure 16 shows the radial profiles of density and floating potential. The density profile has not only become broad but the density has also increased. However, the negative peak of floating potential has increased and shifted towards the centre. Due to the longer confinement of high energy electrons moving on the tightly wound spiral, the plasma production efficiency has increased. Figure 17 shows the vertical density and floating potential profile. Dotted line shows the density profile without the presence of vertical field. In the presence of small vertical field the density profile becomes more symmetric.

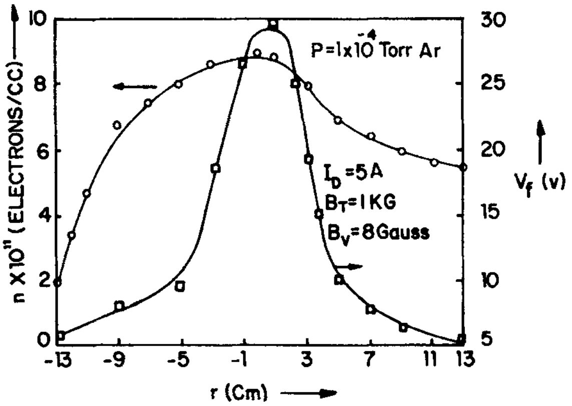

Figure 16. Radial dependence of plasma density and floating potential in the presence of vertical magnetic field.

Plasma particles experience curvature as well as ∇B drift in a toroidal magnetic field. These forces tend to drift the particles in the vertical direction. However in the presence of a vertical field, the $V_{11} \times B_v$ force restricts the particle motion in the vertical direction. Electrons are magnetized and hence do not drift vertically in comparison to ions. Ion drift is restricted by vertical field when the forces balance. Therefore the observed profile symmetrization is due to the cancellation of vertical particle drift. This would increase the residence time of plasma in the systems and is illustrated in the next section.

3.2 *Lifetime measurements*

A pulsed discharge voltage is used during lifetime measurements. A discharge voltage pulse (1 msec 100 V) is applied to the source. The pulse is synchronized to the TF pulse so as to operate at a desired magnetic field value. It is observed that the discharge current falls within 10 μsec which gives the lifetime of the primary electrons. The plasma density decay signal is then measured as a function of time. For higher discharge voltages, the discharge current circuit is broken at a fast speed (few μsec) to measure the plasma decay time.

Figure 18 depicts the plasma lifetime as a function of the toroidal magnetic field. Lifetime is measured in the presence of RF field as well. Measurements are shown in figure 19. Distinct reduction in the lifetime is observed in the presence of RF fields. As

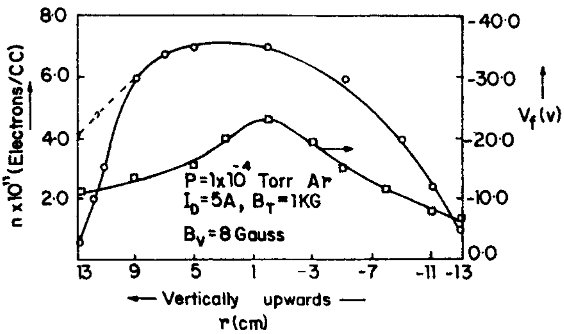

Figure 17. Vertical dependence of plasma density and floating potential. Dotted line shows the density profile in the absence of vertical field.

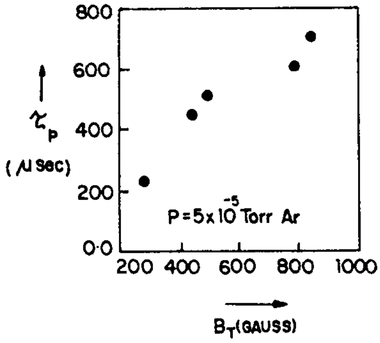

Figure 18. Plasma lifetime as a function of toroidal magnetic field.

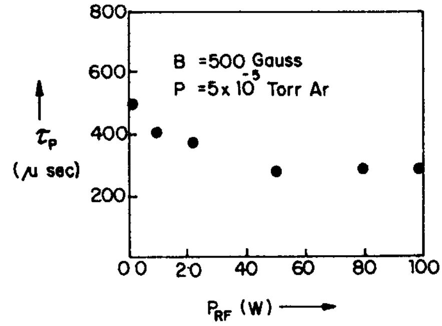

Figure 19. Plasma lifetime (τ_p) as a function of RF power. Other parameters are kept constant.

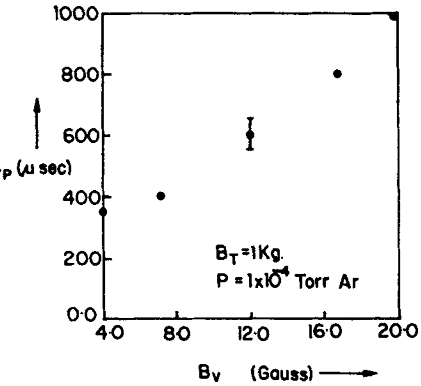

Figure 20. Plasma lifetime as a function of vertical field. Toroidal field is kept constant.

mentioned earlier, RF field interaction with particles results in scattering of particles reducing the residence time of the plasma.

Plasma lifetime in the presence of the vertical field is shown in figure 20. Lifetime increases as a function of vertical field. However the effect is not observed when the vertical field direction is reversed.

Low frequency (few tens of kHz) oscillations are observed at high RF power levels during the high toroidal field experimentations. These oscillations are weak or absent at low magnetic field values. Due to the absence of instabilities at low toroidal magnetic field values, the scattering of the energetic electrons causes reduction in plasma lifetime. However, this excites strong fluctuations at high RF power levels and higher magnetic fields which destabilizes the plasma to a greater extent. Fluctuation measurements will be reported in a separate communication.

3.3 *Conclusion*

Reduction in the plasma lifetime is observed due to initial detrapping of the energetic electrons in a hot cathode discharge toroidal plasma by localized RF field. However, introduction of a small vertical field increases the plasma lifetime for the same external parameters.

Acknowledgements

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