Chapter 4 Experimental study of a toroidal magnetised plasma in the presence of a weak vertical magnetic field.

1 Introduction

In the last chapter we observed that ECR produced toroidal magnetized plasma exhibit slab equilibrium. Mathematically, this class of equilibrium should have $\nabla \cdot J = 0$ but as pointed out earlier, it was difficult to establish it experimentally as discharge current cannot be measured in ECR produced plasma. However, discharge current in filament produced plasma can be measured and it is relatively easier in this case to study if $\nabla \cdot J = 0$. Since presence of ECR layer in ECR produced plasma acted as a line source, it is highly probable that this could have been the reason for observed slab equilibrium, hence it is speculated if slab equilibrium could be generated in a filament produced toroidal plasma using an extended source. With this prescription in mind, filament produced plasma is studied to experimentally evaluate $k_\parallel$, $k_\perp$, $J_\parallel$ and $J_\perp$ to establish if $\nabla \cdot J$ equals to zero in slab equilibrium. A weak but finite vertical magnetic field ($B_v$) introduces $k_\parallel$, which in turn, affects the LF flute modes, observed in toroidal plasma in BETA machine. Based on the study of LF fluctuating modes in the presence of a weak vertical magnetic
Non-existence of equilibrium

In a pure toroidal magnetized plasma, single particle theory suggests that electrons and ions suffer curvature and grad-B drift, which give rise to a charge separation in the vertical direction (z-direction) and hence, vertical electric field and vertical current. This electric field interacts with the toroidal magnetic field and gives rise to drift of the plasma particles, radially outward (i.e. along $\vec{R}$). In terms of a fluid picture, one can see the same physics.

$$\rho \left( \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = -\nabla p + \vec{J} \times \vec{B} + \rho \vec{E}$$

Here, the symbols have their usual meanings. For stationary flow ($\partial \vec{v} / \partial t = 0$) and static equilibrium ($\vec{v} = 0$) with no imposed electric field ($\vec{E} = 0$), the above equation reduces to:

$$\vec{J} \times \vec{B} = \nabla p$$

If we take cross product with $\vec{B}$, the above equation reduces to:

$$\vec{B} \times \left( \vec{J} \times \vec{B} \right) = \vec{B} \times \nabla p$$

or,

$$\vec{J} \left( \vec{B} \cdot \vec{B} \right) - \vec{B} \left( \vec{J} \cdot \vec{B} \right) = \vec{B} \times \nabla p$$

$$\vec{J} = \frac{\vec{B} \times \nabla p}{|\vec{B}|^2}, \quad \text{as} \quad \vec{J} \cdot \vec{B} = 0$$

Taking divergence of $\vec{J}$, we get,

$$\nabla \cdot \vec{J} = \nabla \cdot \frac{1}{|\vec{B}|^2} \left( \vec{B} \times \nabla p \right)$$

or,

$$\nabla \cdot \vec{J} = \frac{1}{|\vec{B}|^2} \left( \nabla \times \vec{B} \right) \cdot \nabla \left( \frac{1}{|\vec{B}|^2} \right) + \nabla \cdot \left( \vec{B} \times \nabla p \right) \cdot \nabla \left( \frac{1}{|\vec{B}|^2} \right)$$

For small $\beta$, $\vec{B}$ is the vacuum toroidal magnetic field and $\nabla \times \vec{B} = 0$, thus $\vec{B} = B_0(R)$, and the above equation may be written as:
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\[ \nabla \cdot \mathbf{J} = -\frac{\partial p}{\partial z} B \frac{\partial}{\partial R} \left( \frac{1}{B^2} \right) = -\frac{2}{BR} \left( \frac{\partial p}{\partial z} \right) \]

The condition, \( \nabla \cdot \mathbf{J} \neq 0 \), implies charge separation results. Note that this charge separation would arises only if \( \frac{\partial p}{\partial z} \neq 0 \). How rapidly does the plasma fall outward, can be pursued by a fluid picture? For non-zero fall velocity, \( \mathbf{v}_f \),

\[ \mathbf{j} \times \mathbf{B} = \nabla p + \rho \frac{\partial \mathbf{v}_f}{\partial t} \]

Again for \( \mathbf{B} = \mathbf{B}_0(R) \), vacuum fields, we get,

\[ \frac{\partial \sigma}{\partial t} = \nabla \cdot \mathbf{J} = -\left( \left( \mathbf{B} \times \nabla p \right) \cdot \nabla \left( \frac{1}{B^2} \right) + \frac{\partial}{\partial z} \left( \frac{\rho}{B} \frac{\partial \mathbf{v}_f}{\partial t} \right) \right) \]

Note that second term is the contribution due to polarization currents and is important.

Since \( \nabla \cdot \mathbf{E} = 4\pi \sigma \) and electric field generated is primarily in vertical direction (we call it z-direction), we get,

\[ \frac{\partial}{\partial t} \frac{\partial E_z}{\partial z} = -4\pi B \frac{\partial}{\partial R} \frac{\partial}{\partial z} \left( \frac{1}{B^2} \right) + \frac{\partial}{\partial z} \left( \frac{\rho}{B} \frac{\partial \mathbf{v}_f}{\partial t} \right) \]

or, \[ \frac{\partial E_z}{\partial t} = -4\pi B p \frac{\partial}{\partial R} \left( \frac{1}{B^2} \right) - \frac{4\pi \rho}{B} \frac{\partial \mathbf{v}_f}{\partial t} \]

For ideal fluids, we have \( \mathbf{E} + \mathbf{v} \times \mathbf{B} = 0 \), thus \( \mathbf{v}_f = E_z / B \), and

\[ \frac{\partial \mathbf{v}_f}{\partial t} = \frac{C_s^2 \left( \frac{4\pi \rho}{B^2} \right)}{R \left( \frac{4\pi \rho}{B^2} \right)} \]

where, we have used \( B \approx R^{-1} \) for the toroidal field. Note that for plasma,

\[ \frac{4\pi \rho}{B^2} = \frac{\omega_m^2}{\omega_{ci}^2} >> 1 \] and this factor would have been absent in denominator if we had ignored polarization current term. Typically,
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\[ \left| \frac{\partial v}{\partial t} \right| = \frac{2C_s^2}{R} \]

For our experimental parameter, \( \frac{\omega_{pe}^2}{\omega_{ci}^2} \sim 10^5 \) for a density of \( \sim 10^{10} \text{ cm}^{-3} \) and magnetic field of \( \sim 0.024 \text{ T} \) and the plasma accelerates radially with an effective gravity \( \sim \frac{C_s^2}{R} \). For a radial displacement of 'a', the minor radius of the machine, the fall time or confinement time is,

\[ \tau_c = \frac{\sqrt{aR}}{C_s} \]

For a \( \sim 9 \text{ cm} \), \( R \sim 45 \text{ cm} \), \( C_s \) (at 10 eV for Ar plasma) \( \sim 10^6 \text{ cm sec.} \), we obtain \( \tau_c \sim 20 \mu \text{sec.} \). Thus, the plasma should disappear in 20 \( \mu \text{sec.} \). If toroidal magnetic field were absent, then the plasma would expand and disappear in \( \tau_{c-s} \sim \frac{a}{C_s} \sim 9 \mu \text{sec.} \). Essentially on comparison between the above two cases, we find that the plasma is unconfined by a pure toroidal field.

**Equilibrium in BETA**

It is obvious from the discussion in the last section that plasma in a pure toroidal magnetic field lacks equilibrium. However, a plasma in a toroidal field is restored to equilibrium by the use of a poloidal field as in tokamaks and stellarators. Another simple way to obtain equilibrium in toroidal plasma, is by using a conducting limiting aperture (Yoshikawa, et. al., 1963). This geometry allowed a finite pressure at the boundary, and did not require the boundary to be an equipotential surface. Consider a plasma supported by an infinitely conducting limiter. Let \( \frac{\partial p}{\partial z} \) be zero everywhere except in the "scrape off layer" (SOL). This corresponds to a spatially constant pressure profile in the core plasma, which implies a vanishing divergence of the charge separation current. The density rapidly drops to zero in the SOL region. However, charges can flow along the toroidal magnetic field in \( \phi \)-direction (toroidal direction), along the limiter in \( \theta \)-direction (poloidal direction) and again along the toroidal magnetic field lines. Thus, a path for
short-circuiting the charge separation is available. Hence there is no space-charge accumulation due to the particle drifts in the core. Excess charge entering the SOL region flows to the limiter along the magnetic field lines, and hence the limiter plays an essential role in short circuiting the vertical charge separation current. If the resistance of this plasma-limiter path is negligible, no electric fields would be set up and the plasma would stay in equilibrium. Under this condition, the only particle loss rate is the time, the particle would take to drift to the limiter. Particle confinement time, in this very favourable limit is:

$$\tau_c = \frac{a}{v_d}$$

where $\tau_c$ is the particle confinement time, $a$ is the minor radius of the machine and $v_d$ is the drift velocity given by:

$$v_d = \frac{cT}{eB} \left( \frac{\vec{B} \times \nabla \vec{B}}{B^2} \right) = \left( \frac{cT}{eBR} \right)$$

where $c$ is the speed of light in vacuum, $e$ is the electronic charge and $R$ is the major radius of the machine. Using above two equations, we get:

$$\tau_c = \frac{\sqrt{aR}}{C_s} \frac{\sqrt{aR}}{\rho_s}$$

where $\rho_s = C_s/\omega_s$ is the larmour radius determined by the acoustic speed. Here, it is to be noted that confinement time is improved by a factor, $\frac{\sqrt{aR}}{\rho_s} \geq 300$, and is typically around 7 msec. In a real situation, the electron flow along the ambient magnetic field lines and in the limiter suffers friction. This leads to a non-zero electric field and an imperfect short-circuiting effect. Thus, a net electric field will persist and plasma will accelerate outwards. In any event, the confinement time should be between two extreme values, i.e. between 20 $\mu$sec and 7 msec.
3 Significance of a weak but finite vertical magnetic field

A weak but finite vertical magnetic field plays a very significant and important role in our experiment. The wavelength of fluctuations parallel to the magnetic field is very large. The experimental measurements are very rare (Huld, et. al., 1991) since the probes for the correlated measurements have to be widely separated on the same field lines. Positioning of the probes on the same field line requires the techniques of tracking the field lines by electron beam (Fairbanks and Shohet, 1979). But the tracking of the field lines is not a sufficient condition because the separation between the probes has to be adjusted according to the values of $\lambda_H$, in order that the phase difference becomes observable. In our experimental system, where opening of filed lines exist, indications are that $\lambda_H$ exceeds $2\pi R$, where R is the major radius of torus. This gives rise to the need of positioning the coordinates of the probe on a given magnetic field line which may not be closing on itself after completion of one circuit. Thus, a novel method has been devised to estimate parallel wave-number in our system using a weak vertical magnetic field. Due to misalignment of the discrete toroidal magnetic field (TF) coils positioned around the experimental vacuum vessel, the error in the toroidal magnetic field exists. This error field results in opening of magnetic field lines in vertical direction. The toroidal magnetic field lines hit the vacuum vessel after encircling within the volume for large number of times in the vertical direction. The extent of opening of toroidal magnetic field lines determine the wavelength accommodated in the direction parallel to the field lines and hence, the parallel wave-number. A set of experiments is performed, by changing this length. This is achieved by adding a small dc vertical magnetic field ($H_v$) component to the toroidal magnetic field ($B_t$) in vertically up/down (negative/positive) direction. However, the addition of $B_v$ component is done in such a way that the equilibrium plasma parameters in the whole poloidal cross-section are not altered beyond the experimental errors. During this experiment, $k_H$ is introduced using a small vertical magnetic field ($\ll B_t$) and keeping the toroidicity of the system intact. Experiments have also been conducted in BETA, where flute type fluctuations are suppressed by introducing end plates into the toroidal system at different toroidal locations from the filament to
introduce varying $k_n$ (Kaur, et. al., 1997). End plates made the system finite in length (quarter, half and three-fourth quadrant) and hence, supported waves of appropriate parallel wave number. However, this suffers from the end plate effects as in the finite curved systems used earlier.

**Effect of vertical magnetic field on $k_n$**

Let us assume that the presence of error field can make the field lines go around, in the torus, making ‘n’ turns instead closing on themselves before being intercepted by the vessel. In this case, the parallel wave number associated with the wavelength in that direction would be,

$$|k_n^\rightarrow| = \frac{1}{nR}$$

where, ‘n’ is the number of times the toroidal field line spirals along $\phi$-direction. The total magnetic field can be resolved into the vertical direction (along $z$ direction) and into the toroidal direction ($\phi$-direction). Now, if we apply a weak vertical magnetic field, we may vary the length of the magnetic field lines (i.e. ‘n’ may increase or decrease) depending on the direction in which the vertical field is applied with respect to the vertical component present due to the error field. It may happen that when we apply a weak vertical magnetic field in a particular direction such that it reduces the effective error field (vertical component), then ‘n’ may increase within the torus. This will only happen when the applied vertical magnetic field is antiparallel to the existing vertical component of the error magnetic field. Similarly, if the applied vertical field adds to the existing vertical component of the error field, then ‘n’ may decrease within the torus. This would correspond to the case of applying the vertical magnetic field parallel to the existing vertical component of the error field. We refer to the former case as compression (where ‘n’ increases) and the latter case as elongation (where ‘n’ decreases). The word compression does not mean an increase in the toroidal magnetic field by moving radially inward but it means that the spiraling pitch of the toroidal field lines reduces. It may also happen that while compressing the magnetic field lines, the imposition of the vertical field lines may exactly cancel the vertical component of the error field, thereby correcting
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the existing error field, which would mean

\[ |\vec{k}_n| = \frac{1}{2\pi R} \text{ or } 0 \]

further increase in the vertical magnetic field in the same direction may result in producing error in the toroidal magnetic field lines in the opposite direction, thereby generating vertical component of the field lines in the opposite direction. Any further increase in \( \vec{B}_v \) would result in decrease of ‘n’, thereby increasing \( k_n \) once again. Thus, there exists a threshold after which application of vertical field will produce elongation irrespective of the direction (positive or negative in the vertical direction) of application.

This threshold value of \( \vec{B}_v \) would give us an estimate of error field present in our experimental system and hence the parallel wavenumber present in our system due to existing error fields in the device.

**Effect of finite \( k_n \) on flute modes**

Flute type instabilities are of transverse nature. The wave number ‘\( \vec{k} \)’ is perpendicular to the ambient magnetic field ‘\( \vec{B} \)’. The waves travel in the azimuthal direction, if the driving force is in the radial direction. When a small but finite component of ‘\( \vec{k} \)’ along ‘\( \vec{B} \)’ is introduced, electrons can flow along ‘\( \vec{B} \)’ to establish a thermodynamic equilibrium among themselves following Boltzmann relation. This will short circuit the radial electric field (the driving force). Thus, growth rate of the flute type instabilities should be reduced with the introduction of \( k_n \) into the system. This will be reflected in the root mean square (r.m.s.) amplitude of different modes in the power spectrum and hence change in the power spectrum with change in the vertical magnetic field. This is how the effect of \( k_n \) on the behaviour of the LF fluctuations has been studied with a weak but finite vertical magnetic field.
4 Investigation of equilibrium parameter

In this section, experimental results of the equilibrium profile of the plasma parameter, with and without vertical magnetic field is presented. The plasma is formed by placing a filament at a radial location of 45 cm. During the experiment toroidal magnetic field is varied from 0.024 T to 0.096 T. A radially movable cylindrical Langmuir probe system with exposed tip of 2.5mm in length and 0.75mm in diameter insulated with glass is used to measure equilibrium profiles of plasma density, floating potential and electron temperature. The density at each radial location is measured by ion saturation currents terminated to the low impedance probe together with current to voltage follower. A high impedance probe terminated with a voltage follower measures the floating potential. The diagnostics used to acquire the equilibrium profiles are located 180° away in the toroidal direction from the filament location. We have kept the discharge current constant during the experiment, which is an indicator of global plasma parameter and this ensures that the global plasma parameters are same. The equilibrium plasma parameter profiles are studied. The coordinate system used in our experimental results assumes origin at the minor axis. As we go out radially, the radial distance increases positively and as one moves radially inside, from the origin, the distance decreases in negative direction. Similarly, if we move vertically in up direction, the vertical direction increases positively and vice-versa.

When $B_v = 0$

In this part of the experiment, no vertical magnetic field is applied. Measurements reveal that toroidal plasma is formed near the filament location (radially), close to the equatorial plane, with a peak density of $\sim 6 \times 10^{10}$ cm$^{-3}$. The density profile exhibits bi-directional nature. The surface of the plasma in the azimuthal direction, $\pi/2 < \theta < 3\pi/2$ contacts concavely with the lines of force where $\theta = 0$ corresponds to a plasma position at the outer edge on the equatorial plane of a poloidal cross section. So, this region has a good curvature, as $\nabla B^2 \cdot VP > 0$. The outer region which is defined by $3\pi/2 < \theta < \pi/2$, has a bad curvature, where $\nabla B^2 \cdot VP < 0$. The density gradients are antiparallel to simulated gravity (due to curvature of the magnetic field lines) in the bad curvature region whereas they are
parallel in good curvature region. Density in the poloidal cross section is measured to generate contours in r-z plane of a toroidal plasma. This has been done by making detail measurements of the d.c. component of density in the poloidal cross-section at a fixed toroidal location. For clarity and easy comparison, the density and floating potential contours are normalized to their respective maximas. Hence, the contour level varies from 1.0 to 0.0. In this kind of representation their absolute value may change but their scalelength will remain intact. A typical contour of plasma density is shown in Figure 4-1.

Figure 4-1 A typical density contour without vertical field for a filament produced plasma at a toroidal field of 0.04 T, showing the slab nature of the profile in the poloidal cross section.

At radial distances away from the filament location the equal density contours are vertically parallel to each other. It supports different density gradients, $L_n = \left( \frac{1}{n dx} \right)$, in
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The radial direction. The density scalelength, $L_n \sim 6\text{cm}$ is observed near the filament region, whereas $L_n \sim 12\text{ cm}$ exists in the region away from the filament location. The filament is located at a radial position of 45 cm with respect to the major axis (i.e. at the minor axis $r = 0$ cm). In the figure, it is seen that the peak of the plasma density occurs at $r \sim 2$ cm. The filament (along $z$-axis) is perpendicular to the ambient toroidal magnetic field (along $\phi$-axis). When a current ($J$) passes through the filament, a radially outward force ($J \times B$) acts on the filament. This force bends the filament radially outward. The observed shift in the plasma center and the geometrical center of the vessel is due to radially outward bending of the filament.

![Potential contours at $B_t=400\text{G}$ and $B_v=0\text{G}$](image_url)

**Figure 4-2** A typical potential contour of filament produced plasma at a toroidal magnetic field of 0.04 T.
Floating potential measurements reveal that toroidal plasma is formed which exhibits floating potential minima of ~ -50 volts near the filament location. The potential profile also exhibits bi-directional nature. Floating potential in the poloidal cross section is also measured to generate contours in r-z plane of a toroidal plasma. This has been done by making detail measurements of the d.c. component of floating potential in the poloidal cross section at a fixed toroidal location. A typical contour of plasma floating potential is shown Figure 4-2.

At radial distances away from the filament location, the equal potential contours are vertically parallel to each other and exhibit slab nature in the vertical direction at radial locations away from the source. In our experiment, the contours near the filament are not perfectly vertical. This may be due to many reasons like presence of hot energetic electrons, inhomogeneous surface temperature of the filament, voltage gradient on the filament, density gradient, etc. on and near the end of the filament. The contours suggest the existence of radial electric field over the poloidal cross section ($r = \pm 7$ cm). The electric field is typically of the order of 1 V/cm at radial locations, $r > 5$ cm. The $\vec{E} \times \vec{B}$ velocity is about $10^5$ cm/s. The radial measurement of the electron temperature shows a radial variation from 3eV to 8eV.

The equatorial radial profiles of density, floating potential and electron temperature measured during the experiment look similar to the measurements of earlier experiments (Prasad, et. al., 1992). The measurements have revealed that the contours of equal density and equipotential are generated within the vacuum vessel. At radially further away positions; they exhibit slab nature in the vertical direction. These measurements confirm the assumption of the effective gravity due to magnetic field curvature being parallel/antiparallel to the density gradient in some earlier experiments (Bora, 1989, Prasad, et. al., 1992).

Most of the experiments in BETA machine have also used a similar source. Discharge characteristics of such a source have already been described earlier (Mattoo, et. al., 1986). The primary electrons are localized along the toroidal field lines in the vicinity of
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the filament position. Hence, the plasma is produced at these locations that fills the whole toroidal volume by diffusion. In such a production scheme it is not a-priori clear whether closed contours of equal density and equipotential contours would be generated within the experimental region. This motivated us to generate dc measurement of equilibrium plasma parameter in the poloidal cross-section (r - z plane). In another set of measurements in the same experiment, the equilibrium contours of equal density and floating potential are measured in the lower half of the poloidal cross section at the same toroidal location. This is done to see if the contours are closed within the vacuum chamber. The density contours obtained from our experimental results is shown in Figure 4-3.

Figure 4-3 Normalised density contour in the lower half portion of the poloidal cross-section showing that the contours close elliptically in the lower half of the poloidal cross-section (r - z plane)
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Measurements of contours of equal density suggest that they close elliptically in the vertical direction, for an extended source. By extended source, we mean the tungsten wire cathode which is located at \( r = 0 \) and extends in \( z \)-direction from \( z = +7 \) cm to \( z = -7 \) cm. The slab nature of the plasma also extends from \( z = +7 \) cm to \( z = -7 \) cm, which is the length of the cathode. This suggests that the slab nature of the plasma could be adjusted using appropriate length of the filament. The potential contours are shown in Figure 4-4.

![Potential contours at B_t=240G and B_v=0G](image)

**Figure 4-4 Normalised potential contours in the lower half of the poloidal cross-section. The contour is generated at a toroidal field of 0.024 T.**

**When \( B_v \neq 0 \)**

Weak vertical magnetic field of \( \pm 3 \times 10^{-4} \) T, \( \pm 6 \times 10^{-4} \) T and \( \pm 9 \times 10^{-4} \) T is applied during the experiment. During the experiment, the toroidal magnetic field is varied from 0.024 T to 0.096 T. Measurements reveal that toroidal plasma is formed near the filament location (radially), close to the equatorial plane, exhibiting bi-directional profiles.
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Figure 4-5 Plot of density and floating potential with B, of 0T, $3 \times 10^{-4}$ T, $6 \times 10^{-4}$ T and $9 \times 10^{-4}$ T
In the presence of a weak vertical magnetic field, the contours and surface plot of equal density and floating potential are generated. A typical result of surface plot of density, without a vertical magnetic field and in the presence of a weak vertical magnetic field of $3 \times 10^{-4}$ T, $6 \times 10^{-4}$ T and $9 \times 10^{-4}$ T is shown in Figure 4-5.

The result shows that the profiles of equal density and floating potential remain similar to those obtained without vertical magnetic field at distances away from the filament region. In the filament region, the surfaces show some variations. These regions comprise hot and energetic primary electrons. Our main interest lies in the outer region ($|r| > 5$ cm) where the density and the floating potential gradients are low (to avoid gradient driven modes as far as possible) and contribution of the primary hot and energetic electrons is negligible. It is also observed at these radial locations that the density gradient is parallel (antiparallel) to effective gravity, due to the curved magnetic field, in the good (bad) curvature region, at planes other than the equatorial plane ($z = 0$ cm). Good curvature region implies the region where the density gradient and the effective gravity force have same direction (inboard side) whereas the bad curvature region is that where they have opposite directions (outboard side). Thus, our results suggest that equilibrium parameter do not vary beyond experimental errors in the region of our interest, in the presence of a weak vertical magnetic field.

5 Investigation of fluctuating parameter

Fluctuations in density and floating potential are measured simultaneously at different radial locations in the equatorial plane ($z = 0$). These signals are analysed using FFT based spectral analysis technique. Digital spectral analysis is used to obtain crosspower, phase and coherence spectra between density and floating potential fluctuations. Here we present the detailed analysis of the low frequency fluctuations studied with and without vertical magnetic field.
When \( B_v = 0 \)

![Figure 4-6](image)

**Figure 4-6** A typical spectrum obtained with a filament produced plasma at \( r = 6 \) cm. The top figure shows the cross power spectrum of the low frequency fluctuations. The middle figure shows the phase difference between the density and potential signals showing the flute nature of the coherent fluctuations. The bottom figure shows a high degree of coherence of the fluctuations.

During this part of the experiment no vertical magnetic field is applied. Low frequency electrostatic coherent fluctuations are observed. The cross power spectrum exhibits a well-defined peak centered \( \sim 3.8 \) kHz. The phase difference at this frequency is close to 180° and shows a high degree of coherence (nearly unity). It is well known that gradient driven drift instability shows a phase difference close to zero between the density and floating potential fluctuations at the same location, while the flute type instabilities show a phase difference of around 180° (Bora, 1989). These fluctuations at this frequency have been identified as R-T instability in earlier similar experiments and its identification has been discussed in detail (Prasad, et. al., 1994). Phase difference observed in our case is also attributed to R-T instability, which is flute in nature. A typical spectrum obtained at a toroidal magnetic field of 0.024 T is shown in Figure 4-6. The phase difference is around 140° between the two signals and the coherence is \( \sim 1.0 \). The observed
We observe that as $B_v$ is increased to $3 \times 10^{-4}$ T, the power in the density fluctuations increases. With further increase of $B_v$ to $6 \times 10^{-4}$ T, the fluctuations get suppressed. Significant suppression is observed when vertical magnetic field is applied in the positive direction ($B_v = 6 \times 10^{-4}$) then when it is applied in the negative direction. This unequal suppression in the fluctuations for the same magnitude of $B_v$ (but opposite in direction) suggests the existence of error field. If there would have been no error field then equal suppression in the fluctuations should have been observed. This observation explains the fact that when vertical magnetic field is applied in the negative direction, it opposes the vertical component of the existing error magnetic field (which is in the positive direction). Under such circumstances the 'n' is large, causing a little decrease of
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Grad $k''_n$ value, thus producing less suppression whereas when the vertical magnetic field is applied in the positive direction, it adds to the vertical component of the existing error magnetic field, resulting into small ‘n’ value, causing a significant increase in the $k''_n$ value, thereby producing large suppression. Similar changes are observed in the radial profile of integrated floating potential power with different $\vec{B}_v$. Suppression in the fluctuation is observed in the floating potential within the region of our interest. However, significant suppression is observed with positive vertical magnetic field in comparison to the negative vertical magnetic field of same magnitude. This occurs only in the bad curvature region. This further supports our inference that flute type instabilities are suppressed more in the presence of finite $k''_n$. R-T instability, being one of them and which should, in principle be excited in the bad curvature region is affected. R-T instability is one of the instabilities identified earlier in this machine under similar conditions (Prasad, et. al., 1995). The phase spectrum shows flute nature during this set of experiments as well. The elongation of the toroidal field lines, which introduces finite $k''_n$ in flute type instabilities, inhibits the growth of electrostatic fluctuations. One would expect that the power content of the mode excited by the flute type instabilities to be reduced with the elongation of the field lines. To see the effect of $k''_n$ on the predominant coherent LF fluctuating component of density, the power content of this particular frequency is plotted as a function of vertical field (which is varied upto $9 \times 10^{-4}$ T in both the direction) in Figure 4-8(a).

Our plot suggests the existence of a threshold on $\vec{B}_v$ (at around $3 \times 10^{-4}$ T), where $k''_n$ tends to 0 or $1/2\pi R$ (corresponding to maximum of integrated power in Figure 4-8(a)). Further increase of $\vec{B}_v$ makes the toroidal lines to slip and open in the opposite direction, accommodating larger $k''_n$, thereby reducing the power content. As we keep elongating the field lines, accommodating larger $k''_n$, the contribution of finite $k''_n$
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increases till the coherence of the peak falls below 0.8 as shown in Figure 4-8c. Reduction in the power content of the fluctuations, both in density and floating potential is observed. However, the density fluctuations initially show an increase in the integrated power as \( B_v \) is increased to \( 3 \times 10^{-4} \) T and then shows reduction in the integrated power as \( B_v \) is further increased as seen from Figure 4-8.

Figure 4-8 Variation in the power content of the coherent LF fluctuating component (3.32 kHz ± 0.19 kHz) of (a) density (b) floating potential and (c) their coherence with different vertical magnetic fields at \( r = 6 \) cm. The peak at \( B_v = 3 \times 10^{-4} \) T in (a) suggests the existence of a threshold of \( B_v \sim 3 \times 10^{-4} \) T. Also the coherence value falls as \( B_v \) is increased.

Figure 4-9(i - vii) depicts the power spectrum for density and potential at different \( B_v \). A well defined peak is observed in the power spectra at a higher frequency, in the presence of a weak vertical magnetic field, as shown in Figure 4-9(i - vii), (around 7kHz for \( B_v = \pm 9 \) G) over the turbulent background. This peak still has a flute nature suggesting a shift only in the frequency. Power content falls by about 15 dB.
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Figure 4-9 Auto power spectrum of (a) density and (b) floating potential at r = 6 cm with (i) \( \mathbf{B}_v = -9 \times 10^{-4} \) T, (ii) \( \mathbf{B}_v = -6 \times 10^{-4} \) T, (iii) \( \mathbf{B}_v = -3 \times 10^{-4} \) T, (iv) \( \mathbf{B}_v = 0 \) T, (v) \( \mathbf{B}_v = 3 \times 10^{-4} \) T, (vi) \( \mathbf{B}_v = 6 \times 10^{-4} \) T and (vii) \( \mathbf{B}_v = 9 \times 10^{-4} \) T. The plot show the shift in the coherent peaks to a higher frequency and reduction in the power level of the fluctuations as \( \mathbf{B}_v \) is increased.
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6 Slab-like equilibrium

In the last chapter (ECR produced plasma), experimental observation shows that density and floating potential contours exhibit slab nature in r-z plane. The above observation implies $\frac{\partial \rho}{\partial z} = 0$. As discussed, if this condition is satisfied, then single fluid model exhibit equilibrium solution and $\nabla \cdot \mathbf{J} = 0$ (which means in particle model, no charge separation, no vertical electric field and no $\mathbf{E} \times \mathbf{B}$, radial drift of particles). Alternatively we can also write, $\nabla \cdot \mathbf{J} = 0$, which implies,

\[
\begin{align*}
\left| \begin{array}{c}
\nabla \cdot \mathbf{J} \\
\mathbf{J}_n
\end{array} \right| &= \left| \begin{array}{c}
k_z \\
k_n
\end{array} \right|
\end{align*}
\]

To establish the above relation (and slab equilibrium, mathematically), the LHS and RHS of the above equation should be evaluated using our experimental parameter and compared. To evaluate the current densities flowing in the parallel and perpendicular direction, we should estimate the area over which these currents would flow. For the perpendicular (vertical) current, the area would be the annulus area, which includes the filament region of width (w) and would be $= 2\pi R w$. The parallel current would be intercepted by the limiter edge and the area of the limiter, which would collect this current, will depend on the magnitude of error fields. Let us assume that the radial width over which the current would be collected by the limiter be $\chi$. This width would be equal to the amount of magnetic field pitch. Hence, we may write:

$$\frac{x}{2\pi R} = \frac{B_{\text{error}}}{B}$$

and the area intercepted by the limiter with the parallel magnetic field line would be $\approx 2\pi a x = 4\pi^2 a R B_{\text{error}} / B$. With simple mathematical steps it can be shown that the ratio of the two current densities can be written as:

$$\left| \frac{\mathbf{J}_n}{\mathbf{J}_z} \right| = \left( \frac{B_n}{B_{\text{error}}} \right) \left( \frac{I_n}{I_z} \right) \left( \frac{w}{2\pi a} \right)$$
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In the above equation three unknowns are there, viz, parallel and perpendicular current and error magnetic field in our system. Now, let us estimate the ratio of two currents in our experiment. In principle, a vertical component of $\nabla p$ at the end of the filament region could provide a charge loss in perpendicular direction, according to charge continuity equation. Suppose this vertical gradient exist on a vertical strip of width $w'$. The magnetic flux tube consisting of the field lines intercepting the filament would be cylindrical annulus of radius $R$. Integrating the continuity equation over the volume of this cylindrical annulus gives:

$$I_p = \int \left( \nabla \cdot J \right) dV$$

where $I_p$ is the perpendicular current, $dV$ is the volume element and the integration is performed over the volume of the cylindrical annulus. For the cylindrical annulus we have, $dV = (2\pi R w) dz$. Hence, we get,

$$I_{dis} = \int \left( \nabla \cdot J \right) (2\pi R w) dz$$

$$I_{dis} = -\int \left( \frac{2}{RB} \frac{dp}{dz} 2\pi R w \right) dz$$

$$I_{dis} = -\left( \frac{4\pi w}{B} \right) \int dp$$

For our experiments, we have typically $w = 10^{-2}$ m, $B = 0.024$ T and $dp = 10^{-2}$ Pa, which gives perpendicular current of about 60 mA. But in our experiments, total discharge current, $I_{dis}$, is around 2 A. Hence, the rest of the current would flow through parallel channel because of open field lines. Suppose, the rest of the current (1.94 A) flows through the open field lines (we call it parallel current), then:

$$\frac{|I_{dis}|}{|I_p|} = 32.3$$

The estimate of the error field present in our system, as deduced from the measurement of the LF fluctuations with weak vertical magnetic field is typically around $\sim 3 \times 10^{-4}$ T. Putting these values in the expression for the ratio of current densities, we get its value, typically around $\sim 27$. Now, we turn our attention to evaluate parallel wavenumber. As
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mentioned earlier, we know that the parallel wavenumber, in the presence of error field, may be written as,

\[ |k_n| = \frac{1}{nR} = \frac{B_{\text{error}}}{B_i} \frac{\pi}{a}, \quad \text{since}, \quad \frac{B_{\text{error}}}{B_i} = \frac{2a}{2mR} \]

For our experimental parameters, the parallel wavenumber turns out to be around \( \sim 0.436 \) \( m^{-1} \). The perpendicular wavenumber is measured with the help of a set of Langmuir probes using correlation techniques. Our measurements reveal that \( k_p \sim 16 \) \( m^{-1} \) and is similar to that reported earlier (Prasad, et. al., 1992). The ratio of perpendicular and parallel wavenumber in our case turns out to be around \( \sim 36 \), whereas the ratio of current densities is typically around \( \sim 27 \). Thus, the calculation just presented in this section, shows that the ratio matches quite well and establishes the vanishing divergence of the charge separation current. It supports our argument that the excess charge is indeed removed by the open field lines and provides a slab equilibrium to the plasma.

7 Conclusion

Filament produced plasma is studied in the presence and absence of a weak vertical magnetic field. A theoretical consideration for plasma equilibrium in toroidal device BETA is considered. The plasma is produced with an extended source at the minor axis. Equilibrium profiles of plasma parameter are measured with and without vertical magnetic field. Measurements show that elongated plasma is formed and exhibits slab equilibrium. It has been shown that due to the presence of error magnetic field, finite parallel wave number is inherent in BETA plasma. The finite \( k_n \) due to error magnetic field present in the system is estimated and our measurements establish the slab nature of the plasma in the vertical direction, away from the filament region. Infact open field lines (error field lines) provide an efficient channel through which excess charge is removed and plasma is in slab equilibrium. Experimental parameter supports the vanishing divergence of the current and supports slab like equilibrium. Measurements also reveal that the plasma parameter contour close elliptically in the lower half portion of the
poloidal cross-section. As referred in earlier chapter, there have been earlier experiments to study LF electrostatic turbulence in a pure toroidal magnetic field. In some of the experiments (Prasad, et. al., 1992, Prasad, et. al, 1994) conducted in this machine, conditions similar to equatorial spread F (ESF) region of the ionosphere, were generated, with plasma density profile exhibiting $\nabla n$ anti-parallel to effective gravity, $v_{en} << \omega_e, \omega_i$, and gravity perpendicular to toroidal magnetic field. $v_{en}, v_{in}$ being the collision frequencies between electron-neutral and ion-neutral, whereas $\omega_e, \omega_i$ being the gyro-frequency of electron and ion respectively. The effective gravity was generated due to the curvature of the toroidal magnetic field. For these experiments, it was also desired to have the effective gravity force to be similar (antiparallel/parallel to the density gradient) at all the transverse locations, away from the filament position where the measurements were taken. In these above experiments, LF fluctuations were also found in the good curvature region of the magnetic field. Similar to the case of ESF, this was explained with the help of poloidal propagation of modes from bad curvature region to good curvature region due to $\vec{E} \times \vec{B}$ motion. The closing contours established in this experiment supports above said explanation. In the presence of error fields, we find flute type of instabilities in both good and bad curvature regions and they are indeed affected by the introduction of finite $k_n$. These observations suggest that parallel wave number plays a crucial role on growth/decay of observed flute like LF fluctuations in a fully toroidal system.