Chapter 4

Helicon Characterization

Helicon mode characterization and initial plasma experiments performed in the newly built diverging magnetic field helicon experiment described in Chapter 3 will be presented in this chapter. Radio frequency (RF) plasma is produced in the experimental set up with all the vacuum systems, electromagnets, RF circuitry and diagnostics which are tested individually. Helicon mode is identified at low magnetic fields (<200 Gauss) by observing the mode transitions of a helicon discharge, radial density profiles and wave field measurements. Initial physics experiments to observe current free double layers are discussed. The chapter will describe antenna efficiency measurements, discharge mode transitions, mode structure at low magnetic field and CFDL observation.

4.1 Antenna Efficiency

The half helical \( m = +1 \) antenna is designed for two purposes, one for RF plasma production and the other is helicon wave excitation with the later dependent on the density produced by the former through the helicon dispersion relation for a certain ambient magnetic field. So it is necessary to find out the efficiency of the antenna and its associated circuitry to deliver significant power to the plasma. The power transfer efficiency has been calculated to estimate the RF power absorption in the plasma, using the relation [1-2]

\[
\eta = \frac{R_p}{R_p + R_A} \quad (4.1)
\]

Where \( \eta \) is the power transfer efficiency, \( R_p \) is the plasma resistance and \( R_{\text{ant}} \) is the vacuum resistance. The equivalent circuit of the antenna (Figure 3.3) is composed of an effective inductance, \( L_A \), a circuit resistance, \( R_A \), which includes all Ohmic and contact resistances, and
any eddy current losses relevant to the antenna, transmission line and the matching network. The plasma resistance, \( R_p \) includes all power losses attributed to the plasma, including power losses due to capacitive, inductive and wave coupling. Since the total reactance of the combination of antenna and plasma is matched under every measurement condition and the observed reflected power is < 1\%, total input power from the RF generator must be dissipated in the combined antenna-plasma system. The total current in the antenna is related to the total effective antenna loading resistance, \( R_{eff} = R_A + R_p \), and the net power flow to the antenna is given by [2]

\[
P_F - P_R = I_{rms}^2 R_{eff}
\]  

(4.2)

Where \( P_F \) and \( P_R \) are the forward and reflected powers respectively and \( I_{rms} = I_{rf}/\sqrt{2} \) with \( I_{rf} \) is the amplitude of the sinusoidally varying current measured by a RF current probe coaxially held around the reference leg of the transmission line. The external circuit resistance \( R_A \) is estimated by measuring the antenna current in the absence of plasma.

![Figure 4.1 Variation of antenna RMS current and antenna resistance with RF power in vacuum at 5 × 10⁻⁵ mbar.](image-url)
Figure 4.1 shows the variation of antenna current in vacuum with RF power at $5 \times 10^{-5}$ mbar. The estimated value of the antenna resistance $R_A$ is $\approx 0.34$ Ohm. In this case all of the input power is dissipated in the matching network-antenna system. Figure 4.2 (a) shows the variation of antenna current, $I_{\text{rms}}$, with input power in the presence of plasma. Using the known power output from the generator (calibrated with a 50 Ohm resistive load) and measured reflected power, the plasma resistance is calculated from Equation 4.2. The variation of plasma resistance with input power at constant gas fill-in pressure of $2 \times 10^{-3}$ mbar and a constant magnetic field of 100 Gauss near source is shown in Figure 4.2 (b). It can be clearly seen from Figure 4.2 (b) that at low input power, the plasma resistance remains low ($\approx 0.16$ Ohm) before increasing to around 0.8 Ohm above 500 W of input power. Figure 4.2 (b) also reveals that the value of plasma resistance does not change monotonically but exhibits jumps at specific values of input power.

![Graph showing variation of antenna current and plasma resistance with RF power](image)

*Figure 4.2 (a) Antenna current and (b) estimated antenna-plasma resistance variation with RF power at $2 \times 10^{-3}$ mbar Ar and 100 G magnetic field measured at Z=22 cm.*
These jumps in plasma resistance at around 40 W and 450 W of input power are indicative of transitions from capacitive to inductive mode and inductive to helicon mode respectively, which will be discussed elaborately in the next section. After determining the plasma resistance, the power transfer efficiency $\eta$ has been calculated. For low input powers (< 50 W), the power transfer efficiency is less than 30% and it rises up to 75% for input power of > 1200 W which is typical for a helicon discharge [1].

### 4.2 Discharge mode transitions

As discussed in Chapter 2, the discharge mode transitions are observed in all RF discharges. In helicon literature [3] the modes are named E, H or W depending on the dominant electric field responsible for maintain the discharge is of capacitive, inductive or wave origin respectively. EHW mode transitions in helicon discharges are observed by changing source parameters either of RF power [1, 3-4] and ambient magnetic field [5]. These transitions are observed by monitoring the density [3-6], Q-factor of matching circuit [6], plasma potential [7] or antenna plasma resistance [8]. In this thesis mode transitions are studied by increasing the RF power at 110 G magnetic field with four different argon neutral pressures ($3 \times 10^{-4}$ mbar, $6 \times 10^{-4}$ mbar, $9 \times 10^{-4}$ mbar and $40 \times 10^{-4}$ mbar) and measuring density in the upstream region at $z = 22$ cm along with load capacitance values of matching network for zero RF power reflection. The helicon dispersion (Equation 2.x) suggests transition to helicon mode at lower density i.e. lower RF power for a lesser ambient magnetic field.

Figure 4.3 (a) shows the variation of plasma density with RF power as measured by a triple Langmuir probe at $z = 22$ cm. At $3 \times 10^{-4}$ mbar (lowest pressure) the transition from capacitive to inductive discharge though possible in the applied RF power range, the transition to helicon sustained discharge is not visible. But in all the other three higher pressures clear transitions to helicon discharge are possible. As per the design of the matching network [Chapter 3] $G_L \propto 1/\sqrt{R_p}$, the value of the load capacitor gives an indirect feedback of the antenna-plasma resistance. So the $G_L$ values are noted and their variations with RF power are plotted in Figure 4.3 (b). As evident from the figure, the transitions in density values of Figure 4.3 (a) are magnified in $G_L$ plots with clear and distinct transitions well visible. The reason for antenna-plasma resistance or $G_L$ value to be more sensitive to external plasma parameters is because it represents
a macroscopic change of the discharge in total corresponding to antenna plasma resistance whereas the density measurement using Langmuir probe is a single point local microscopic sampling. For the lowest pressure there is only one transition (E-H) but for all other higher pressures there are two transitions (E-H and H-W). The transitions to helicon mode from an inductive mode happened at a lower RF power for a higher pressure. Another observation from this study is that the slope of density variation is different in all the sustained modes indicating different mechanisms of sustaining the discharge.

Figure 4.3 Mode transitions observed at 100 Gauss for different Argon pressures. Transitions are observed (a) in density variation with power at z=20 cm and (b) in load capacitor values of the matching network.
However, from all these above-mentioned observations we can conclude that at low powers (< 50 W) the plasma discharges are capacitive in nature i.e. the power is coupled to the plasma capacitively. As we increased the input power > 50 W up to < 500 W, the power is coupled to the plasma inductively and higher densities compared to the capacitive mode are observed. At higher powers (> 500W), the power coupling to the plasma happens due to the direct coupling of antenna fields to helicon wave fields as the density rises more sharply compared to the inductive mode.

![Radial density profile for two different RF powers (50W and 600W)](image)

*Figure 4.4 Radial density profile for two different RF powers (50W and 600W)*

The existence of inductive and helicon modes are further supported by the measurement of density profile at 22 cm away from the source as it is expected that for an inductive mode the power deposition will be away from the center and near the boundary unlike the helicon mode in which maximum power is deposited away from the radial boundary of the discharge [4, 9-10].
At low input power (~ 50 - 500 W), radial profile of electron density remains hollow (Figure 4.4), a signature of inductive mode discharge. However, at higher input power (>500 W) peaked radial profile of density is observed (Figure 4.4), indicating the existence of helicon mode in the plasma.

**4.3 Mode structure at Low magnetic field**

Excitation of helicon $m = +1$ mode is confirmed by measuring the axial component of wave magnetic field along the radius. Figure 4.x shows the variation $B_z$ amplitude normalized to unity, measured with a single loop B-dot probe at $z = 22$ cm with 300 W RF power and $2 \times 10^{-3}$ mbar pressure. Along with are shown theoretical $m = +1$ curves of $B_z$ of helicon waves in a cylindrical boundary [24] with a perpendicular wave number of 76 m$^{-1}$.

![Figure 4.5 Radial variation measured $B_z$ (circles) at 30 G, 300W and $2 \times 10^{-3}$ mbar. The solid lines are theoretical curves of pure $m = +1$ mode along with mixed modes with 25%, 50%, 75% and 100% additional $m = 0$ mode content. All values are normalized to 1.](image-url)
The variations are asymmetric with respect to the origin and also the minimum on axis is shifted to negative radius values. These kinds of variations at low magnetic field have been reported earlier [11-13]. The reason for \( m = 0 \) antenna field structure is not clear.

To see the effect of pollution, theoretical \( B_z \) radial profiles are plotted in Figure 4.5 for a mixed mode with 100\% \( m = +1 \) mode content in addition to a variable \% of \( m = 0 \) mode. \( m = +1 \) is basically a \( J_1(k \perp r) \) function which is asymmetric in radius (argument) for a given value of \( k \perp \).

But as we measure the peak-to-peak values we cannot distinguish the positive and negative amplitudes. Whereas, \( m = 0 \) mode is symmetric with respect to the argument of the Bessel component it consists of. So on one side of radial variation has values decreased and the other

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**Figure 4.6** Radial variation of \( B_z \) amplitude in normalized units for 300W RF power, 30 G and Argon neutral pressure of \( 2 \times 10^{-3} \text{mbar} \) measured at \( Z=40 \text{ cm} \).
side the values are increased, the total radial variation which on normalization gives an asymmetrical behavior.

Though it is expected that the induced fields (or antenna fields) will die down in a thin skin depth, the application of magnetic field has already been proposed by Chen [14] to increase the skin depth giving rise to an anomalous skin depth.

Figure 4.5 shows that a pollution of ~ 25% $m = 0$ mode is there. To confirm that the antenna fields are causing the asymmetric radial variation, $B_z$ in the downstream plasma is measured at $z=40$ cm. Figure 4.6 shows a radial profile which is symmetric which confirms that $m = 0$ mode pollution is negligible. So, the mode structure measured near the antenna shows $m = +1$ mode

*Figure 4.7 Variation of axial magnetic field of Helicon wave along the axis for 600 W RF power at pressure ~ $2 \times 10^{-3}$ mbar and magnetic field ~ 100 Gauss.*
excitation with pollution from $m = 0$ mode with a pure $m = +1$ mode downstream of the source.

The existence of helicon wave in the plasma at higher input powers (>500 W) is further substantiated by the measurement of axial profile of wave magnetic field using a single loop B-dot probe as shown in Figure 4.7 for 600 W RF power and a pressure of $2 \times 10^{-3}$ mbar with 100 Gauss magnetic field. From the slope of the axial phase variation of the wave magnetic field, the wavelength was calculated ~ 22 cm in the source region and ~19.5 cm in the diffusion region using the phase axial slope as shown from Figure 4.8.

![Figure 4.8 Axial variation of helicon wave phase measured at r=0 with a single loop B-dot probe at $\sim 2 \times 10^{-3}$ mbar, 300W and 100 G magnetic field.](image)

### 4.4 Axial density profile

One of the primary aims of this thesis is study of CFDL. CFDL in a helicon discharge are typically performed in an expanding geometry and an expanding magnetic field with 100’s of Gauss in the source chamber and 10’s of Gauss in the diffusion chamber [15-19]. The combined
effect of both geometry and magnetic field expansion sets up a density gradient in the axial direction which gives rise to an ambipolar potential drop. This potential drop evolves into a free standing often stable potential structure as the neutral pressure is reduced. An experiment is performed to look for density gradients set up in the axial direction at $2 \times 10^{-3}$ mbar and 110 Gauss magnetic field near the antenna. Figure 4.8 shows axial variation of density measured by a double Langmuir probe for three different powers at $r = 0$.

![Figure 4.8 Axial variation of density measured by a double Langmuir probe for three different powers at $r = 0$.](image)

Upstream-to-downstream density ratios of ~ 2.7, 5.3 and 8.8 are obtained for RF input power of 200 W, 300 W and 400 W respectively. The variation of upstream and downstream densities shows that the maximum power deposition is happening near the source only. But one of the interesting features is a hump in the density near axial locations of $z = 35-55$ cm in the diffusion chamber, the hump getting peaked for higher RF powers. Though the occurrence of downstream density peaks much away from the antenna are reported in high power and high magnetic field
experiments [20-22], these downstream density peaks which are observed here at low magnetic field low RF power are not reported so far. Thorough investigation of these downstream density peaks will be discussed in Chapter 5.

### 4.5 Observation of Current free double layer

CFDL formation in the expanding helicon plasma is studied at 600W RF power, 280 G magnetic field and Argon neutral pressure of \(1.2 \times 10^{-4}\) mbar. On axis plasma potential is measured along the axial direction with a saturated emissive probe in floating potential method (discussed in chapter 3) by passing a filament current of 2.7 Ampere in a 0.125 mm tungsten filament. The variation of plasma potential and density are shown in Figure 4.3 (a) and (b) respectively. The axial magnetic field profile used for this experiment is shown in Figure 3.3.

![Figure 4.10 Axial variations of (a) plasma potential and (b) plasma density at \(2 \times 10^{-3} \text{ mbar}\) and \(1.2 \times 10^{-4} \text{ mbar}\) of Argon with RF power of 600W and 280 G magnetic field in source.](image)
Plasma expansion leads to a density fall with upstream and downstream densities of $5.5 \times 10^{16} / \text{m}^3$ and $1.7 \times 10^{16} / \text{m}^3$ respectively with a nearly equal temperature of $T_e \sim 6 \text{ eV}$ in the potential fall region. The axial density is measured by a double probe and electron temperature is measured by a RF compensated Langmuir probe. For this expansion to be a Boltzmann expansion which relates upstream ($n_0$, $V_0$) and downstream ($n_z$, $V_z$) densities and plasma potentials by $V_z - V_0 = -T_e (\text{eV}) \times \ln(n_z / n_0)$ [15, 17, 23], the maximum drop should be $\sim 7.5 \text{ V}$. This observation plasma potential drop of $\sim 50 \text{ V}$ in bulk plasma is more than the local $T_e$ can be termed as a CFDL as it cannot be explained through a simple Boltzmann plasma expansion. The average thickness of the CFDL is $\sim 1000 \lambda_D$ taking into consideration of upstream and downstream plasma density and electron temperature.

Measurement of density and plasma potential at a higher pressure of $2 \times 10^{-3} \text{ mbar}$ is presented in Figure 4.3 (a) and (b) respectively where a potential drop of $\sim 6 \text{ V}$ is observed which is of the order of the local electron temperature of $\sim 5 \text{ eV}$ and for this the expected plasma potential drop due to a Boltzmann plasma expansion is $\sim 4.4 \text{ V}$.

So, we have observed a CFDL in the source chamber plasma before the geometrical expansion into the diffusion chamber with a potential drop $\phi_{DL} \equiv 8T_e$ and thickness of $\sim 1000 \lambda_D$ which form at low pressure and are not observed at higher pressure. Though this kind of CFDL with thickness $> 50$-$100 \lambda_D$ are observed in few recent experiments [15-16], there are experiments with observation of sharp CFDL with thickness $< 100 \lambda_D$ [17-19]. Further studies on sharp CFDL formation and the effect of magnetic field gradient will be presented in Chapter 6.

**4.6 Summary of Chapter 4**

Antenna resistance is measured without plasma. Helicon antenna efficiency is shown to increase with RF power in the presence of plasma. Discharge mode transitions are observed at different pressures. At lower pressure the transitions are obtained at higher RF powers for a constant magnetic field. Radial density profiles are shown to confirm the inductive and helicon modes. Helicon wave excitation with half helical $m = +1$ mode is confirmed by measuring the radial variation of the axial component of magnetic field. Additionally, the mode is shown to be
polluted by the antenna fields near the antenna and pure away from the antenna in the diffusion chamber. Axial variation of the phase of the helicon wave gives a wave length of 22 cm in the source and 19.5 cm in the diffusion chamber. Axial density profiles in a diverging magnetic field configurations shows upstream-to-downstream density ratios of ~ 2.7, 5.3 and 8.8 are obtained for RF input power of 200 W, 300 W and 400 W respectively. Downstream density peaks are observed in the diffusion chamber which gives indication of helicon power deposition away from the antenna. Current free double layer is observed at low pressures with a potential drop of ~ 8 \( kT_e/e \) and thickness of ~ 1000 \( \lambda_D \). The double layer vanished at higher pressure with the potential drop of the order of \( T_e \) and can be explained through a simple Boltzmann expansion. The DL is formed inside the source chamber and in the bulk of the plasma aligned to magnetic field.
References


