Role of Helicon Waves in Helicon Sources

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Abstract. The radial and axial helicon wave characteristics and plasma parameters have been measured in a high aspect ratio helicon plasma discharge source. The right polarized azimuthal mode ($m = +1$) dominated for all excitation configurations. Axial wave field amplitude profile measurements revealed a beating phenomenon rather than a standing wave in the system. This was found to be consistent with theory if two radial eigenmodes are launched by the antenna. Optical emission measurements show that propagating helicon waves are necessary for high density plasma production. Wave damping is consistent with collisional theory without the inclusion of the Landau damping phenomenon.

1. Introduction

Helicon discharge plasma sources have proven to be high density, low pressure sources with a notable ionization efficiency. This has led to their use in a number of applications including semiconductor processing [1-4]. The existence of a propagating helicon wave in these discharges is necessary for their high density characteristic which is not observed in ordinary inductively coupled plasma (ICP) discharges. We present here a summary of work aimed at understanding the physics of the helicon source.

The experiments were carried out in a 5 cm diameter, 1.6 m long quartz tube (figure 1). An axial magnetic field, $B_0 z$, of 800 G was impressed on 15 mT fill pressure of argon with 2 kW of input power at 27.12 MHz. Right and left helical, as well as straight antennas [5] were used. Radial and axial probes were constructed to measure plasma parameters and wave quantities [5-7].

2. Azimuthal Mode Content

Single turn, unbalanced magnetic probes were used to obtain radial magnetic wave field profiles of B_r, B_θ, and B_z [5]. Figure 2 shows these profiles compared to theory for the $m = +1$ and $m = -1$ azimuthal modes taking in to account the measured radial density profiles. In figure 2(a) the excitation configuration was designed to launch an $m = +1$ mode, and an $m = -1$ mode for 2(b). However, it is evident from the data that the $m = -1$ mode was not observed. The data agree very well with the $m = +1$ theory for both cases. This result was observed regardless of the excitation configuration and was verified by direct measurement of pattern rotation. Antenna/$B_0 z$ configurations designed to couple to the $m = +1$ mode gave the highest density both radially and axially (with the axial profile extending further) than other configurations.

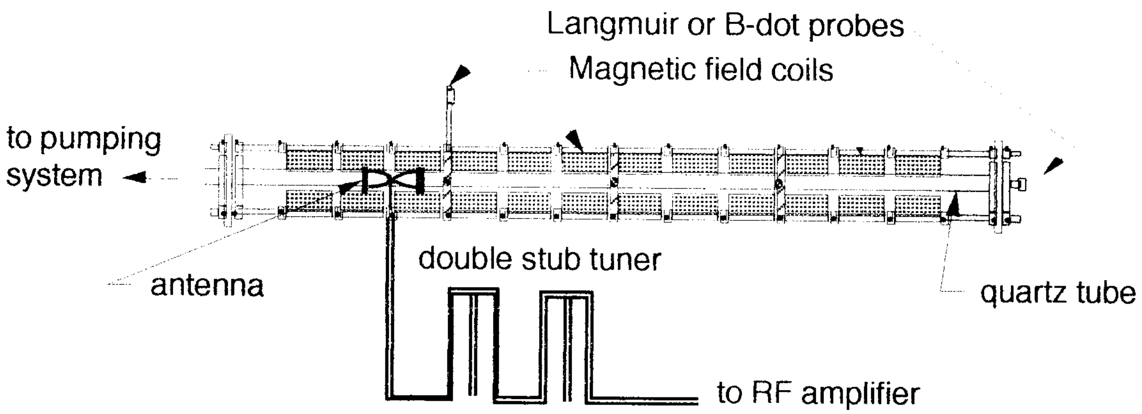

Figure 1. Experimental apparatus.

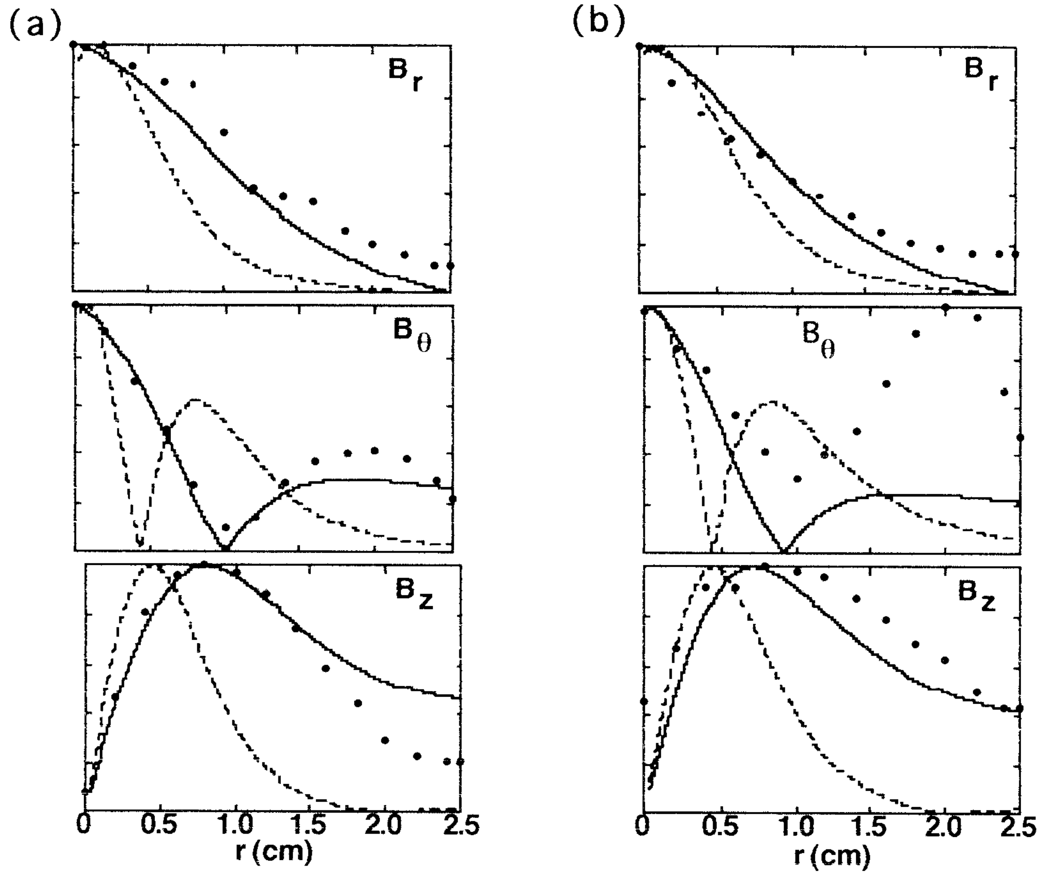

Figure 2. Radial measurements of the wave magnetic field components (points),normalized to unity, in an 800 G helicon discharge at 7.5 mTorr argon fill pressure excited by an R antenna. (a) $B_0 z$ parallel to $\boldsymbol{k}$ and (b) $B_0 z$ antiparallel to $\boldsymbol{k}$. Curves are theory for the $m = +1$ (solid line) and $m = -1$ (dashed line) modes using the measured radial density profile for each calculation.

Figure 3 demonstrates the necessity of resonant helicon wave excitation and propagation for high density operation as opposed to a nonresonant ICP. Local measurements of 488 nm Ar^+ light intensity were made using a small lens and optical fiber connected to a monochromator [7]. In figure 3(a), the light intensity is localized under the antenna for a nonresonant ICP driven with the Nagoya antenna. Inclusion of the 800 G dc magnetic field greatly increases the measured intensity, which is no longer localized under the antenna. Two peaks are observed on either side of the antenna (which was expected to launch equal azimuthal mode content in either direction) regardless of the direction of $B_0 z$. The R antenna shows quite different results (figure 3(b)). Only one peak in light intensity was observed, which moved to the rear of the antenna when $B_0 z$ was reversed, and was located at the same distance away from the antenna midplane as for the Nagoya case. When the direction of $B_0 z$ is reversed, this antenna was expected to launch an $m = +1$ mode in the opposite direction (in the new direction of $B_0 z$). These data show that plasma production is greatly enhanced for resonant helicon excitation. Furthermore, the observed directionality shows that a propagating helicon wave is necessary for operation of this discharge in the distinct high density regime.

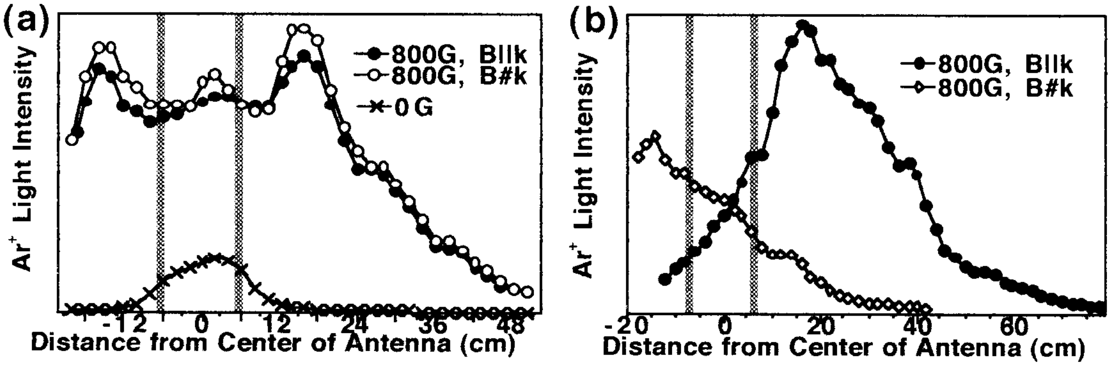

Figure 3. Optical emission measurements of the 488 nm Ar^+ line intensity.
(a) Nagoya antenna with both directions of $B_0\mathbf{z}$ and no $B_0\mathbf{z}$.
(b) R antenna with both directions of $B_0\mathbf{z}$. Shaded areas indicate antenna rings.

3. Downstream Wave Axial Behavior

Axial propagation behavior of the helicon was investigated by measuring the wave axial magnetic field component amplitude, $|B_z(z)|$, downstream of the antenna. This is given in figure 4. A large decrease in wave amplitude at the end of the tube does not point toward a standing wave phenomenon due to reflections from the grounded end flange. This pattern can be understood assuming different modes are excited by the antenna which create a beat. Evaluation of the k-spectrum of the current distribution of the antenna showed that only the first and second radial modes (n = 1,2) of the m = +1 azimuthal mode had k values corresponding to the largest peak in the spectrum. Assuming the (m,n) = (1,1) and (1,2) modes were excited, k values of theses modes were calculated from theory taking into account the modulation depth of the observed pattern and the axial and radial density profiles. The resulting beat created by these values showed good agreement in minima spacing near the antenna supporting the two mode hypothesis, however, evidence for other modes was noted far from the antenna.

Figure 4 also gives the calculated decay in amplitude assuming collisional damping only. This was done using the uniform plasma theory [8] with a radially averaged density. Landau damping was found to be a nonfactor in the wave damping calculation.

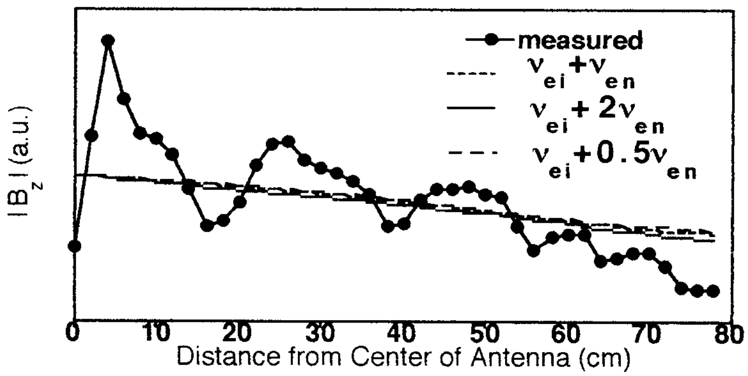

Figure 4. $|B_z(z)|$ profile for the R antenna with $B_0\mathbf{z}$ = 800 G.
Wave $\mathbf{k}$ is parallel to $B_0\mathbf{z}$. The dashed lines show the effect of varying the neutral pressure a factor of 2 in either direction.

The phase of $B_z(z)$ was also measured, using a fixed reference probe. This gave the traveling wavelength of the "collective" helicon mode. The basic dispersion relation for helicon waves [6] predicts an inverse relationship between traveling wavelength and plasma density. This was qualitatively observed.

Axial scans of the electron temperature (T_e) and plasma density for the nonresonant ICP case showed both T_e and n peaking under the antenna, while for the helicon excitation case T_e peaked near the antenna (where the Ar^+ light profile peaked) and n reached its greatest value 50 cm downstream. This was explained in terms of axial pressure balance alone without any wave heating assumptions [7]. The measured axial T_e profile was shown to agree with the predictions of the steady state electron heat flow equation. The heat flow prediction was insensitive to the inclusion of wave heating, showing that this mechanism was negligibly small downstream of the antenna [7].

4. Conclusions

A high density plasma can be achieved by exciting propagating helicon waves in this discharge source which is not attainable with a nonresonantly excited ICP. An azimuthal $m = +1$ mode is preferentially excited regardless of excitation scheme.

The density peak downstream from the antenna can be explained in terms of pressure balance. This gives the plasma a low temperature, high density characteristic downstream from the antenna. Furthermore, results from electron temperature measurements and wave damping calculations show that RF energy is apparently being absorbed by the waves in the near field region of the antenna.

References.

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