Wave modelling in a cylindrical non-uniform helicon discharge

L. Chang\textsuperscript{1}, M. J. Hole\textsuperscript{1}, J. F. Caneses\textsuperscript{1}, G. Chen\textsuperscript{2}, B. D. Blackwell\textsuperscript{1}, C. S. Corr\textsuperscript{1}

\textsuperscript{1} Plasma Research Laboratory, Research School of Physics and Engineering, Australian National University, Canberra, ACT 0200, Australia
\textsuperscript{2} Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

Abstract

A radio frequency (RF) field solver based on Maxwell’s equations and a cold plasma dielectric tensor is employed to describe wave phenomena observed in a cylindrical non-uniform helicon discharge.

Experimental setup

Figure 1 shows a schematic of MAGPIE (MAGnetized Plasma Interaction Experiment) and introduces a cylindrical \((r, \theta, z)\) coordinate system.\cite{1} For the present study, an RF power of 2.1 kW and 13.56 MHz, and an antenna current of magnitude \(I_a = 38.8\) A are used. Argon gas is used with a filling pressure of \(p_B = 0.41\) Pa.

Plasma profile diagnostics

A passively compensated Langmuir probe was employed in our experiment to measure the plasma density and electron temperature. Typical measured axial profile of field strength and radial profiles of plasma density and electron temperature in MAGPIE are shown in Fig. 2.

Wave field diagnostics

Helicon wave fields were measured by a 2-axis “B dot” or Mirnov probe. To measure the axial profiles of \(B_r\) and \(B_z\), the probe was inserted on axis from the end of the target chamber,
Fourier components of the antenna current density are given by
\[
\left(\begin{array}{c}
\frac{1}{40} \\
\frac{1}{40}
\end{array}\right)
\]
and
\[
\left(\begin{array}{c}
\frac{1}{40} \\
\frac{1}{40}
\end{array}\right)
\]
\[ j_{ar} = 0, \]
\[ j_{a\theta} = I_a e^{im\pi} \left( \frac{1}{2} \delta(r - R_a) \left( \delta(z - z_a) + \delta(z - z_a - L_a) \right) ight), \]
\[ j_{az} = I_a e^{i\pi} \left( \frac{1}{2} \delta(r - R_a) \times H(z - z_a)H(z_a + L_a - z) \right), \]
\[ \text{where } L_a \text{ is the antenna length, } R_a \text{ the antenna radius, } z_a \text{ the distance between the antenna and} \]
\[ \text{the endplate in the source region, and } H \text{ the Heaviside step function.} \]

**Boundary conditions**

The radial wall of the target chamber and the axial endplates are ideally conducting so that the tangential components of \( E \) vanish at the surface of these boundaries,

\[ E_\theta(L_r, z) = E_z(L_r, z) = 0, E_r(r, 0) = E_\theta(r, 0) = 0, E_r(r, L_c) = E_\theta(r, L_c) = 0, \]
\[ \text{where } L_r \text{ and } L_c \text{ are the radius of the target chamber and the length of the whole machine, respectively. Moreover, all field components must be regular on axis, thus, } B_\theta|_{r=0} = 0 \text{ and} \]
\[ (rE_\theta)|_{r=0} = 0 \text{ for } m = 0; \ E_\theta|_{r=0} \text{ and } (rE_\theta)|_{r=0} \text{ for } m \neq 0. \]

**Computed and measured wave fields**

The RF field solver solves Eq. (1)-(2) for \( E \) based on given antenna current \( j_a \) and boundary conditions. Figure 3 shows the axial profiles of the computed \( B_r \) amplitude and phase on axis, and their comparisons with experimental data. A qualitative match between measurement and simulation of the axial variation of \( B_r \) is found using an enhancement in collisionality of \( \nu_{eff} = \zeta (\nu_{ei} + \nu_{ie}) \approx \zeta \nu_{ei} \) with \( \zeta = 9.5 \), and an adjustment in antenna dimension of \( R_{sim} = \zeta R_{exp} \) with \( \zeta = 0.88 \). Calculation of the axial gradient of the computed phase variation shows a travelling wave, with a good agreement with data.

![Figure 3: Variations of magnetic wave field in axial direction (on-axis): (a) \( |B_r|_{rms} \), (b) phase of \( B_r \). Computed results (lines) are compared with experimental data (dots).](image)
Figure 4 shows the radial profiles of computed wave fields for $\nu_{\text{eff}} = 9.5\nu_{ei}$ and $R_{\text{sim}} = 0.88R_{\text{exp}}$ at three axial positions in the target region, together with the experimental data measured at $z = 0.17$ m. Inspection of Fig. 4 reveals that it is possible to find a reasonable agreement to the wave amplitude and phase profile, albeit independently.

![Graph](attachment:image.png)

Figure 4: Variations of magnetic wave field in radial direction: (a), (c) and (e) are $|B_r|_{\text{rms}}$, $|B_\theta|_{\text{rms}}$ and $|B_z|_{\text{rms}}$, respectively; (b), (d) and (f) are the corresponding phase variations. Dots are experimental data.

**Conclusion**

With an enhancement factor of 9.5 to the electron-ion Coulomb collision frequency, 12% reduction in the antenna radius, and the same other conditions as employed in the experiment, the solver produces axial and radial profiles of wave amplitude and phase that are consistent with measurements.

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**References**
