Electric Field in Magnetized Inductively Coupled Plasma

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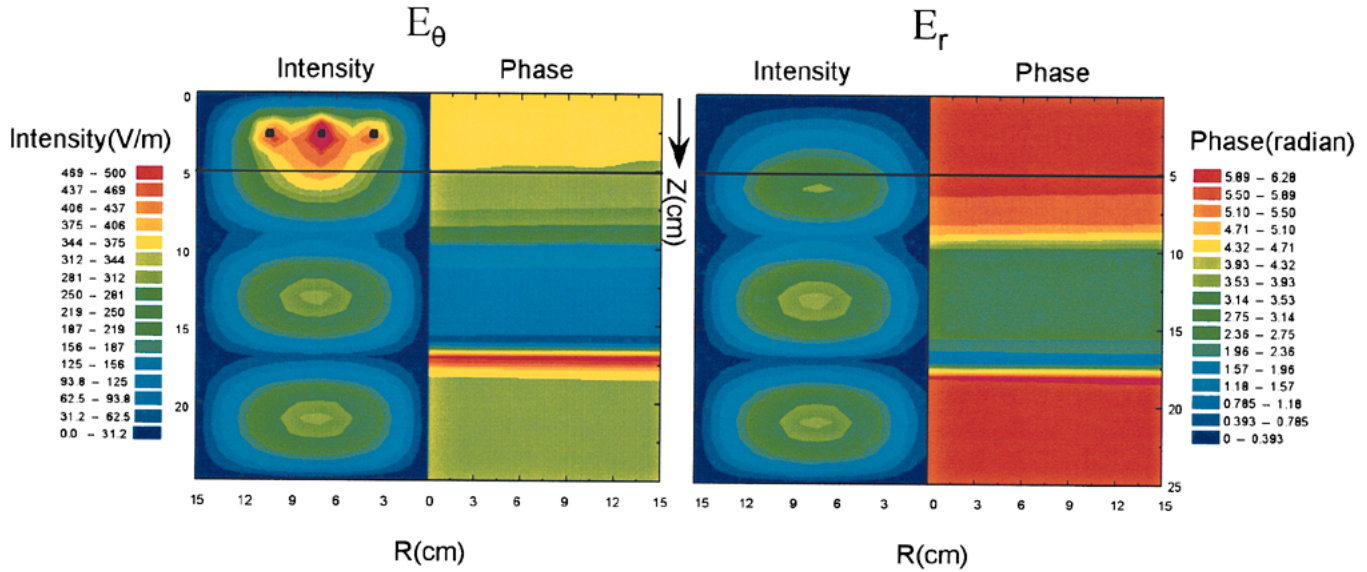

Fig. 1.   Strength and phase angle of E_θ and E_r for electron density $1 \times 10^{11}/cm^3$, magnetic induction 10 G, collision frequency 3 MHz, and coil current 10 amp. The calculation domain is 30 cm in diameter and 25 cm in total length. Plasma is filled uniformly from 5 cm to 25 cm. Black rectangles represent the position of the source current. The wave length calculated from (3) is 10.9 cm.

Abstract— A wave equation has been solved to visualize two-dimensional axis symmetric electric field profiles in magnetized inductively coupled discharge having flat, concentric current loops operated at 13.56 MHz. The dc magnetic induction level of interest is 0–20 gauss. We assumed that the plasma is uniform throughout the discharge volume. The conductivity tensor derived from cold plasma approximation was used to consider electrical properties of the discharge. For a typical operation regime of high density materials processing plasmas (electron density $\sim 1 \times 10^{11}/cm^3$, collision frequency ~ 3 MHz, length of the vessel $= 25$ cm), we observed a standing wave structure of RF electric fields.

Index Terms— Electric field, magnetized inductively coupled plasma, standing wave structure.

V ARIOUS high density, low pressure plasma sources are being developed for materials processing such as deposition and etching of fine feature. Radio frequency inductive (RFI) plasma equipped with flat-spiral antenna at the top of the vessel is thought to be suitable for large area processing and low aspect ratio chamber configuration [1]. It has been reported that if a weak external dc magnetic field (~ 10 G) is applied to this RFI source powered at the typical frequency

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of 13.56 MHz, power transfer efficiency and stability of the reactor can be greatly improved [2]. The electric field structure for this case is expected to be similar to that of the helicon wave plasma with $m = 0$ azimuthal mode [3]. However, studies on the helicon plasma have been relatively limited to long cylindrical geometry or source-diffusion chamber configuration. In the short axial boundary condition, an excited wave cannot propagate freely and there should be a standing wave-like structure if the wave is not sufficiently damped. We visualize the electric field profiles for this particular case.

Fig. 1 displays the magnitudes and phase angles of E_θ and E_r. The diameter and length of the calculation domain is 30 cm and 25 cm, respectively. Uniform plasma is filled from $z = 5$ cm to $z = 25$ cm and the region from $z = 0$ to 5 cm has zero conductivity. In our calculation, the antenna was simplified as three concentric circular loops where the current flows at the same phase. We assumed that the electric field has the following form and no z component in cylindrical symmetry geometry

$$E_{r,\theta}(r,z,t) = E_{0r,\theta}(r,z)\exp[-j(\omega t + \phi(r,z))]. \quad (1)$$

The conjugate gradient (CG) method was used to solve the wave equation

$$\nabla^2 \boldsymbol{E} = \frac{1}{c^2}\frac{\partial^2 \boldsymbol{E}}{\partial t^2} + \mu\frac{\partial}{\partial t}\left(\overset{\leftrightarrow}{\sigma}\cdot\boldsymbol{E} + \boldsymbol{J}_0\right) \quad (2)$$

where c is the velocity of light in free space and J_0 is the source current term. It should be noted hat the solution was not
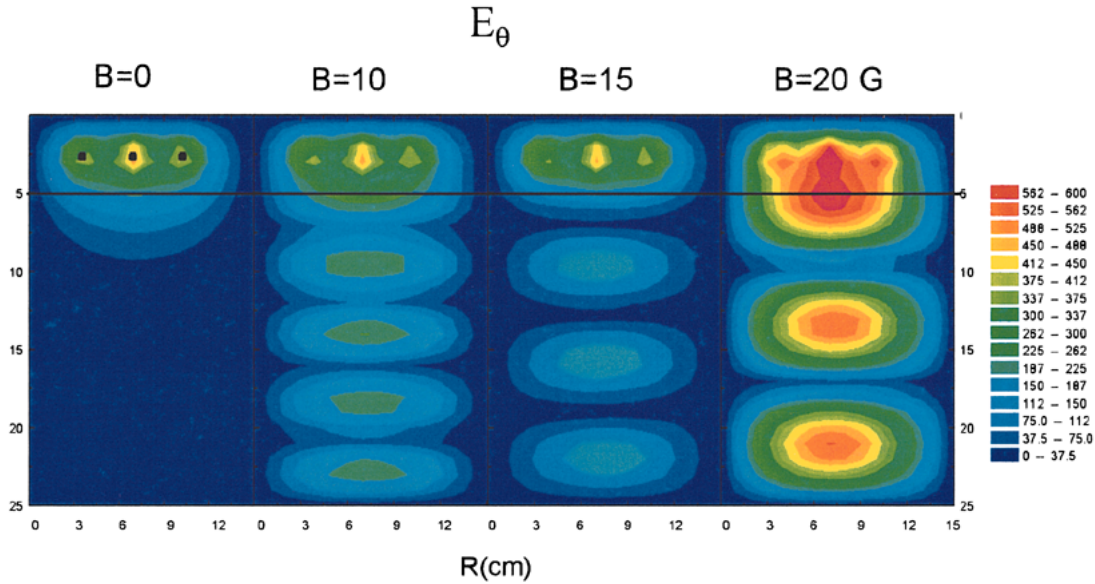
Fig. 2. Contour plot of E_θ for several different magnetic induction levels. Electron density and collision frequency for this case is $2.5 \times 10^{11}/\text{cm}^3$ and 3 MHz, respectively. The wave length calculated from the (3) is 6.9, 9.7, and 11.8 cm for $B = 10, 15, 20$ G condition, respectively.

well converged with a fully explicit method such as successive over relaxation (SOR). E_θ and E_r are set to zero at all conducting boundaries and at $r = 0$, the following boundary conditions were used:

$$E_\theta = 0 \quad \text{and} \quad \frac{\partial E_r}{\partial r} = 0.$$

The contribution of the plasma is lumped into the conductivity tensor given by

$$\overleftrightarrow{\sigma} = \omega_{pe} \begin{pmatrix} \frac{\nu+j\omega}{(\nu+j\omega)^2+\omega_{cc}^2} & -\frac{\omega_{cc}}{(\nu+j\omega)^2+\omega_{cc}^2} & 0 \\ \frac{\omega_{cc}}{(\nu+j\omega)^2+\omega_{cc}^2} & \frac{\nu+j\omega}{(\nu+j\omega)^2+\omega_{cc}^2} & 0 \\ 0 & 0 & \frac{1}{\nu+j\omega} \end{pmatrix}$$

where ω is the excitation frequency, ω_{pe} is the electron plasma frequency $n_e e^2/m_e$, ω_{ce} is the electron cyclotron frequency eB/m_e, and ν is the electron neutral collision frequency.

As can be seen from Fig. 1, the spatial distribution of E_r is almost the same as E_θ within the plasma region and the phase angle difference between them is about $\pi/2$. The phase difference between the adjacent maxima is π for both E_r and E_θ. From these results, we can recognize that the nonpropagating electric field is oscillating spirally from r to θ direction and the directions of the electric fields of the neighboring maxima are opposite to each other. Fig. 2 shows the distribution of E_θ as a function of the magnetic induction level. The electron density for this case is 2.5 times higher than that of Fig. 1. The characteristic length of the RF electric field is with external magnetic field strength. Comparing the result for $B = 10$ G condition in Fig. 2 to Fig. 1, it can also be

found that the scale length of the electric field is decreased with electron density. These tendencies are well correlated with the dispersion relation of the R wave obtained by the normal mode analysis of cold collisionless plasma

$$k = \frac{\omega}{c} \left\{ 1 + \frac{\omega_{pe}^2}{\omega(\omega_{ce} - \omega)} \right\}^{\frac{1}{2}}. \tag{3}$$

Electric field intensity variation shown in the figures is a result of an interaction between system length and characteristic wave length (λ_p) of the plasma. Since wave length in a system which has an excitation source at one end with length L should satisfy the relation $\lambda = 4L/2m - 1$ ($m = 1, 2, 3 \ldots$), electric field intensity is maximized when $\lambda_p = \lambda$.

In summary, we have shown the electric field profiles of magnetized inductively coupled plasma by solving the wave equation with a cold plasma conductivity tensor. In spite of its simplicity, the axial profiles of the electric field are well agreed with that of RF magnetic fields measured by a magnetic probe [2].

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