Observation of Second Harmonic Currents in Inductively Coupled Plasmas

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Second harmonic currents circulating around the main discharge current of fundamental frequency have been found in a low-pressure cylindrical inductive discharge with a planar inductor coil. These currents exist over a wide range of discharge conditions and are more pronounced at lower frequency and lower gas pressure. The observed second harmonic currents presumably are driven by the rf Lorentz force produced by the electron oscillatory velocity and the rf magnetic field.

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Inductively coupled plasmas (ICP's) are maintained by a time varying magnetic field $\mathbf{B}_\omega$ induced by rf currents flowing in nearby (outside or immersed in plasma) conductors. While in the case of electroded discharges the magnetic field becomes appreciable only at very large current densities, for an ICP a considerable magnetic field is required just to maintain discharge, even at the minimal possible discharge current [1]. Therefore, even at relatively small discharge current density, a situation may occur when the rf Lorentz force acting on electrons $\mathbf{F}_L \propto [\mathbf{v} \times \mathbf{B}_\omega]$ can affect electron dynamics in the skin layer of an ICP where the magnetic field and the electron rf drift (oscillatory) velocity $\mathbf{v}$ are large.

A variety of nonlinear effects associated with the rf magnetic field in a one-dimensional ICP were discussed in recent theoretical works [2–7]. There, the possibility of nonlinear rf polarization and depletion of the plasma density by ponderomotive force in the skin layer of an ICP have been shown. An enhanced penetration of rf magnetic field [8] and a rich spectrum of higher harmonics in the plasma potential [9] have been demonstrated in experiments with low-pressure ICP's, and these results were explained as a consequence of the rf magnetic field.

Here we report on the observation of second harmonic currents flowing in an ICP in a direction normal to the main discharge current at the fundamental frequency. Experiments have been carried out in a low-pressure cylindrical ICP (20 cm in diameter and 10.5 cm in length) with a quartz window separating a planar coil from the plasma, as described in detail in Ref. [9]. The axial $J_{z2\omega}$ and radial $J_{r2\omega}$ current densities at the second harmonic 2ω were found with magnetic probes using one of Maxwell's equations $\mathrm{rot}\mathbf{B} = \mu_0\mathbf{J}$ as $J_{z2\omega} = (\mu_0 r)^{-1} d(rB_{\theta 2\omega})/dr$ and $J_{r2\omega} = -\mu_0^{-1} B_{\theta 2\omega}/dz$, assuming azimuthal symmetry $d/d\theta = 0$. Here μ_0 is the vacuum permeability.

The probe construction, measurement techniques, and spatial distributions of the measured rf electric field and current density at the fundamental frequency are given in Refs. [10,11]. The plasma density n and electron temperature T_e measured in this ICP with Langmuir probes are given in Ref. [10].

The magnetic probe measurements presented in this Letter were performed along the radial direction behind the skin layer at a fixed axial position 3.2 cm from the plasma boundary adjacent to the inductor coil, and along the axial direction at the fixed radius of 4 cm corresponding to a maximum in the radial distribution of the azimuthal rf electric field at the fundamental frequency. Measurements were made at three driving frequencies, $\omega/2\pi = 3.39$, 6.78, and 13.56 MHz, and three argon pressures, $p = 1$, 10, and 100 mTorr. Over this pressure range the discharge covered both collisionless and collisionally dominated ICP regimes corresponding to the condition of anomalous and normal skin effects.

Measurements in this ICP at the fundamental frequency ω [10] have shown the presence of an azimuthal rf electric field $E_{\theta\omega}$, an azimuthal current density $J_{\theta\omega}$, and two components of rf magnetic field, axial $B_{z\omega}$ and radial $B_{r\omega}$. The measurements reported in this Letter have revealed the presence of significant rf currents at the second harmonic 2ω, flowing in axial and radial directions normal to the main discharge current.

The radial distribution of the axial rf current density $J_{z2\omega}$ at the second harmonic and its relative phase are

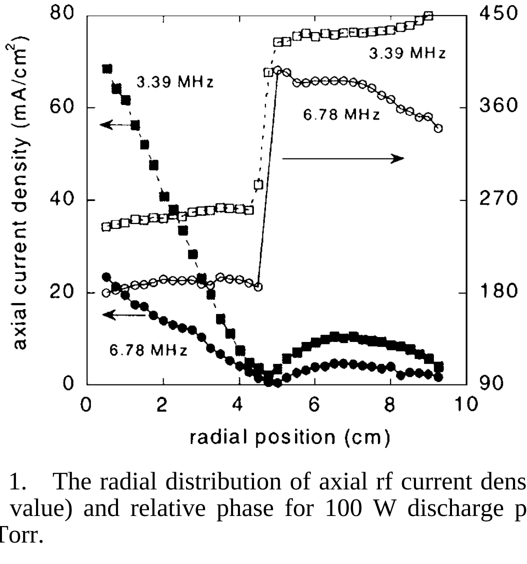

FIG. 1. The radial distribution of axial rf current density $J_{z2\omega}$ (rms value) and relative phase for 100 W discharge power at 1 mTorr.

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shown in Fig. 1 for 100 W discharge power at 1 mTorr at driving (fundamental) frequencies, $\omega/2\pi = 3.39$ and 6.78 MHz. No measurements are shown at 13.56 MHz since at this frequency $J_{z2\omega}$ is relatively small and our ability to reliably measure $J_{z2\omega}$ was limited by the low signal-to-noise ratio. As shown in Fig. 1, for both frequencies the radial dependence of $J_{z2\omega}$ crosses zero with a corresponding phase reversal. Integration of current density $J_{z2\omega}$ over the discharge axial cross section has shown that the total axial current is nearly zero. That suggests that a second harmonic current circulates within the plasma, inducing an azimuthal (toroidal) rf magnetic field $B_{\theta 2\omega}$ at the second harmonic of the driving frequency. Note, $J_{z2\omega}$ is inferred from the measurement of this very (azimuthal) magnetic field. Circulation of the second harmonic current implies the existence of both axial as well as radial components. The measured axial dependence of the radial current density on the second harmonic $J_{r2\omega}$ is shown in Fig. 2 for a 100 W discharge at 1 mTorr at a fundamental frequency of 3.39 MHz. At the same discharge condition the magnitudes of $J_{z2\omega}$ and $J_{r2\omega}$ are comparable, while the radial phase dependence of $J_{z2\omega}$, $\phi_z(r)$ and axial phase dependence of $J_{r2\omega}$, $\phi_r(z)$ seen in Figs. 1 and 2 are essentially different. The $J_{z2\omega}$ phase varies slowly along the radial direction and reverses abruptly at $r = 4.3$ cm, while the $J_{r2\omega}$ phase varies evenly along the axial direction, making almost one full rotation cycle. It is interesting that the phase velocity of $J_{r2\omega}$, $v_{\mathrm{ph}} = 2\omega(d\phi/dz)^{-1}$, is nearly equal to the electron thermal velocity $v_{\mathrm{th}} = (2T_e/m)^{1/2}$. Similarly, v_{th} and the phase velocity of the main azimuthal discharge current at the fundamental frequency propagating along the axial direction have been found to be nearly equal [12]. In both cases, the rf currents (azimuthal at the fundamental frequency and radial at the second harmonic) are transferred along the axial direction by electron thermal motion. This phenomenon is known as current diffusion or anomalous skin effect [13] and is typical for an ICP at low gas pressure [10].

The radial distribution of the axial rf current density at the second harmonic $J_{z2\omega}$ is shown in Fig. 3 for the driving frequency of 3.39 MHz and argon pressure of 10 mTorr, for discharge powers of 50, 100, and 200 W. One can see a pattern similar to the 1 mTorr case (Fig. 1) in the $J_{z2\omega}$ magnitude distribution, but with less pronounced minimum and smoother phase reversal. The magnitude of $J_{z2\omega}$ scales nearly as a square root of the discharge power (plasma density). Since the measurement of $J_{z2\omega}$ was made at the fixed distance ($z = 3.2$ cm) from the plasma boundary adjacent to the inductor coil, the shrinking skin depth and larger rf field attenuation seem to be the reason for the slow increase of $J_{z2\omega}$ with discharge power.

The dependence of $J_{z2\omega}$ on gas pressure is given in Fig. 4 at a driving frequency of 3.39 MHz and a discharge power of 100 W. The second harmonic current $J_{z2\omega}$ shown in Fig. 4 falls with gas pressure, although the main azimuthal discharge current at the fundamental frequency grows with the gas pressure [14]. Also, the phase reversal occurs smoothly and its radial position is smaller at higher gas pressure.

Our experiments carried out over a wide range of ICP conditions, covering both collisionless and highly collisional regimes, have shown the following general features and trends in the second harmonic current for a cylindrical ICP with a planar induction coil: (i) $J_{2\omega}$ is normal to the main discharge current and forms a poloidal structure inducing a toroidal (azimuthal) magnetic field of doubled frequency $B_{\theta 2\omega}$. (ii) $J_{2\omega}$ is rising with decreasing driving frequency and gas pressure.

These observations suggest that the rf current on the second harmonic found here originates from a Lorentz force $\propto[\mathbf{v} \times \mathbf{B}_\omega]$. Indeed, the energy balance of a weakly ionized bounded ICP requires a nearly frequency-independent induced rf electric field E. Since $E \propto \omega B_\omega$, the rf magnetic field $B_\omega \propto \omega^{-1}$. On the other hand,

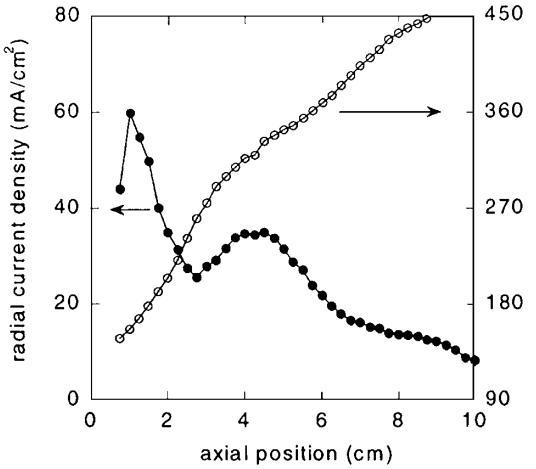

FIG. 2. The axial dependence of radial current density $J_{r2\omega}$ (rms value) and relative phase for 100 W, 3.39 MHz discharge at 1 mTorr.

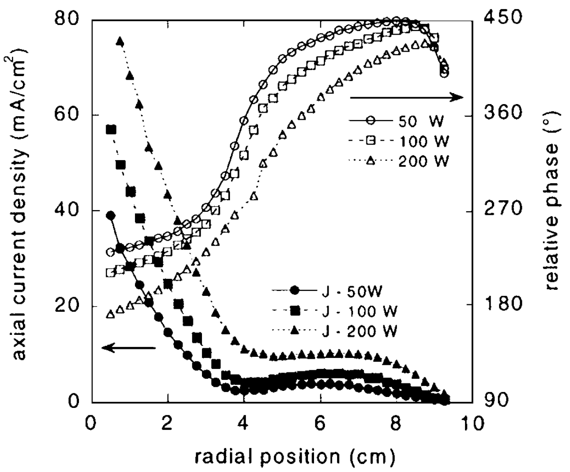

FIG. 3. The radial distribution of axial rf current density $J_{z2\omega}$ for 3.39 MHz driving frequency at 10 mTorr.

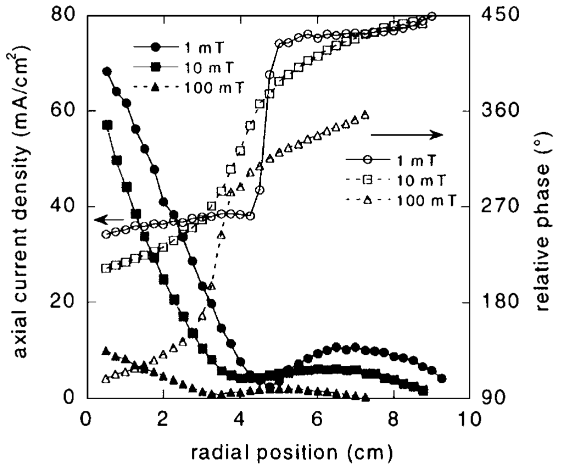

FIG. 4. The axial current distribution $J_{z2\omega}$ for 3.39 MHz driving frequency and 100 W.

the rf drift velocity v is proportional to E and is larger at lower gas pressure. Thus, the rf Lorentz force $\propto B_{\omega}[\cos(\omega t)]^2 \propto \omega^{-1}\cos(2\omega t)$ and the second harmonic current, presumably originated by the Lorentz force, should be larger at lower driving frequency and at lower gas pressure, as observed in our experiment.

The relationship between the rf Lorentz force and the second harmonic current is not evident, and is even counterintuitive (the maximum of $J_{z2\omega}$ is at $r = 0$, where the azimuthal drift velocity $v = 0$ and there is no Lorentz force). Accounting for an rf Lorentz force in a one-dimensional steady state ICP [4] results in just rf polarization with doubled frequency within the skin layer in the direction normal to both $\mathbf{v}$ and $\mathbf{B}_{\omega}$ vectors. But in a common practical two-dimensional cylindrical ICP, there are two components of rf magnetic field, $B_{z\omega}$ and $B_{r\omega}$, and two corresponding components of the rf Lorentz force, radial and axial. The field of the Lorentz force is localized within the skin layer and drives rf currents of doubled frequency along closed paths in the z-r plane forming a poloidal current structure. Note that the current density $J_{2\omega}$ is not a local function of the Lorentz force, but (according to Ohm's law for a closed circuit) is defined by the local plasma conductivity, and by the total impedance and the Lorentz force integrated along a closed current path.

Because of the continuity of the total poloidal current, one has to expect the maximal current density at the discharge axis where $J_{2\omega}$ converges. The peaking of the plasma density at the discharge axis (especially at higher gas pressure) moreover enhances the current density there. At low gas pressure (at 1 and 10 mTorr in our experiment) in the condition of anomalous skin effect, the picture described here would be somewhat distorted by the electron thermal motion.

The axial rf current density $J_{z2\omega}$ has also been independently measured with a two-sided differential flat Langmuir probe biased at the plasma potential. Good qualitative agreement with magnetic probe data was found for the radial distribution of $J_{z2\omega}$, although the absolute values of $J_{z2\omega}$ were found to be a few times less than those obtained with magnetic probes. This discrepancy occurs because of significant plasma density depletion around the large two-sided probe biased at plasma potential due to a large electron dc current drawn to the probe.

The second harmonic rf currents found here are essentially a two-dimensional effect and account for just a small portion (less than 15%) of the main discharge current density $J_{\theta\omega}$. Therefore, its contribution to the total ICP energy balance, scaling as $(J_{2\omega}/J_{\theta\omega})^2$, is negligible. The nonlinear effect of the second harmonic current is expected to be considerably larger in a low frequency and a high rf power density ICP, where the Lorentz force is comparable to, or larger than, the force acting on an electron in the induced rf electric field. Such a situation has a more general implication defining the condition when normal or anomalous skin effect transits to a nonlinear one accompanied by the variety of nonlinear phenomena associated with rf magnetic field [2–8]. The transition from linear to nonlinear skin effect occurs at $\omega_B \geq (\omega^2 + \nu_{\mathrm{eff}}^2)^{1/2}$, where $\omega_B = eB_{\omega}/m$ is the cyclotron frequency of the rf magnetic field and ν_{eff} is the effective electron collision frequency.

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