Negative Power Absorption in Inductively Coupled Plasma

V. A. Godyak
OSRAM SYLVANIA Products Inc., 71 Cherry Hill Drive, Beverly, Massachusetts 01915

V. I. Kolobov*
Department of Chemical Engineering, University of Houston, Houston, Texas 77204-4792
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We report an observation of negative power absorption of electromagnetic field in a low-pressure cylindrical inductive discharge. The spatial distribution of the absorbed power is found experimentally from measurement of the azimuthal rf electric field and current, and theoretically by solving the Maxwell-Boltzmann equations by Fourier method. It appears that plasma electrons, which absorb electromagnetic energy in the skin layer, can apparently return a part of their energy to the rf field deeper into the plasma. [S0031-9007(97)04764-9]

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Electrodynamics of gas discharges has recently attracted considerable interest due to the advent of high density plasma sources sustained by radio-frequency (rf) electromagnetic fields at low gas pressure. These plasma sources operate in a near-collisionless regime where the electron mean free path λ is comparable or larger than the plasma dimensions. In contrast to a collisionally dominated plasma (where a local relation holds between the rf current density and the electric field) the current density in a nearly collisionless plasma is nonlocal and depends on the distribution of the electric field in the whole plasma and the shape and size of the discharge device. This phenomenon caused by electron thermal motion is known as the spatial dispersion of plasma conductivity (or rf current diffusion) and is typical for the anomalous skin effect [1–3].

When the electron mean free path is about the size of the discharge, the current induced by the field at one point can be transferred by thermal electron motion to another point and produce there an additional field interfering with local field. The field and current become independent to some extent: the field is determined by geometry of the coil and the shape of metallic surfaces, whereas the current depends on thermal electron motion including electron collisions with the walls. Different mechanisms in the penetration of the electric field and current can generate a variety of patterns in spatial distributions of electromagnetic fields and current density. Measurements and calculations of the field distributions under conditions of the anomalous skin effect have demonstrated an anomalous penetration and non-monotonic decay of the rf fields in warm plasmas [2–8].

The rf current transferred by thermal electron motion can be opposite in phase to the local electric field resulting in a local negative energy transfer from the rf field to electrons. Such a possibility was first demonstrated theoretically for propagation of an electromagnetic wave along a static magnetic field in a semi-infinite warm plasma under conditions of electron cyclotron resonance [5]. Negative power absorption was also found for longitudinal rf fields in particle-in-cell simulations of capacitively coupled discharges [9,10]. To our knowledge, no negative power absorption has yet been demonstrated in experiment.

In the present Letter we report on negative power absorption in an inductive discharge under conditions of the anomalous skin effect. The rf power absorption was found as the product of the rf electric field and current density measured with magnetic probes. The distribution of the absorbed power was also calculated in the framework of the theory of the anomalous skin effect [11] extended to the two-dimensional bounded system studied in the experiment. A plausible agreement is found between the experiment and calculations.

The experiments were carried out in a cylindrical inductively coupled plasma maintained by a planar inductor coil in a stainless steel chamber with a Pyrex glass bottom, as shown in Fig. 1. The chamber inside diameter was 19.8 cm, its length L was 10.5 cm, and the glass thickness

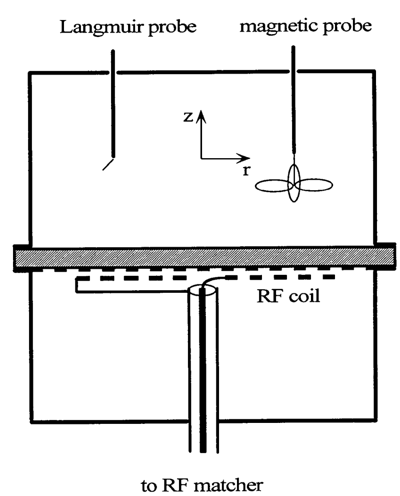

FIG. 1. Experimental discharge chamber with Langmuir and magnetic probes.

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was 1.27 cm. A five turn planar induction coil was mounted 1.9 cm below the bottom surface of the discharge chamber. To achieve a high degree of azimuthal symmetry, each turn of the coil was made concentric about the center of the discharge chamber with a radial conducting bridge between each turn. The current return lead from the coil was placed 2 mm below the bridges to cancel, as much as practically possible, the magnetic field created by the radial component of the coil current along the bridges and thus to minimize perturbation of the coil's azimuthal symmetry.

An electrostatic shield and an air gap between the glass and the coil has practically eliminated capacitive coupling between the induction coil and the plasma to the extent that the rf plasma potential referenced to the grounded chamber was much less than 1 V. The coil screening has made it possible to obtain a large dynamic range (over 60 db) in the magnetic probe measurement and thus to reveal some new features in the electromagnetic field structure behind the skin layer. An aluminum kettle covered the induction coil from below and acted as an rf shield preventing electromagnetic interference on the measurement apparatus and wiring.

A two-dimensional magnetic probe was used for measurement of the radial and axial components of the rf magnetic field magnitude and phase along the axial direction (corresponding to propagation of the electromagnetic field) at a fixed radius of 4 cm, within the maximum of the radial distribution of the azimuthal electric field [7]. These data were used to infer the azimuthal rf electric field and current density, correspondingly, by spatial integration and differentiation of the magnetic probe signals in the magnitude and the phase domain. The probe was designed to minimize plasma and rf current distortion around the probe. Detailed probe description, signal processing, and validation of results obtained with this probe are given in Ref. [7]. The basic plasma parameters such as the plasma density and the electron energy distribution function (EEDF) measured by a Langmuir probe in this system are published elsewhere [12].

Measurements were made at driving frequencies $\omega/2\pi = 3.39$; 6.78 and 13.56 MHz in an argon discharge at a gas pressure of 10 mTorr and a discharge power $P_{\mathrm{pl}} = 100$ W. P_{pl} was determined by measuring the power transmitted to the inductor coil (forward minus reflected power) and subtracting matcher and coil losses determined *a priori* as a function of coil current and temperature. In what follows, all mention of power refers to power dissipated in the plasma.

The axial distribution of the azimuthal rf electric field E and current density J (rms values) together with the corresponding phase distributions are shown in Fig. 2. The measured phases are referenced with respect to the vacuum rf electric field, i.e., 90° shifted from the phase of the current in the inductor coil. Langmuir probe measurements [12] in the discharge center ($r = 0$ and

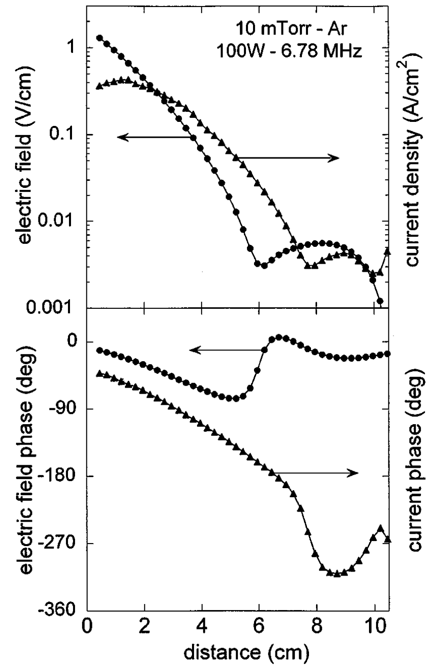

FIG. 2. Axial distribution of the measured rf electric field and current.

$z = 5$ cm) showed a near-Maxwellian EEDF with plasma density $n = 2.2 \times 10^{11}$ cm^{-3} and electron temperature $T_e = 3.2$ eV. The plasma density falls by about 5 times to the axial chamber walls and about 10 times to the radial wall. Along the axis of the magnetic probe measurements ($r = 4$ cm) the plasma density was 73% of that on the central axis ($r = 0$). The electron mean free path λ and the electron-atom collision frequency in the rf field ν were found as corresponding integrals of the measured EEDF and were $\lambda = 4$ cm and $\nu = 3.6 \times 10^7$ s^{-1}.

The nonmonotonic distributions shown in Fig. 2 are typical for the anomalous skin effect and are very similar to those measured in the present experimental setup for an argon pressure of 1 mTorr [4,7]. The slower spatial decay of the current density distribution than that of the electric field demonstrates the effect of the rf current diffusion due to thermal electron motion. The phase distribution profiles are also different for the electric field and current density and suggest the different mechanisms of propagation of electric field and current. Recall that for the normal skin effect in a cold plasma the field and current phase distributions are similar and just shifted by $\Delta\phi = \arctan(\omega/\nu)$ which is always less than 90°. As one can see in Fig. 2, the phase difference in the measured phase distributions at some distance from the glass window exceeds 90°, indicating the presence of negative power absorption.

The distributions of the rf power density absorbed along its propagation in the axial direction calculated (from the measured E and J and the phase difference between them $\Delta\phi$) as $P = EJ\cos\Delta\phi$ are shown in

Fig. 3(a) for different frequencies and a fixed discharge power of 100 W. As expected, the rf power is mainly absorbed in the skin layer near the window and decays faster for higher frequency. Deeper into the plasma the power absorption changes sign and becomes negative.

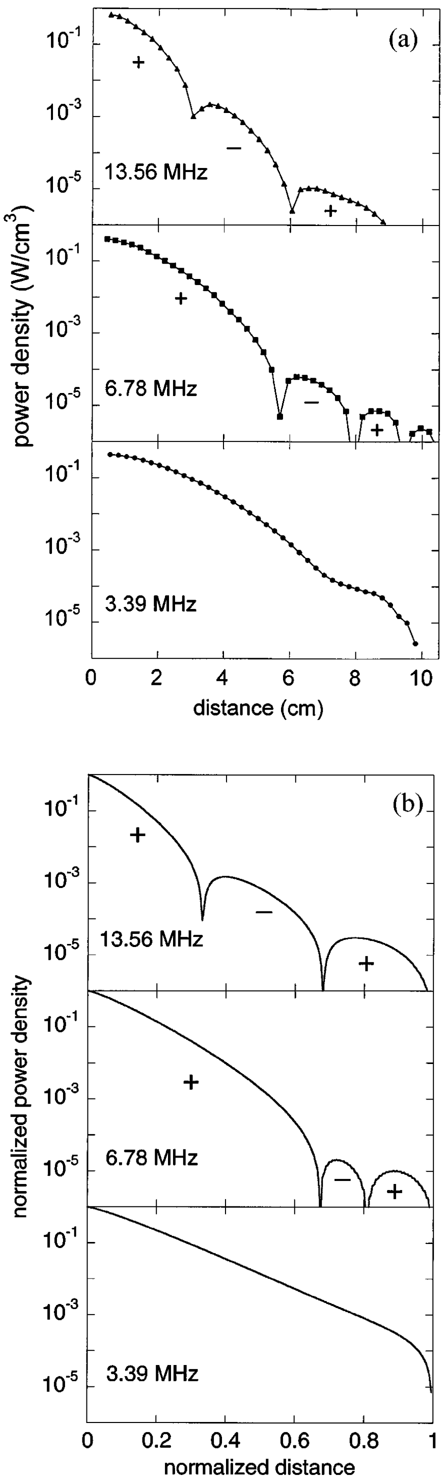

FIG. 3. Experimental (a) and theoretical (b) power absorption profile.

The number of regions with negative power absorption depends on the driving frequency, and there is no negative power absorption for $\omega/2\pi = 3.39$ MHz. The distance between the maximum in the rf current density and first zero crossing point is inversely proportional to the driving frequency.

The calculated power absorption profile for this experimental condition is shown in Fig. 3(b). We solved the coupled set of Maxwell equations for electromagnetic fields and Boltzmann equation for conducting electrons assuming a spatially uniform Maxwellian plasma with sharp boundaries at $z = 0$ and $z = L$. The experimental values of T_e and volume-averaged plasma density $n = 1 \times 10^{11}$ cm^{-3} were used in calculations. The azimuthal electric field was sought in the form

$$E(z,r) = J_1(3.8r/R) \sum_{n=0}^{\infty}{}' \alpha_n \cos(\pi n z/L), \qquad (1)$$

where J_1 is the Bessel function and the prime means that the term $n = 0$ is multiplied by $1/2$. A metallic boundary is assumed at $z = L$.

To find the rf current, the Boltzmann equation for the electron distribution function f is linearized by setting $f = f_0 + f_1$ where f_0 is the isotropic part of the EDF and f_1 is a small addition $f_1 \ll f_0$. Neglecting effects of thermal electron motion in the radial direction and accounting for these effects along the discharge axis (as in [8]), the oscillating part of $f_1 \propto \exp i\omega t$ is found in the form [4]

$$f_1 = e v_\theta J_1(3.8r/R) \frac{\partial f_0}{\partial \varepsilon} \times \sum_{n=0}^{\infty}{}' \alpha_n \frac{(i\omega + \nu)\cos(\pi n z/L) - n\Omega \sin(\pi n z/L)}{(i\omega + \nu)^2 + (n\Omega)^2}, \qquad (2)$$

where $\Omega = \pi v_z/L$ is the bounce frequency for an electron with velocity v_z, and v_θ is the azimuthal electron velocity.

For a Maxwellian EDF $f_0(\varepsilon)$, the azimuthal current density is [4]

$$J(z,r) = \frac{i n_e e^2 l}{m v_{\rm th}} J_1(3.8r/R) \times \sum_{n=0}^{\infty}{}' \frac{\alpha_n}{k_n} \cos(\pi n z/L) Z(is/k_n), \qquad (3)$$

where $k_n = \pi n l/L$, $l = v_{\rm th}/\sqrt{\omega^2 + \nu^2}$ is the distance an electron with velocity $v_{\rm th} = (2T_e/m)^{1/2}$ traverses during the field period or during the time between subsequent collisions, $s = i \exp[-i \arctan(\nu/\omega)]$ is a characteristic of the plasma collisionality, and $Z(x)$ is the plasma dispersion function [13]. The solution of Maxwell equations with the current density (3) gives the Fourier coefficients [11]

$$\alpha_n = \frac{2i\omega l^2 B_0}{Lc} \frac{[1 - (-1)^n \xi]}{D(k_n)}, \qquad (4)$$

where $\xi = B(L)/B(0)$ is the ratio the magnetic field at the boundaries [11]

$$\xi = \sum_{n=0}^{\infty}(-1)^n D^{-1}(k_n) / \sum_{n=0}^{\infty}{}' D^{-1}(k_n) \qquad (5)$$

and $D(k)$ for $\omega \ll \omega_p$, where ω_p is the plasma frequency, is given by

$$D(k) = k^2 + \Lambda Z(is/k)/k + (3.8l/R)^2. \qquad (6)$$

The last term of $D(k)$ accounts for radial inhomogeneity of the rf electric field, the nonlocality parameter

$$\Lambda = \left(\frac{l}{\delta}\right)^2 = \left(\frac{\omega_p v_{\rm th}}{c}\right)^2 \frac{\omega}{(\omega^2 + \nu^2)^{3/2}} \qquad (7)$$

is a measure of nonlocality for electromagnetic phenomena in plasmas, and δ is the classical skin depth [3]. The spatial distribution of the absorbed power density $P \propto \mathrm{Re}(JE^*)$ calculated from these formula is shown in Fig. 3(b).

Comparison of the theory with the experiment shows rather good agreement in spite of the simplifying assumption of a homogeneous plasma and neglect of radial electron motion. One has to expect the largest discrepancies between calculation and experiment at the plasma boundaries where the plasma density gradient is the largest and the plasma density is essentially smaller than the averaged one. Indeed, there is a difference in the slopes of calculated and measured power absorption near the window. Nonetheless, the profile of the power absorption, including the areas of negative absorption and the positions of zero crossing points, are reasonably described by the presented theory.

In the present work, the electron-atom collision frequency is close to rf frequency ($\nu \approx \omega$). However, the nonlocal effects due to electron thermal motion are well pronounced since $\Lambda \approx 1$. Moreover, the phase velocities of the rf electric field $v_{\text{ph-}E}$ and the current $v_{\text{ph-}J}$ calculated in this experiment as $v_{\rm ph} = \omega(d\phi/dz)^{-1}$ are close to the electron thermal velocity $v_{\rm th}$. Thus, at $\omega/2\pi = 6.78$ MHz, $v_{\text{ph-}E} = 1.65 \times 10^8$ cm/s and $v_{\text{ph-}J} = 1.08 \times 10^8$ cm/s while $v_{\rm th} = 1.06 \times 10^8$ cm/s between the window and plasma midplane where phases linearly depend on the distance. When $v_{\text{ph-}E} \approx v_{\rm th}$ (a condition known as Cherenkov resonance) there is a strong interaction of particles with rf field and collisionless effects caused by electron thermal motion are dominant. The measurements at 1 and 100 mTorr showed that negative power absorption is more pronounced at 1 than at 10 mTorr and completely disappears at 100 mTorr where electron motion is collisionally dominated.

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*Current address: CFD Research Corp., 215 Wynn Dr., Huntsville, AL 35805.

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