Nonlinear Skin Effect of High-Power Microwaves Incident on a Collisionless Magnetized Plasma

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Experimental results are presented which verify a nonlinear skin effect of high-power microwaves incident on a collisionless, uniform plasma having a sharp boundary. The skin depth, observed by microwave reflection techniques, increases with the incident microwave power.

A few years ago, Gekker and Sizukhin[1] measured the reflection coefficient from a nonuniform plasma, which decreased with increasing incident power. The anomalous absorption they observed was attributed by Kaw, Valeo, and Dawson[2] to a parametric excitation of ion waves and longitudinal plasma modes by the high-power microwaves. It should be emphasized, however, that Gekker and Sizukhin measured only the absolute values of the reflection coefficient. Therefore, one could not know whether or not there was nonlinear penetration for a strong incident power. In this Letter, we describe the experimental results for the nonlinear skin effect of high-power microwaves incident on a collisionless plasma. Although predicted by theory, this Letter presents what seems to be the first quantitative experiment where the skin depths of the microwaves are observed to be dependent on the incident power. In the present experiment, a semi-infinite uniform plasma is used for analysis in order to make the theory tractable.

Silin[3] developed a nonlinear theory for the reflection of plane monochromatic electromagnetic waves incident normally on the surface of a uniform, fully ionized plasma. Considerations are limited to a collisionless plasma above the cutoff density. Taking into account the radiation pressure on the plasma due to the electromagnetic field, the phase angle θ of the reflection coefficient is given by[3]

$$\cos^2\frac{\theta}{2} = -\frac{1}{b}\ln\left[1-\frac{b}{(\omega_p/\omega)^2}\right], \qquad (1)$$

where

$$b = 4(E_i/E_c)^2, \quad E_c^2 = 2m\omega^2\kappa T_e/e^2,$$

ω_p and ω are the plasma and microwave angular frequencies, E_i and E_c are the amplitudes of the incident wave and the critical electromagnetic field, respectively. Equation (1) reduces to the linear relationship

$$\cos(\theta/2) = \omega/\omega_p \qquad (2)$$

when b approaches zero.

The electric field[3] $E(z)$ does not necessarily fall off exponentially in the plasma when the nonlinear skin effect occurs. Hence, the skin depth d is defined here by the slope of $E(z)$ at the boundary $z=0$ as $d = -E(0)/E'(0) = k_0^{-1}\cot(\theta/2)$, where k_0 is the wave number in vacuum. Then the skin depth d can be recovered from the measurement of θ. It is obvious that the skin depth d would increase with b for a given $(\omega_p/\omega)^2$.

We modify Silin's formula, Eq. (1), to include the longitudinal magnetic field, in order to compare with our experimental results. An electromagnetic wave in a rectangular wave guide without plasma is a linearly polarized wave, which decomposes into right-hand and left-hand circularly polarized waves, E_r and E_l, respectively, with identical phases in time. When skin effects occur in the plasma for both waves, as in our experiment, d's in the wave guide are assumed to be the same as those in free space since (being of order of millimeters) they are considerably smaller than the side dimensions of the wave guide. In other words, the plasma in the wave guide will not be different from that in free space, when the skin effect occurs. Then circularly polarized fields having different phases in time will exist in the plasma. If so, one can consider the phase shifts, θ_r and θ_l, of the waves reflected from the plasma, having right-hand and left-hand circular polarizations, respectively, even though the waveguide cross section is rectangular. Using the expressions for circularly polarized waves, $E_{r,l} = E_x \mp iE_y$, it is easily shown that the phase shift θ of a reflected wave which is linearly polarized with the same direction of polarization as the incident wave is given by

$$\cos^2\frac{\theta}{2}=\frac{1}{2}\left(\cos^2\frac{\theta_r}{2}+\cos^2\frac{\theta_l}{2}\right). \quad (3)$$

The angle θ in Eq. (3) is observed by a standing-wave detector in the wave guide. In the linear theory, both waves can exist independently in the plasma, and their phase angles are given by $\cos^2(\theta_{r,l}/2)=(1\mp\omega_c/\omega)/(\omega_p/\omega)^2$, where ω_c is the electron-cyclotron frequency. Substituting these expressions into Eq. (3), one directly obtains Eq. (2), which is independent of the applied magnetic field.

When the nonlinear effect is included, the circularly polarized waves in the plasma are no longer independent of each other. We write[4] in our notation the density correction factor, $f(E)$, due to the radiation pressure as

$$f(E_r,E_l)=\exp\left[-\frac{1}{2E_c^2}\left(\frac{|E_r|^2}{1-\omega_c/\omega}+\frac{|E_l|^2}{1+\omega_c/\omega}\right)\right], \quad (4)$$

instead of Eq. (2.3) of Ref. 3. Equation (4) results in a set of nonlinear differential equations[5] in E_r and E_l which cannot be separated out unless some assumption is made about the field amplitudes. We therefore make three different assumptions: (i) $|E_l|\gg|E_r|$, (ii) $|E_r|=|E_l|$, and (iii) $|E_r|\gg|E_l|$ in the plasma to obtain the expressions for θ. Using Eqs. (3) and (4), Eq. (1) is modified, for Assumption (ii), to

$$\cos^2\frac{\theta}{2}=-\frac{1-(\omega_c/\omega)^2}{2b}\ln\left\{\left[1-\frac{b}{(1+\omega_c/\omega)(\omega_p/\omega)^2}\right]\left[1-\frac{b}{(1-\omega_c/\omega)(\omega_p/\omega)^2}\right]\right\}. \quad (5)$$

Equation (5) reduces to Eq. (2), as b approaches zero.

A steady-state plasma is produced in helium at a pressure of a few Torr between a hot cathode and a water-cooled anode. The plasma is introduced into a glass chamber through a small hole in the anode. The glass chamber is differentially evacuated to the pressure of 10^{-3} Torr, where the present experiment is carried out. A uniform magnetic field B of several thousand gauss is applied axially to keep the electron density high. The plasma column has a Gaussian radial density distribution with 1 cm half-width. The plasma density N_e and the electron temperature T_e change, respectively, from 5×10^{11} to 4×10^{12} cm^{-3} and from 8 to 12 eV when the discharge current I_d is varied from 10 to 50 A, for the magnetic field B = 3020 G. A standard X-band rectangular wave guide with a water-cooled target is inserted axially into the plasma. The experimental setup, where the skin depths in the wave guide are measured, is shown in Fig. 1. A quartz block of 1.1-cm thickness is placed in the wave guide to make the plasma boundary clear and sharp. The length of the plasma-loaded wave guide is 2.5 cm. The plasma in the wave guide seems to be uniform in the axial direction, because the experimental results are insensitive to the length of the plasma wave guide. Microwave pulses up to 15 kW and time width $\tau=1.2$ μsec at a frequency of 9.37 GHz are launched into the plasma through a power divider and a slotted section.

The present experiment on skin effect is carried out in a magnetic field $2800<B<3050$ G,[6] where the low-level incident microwaves are almost totally reflected from the plasma for N_e greater than the cutoff density. The standing-wave patterns[7] observed by a crystal detector through a slotted section are recorded using a boxcar integrator. It is observed[8] that the phase angle θ decreases for a given B and I_d as the incident power increases. When the neutral pressure is increased to 1 Torr, θ changes in opposite way to that at low pressures, with increase in incident power, because of the additional ioni-

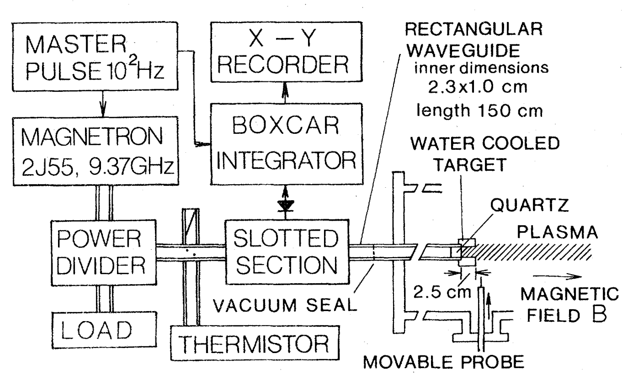

FIG. 1. Experimental arrangement.

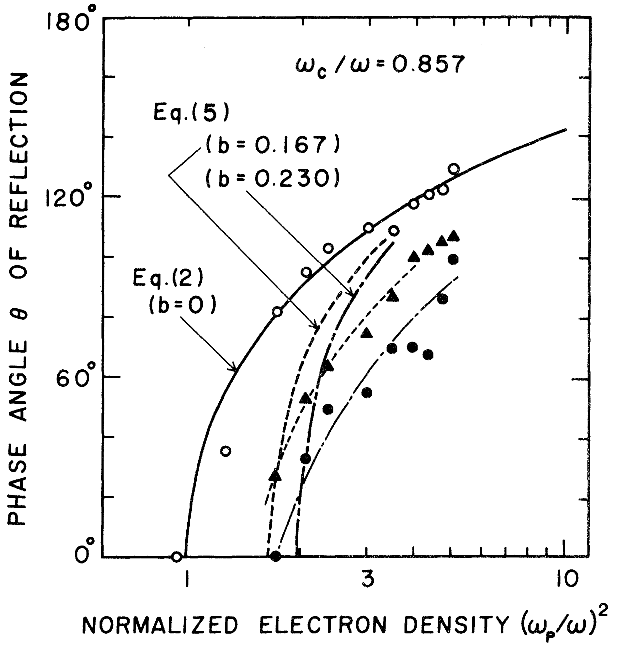

FIG. 2. Comparison of the experimental results with the theoretical predictions for the variation of θ versus $(\omega_p/\omega)^2$. Open circles, small power of the order of 10 mW, adjusted to the theoretical line for $b = 0$; triangles, 2.9 kW, to be compared with the thick dashed line ($b = 0.167$); closed circles, 4.0 kW, to be compared with the thick chained line ($b = 0.230$).

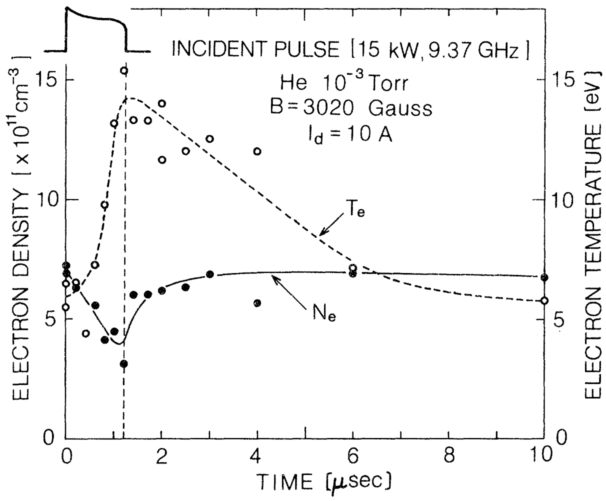

FIG. 3. Change in the plasma parameters due to the incidence of high-power microwaves.

zation by the high-power microwaves. Thus, we conclude that our results are clearly due to the nonlinear skin effect.

In Fig. 2, the experimental results are compared with the theoretical predictions for $b = 0.167$ (thick dashed line) and 0.230 (thick chained line), which correspond, respectively, to 2.9 and 4.0 kW of incident power at $T_e = 8$ eV. The solid line is the linear relationship calculated from Eq. (2). Calculated lines for Assumptions (i) and (iii) are not shown, since they are very close to the solid line. We find that Assumption (ii) is the closest to the experimental values among the three. This suggests that the assumption $|E_r| = |E_t|$, from which Eq. (5) is derived, holds approximately in our experiment. In other words, the results suggest that an enhanced penetration of E_r occurs in the plasma for the high-power incident microwaves, since the inequality $|E_r| < |E_t|$ holds at the cutoff region for both the waves in the linear theory.

Using the boxcar integrator, the plasma parameters N_e and T_e are measured by the Langmuir probe located just in front of the target for various periods after the incidence of the high-power microwave pulse. Here, T_e is obtained from the Langmuir probe characteristic neglecting the effect of B, and N_e is calculated from the ion saturation current and T_e. An example is shown in Fig. 3, where the plasma becomes transparent for a microwave pulse of 15 kW even for $(\omega_p/\omega)^2 > 1$. The probe measurement will be reliable even in the microwave field, since the high-frequency drift velocity of electrons, $eE/m\omega$, in the plasma is much smaller than the electron thermal velocity. During the incidence of the microwave pulse, N_e decreases considerably from the steady-state value.[9] This fact is further evidence of the nonlinear skin effect.

Gurovich and Karpman[10] analyzed an electromagnetic envelope soliton propagating through a high-density plasma. In a limiting case, they obtained an expression for the electric field in the plasma for the stationary soliton that is just the same as the nonlinear skin effect.[3] Our experimental results, that the skin depths are dependent on the incident power, suggest the existence of an electromagnetic field in the plasma similar to the stationary envelope soliton.

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X-Ray Emission from Laser-Produced Plasmas*

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We measured several characteristics of the x-ray emission from plasmas produced at the focus of a high-power (~10 GW) laser. X-ray spectra in the 1–2-keV region show that the plasmas contain highly stripped atoms (10–12 electrons missing from Al, 20–22 from Zn, and 36–38 from Gd). The laser-plasma x-ray source can emit about 0.1 J of x rays above 1 keV in 1 nsec from a volume about 100 μm in diameter. This corresponds to more than 10^{13} W/cm^3.

Laser-generated plasmas sufficiently hot to emit kilovolt x rays have been produced recently by the use of focused laser power densities exceeding 10^{12} W/cm^2 on solid targets. K radiation from elements up to Al was measured and interpreted by Peacock, Hobby, and Galanti.[1] Mallozzi *et al.*[2] and Aglitskiy *et al.*[3] resolved many L lines of Fe but the latter authors have not interpreted the spectra. Mead *et al.*[4] measured unresolved clusters of M lines from Au. But to date, there has been no systematic study of x-ray emission from plasmas produced by any single high-power laser. In this Letter, we report the results of a survey of x-ray spectra from elements across the periodic system. The work has two motivations: plasma diagnostics including tests of laser-plasma models,[5,6] and characterization of the laser plasma as a fast, intense source of soft x rays with several applications.

The Nd laser system used in this work consisted of a mode-locked oscillator and five amplifier stages.[7] Pulses of the 1.06-μm light [< 1 Å full width at half-maximum (FWHM)] containing up to 5 J in 250 or 900 psec were focused on flat targets to spots about 50 μm in diameter. Hence, power densities exceeding 10^{14} W/cm^2 were available. Spectra were measured in single shots with simple, slitless spectrographs using flat potassium acid phthalate crystals ($2d = 26.6$ Å) and Kodak No-Screen film behind 25-μm Be foils (1% transmissive at 800 eV). Resolution was not optimized since it was desired to survey a wide photon-energy range. Energy calibration of new spectra was accomplished by coating the targets with powdered compounds of Na, Mg, or Al, the energies of whose lines are accurately known. Other x-ray characteristics (angular distribution, emission time, and source size) were also measured, as will be described later.

K spectra resulting from transitions to the 1s level have been obtained from Na (in NaF), Mg, Al, Si, and S. Spectra from all these elements are similar. Figure 1 shows the Al spectrum. Classification of lines in spectra such as this presented no problem because of many laboratory[8] and solar[9] measurements of similar emission lines from elements in this range. As indicated in Fig. 1, lines from three ion species appear. An intense Rydberg series and free-to-bound continuum from He-like (two-electron) Al are evident, as is the Lyman series of H-like (one-electron) Al. Poorly resolved satellites