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Y. Takase, J. D. Moody, C. L. Fiore,
F. S. McDermott, M. Porkolab, and J. Squire

Plasma Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

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Plasma Fusion Center, Massachusetts Institute of Technology

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Excitation, propagation, and absorption of directly launched ion Bernstein waves (IBW) were studied with CO_2 laser scattering in the Alcator C tokamak. Optimum excitation is obtained when an ion-cyclotron harmonic layer is located just behind the antenna. Wave absorption at the $\omega = 3\Omega_D = 1.5\Omega_H$ layer was observed. Ion heating and the scattered signal from waves in the plasma interior are both maximized at a density of $\bar{n}_e \simeq 1 \times 10^{14}\,\mathrm{cm}^{-3}$.

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Recently, plasma heating by directly launched IBW was proposed by Ono,[1] and encouraging results have been obtained at moderate power levels.[2,3] However, the excitation, propagation, and absorption of IBW in a hot tokamak plasma are still not well understood. In this Letter, we report the results of the first experimental study of such characteristics obtained by collective scattering of CO_2 laser radiation from the directly excited IBW in the Alcator C tokamak. The details of the heating experiment will be reported in a separate publication.

During the IBW experiments, reduced size molybdenum limiters of $a = 12.5\,\mathrm{cm}$, $12.0\,\mathrm{cm}$, or $11.5\,\mathrm{cm}$ defined the plasma minor radius while the major radius was

$R_0 = 64\,\mathrm{cm}$. The transmitter frequency was $\omega/(2\pi) = 183.6\,\mathrm{MHz}$ and up to 150kW of rf power was coupled into the plasma from a Faraday shielded toroidal loop antenna located on the low magnetic field side of the torus.[4] The majority ion species was hydrogen, with varying concentrations (0–20%) of minority deuterium. The toroidal magnetic field was varied in the range $5 \leq B \leq 11\,\mathrm{T}$ which corresponds to $2.4 \geq \omega/\Omega_H \geq 1.1$ at the plasma center, where Ω_H is the hydrogen ion-cyclotron frequency.

The scattering arrangement was similar to that described in Ref. 5. The scattering diagnostic was located at the same toroidal location as the IBW antenna. The horizontal resolution (defined as $1/e^2$ in power) ranged from $\pm 8\,\mathrm{mm}$ to $\pm 3\,\mathrm{mm}$ depending on the optical geometry. The measurements were essentially chord averaged in the vertical direction. The location of the scattering volume is denoted by the horizontal distance from the plasma center, $x \equiv R - R_0$. The range of wavenumbers accessible by the present scattering arrangement was $10 < k < 140\,\mathrm{cm}^{-1}$ with resolutions of $\pm 5\,\mathrm{cm}^{-1}$ to $\pm 7\,\mathrm{cm}^{-1}$.

A wavenumber spectrum of IBW can be obtained from a shot-by-shot scan of the scattering angle. As shown in Fig. 1(a), the wavenumber spectrum is well defined in spite of poor vertical resolution. The dispersion relation can be mapped out by scanning the scattering volume horizontally while keeping the plasma parameters constant. The result is displayed in Fig. 1(b). The solid curve represents the theoretical dispersion curve obtained by solving $|\overleftrightarrow{G}| = 0$, where $\overleftrightarrow{G}$ is defined by $\overleftrightarrow{G} \cdot \vec{E} \equiv \vec{n} \times (\vec{n} \times \vec{E}) + \overleftrightarrow{K} \cdot \vec{E}$, $\vec{n} \equiv c\vec{k}/\omega$, and $\overleftrightarrow{K}$ is the hot plasma dielectric tensor.[6] The value of the wavenumber corresponding to the peak in P_{sc} was used, and the hydrogen Larmor radius ρ_H was evaluated from the measured hydrogen ion temperature at the midplane of the torus. The agreement between the experimentally obtained dispersion relation and the theoretical dispersion relation suggests that most of the scattered signal originates from a region close to the plasma midplane, in agreement with ray tracing calculations.[4] The scattered power varied linearly with the injected rf power.

The spectral power density of the IBW, defined as[6] $\Gamma_\perp(k) = -(c/4\pi)\vec{E}^* \cdot (\partial\overleftrightarrow{G}/\partial n_\perp)\cdot\vec{E} \simeq -(c/4\pi)(\partial K_{xx}/\partial n_\perp)\,|E_x|^2$, can in principle be obtained from the scattered signal, which is proportional to $\tilde{n}_e^2(k)$. The fluctuating electron density associated with the wave is given by

$$\frac{\tilde{n}_e}{n_e} = i\frac{e}{m_e c\omega}\left(\frac{\omega^2}{\omega_{ce}^2} - i\frac{\omega}{\omega_{ce}}\frac{K_{xy}}{K_{xx} - n_\parallel^2 - n_\perp^2} - \frac{n_\parallel^2}{n_\perp^2 - K_{zz}}\right) n_\perp E_x, \qquad (1)$$

where the z-direction is parallel to the magnetic field. In this paper the scattered power is displayed because the conversion of the scattered power to the wave power is subject to uncertainties in $n_\parallel$ of the IBW, which cannot be determined experimentally by scattering. Nevertheless, the scattered power still represents the variation of the actual wave power well (within factors of two) under the conditions reported in this paper.

First we show the scattering results from the case of second harmonic launching in a hydrogen plasma at $B \simeq 7.6\,\mathrm{T}$. The wave power is expected to be absorbed nonlinearly[7,8] at the $\omega = 1.5\Omega_H$ ($= 3\Omega_D$) layer located at $x/a \simeq -0.3$. In the presence of a deuterium minority species, the wave can also damp linearly on the deuterium ions. The scattered power measured at $x/a = +0.4$ is plotted as a function of the toroidal magnetic field in Fig. 2(a). In agreement with theoretical expectations, the scattered signal is maximized at $B \simeq 7.6\,\mathrm{T}$, when $\omega/\Omega_H \simeq 1.9$ in front of the antenna and the $\omega/\Omega_H = 2$ layer is located just behind the antenna. For direct excitation of IBW, launching is expected to be optimized when $k_\perp$ is smallest [see Fig. 1(b)]. As shown in Fig. 2(b), such a resonant peak is also observed on the antenna loading resistance, and corresponds to the direct excitation of the IBW. In addition, an almost field independent loading of 1Ω was also observed.

The scattered power observed at $x/a = +0.4$ is plotted as a function of density in Fig. 3(a). The scattered power decreases rapidly as the density is raised above a value of $\bar{n}_e \simeq 1 \times 10^{14}\,\mathrm{cm}^{-3}$. If the scattered power were dominated by low (high) $n_\parallel$ components (the boundary is around $n_\parallel \simeq 1$ for typical Alcator parameters), the actual wave power density would fall off more rapidly (more slowly) with increasing density than the scattered power plotted in Fig. 3(a). The ion temperature increase[3] also exhibits a sharp drop above $\bar{n}_e \simeq 1 \times 10^{14}\,\mathrm{cm}^{-3}$ and no clear evidence of heating is observed above $\bar{n}_e \simeq 2 \times 10^{14}\,\mathrm{cm}^{-3}$. On the other hand, the loading resistance (not shown) increases with density up to $\bar{n}_e \simeq 3 \times 10^{14}\,\mathrm{cm}^{-3}$.

The disappearance of ion heating at high plasma density can in principle be explained by the scaling of the threshold power for nonlinear cyclotron damping with density.[7] Even at high density, however, linear damping of the IBW on the minority deuterium should still occur. The scattering result suggests that no ion heating occurs at high plasma density because the IBW is not able to penetrate to the plasma center [see Fig. 3(a)]. The cause for the decrease in IBW power with plasma density is not fully understood at present. It may be that the present antenna does not couple efficiently to the IBW at high plasma density. Another mechanism that could prevent penetration of wave power to the plasma interior is scattering of IBW from the low-frequency density fluctuations near the plasma edge.[9] In Fig. 3(b) the scattering data from the low-frequency density fluctuations, integrated up to $5\,\mathrm{cm}^{-1}$ in wavenumber and 400kHz in frequency, and observed along a chord located at $x/a = +0.83$, is shown as a function of plasma density. The quantity plotted on the vertical axis is $P_{sc}/\bar{n}_e^2$, which is proportional to $(\tilde{n}_e/n_e)^2$. Here $\tilde{n}_e$ refers to the amplitude of the low-frequency density fluctuation. The absolute magnitude of $\tilde{n}_e/n_e$ could not be determined with accuracy, but based on previous measurements[10] it is estimated to be in the range 0.1 to 0.5 at $\bar{n}_e \simeq 2 \times 10^{14}\,\mathrm{cm}^{-3}$. The correlation between Figs. 3(a) and (b) suggests that scattering of IBW by low-frequency density fluctuations may be important in determining wave accessibility to the plasma interior.

The radial profile of the scattered power from the IBW is plotted in Fig. 4. The strong radial attenuation of wave power near the plasma edge is observed at all densities. This may be caused by a spatial spreading (especially in the toroidal direction) of the waves,[4] and possibly by scattering from low-frequency density fluctuations. A fairly significant attenuation of the scattered power is observed on the high field side of the plasma center, near the $\omega = 1.5\Omega_H$ nonlinear resonance, which may be an indication of nonlinear absorption since the deuterium concentration was negligibly small ($n_D/n_e \ll 1\%$).

In order to investigate the effects of local plasma parameters at the antenna surface on excitation of IBW, the antenna was moved radially with respect to the plasma surface (defined by the limiter) under fixed plasma conditions. Both the ion temperature increase and the scattered signal reached a maximum when the front surface of the antenna Faraday shield was located 4mm in the shadow of the limiter regardless of the limiter size (the density scrape-off length is typically 2–3mm in Alcator). However, the loading resistance increased monotonically as the antenna was moved in radially, possibly indicating an increased power loss near the antenna when the local density is excessively high.

At magnetic fields of $9 \lesssim B \lesssim 10\,\mathrm{T}$, the $\omega = 3\Omega_D = 1.5\Omega_H$ layer is located in the outer plasma edge region in front of the antenna. A strong attenuation of the scattered signal was observed when the $\omega = 3\Omega_D$ layer was located between the antenna and the scattering volume, which indicates a nearly complete absorption of the IBW power; either linearly by deuterium minority ions, or nonlinearly by hydrogen ions. We note that the signal level detected under these conditions is much smaller (two orders of magnitude) than the case of second harmonic resonant launching, and no scattered signal was detected in the plasma interior. Nevertheless, significant central ion heating and centrally peaked deuterium minority tail were observed even in this regime.[3] It is also noted that the ion temperature at $r/a \simeq 0.85$, deduced from the IBW dispersion relation,[11] correlated well with the central ion temperature increase. At present this phenomenon is not understood.

In summary, excitation, propagation, and damping of the directly launched IBW in a tokamak plasma were studied for the first time, using CO_2 laser scattering techniques. The IBW was identified by mapping out the dispersion relation, and the scattered power varied linearly with the injected rf power. Wave launching was optimized when an ion-cyclotron harmonic layer was located just behind the antenna, and when the antenna was placed 4mm into the shadow of the limiter. Wave damping at the $\omega = 3\Omega_D = 1.5\Omega_H$ layer was observed. Ion heating and the scattered signal both decrease above a density of $\overline{n}_e \simeq 1 \times 10^{14}\,\mathrm{cm}^{-3}$. The correlation with the increase of low-frequency edge density fluctuations suggests that the scattering of IBW by these fluctuations may be preventing the wave penetration. The local plasma parameters near the antenna surface may also play an important role in determining the wave excitation. Direct observation of IBW by scattering is a powerful tool for investigating wave physics. This technique can also be used to measure the ion temperature profile in hot plasmas.

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[1]M. Ono, K. L. Wong, G. A. Wurden, Phys. Fluids **26**, 298 (1983).

[2]M. Ono, et al., Phys. Rev. Lett. **54**, 2339 (1985); J. Hosea, et al., Plasma Phys. and Controlled Fusion 28A, 1241 (1986).

[3]M. Porkolab, et al., in Plasma Phys. and Contr. Nucl. Fusion Res. (IAEA 11th Int. Conf., Kyoto, 1986) proc. to be published.

[4]J. Moody, et al., Bull. Am. Phys. Soc. **31**, 1586 (1986).

[5]Y. Takase, et al., Phys. Rev. Lett. **53**, 274 (1984).

[6]T. H. Stix, The Theory of Plasma Waves (McGraw-Hill, New York, 1962).

[7]M. Porkolab, Phys. Rev. Lett. **54**, 434 (1985).

[8]H. Abe, et al, Phys. Rev. Lett. **53**, 1153 (1984).

[9]M. Ono, Phys. Fluids **25**, 990 (1982).

[10]R. L. Watterson, R. E. Slusher, C. M. Surko, Phys. Fluids **28**, 2857 (1985).

[11]G. A. Wurden, M. Ono, K. L. Wong, Phys. Rev. A **26**, 2297 (1982).

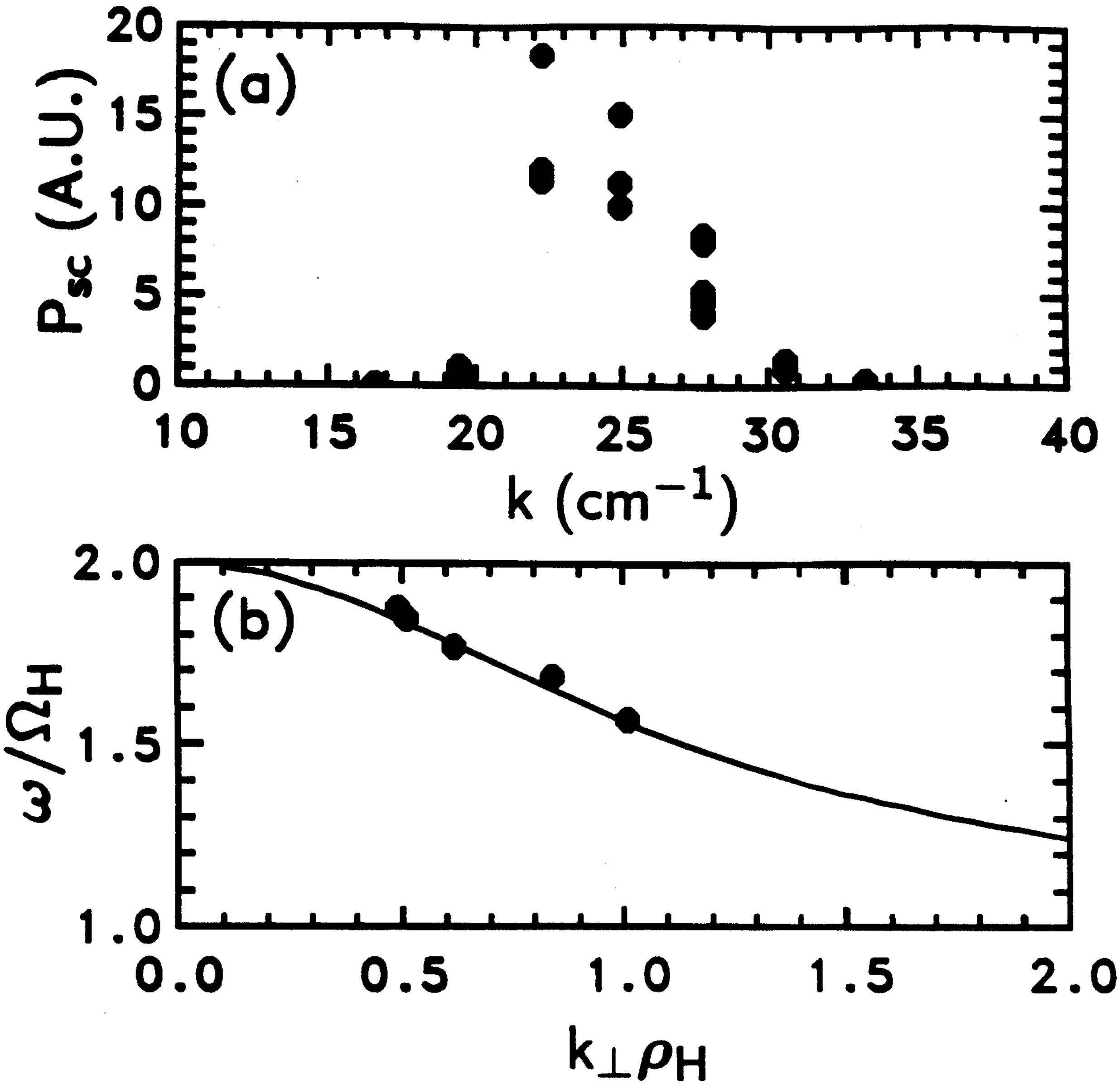
Figure Captions

FIG. 1. (a) A typical k-spectrum of the IBW. Hydrogen, $B = 7.6\,\mathrm{T}$, $I_p = 250\,\mathrm{kA}$, $\bar{n}_e = 2 \times 10^{14}\,\mathrm{cm}^{-3}$, $x/a = -0.16$. (b) The dispersion relation determined from CO_2 scattering data. Hydrogen, $B = 7.6\,\mathrm{T}$, $I_p = 290\,\mathrm{kA}$, $\bar{n}_e = 2.3 \times 10^{14}\,\mathrm{cm}^{-3}$. Data shown as circles were obtained from a spatial scan of the scattering volume. The solid line represents the theoretical dispersion curve.

FIG. 2. (a) The scattered power and (b) the loading resistance as functions of the toroidal magnetic field. Hydrogen, $I_p = 290\,\mathrm{kA}$, $\bar{n}_e = 2.3 \times 10^{14}\,\mathrm{cm}^{-3}$, $x/a = +0.4$.

FIG. 3. (a) The scattered power as a function of density. Hydrogen, $B = 7.6\,\mathrm{T}$, $I_p = 200$–$300\,\mathrm{kA}$, $x/a = +0.4$. (b) The scattering data from the low-frequency density fluctuations as a function of density. Same parameters, $x/a = +0.83$.

FIG. 4. A radial profile of the scattered power. Hydrogen, $B = 7.6\,\mathrm{T}$, $I_p = 290\,\mathrm{kA}$, $\bar{n}_e = 0.8 \times 10^{14}\,\mathrm{cm}^{-3}$, $a = 12.5\,\mathrm{cm}$.



(a)
P_{sc} (A.U.)
0
5
10
15
20
10
15
20
25
30
35
40
k (cm^{-1})
(b)
ω/Ω_H
1.0
1.5
2.0
0.0
0.5
1.0
1.5
2.0
$k_\perp \rho_H$

Fig. 1

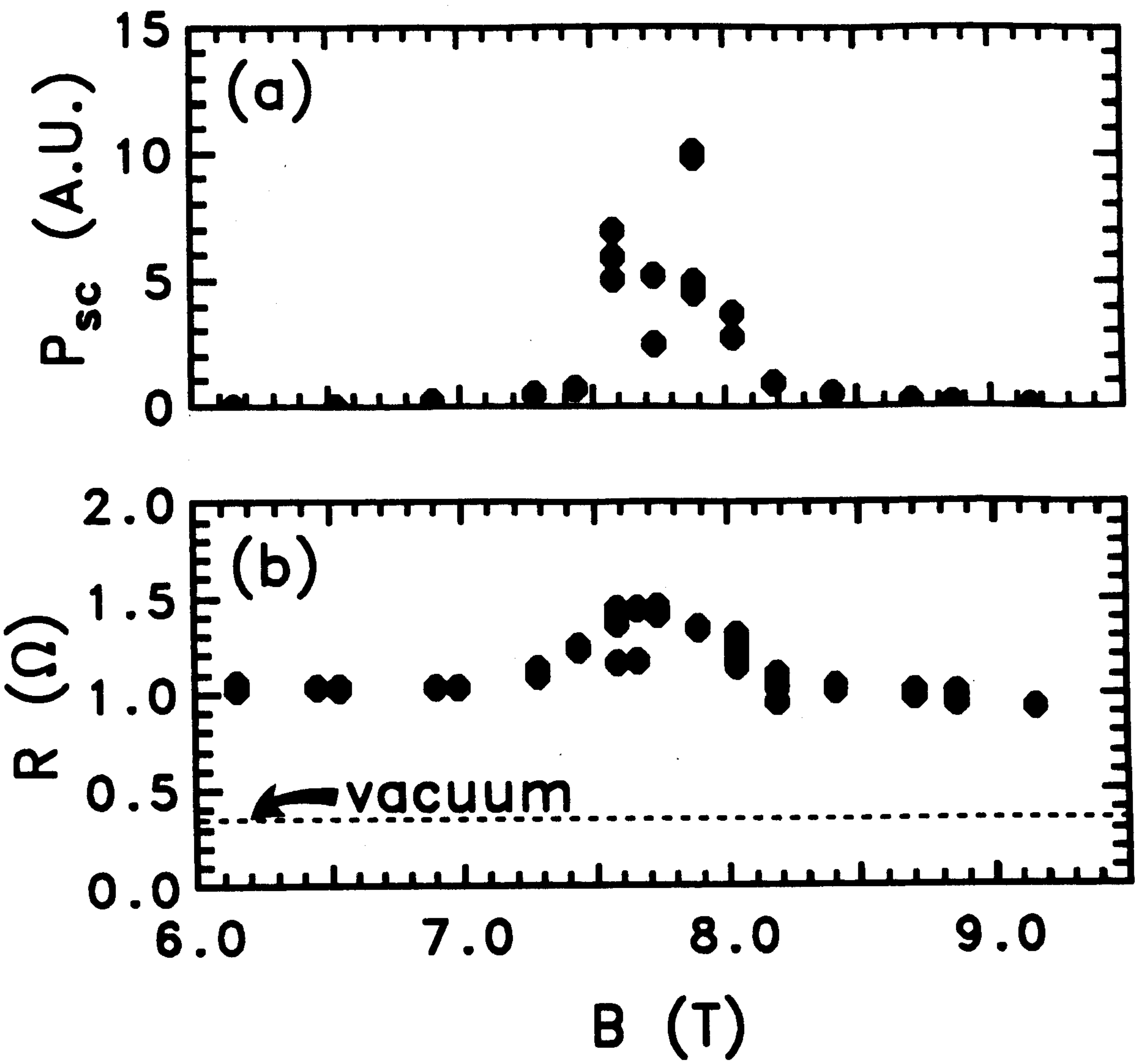


Fig. 2

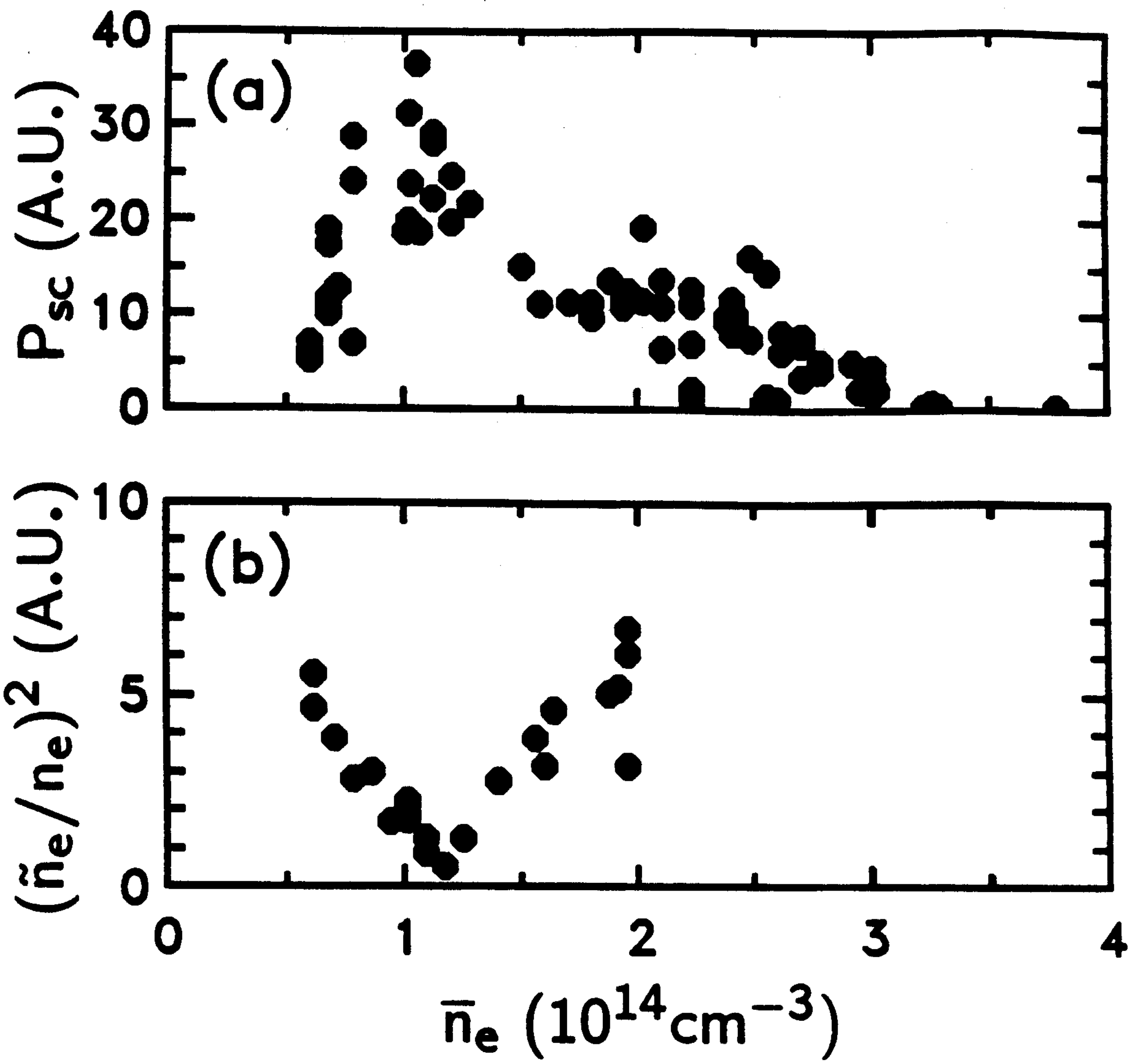


Fig. 3

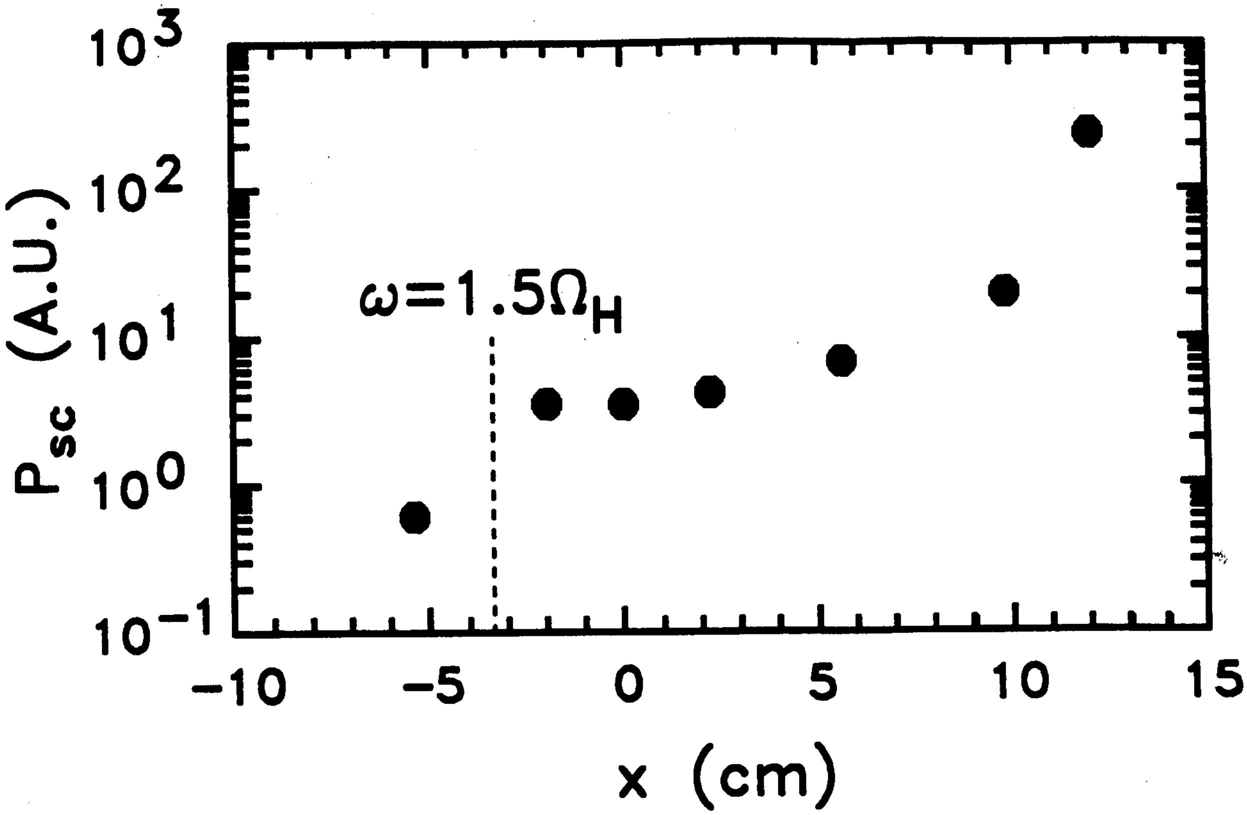


Fig. 4