Study of the Density Fluctuations in the Adiabatic Toroidal Compressor Scattering Tokamak Using CO_2 Laser

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We report a study of electron density fluctuations in the adiabatic toroidal compressor tokamak using heterodyne detection to study the small-angle scattering of CO_2 laser radiation. Data are presented for the frequencies, radial and poloidal wave vectors, and amplitudes of the turbulent low-frequency modes present in the adiabatic toroidal compressor. The results of searches are reported for scattering from the "thermal" ion feature and from a driven wave at 800 MHz (near the lower hybrid resonance).

Electrostatic waves and fluctuations in high-temperature and fusion plasmas are of interest since they are expected to play an important role in electron transport phenomena and in the details of resonant heating when electromagnetic waves are incident upon the plasma. We report a study of electrostatic fluctuations in the adiabatic toroidal compressor (ATC) tokamak[1] by heterodyne detection of CO_2 laser radiation scattered at small angles. We are able to study electron density fluctuations with wavelengths between 1 and 10^{-3} cm, frequencies between 10 kHz and 1 GHz, and fluctuation amplitudes $\tilde{n}/n$ as low as 10^{-5} (where $\tilde{n}$ is the total density-fluctuation amplitude and n is the electron density).[2] We have studied the low-frequency fluctuations in the ATC similar to those observed using microwave scattering.[3] The wave-number distributions of the fluctuation amplitude are nearly identical in the radial and poloidal directions, and the wave vectors $\vec{k}$ are oriented nearly perpendicular to the toroidal magnetic field B_T. The data suggest that there is a large range of frequencies associated with a particular $\vec{k}$ mode. We determine the total density fluctuations $\tilde{n}/n$ associated with these waves to be 3×10^{-2}. The effect of lower hybrid and ion-cyclotron resonance heating on these modes was studied. We also report a negative search for a directly driven 800-MHz wave (near the lower hybrid resonance) in the ATC plasma in the presence of incident microwave powers up to 150 kW. An upper limit on the scattered intensity due to ion acoustic waves in the ATC is set at ten times the value predicted for thermal equilibrium.

The experimental apparatus is shown in Fig. 1. A 200-W cw CO_2 laser beam I is incident upon the plasma in a direction perpendicular to the major plane of the torus. Scattered radiation S, oriented at a small angle with respect to I, is directed with a system of mirrors to the detector. The scattering angle φ is related to the CO_2 wavelength λ_L of 1.06×10^{-3} cm by the Bragg condition that φ is approximately λ_L/λ, where λ is the wavelength characteristic of the electron density fluctuation. Wave-vector conservation requires that the wave vectors $\vec{k}$ ($|\vec{k}| = 2\pi/\lambda$) associated with the electron density fluctuations which scatter the light be oriented in a direction very nearly perpendicular to the beams I and S. Thus when the laser beam passes through the center of the plasma, scattering will be due to fluctuations with wave vectors parallel to B_T ($k_\parallel$) or wave vectors in the poloidal direction (k_θ). Similarly when the beam passes near the edge of the plasma, scattering will be due to fluctuations with wave vectors k_r and $k_\parallel$.

Using a 10-m beam path from the plasma to the detector and appropriate focusing of I, we are

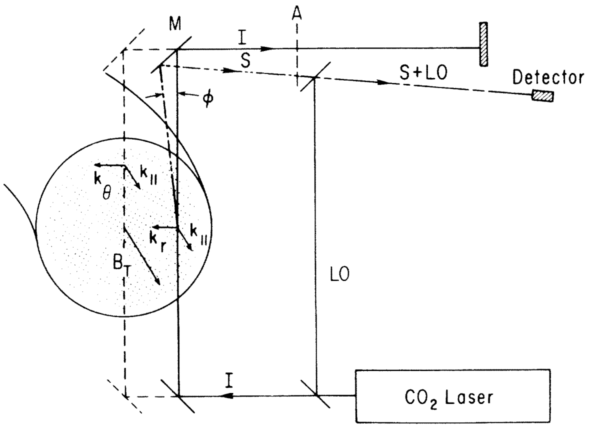

FIG. 1. The arrangement of scattering apparatus used in the ATC experiment. The laser, detector, and optics move as a unit so that the beam can scan an 11-cm distance across the minor cross section of the plasma.

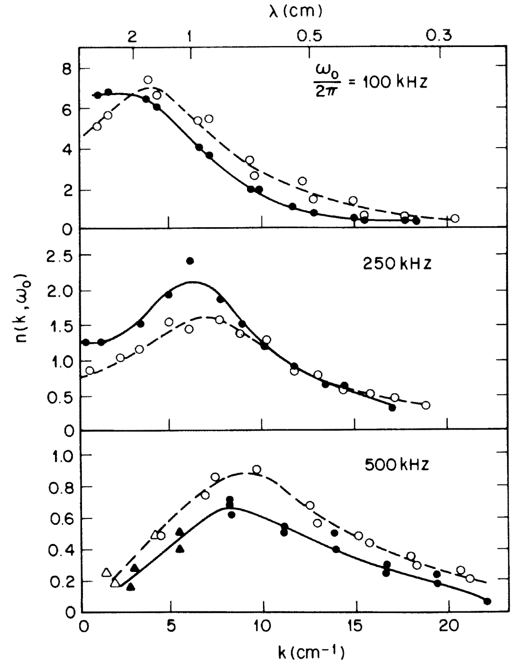

FIG. 2. The wave-vector spectrum of the electron density fluctuations at fixed frequency. The solid and open symbols correspond to scattering from fluctuations with poloidal wave vectors k_θ and radial wave vectors k_r, respectively. The triangles in the 500-kHz data are upper limits on the intensity at those wave vectors.

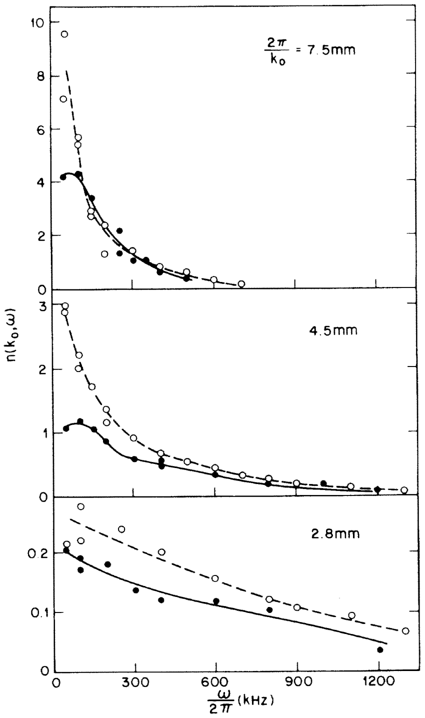

FIG. 3. The frequency spectrum of the fluctuations at fixed wave vector. The symbols and curves have the same meaning as in Fig. 2.

able to resolve scattering at an angle of 1×10^{-3} rad corresponding to a k resolution of 5.5 cm^{-1} [half width at half-maximum (HWHM)]. The diameter of I at the plasma in this arrangement is 7 mm full width at half-maximum. For wavelengths longer than 2 mm, scattered radiation is collected from the entire interaction volume defined by the intersection of I with the region of turbulent plasma so that no localization of the turbulence along I is possible. The position of I with respect to the machine center line is variable from 90 to 101 cm. The radius of the plasma center R_P was located at 88 cm with a minor radius to the plasma limiter of 17 cm. A local oscillator beam LO split off from the main laser beam I illuminates the Sb counterdoped Ge:Cu photoconductive detector in a direction nearly parallel to S. The detector has a quantum efficiency of 0.11 and has frequency response to 1 GHz. In order to investigate fluctuations with λ greater than 1.5 mm an attenuator A, which attenuates the beams by a factor of 20, is placed in beams I and S, so that the intensity of the LO beam is large compared to that of I and S. The heterodyne photocurrent produced in the detector by the interference of S and LO is frequency analyzed using a tuned filter which is adjusted manually between tokamak discharges.

At wavelengths between 20 and 2 mm, scattering was observed under virtually all discharge conditions from fluctuations with frequencies up to 2 MHz. At any given wavelength and frequency the heterodyne photocurrent was roughly constant throughout the discharge which was 45 msec in duration. We report the average value of photocurrent between 25 and 35 msec. Shown in Fig. 2 is the rms heterodyne photocurrent at fixed frequency as a function of wave vector for the low-frequency fluctuations. The filter bandwidth is 10 kHz at 100 and 250 kHz and 30 kHz at 500 kHz. The widths of the peaks are limited by the wave-vector resolution of 5.5 cm^{-1} (HWHM). The solid circles are for I at 91.5 cm (3.5 cm from the plasma center), and these data correspond, therefore, to scattering from fluctuations with poloidal wave vectors k_θ. The open circles are taken with I at 101 cm (13 cm from the plasma center) and correspond to scattering from fluctuations with radial wave vectors k_r. No scattering is observed out of the plane perpendicular to B_T except that which is expected due to our finite wave-vector resolution by scattering from fluctuations with wave vectors in this plane. The data indicate that $k_{\parallel}$ is less than 10% of our resolution. This implies that the parallel wavelengths associated with the observed fluctuations are larger than 10 cm. Shown in Fig. 3 are the frequency spectra of the photocurrent at fixed wave vector. The bandwidths are 3 kHz at frequencies $\omega/2\pi$ up to 100 and 10 kHz at larger frequencies. The solid and open circles have the same meaning as in Fig. 2. The absolute value of the units in Figs. 2 and 3 is arbitrary. The heterodyne photocurrent is proportional to the spectrum of electron-density fluctuations $n(k, \omega)$ at a given position in the plasma integrated over the path of the incident beam I. Consequently the spatial extent of the turbulence is not localized by these measurements and this introduces an uncertainty of ± 30% in relating the intensities of the turbulent k_r and k_θ spectra and in determining the absolute value of $\tilde{n}/n$. Radial scans indicate that the turbulent region is at least 10 cm in radial extent and extends to the limiter position. These spectra, when integrated over frequency and wave vector, yield a value of $\tilde{n}/n$ of approximately 3×10^{-2}. The ATC plasma had a center density of 1.6×10^{13} cm^{-3}, an average density n in the region of turbulence of 1×10^{13} cm^{-3}, an electron temperature T_e of 800 eV, a plasma current of 70 kA, a B_T of 16 kG, and an effective charge of 5. The filling gas was H_2. Similar spectra and fluctuation levels were observed with filling gases of D_2 and He and in a H plasma before and after addition of 1% O. The spectra shown in Fig. 3 agree quantitatively with the microwave scattering results[3] for the long-wavelength spectrum of these fluctuations in the ATC plasma.

In a contained plasma, gradients of density and temperature can provide a free-energy source to drive fluctuations at frequencies low compared to the ion-cyclotron frequency and wavelengths small compared to the density gradient length l [where l^{-1} is $d(\ln n)/dr$]. A well-known example of such fluctuations is drift waves which have a phase velocity in the poloidal direction near the electron diamagnetic drift velocity c_D given by T_e/eB_Tl.[4] If the observed fluctuations were due to a linear superposition of drift waves one would expect that a particular k_θ would be associated with a single frequency proportional to l^{-1}. However, the data in Fig. 3 show that to a fixed wave vector there is associated not a single frequency but a broad range of frequencies of width $\Delta\omega$. The fact that the observed range of frequencies is relatively insensitive to position in the plasma tends to rule out the possibility that this spread is due to an average over many different gradient lengths l. The data therefore indicate that the turbulent state is not well described by a superposition of linear modes.[5] A phenomenological description of the frequency spectra can in fact be obtained by associating with each wave vector an imaginary frequency (i.e., a growth or damping coefficient) through the relation that $\Delta\omega$ is proportional to k^2 with a constant of proportionality of the order of 10^4 cm^2 sec^{-1}. The measured value of $\tilde{n}/n$ implies fluctuating $\vec{E}\times\vec{B}_T$ drift velocities large compared to c_D. This fact and the relatively large values of $\Delta\omega$ indicate that quasilinear estimates of the transport coefficients may be inappropriate.

As shown in Fig. 2, the k_r and k_θ spectra are nearly identical in level and spectral shape indicating that the turbulence is nearly isotropic in the plane perpendicular to B_T.[5] Shear stabilization, which is frequently invoked to predict the radial mode structure of drift waves, does not compel the k_r spectra to be similar to the k_θ spectra. In particular shear stabilization models (of a linear system) would predict the peak of the radial wave-vector distribution at all frequencies to occur at k_r of zero. This is not observed in our experiments where this peak occurs at a nonzero value of k_r which depends on frequency.

The observed spectra were found to be altered when the plasma was subjected to electromagnetic waves at 25 MHz (near the ion cyclotron resonance) and at 800 MHz (near the lower hybrid resonance) at power levels up to 80 and 150 kW, respectively. The particular portions of the spectra affected and the time dependence of these effects depended on the position of I with respect to the plasma and on the plasma parameters. effects of the heating experiments on the turbulence occurred predominantly near the edge of the plasma (within 10 cm of the limiter) and wave vectors associated with the enhanced fluctuations were predominantly radial. In all cases, the fluctuation amplitude was found to increase, but by a factor of less than 3, and even this increase occurred over a relatively small portion of the ω and k spectrum.

A search was made for the directly driven 800-MHz wave (near the lower hybrid resonance) launched at the edge of the plasma via a four-port wave-quide array at incident powers up to 150 kW. In this experiment the driven wave is expected to have an associated electron density modulation $\tilde{n}/n$ of approximately 5×10^{-3} and a wavelength of 1.5 mm at the laser interaction volume located 135° around the torus from the wave guide. We scanned wavelength from 1 mm to 1 cm at positions of l from the center of the plasma to the limiter radius and did not observe the driven wave. The estimated sensitivity was greater than the expected level of fluctuations by a factor of 5.

In the ATC, the thermal ion feature in the scattered spectrum is expected to be peaked near 400 MHz for a 1-mm-wavelength fluctuation. Scattering was not observed from this feature and this implies the absence of an ion-acoustic wave turbulence during the ATC discharge at levels larger than ten times the thermal level.

We wish to acknowledge the collaboration of M. Porkolab in developing the CO_2 scattering diagnostic for plasma research, of J. Cecchi in interfacing the present apparatus to the ATC, and D. R. Moler in the design and operation of this experiment. We also are indebted to many members of the staff at the Princeton Plasma Physics Laboratory for helpful discussions and for their encouragement, and to the members of the ATC crew for their technical assistance. We also wish to acknowledge helpful conversations with A. Hasegawa, W. Horton, and H. Ikezi.

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[2] C. M. Surko, R. E. Slusher, D. R. Moler, and M. Porkolab, Phys. Rev. Lett. 29, 81 (1972); R. E. Slusher, C. M. Surko, D. R. Moler, and M. Porkolab, Phys. Rev. Lett. 36, 674 (1976).

[3] E. Mazzucato, Phys. Rev. Lett. 36, 792 (1976).

[4] See, for example, S. Yoshikawa, in *Methods of Experimental Physics*, edited by H. Griem and R. Lovberg (Academic, New York, 1970), Vol. 9, Part A, pp. 305–343; W. Horton, Phys. Fluids 19, 711 (1976), and to be published.

[5] Hasegawa has called to our attention that at values of $\tilde{n}/n$ of 10^{-2} the nonlinear coupling of radial and poloidal modes through the $\vec{E}(k,\omega)\times\vec{B}_T$ drift of ions can produce an effective frequency shift comparable to the drift-wave frequency [A. Hasegawa, Phys. Lett. 75A, 143 (1976)]. This might explain both the observed frequency spread at fixed wave vector and the isotropic nature of the turbulence in the plane perpendicular to $\vec{B}_T$.

Resonances in Binary Charged-Particle Collisions in a Uniform Magnetic Field

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I have considered the two-body problem in a uniform magnetic field. For the case of like-particle collisions, a resonance between the velocities transverse to the magnetic field of the test and field particles reduces the problem to that without a magnetic field for the relative-velocity scattering angle and scattering cross section. This resonance condition results in large changes in the test-particle collisional parameters. A secondary resonance for like-particle and resonances for unlike-particle collisions have also been found.

The binary collisional scattering and the related collisional parameters of a plasma in a magnetic field are important for the transport,[1-3] heating,[4-6] and magnetic confinement[7,8] of thermonuclear plasmas in open-ended as well as toroidal configurations. The transport of intense relativistic electron beams, radially confined by their self-pinch magnetic fields, through gas-plasma media over long distances,[9] as well as the interaction of intense electron beams with virtual cathodes in the presence of externally applied magnetic fields[10] also depend on the binary collisional scattering. Previous treatments[11,12] of the binary collision problem in a magnetic field have been approximate, to the extent that ultimately only the maximum impact parameter is altered from the Debye length λ_D to an appropriate average Larmor radius ρ_a whenever $\rho_a < \lambda_D$, thus resulting only in small changes in the value of the Coulomb logarithm.

I start with a test particle of mass m_t, charge q_t, velocity $\vec{v}_t$, and position $\vec{r}_t$ and a field particle of