tems where the above effect can be seen. A candidate for the first case would be the excited line in Cu_2O where the values of the parameters predict a large effect with crucial consequences on the interpretation of some experiments on the excitons and biexcitonic states using counterpropagating beams. In a different context the soft modes near a paraelectric-to-ferroelectric transition in a crystal will be another interesting system; these modes are highly anharmonic and the damping will play a very crucial role.

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Study of Low-Frequency Microturbulence in the Microtor Tokamak by Far-Infrared Laser Scattering

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The first far-infrared laser scattering measurements from a tokamak plasma are reported. Spatially and temporally resolved power spectra of density fluctuations in the Microtor plasma have been studied with an absolutely calibrated far-infrared scattering system which allowed measurement of the wide range of wave numbers from $k = 3$ to 50 cm^{-1}. The wave-number dependence of the scattered power of $0.6 \lesssim k_\perp \rho_i \lesssim 2$ was found to satisfy a $k^{-3.5}$ form.

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Low-frequency microturbulence may explain the anomalous transport and energy loss observed in toroidal magnetic confinement devices. One way of studying such turbulence is by the scattering of electromagnetic waves from small-scale density fluctuations.[1-3] We report herein the first study of collective scattering of far-infrared (FIR) laser light (447 and 1222 μm) in a tokamak. This represents an important alternative diagnostic to microwaves,[1] and CO_2 lasers.[3] FIR lasers are capable of simultaneously providing localized measurements ($\Delta x = 1.5$–3 cm) with good wave-number resolution [$\Delta k \lesssim 3$ cm^{-1} full width at half maximum (FWHM)]. The ease of source wavelength variation in the far infrared permits the determination of $S(\vec{k})$ over a wide wave-number region, and also allows the observation of the same wave number at different scattering angles. This is of importance when calculating absolute density fluctuation levels.

The output of a cw optically pumped FIR laser[4] ($C^{13}H_3F$, $\lambda = 1222$ μm, $P \simeq 3$ mW; or CH_3I, $\lambda = 447$ μm, $P \simeq 10$ mW) is directed into a wire-grid beam splitter which can be rotated to vary the coupling ratio. A portion of the beam is collected by a lens and focussed into a quasioptical biconical Schottky-barrier diode mixer,[5] thereby serving as local oscillator for the homodyne receiver. The remainder of the FIR beam enters along a vertical plane and is focussed at a point located on a horizontal plasma diameter, and thus scatters primarily from k_θ at the plasma center and k_r at the plasma edge. The scattered light in the same plane as the input beam is collected by a movable mirror which allows the variation of the scattering angle from 0° to 20°. An absolute calibration of the scattering system sensitivity was obtained by comparing the noise-power difference between 77 °K and 298 °K blackbody loads. The measured system noise temperature was ≃ 20 000 °K double sideband. In addition, test scattering from driven ion acoustic waves in a controlled laboratory plasma, with a nearly identical apparatus, permitted the direct measurement of wave-number resolution ($\Delta k \simeq 2$ cm^{-1}) and also allowed confirmation of the system sensitivity.[6]

The parameters of the Microtor tokamak at the University of California at Los Angeles are toroidal field B = 15 kG, I = 50 kA, $T_e \simeq 350$ eV, minor radius r = 10 cm, and major radius R = 30 cm, with a plasma pulse duration of ≳ 20 msec. The density profile was parabolic with a peak density of $n \simeq 3\times10^{13}$ cm^{-3}. Temperature profiles were obtained with calibrated 60- and 90-GHz heteordyne receivers to observe optically thick second-harmonic emission. Peak temperatures of ≃ 350 eV were typical with an approximately parabolic profile.

Fluctuation spectra were obtained by changing parameters such as scattering volume position, scattering angle, and probe wavelength. The Fourier-analyzed signal from the digitizers, P_s, is related to the spectral power density $S(\vec{k},\omega)$ by

$$P_s = P_i r_0^2 n_0 L_s S(\vec{k},\omega)\Omega_s, \qquad (1)$$

where r_0 is the classical electron radius, n_0 is the mean plasma density, P_i is the incident laser power, Ω_s is the solid angle of collection, and L_s is the scattering length.

Typical examples of the frequency spectra of P_s are shown in Fig. 1 for λ_i = 1222 μm. These were obtained with a scattering angle of θ = 3.5° (k = 3.1 cm^{-1}), and a radial position r = 3.75 cm from the minor axis. Time is measured relative to the onset of the tokamak discharge current. The spectra typically extend in frequency to 500 kHz; however, most of the energy resides below ≃ 200 kHz. Above 100 kHz, the scattered power exhibited a power-law falloff $\omega^{-2.5}$. This represents the best straight-line fit to the data displayed in Fig. 2(b). Over the course of the experiment, a variation in the exponent of ± 0.3 was observed. This spectral shape seems to be independent of r and k for $k \gtrsim 10$ cm^{-1}. With $S(\vec{k},\omega)$ as a known function of ω, the wave-number spectral density, $S(\vec{k})$, is obtained by integrating over the frequency.

Figure 2(a) shows the time-resolved wave-number spectrum (averaged over $\Delta t < 500$ μs) at r = 5.0 cm obtained with λ_i = 1222 and 447 μm. We should note here that the absolute values of $S(\vec{k})$ obtained with these two incident beams agree well with each other at the same values of k without adjustment. It is seen that $S(\vec{k})$ varies as $k^{-3.5}$ for 6 cm$^{-1} \lesssim k_\perp \lesssim 20$ cm^{-1} with a flattening of the spectrum below 6 cm^{-1}. $S(\vec{k})$ seems to be independent of k for $k_\perp \gtrsim 20$ cm^{-1} (however, the signal-to-noise ratio is rather low in this region, ≃ 2). Furthermore, the spectral shape of $S(\vec{k})$ is independent of radial position r which suggests than an isotropic turbulence spectrum is formed in a two-dimensional plane[7] as previously observed in tokamaks.[1,3]

The frequency-integrated scattered power is shown in Fig. 3 as a function of minor radius and

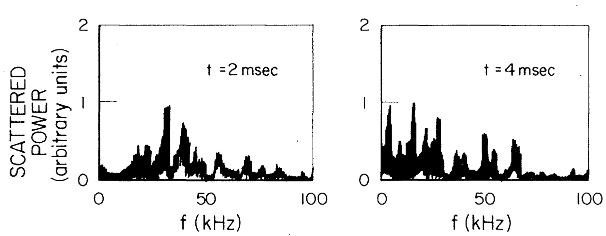

FIG. 1. Frequency spectrum of scattered 1222-μm radiation at two times in the tokamak discharge.

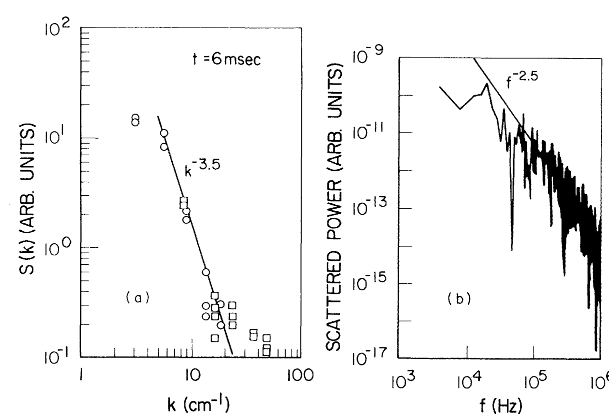

FIG. 2. (a) Wave-number spectrum of scattered 1222-μm (circles) and 477-μm (squares) radiation. (b) Frequency spectrum of scattered 1222-μm radiation.

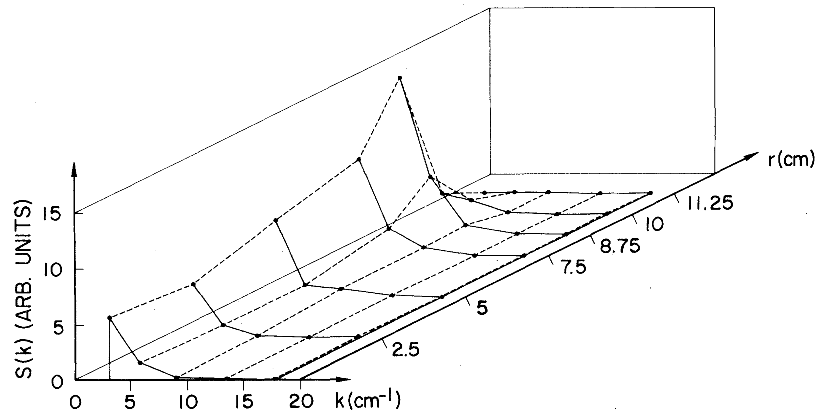

FIG. 3. Frequency-integrated power from $C^{13}H_3F$ laser scattering as a function of wave number and radial position.

wave number. The fluctuations are observed to peak toward the outer edge and toward lower wave number. The total mean square density fluctuations are obtained by integration of $S(\vec{k},\omega)$ over ω and $\vec{k}$. If we make the assumption that $k_r \simeq k_\theta \gg k_\parallel$, we then obtain,[1,8] employing the random-phase approximation,

$$\langle|\tilde{n}(r,t)|^2\rangle \simeq n_0 \int S(\vec{k})\, d^3k$$
$$\simeq (2\pi)^2 n_0 \int S(k_\perp) k_\perp\, dk_\perp, \qquad (2)$$

where the angular brackets denote the time average. Typical normalized density fluctuation levels of $\simeq 1.5\%$ rms are observed near the outer edge of the plasma ($r \simeq 7.5$ cm).

Fluctuation measurements were also performed with Langmuir probes inserted up to $\simeq 7$ cm from the minor axis. This allowed for the first time a direct comparison between scattering and probe measurements in the interior of a fusion plasma. In the range 20 kHz to 1 MHz the probe and FIR spectra were identical. In addition, the saturation current fluctuation level $\tilde{I}/I_0$ was also found to peak toward the edge of the plasma. However, the absolute level $\tilde{I}/I_0$ was found to be significantly larger ($\tilde{I}/I_0 \simeq 0.1$ rms) than the density fluctuation amplitude determined from FIR scattering data.

Several possible sources for the above disagreement between probe and scattering measurements of the fluctuations suggest themselves. First, since the saturation current $I \propto nT_e^{1/2}$, a large $\tilde{T}_e/2T_e$ represents a possible explanation for the large probe $\tilde{I}/I_0$. However, the second-harmonic fluctuation spectrum possessed a weak frequency dependence and was quite different from the probe/FIR spectra. In addition the data was consistent with an interpretation based on classical radiometer fluctuations, similar to the TFR results.[9] A second explanation for the probe/FIR discrepancy is that the probe itself perturbs the local value of $\tilde{n}/n_0$. However, the similarity of the probe/FIR frequency spectra and spatial fluctuation distribution makes this seem unlikely. Finally, in order to perform the integration indicated in Eq. (2), $k_\parallel$ was assumed to be $\ll k_r \simeq k_\theta$. A finite-$k_\parallel$ distribution could explain the probe/FIR disagreement but appears unlikely in view of previous scattering measurements.[3]

It is instructive to compare the scattering results with current theoretical predictions keeping in mind the inherent limitations. In Microtor, both collisionless drift waves and dissipative trapped-electron modes are possible candidates for the above-mentioned observations. With our measured plasma parameters, the collisionless drift wave appears to be more unstable. Linear theory predicts that for $k_\perp = 3$ cm^{-1}, the observed spectrum should peak sharply in the vicinity of $f = 50$–150 kHz. However, as seen in Fig. 1, the actual spectrum is quite broad with significant energy below 25 kHz, as observed also in previous tokamak scattering experiments.[1,3]

There have been several calculations[7,10,11] which predict wave-number spectra similar to those observed in this experiment. Specifically these theoretical models predict a k^{-n} falloff with $n = 4$–6,[7] 2,[12] and 2.6,[10] as opposed to the experimental value $n = 3.5$. Each of these theories, however, predicts a flattening of $S(\vec{k})$ for $k_\perp\rho_s \lesssim 1$, roughly as observed experimentally. Cheng and Okuda[11] have carried out large-scale, fully three-dimensional particle simulations of collisionless drift instabilities, and observe that convective cells can be excited nonlinearly by drift instabilities. These cells have different frequency and wave-number spectra from those of the drift waves with more spectral weight at small ω and k in qualitative agreement with the data shown in Figs. 1 and 2.

The fluctuation level has also been calculated by various authors. At quasilinear saturation $e\tilde{\varphi}/kT_e \simeq 1/k_\perp L_n$ (L_n is the density scale length) which yields $\tilde{n}/n_0 = 1-2\%$. More sophisticated treatments such as that by Lee *et al.*[13] also predict fluctuation levels in this range. The radial variation of $\tilde{n}/n_0$ of Fig. 3, of course, implies that considerable care needs to be taken in relating these calculations to the experimental results; however, the predicted levels do appear to be in the range observed by the FIR measurement.

The gross Microtor energy-confinement time, calculated from the measured plasma parameters, is $\simeq 1$ msec. This allows an estimate of the global heat diffusion coefficient $D_E = a^2/4\tau_E \simeq 3\times10^4$ cm^2/sec. This can be compared with the enhanced diffusion expected from low-frequency microturbulence. The cross-field diffusion coefficient due to electrostatic-drift-wave fluctuations can be obtained from a quasilinear procedure; this gives $D_s \simeq \nu L_n^2 |\tilde{n}/n_0|^2$, where ν is the growth rate of the linearly unstable wave. If we assume that ν^{-1} is roughly given by the measured autocorrelation time of the fluctuation signal ($\simeq 4$ μsec), we find $D_s \simeq 6\times10^3$ cm^2/sec assuming $(\tilde{n}/n_0) \simeq 1.5\%$ from the FIR scattering. This is somewhat less than the value computed from the energy confinement time; a density fluctuation of $\simeq 3\%$ is required for absolute agreement. A resolution of the probe/FIR disagreement will therefore permit a more critical assessment of theoretical predictions regarding anomalous transport phenomena.

In conclusion, the first FIR scattering measurements of density fluctuations in a tokamak have corroborated many of the features of previous scattering experiments, e.g., the broad frequency spectra, an isotropy in the plane perpendicular to B_T, and a peaking of $\tilde{n}/n_0$ near the outside of the discharge. New information has also been obtained regarding frequency and wave-number spectra. In particular, power-law dependences of $S(\vec{k}) \propto k^{-3.5}$ and $S(\omega) \propto \omega^{-2.5}$ have been observed together with a flattening of $S(\vec{k})$ at $k_\perp \rho_i < 1$. In addition, the first comparison of scattering measurements with Langmuir probe results in a tokamak plasma has been made. An examination of several theoretical models has shown that partial agreement is observed with these experimental results [e.g., $S(\vec{k})$ and $\tilde{n}/n$], but there is as yet no single model which accounts for all the observed phenomena.

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