Study of Density Fluctuations in the Absorption of Oxygen on Silicon

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We describe a new technique to measure the spatial distribution of plasma density fluctuations integrated over both frequency and wave vector. Measurements are reported of the frequencies, wave vectors, amplitudes, and also the spatial distributions of low-frequency density fluctuations present in the alcator tokamak. Two regimes can be identified. In high-density plasmas ($\bar{n} > 10^{14}$ cm^{-3}) the fluctuations are peaked at the limiter radius with a fluctuation amplitude of $\tilde{n}/n \simeq 1$. At lower densities the fluctuation amplitudes peak in the interior of the plasma with $\tilde{n}/n \simeq 0.07 \pm 0.03$.

Density fluctuations in magnetically confined plasmas are thought to provide important mechanisms for the transport of particles and energy both in and out of the plasma. The alcator tokamak provides a particularly interesting device for the study of such phenomena. It is capable of achieving plasmas with a wide range of average densities $\bar{n}$ between 10^{13} cm^{-3} and 5×10^{14} cm^{-3}.[1] In this range of densities the energy containment time is found to increase as $\bar{n}$ increases, and it has been hypothesized that small-scale density fluctuations are responsible for this behavior. At densities $\bar{n} > 3\times10^{13}$ cm^{-3} the central density is increased by introducing cold gas at the plasma edge, and it has been suggested[2] that the observed rapid penetration of cold plasma into the central region is due to a high level of fluctuations near the plasma edge. In this Letter we describe a new technique which we have developed to measure the spatial distributions of density fluctuations in plasmas by correlating the forward scattering from two CO_2 laser beams which intersect in the plasma. Using this new technique and angularly resolved CO_2-laser-light scattering[3] we have measured the frequencies, wave vectors, amplitudes, and spatial distributions of density fluctuations in alcator. At low densities and toroidal magnetic fields ($\bar{n} < 5\times10^{13}$ cm^{-3}, $B_T \simeq 40$ kG) fluctuations are observed in the interior of the plasma with amplitude $\tilde{n}/n \simeq 0.07 \pm 0.03$ (where n is the local value of the plasma density). At densities greater than 1×10^{14} cm^{-3} the fluctuations are found to be peaked at the plasma edge with $\tilde{n}/n$ of the order of unity. In this latter regime, the transport of particles and energy at the plasma edge should occur at the rate given by Bohm diffusion.

The experimental arrangement and apparatus for measuring the frequencies, wave vectors, and amplitudes of the fluctuations using the small-angle scattering of CO_2-laser radiation is nearly identical to that described previously.[3] For the long-wavelength phenomena reported here ($\lambda \simeq 0.5$ cm) the technique provides a measure of these quantities integrated along a chord corresponding to the intersection of the laser beam with the minor cross section of the plasma. In alcator the optical access is such that this chord was oriented perpendicular to the major plane of the torus and can only be located at -4, 0, 4, and 8 cm from the magnetic axis (where the minor radius of the limiter in alcator is at 10 cm). Scattered light at a given angle is detected for each discharge using heterodyne detection in a photoconductor.[3] The heterodyne photocurrent is proportional to $[S(\vec{k},\omega)]^{1/2}$ which is proportional to the fluctuating electron density at angular frequency ω and wave vector $\vec{k}$. [Here $S(\vec{k},\omega)$ is the dynamic structure factor.] The rms value of this quantity is monitored as a function of time during each plasma shot at two fixed frequencies and integrated over all frequencies. Fluctuations were observed in all alcator discharges. The chord-integrated fluctuation amplitude was found to be roughly proportional to the chord-averaged plasma density until late in the discharge when the density decreases with time. In the following we report data for the fluctuations averaged over a 30 msec interval centered at the time at which the density reaches its maximum value. Typically the frequency spectrum of the fluctuations at fixed wave vector decreases monotonically as a function of frequency. As the magnitude of the wave vector increases the corresponding frequency width increases. At the mean wave vector the frequency width at half-maximum amplitude is approximately 150 kHz. The wave vector spectrum of the fluctuations integrated over frequency, $S(k)$, can be fitted empirically by the Gaussian form

$$S(k) = A \exp(-2k^2/\bar{k}^2), \qquad (1)$$

where A is a constant and $\bar{k}$ ranges from 6 to 14 cm^{-1} depending on the magnetic field and density. In all plasmas in alcator it was found that the component of the wave vector parallel to $\vec{B}_T$ is small compared to that perpendicular to $\vec{B}_T$.

We have developed a new correlation technique to measure directly the spatial distribution of fluctuations. In the ATC tokamak we were able to infer qualitative information about the spatial distribution of the fluctuations by a continuous scan of the laser beam across the plasma.[3] Such a scan was not possible in alcator due to the limited optical access. The correlation technique has two important advantages: It does not require assumptions about the homogeneity of the fluctuations in either real space or wave vector space, and it requires minimal optical access to the plasma chamber.

The experimental arrangement for the correlation technique is shown in Fig. 1. A CO_2-laser is split into two beams A and B which are focused by the lens $L1$ and intersect in the plasma at an angle θ of 3°. The beams are focused to a beam of radius w_0 ($\simeq 0.05$ cm) which is sufficiently small ($\bar{k}w_0 \ll 1$) that wave vectors of all magnitudes and orientations perpendicular to the laser beam contribute to the forward scattering. (This is in contrast to the angularly resolved scattering experiment described above where we require $\bar{k}w_0 \gtrsim 1$ in order to resolve wave vectors of magnitude $\bar{k}$.) The phase modulation of each beam is detected on separate detectors DA and DB by interference with the local oscillator beam LO. The photocurrents from the two detectors are correlated in a doubly balanced mixer to yield an equal-time cross-correlation function C_{AB}. Our angularly resolved scattering measurements indicate that superthermal fluctuations with many different wave vectors are present in the plasma [see Eq. (1)] and so the correlation length l of the fluctuations is expected to be of the order of $\bar{k}^{-1}$. The forward scattering from beams A and B will be correlated only from regions of the plasma near the intersection of the beams where the beams are separated by a distance less than l. For density fluctuations localized in a layer at $y=0$, the correlation function $C_{AB}(y)$ is proportional to the correlation of the density fluctuations, $\langle\tilde{n}(\theta y)\tilde{n}(0)\rangle$, at the two points where the beams intersect the turbulent layer. Specifically in terms of the Gaussian form of Eq. (1),

$$C_{AB}(y)=B\exp[-(\bar{k}\theta y)^2/8], \quad (2)$$

where B is a constant. The spatial resolution, Δy, in the direction parallel to the incident beams is of the order of l/θ. By moving the point of in-

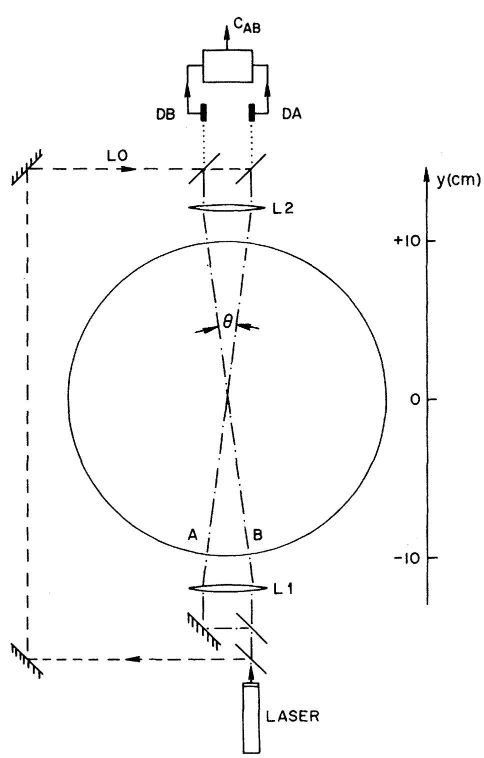

FIG. 1. The experimental arrangement is shown which was used to measure the spatial distributions of fluctuations by correlating forward scattering from two intersecting laser beams.

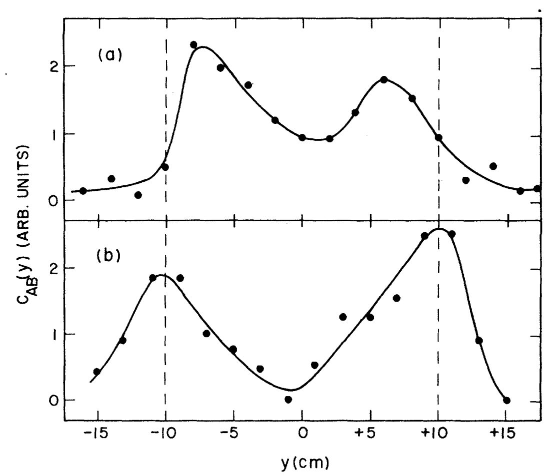

FIG. 2. The spatial distribution of fluctuations in alcator is shown along a chord through the magnetic axis. For case (a) $\bar{n}$ is 2.5×10^{13} cm^{-3} and B_T is 40 kG; for case (b) $\bar{n}$ is 2.6×10^{14} cm^{-3} and B_T is 60 kG. The peaks are nearly resolution limited. The limiter is at ± 10 cm.

tersection of the beams through the plasma we measure the spatial distribution of the fluctuations. This is accomplished by translating the lenses $L1$ and $L2$ parallel to the y axis. In Fig. 2 are shown data for two plasmas. In Fig. 2(a) is shown the spatial distribution of fluctuations in a plasma with $\bar{n}$ of 2.5×10^{13}, and B_T of 40 kG and a plasma current I of 70 kA. In this case the fluctuations are peaked in the interior of the plasma at a minor radius of 7 cm. For this plasma the central electron temperature is 900 eV and the center ion temperature is estimated to be 200 eV. At a radius of 7 cm the electron temperature is 230 eV and the plasma density is 2×10^{13} cm^{-3}. The value of $\bar{k}$ measured for this plasma is 5 cm^{-1}. Figure 2(b) corresponds to a plasma with B_T of 60 kG, $\bar{n}$ of 3×10^{14} cm^{-3}, and I of 160 kA and is typical of plasmas with $\bar{n} > 5\times10^{13}$. The fluctuations are peaked at the limiter radius. The value of $\bar{k}$ for this case is 12 cm^{-1}. From the estimate given above for Δy, the widths of the distributions are consistent with their being resolution limited, although the asymmetries of the data indicate some structure in the spatial distributions. We can conclude only that the data in Fig. 2 are consistent with (possibly asymmetric) annular distributions with thicknesses of from 1 to 4 cm.

With the measured spatial distributions and the angularly resolved scattering measurements at various positions with respect to the magnetic axis, we can infer the orientation of the wave vectors of the fluctuations. For the low-density case [Fig. 2(a)] fluctuations with comparable magnitude are observed with nearly equal wave vectors in both the radial and the poloidal directions, and therefore the turbulence is isotropic in the plane perpendicular to $\vec{B}_T$. For the high-density case [Fig. 2(b)] we are only able to study fluctuations with wave vectors in the poloidal direction and at angles up to 55° away from the poloidal direction (due to the limited optical access). These measurements are also consistent with nearly isotropic fluctuations in the plane perpendicular to $\vec{B}_T$.

Using the measured spatial distributions, the isotropic nature of the wave vector distribution in the plane perpendicular to $\vec{B}_T$, and the chord-integrated values of $\tilde{n}$ we can deduce values of $\tilde{n}/n$. For the high-density plasmas [similar to Fig. 2(b)] $\tilde{n}/n$ at the limiter is in the range from 0.3 to 1. The major uncertainty is the value of n at the limiter which is taken to be approximately 0.1 of the peak density.[4] In this regime we do not clearly resolve the level of fluctuations in the interior of the plasma. Our measurements are consistent with a value of $\tilde{n}/n$ between zero and 0.05 at radii less than 8 cm. For the low-density case [Fig. 2(a)], the maximum value of $\tilde{n}/n$ is 0.07 ± 0.03 at a radius of 7 cm.

In terms of the length ρ_s which is the ion gyroradius using the electron temperature [i.e., $\rho_s = c(T_e m_i)^{1/2}/eB$], $\bar{k}\rho_s$ is 0.3 for the low-density case. For the high-density case, $\bar{k}\rho_s = 0.13$ for the fluctuations at the edge assuming that T_e at the plasma edge is 20 eV.[4]

For the low-density plasma described above the broad frequency and wave vector spectra, $\tilde{n}/n$, and the spatial distribution of the fluctuations are similar to those observed in the ATC tokamak.[3,5] However, the value of $\bar{k}\rho_s$ for the low-density plasma is a factor of 2 smaller than that observed in ATC. For both the alcator and ATC experiments no correlation was observed between the density fluctuations described here and magnetohydrodynamic activity.

From the present experiments we are not able to point to a physical model which describes the fluctuations in detail. For the low-density case, the typical angular frequency ω divided by $\bar{k}$ yields a "phase velocity" of the order of 2×10^5 cm/sec which is comparable to the electron diamagnetic drift velocity V_D of 10^5 cm/sec. The phase velocity V_D would be expected for drift waves with $\bar{k}\rho_s \ll 1$. Because of the broad frequency spectra at fixed $\bar{k}$ and the isotropic nature of the turbulence, an unambiguous identification is not possible. This broad frequency spectrum and the isotropic wave vector spectrum are probably due in part to the nonlinear coupling between modes with poloidal and radial wave vectors.[6] In a linear drift-wave model, electric fields and electric field gradients can also produce a broad frequency spectrum.[7] The large level of fluctuations at the plasma edge in the high-density plasmas may be associated with increased collisionality or modified temperature, density, and potential gradients. Electric field gradients could also produce a Kelvin-Helmholtz instability[8] at the plasma edge.

In the high-density plasmas, the large fluctuation amplitude ($\tilde{n}/n \simeq 1$) near the plasma edge can be expected to have important physical consequences. Particles and energy will be transported at the rate given by Bohm diffusion. Such rapid transport may explain the rate of penetration of cold plasma typical of high-density alcator discharges.[1,2] Also, the large fluctuations near the plasma edge can be expected[9] to cause strong scattering of microwave radiation such as that incident upon the plasma during lower-hybrid heating experiments. Consequently the wave fronts of the radiation will be distorted and the intensity of the radiation will vary in the poloidal direction on the scale of the correlation length of the density fluctuations ($l \simeq 3$ mm).

In the interior of the low-density plasmas, the fluctuation amplitude is large enough to lead to appreciable transport; however questions remain about the spatial extent of the fluctuations and the appropriate diffusion coefficient (e.g., from strong- or weak-turbulence theory). Similar statements can be made about the transport to be expected in the interior of the high-density plasmas if the fluctuation amplitude is near the upper limit ($\tilde{n}/n \simeq 0.05$) set by our measurements. Using the techniques described above, the question of the spatial extent of the fluctuations could be resolved either in a larger plasma or in a plasma with greater angular access such as that which will be available in the alcator *C* tokamak.

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[1]M. Gaudreau *et al.*, Phys. Rev. Lett. 39, 1266 (1977).
[2]Ref. 1 and M. Hughes, to be published.
[3]C. M. Surko and R. E. Slusher, Phys. Rev. Lett. 37, 1747 (1976).
[4]L. S. Scaturro and R. R. Parker, Bull. Am. Phys. Soc. 22, 1148 (1977).
[5]R. J. Goldston, E. Mazzucato, R. E. Slusher, and C. M. Surko, in *Proceedings of the Sixth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Berchtesgaden, West Germany, 1976* (International Atomic Energy Agency, Vienna, 1977).
[6]A. Hasegawa and K. Mima, Phys. Rev. Lett. 39, 205 (1977).
[7]D. L. Jassby, Phys. Fluids 15, 1590 (1972).
[8]R. A. Koch and W. M. Tang, Princeton Plasma Physics Laboratory Report No. 1381, 1977 (unpublished).
[9]P. M. Bellan and K. L. Wong, Princeton Plasma Physics Laboratory Report No. 1314, 1977 (unpublished).

New Phenomenon in the Absorption of Oxygen on Silicon

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An O_2 adsorption state on the Si(111) 2×1 surface has been found which will remove surface states without producing a chemical shift of the Si 2*p* core level, suggesting a strongly covalent bond. This is accomplished by using an initial exposure pressure of 10^{-8} Torr. Exposures using an initial exposure pressure of 10^{-6} Torr also remove the surface states but produce a 2.0 eV Si 2*p* chemical shift indicating an ionic bond different from that of SiO_2 (shift of 3.8 eV).

Historically, surface states on Si have been associated with "dangling" bonds, i.e., bonds broken by formation of the surface. It followed that removal of these surface states by adsorption of a foreign gas—for example, oxygen—was associated with a strong chemical bond between the gas and the Si "dangling" bond.[1] Such a bond should lead to a chemical shift of the Si core levels. For example, a shift of 3.8 eV is found for the Si 2*p* levels in SiO_2,[2] and smaller shifts have been consistently reported previously for oxygen adsorbed on Si.[3]

Here, we report the surprising result of surface-state removal from the Si(111) surface without production of any measurable chemical shift (≤ 0.3 eV) of the Si 2*p* core levels even though the oxygen coverage is almost a monolayer. Thus, a new phenomenon in the adsorption of oxygen on Si has been found (similar adsorption appears[3] to occur on Ge), which should give new and important insight into the nature of surfaces and of the interaction of gases with them. Previously, Rowe *et al.*[4] reported on the adsorption of molecular O_2 on Si and interpreted the sorbed oxygen state as being O_2^-. However, the large electron transfer associated with this model can be excluded on the basis of our core level results as described below.

In these experiments, degenerate *n*-type silicon samples were cleaved [resulting in the 2×1