New Fluctuation Phenomena in the H-Mode Regime of Poloidal-Diverter Tokamak Plasmas

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A new kind of fluctuation is observed near the edge of plasmas in the PDX tokamak operating in the "H-mode" (improved-confinement) regime. These fluctuations are evidenced as vacuum-uv and density-fluctuation bursts at well-defined frequencies ($\Delta\omega/\omega \lesssim 0.1$) in the range between 50 and 180 kHz. The bursts are correlated, both in space and in time, with changes in the temperature-density product near the plasma edge where large density and temperature gradients develop during the H mode.

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The transport processes near the boundaries of tokamak plasmas are not well understood but are known to be anomalous. In particular, the transport of energy and particles is larger than the flux expected from simple Coulomb collisions of electrons and ions orbiting in the sheared magnetic field. Scattering and probe measurements (e.g., Surko and Slusher,[1] Mazzucato,[2] and Zweben and Taylor[3]) have shown that there are density fluctuations in tokamak plasmas whether the plasmas are bounded by a limiter or by a magnetic diverter. These fluctuations peak in amplitude near the plasma edge. The level $\tilde{n}/n$ is nearly as large as possible, in the range from 0.1 to 0.5 (n is the local density and $\tilde{n}$ is the local fluctuating density). The fluctuation spectra are broad with typical frequencies, $\omega/2\pi$, near 50 kHz for plasmas in PDX (the Poloidal Diverter Experiment tokamak); typical wave vectors $\vec{K}$ are near 3 cm^{-1} for PDX. In small tokamaks (where probe measurements can be made),[3] the transport associated with these large fluctuations is consistent with the "anomalous" transport observed near the plasma edge.

A new kind of "quasicoherent" fluctuation (QCF) has been observed in PDX plasmas which is characterized by an unusually sharp frequency spectrum. The QCF always begins within a few milliseconds (e.g., $\lesssim 5$ msec) after the abrupt transition to the "H mode." The H mode is a regime of magnetic diverter plasmas characterized by improved energy confinement.[4,5] Density fluctuations associated with the QCF are observed both by a CO$_2$ laser interferometer intersecting the outer edge of the plasma and by a 2-mm microwave scattering system sensitive to a nearly horizontal half chord midway between the plasma center and the outer separatrix.

Frequency spectra of both the broadband density fluctuations and the QCF during the H mode are shown in Fig. 1 as measured with the 2-mm mi-

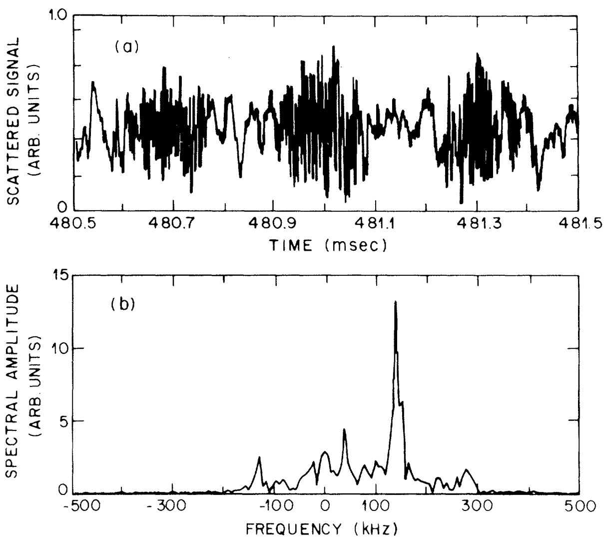

FIG. 1. (a) The time record and (b) the spectrum of microwave scattering from density fluctuations during a PDX H-mode discharge. Nearly coherent QCF bursts are seen in (a) near 480.7, 481.0, and 481.3 ms. The spectrum in (b) is obtained during the burst centered at 481 ms. The scattering volume is a predominantly horizontal chord with a length of the order of the plasma radius and a width of 2 cm located midway between the plasma center and the outer separatrix. The sign of the frequency shift indicates that the waves are propagating in the electron diamagnetic drift direction (or the plasma is rotating in that direction).

crowave scattering apparatus. The spectrum in Fig. 1(b) is obtained during the second QCF burst shown in Fig. 1(a). The high-frequency bursts (near 120 kHz in Fig. 1) are nearly coherent $(\Delta\omega/\omega \sim 0.1)$ for 10 to 20 cycles and are separated by periods of the same duration as the bursts. The frequency of the bursts for coinjected beams is in the range between 50 and 100 kHz, which is considerably below the range from 100 to 180 kHz observed for counterinjected beams (as shown in Fig. 1). The frequency of each burst is nearly coherent; however, there is a tendency for the frequency to drift downward after the *H*-mode transition.

The sign of the frequency shift of the QCF for both coinjected and counterinjected neutral beams corresponds to wave propagation with a phase velocity in the electron diamagnetic drift direction for a stationary plasma. However, some of the frequency shift may also be due to poloidal and/or toroidal plasma rotation. This may also explain the frequency difference between coinjected and counterinjected neutral beams. The wave vector corresponding to the scattering angle for the data in Fig. 1 is oriented in the poloidal direction and is in the range between 0.5 and 3 cm^{-1} (i.e., wavelengths between 2 and 12 cm or poloidal mode numbers m between 20 and 120 for modes near the plasma edge).

The QCF's are also observed on a vacuum-ultraviolet/x-ray detector array, which is sensitive to emission from the plasma edge region that is dominated by vuv energies in the range of a few hundred electronvolts. Several vuv chords are observed simultaneously and a comparison of the phases of these signals yields an estimate of the poloidal mode number, m, of between 15 and 30; this is consistent with the lower range of m numbers deduced from the microwave scattering results.

The spatial distribution of the QCF is determined by analysis of the amplitude of the CO_2 laser interferometer signal. The data for the line integral of $\tilde{n}$ along a vertical chord as a function of the major radius of the chord are shown in Fig. 2(c). For this analysis, the QCF is modeled as having a coherent poloidal mode number m and a Gaussian radial distribution centered at a minor radius r_F with $1/e$ width W_F. Fitting this simple model to the data yields $W_F = 0.6$ cm and $r_F = 38$ cm. The separatrix at the outside edge of the plasma is near a minor radius of 40 cm which corresponds to a major radius of 180 cm. Thus this model is consistent with the QCF's filling an annulus ~ 1 cm wide, located just inside the separatrix. Note that this annulus overlaps the region where large increases (up to a factor of 3) in the density and temperature gradient develop after the *H*-mode transition [Figs. 2(a) and 2(b)].

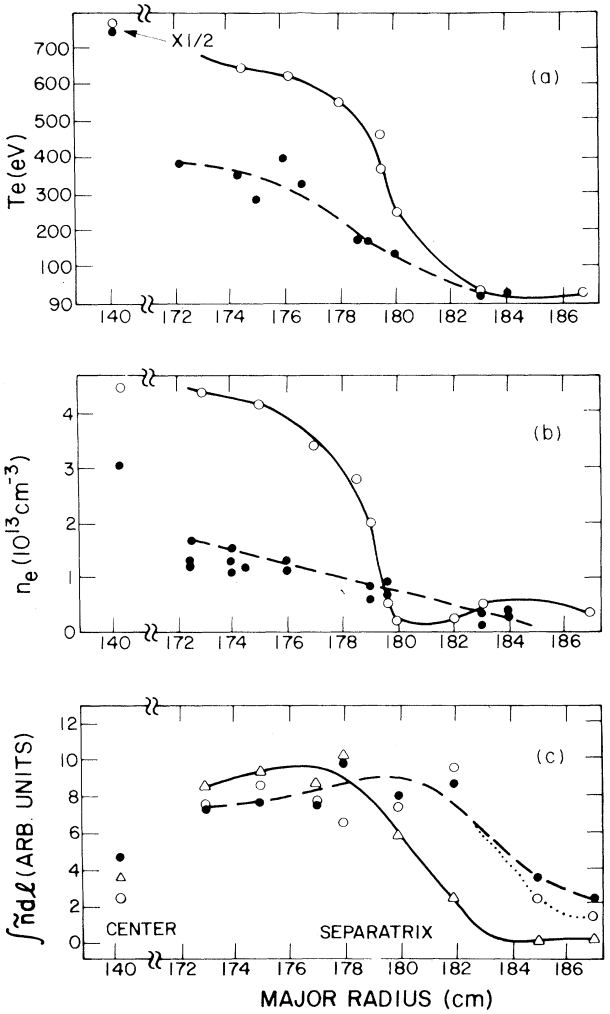

FIG. 2. The temperature, density, and fluctuation level profiles are shown in (a), (b), and (c), respectively, as a function of major radius at the outer edge of the PDX plasma before (closed symbols) and during (open symbols) the *H* mode. Each datum point represents a single discharge or the average of several discharges. The solid and dashed lines are guides to the eye. The circles in the $\tilde{n}$ data correspond to the broadband fluctuations, and the triangles correspond to the QCF mode.

The magnetic field fluctuations $\tilde{B}$ associated with the QCF are estimated from the current induced on a sensing coil near the "X" point of the magnetic separatrix. The field fluctuations $\tilde{B}/B$ at the QCF annulus are in the range from 0.01% to 0.1%. For comparison, $\tilde{B}/B$ for an $m = 2$ instability is of the order of 1%, where B is the static magnetic field.

Correlation of the QCF with vuv emission and H_α emission is shown in Fig. 3. The vuv signal in

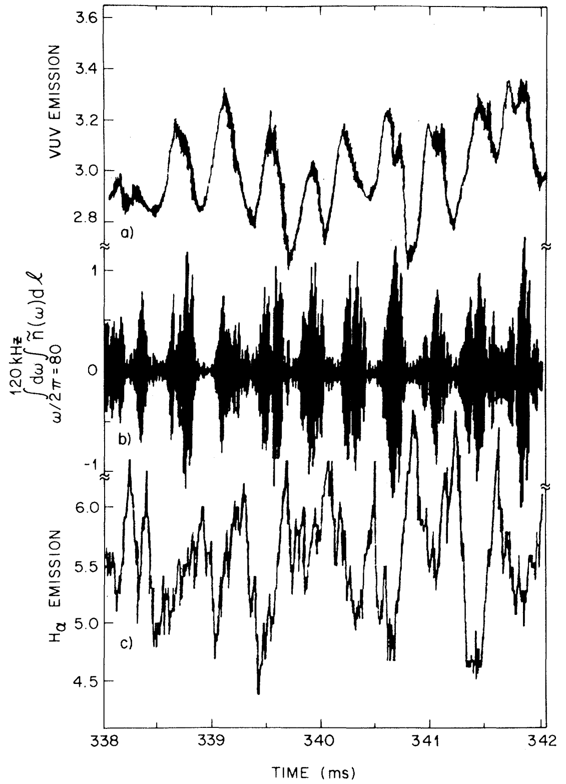

FIG. 3. vuv emission fluctuations, high-frequency QCF density fluctuation bursts, and H_α emission from the dome region above the plasma are shown in curves *a*, *b*, and *c*, respectively, for a 4-ms time period during the *H* mode. QCF density fluctuation bursts in *b* are correlated with decreases in the vuv emission in *a* and H_α emission *c*. The QCF vuv fluctuations (near 80 kHz for this time period) are nearly coherent with the density fluctuations in *b* and can be seen in *a* as a periodic broadening of the vuv trace.

curve *a* has been filtered to show only fluctuations in the frequency bands from 0 to 5 kHz and from 80 to 100 kHz and the density fluctuations in curve *b* have been filtered to include only the QCF frequency range between 80 and 120 kHz. Excursions in the vuv emission and H_α emission (measured in the dome region) of $\sim 10\%$ are synchronized with the QCF bursts. In Fig. 3 a sharp rise in vuv emission is followed by a gradual decrease in level during the QCF burst. For bursts of this duration, a vuv emission signal is proportional to a positive power of local density and temperature. This indicates that the QCF activity is correlated with edge density temperature, probably through the transport that determines these quantities. It suggests a model where the QCF is associated with an instability which limits the sharp rise in either local density or temperature and/or the gradients of these quantities.

One feature of *H*-mode operation is the occurrence, especially at high neutral-beam intensities, of sharp bursts in the edge H_α emission ("H_α spikes"). During the H_α spikes, the mean density decreases and density and magnetic field fluctuations in the frequency range between 10 and 50 kHz are observed. The QCF typically becomes erratic in time and decreases in amplitude during one of these H_α spikes. However, within a few milliseconds the QCF is bursting again, often at a higher frequency than before the spike. There is no obvious correlation between the timing or phase of the QCF and the H_α spikes.

It is relevant to discuss the level and spatial distribution of the fluctuations with a broad frequency spectrum [Fig. 1(b)] before and after the *H*-mode transition in order to compare the broadband fluctuations with the QCF. Major-radius scans of the CO_2 laser interferometer including only the broadband fluctuations (i.e., the QCF is removed by filtering) are shown in Fig. 2(c) both before and during the *H* mode. Before the *H*-mode transition, the data are best fitted by an annular Gaussian radial distribution with a width $W_F = 5$ cm and a peak several centimeters outside the separatrix radius at $r_F = 43$ cm. Several milliseconds after the *H*-mode transition, the broadband fluctuation levels decrease by nearly a factor of 2 for CO_2 laser chords at the plasma center and 5 to 10 cm outside the separatrix, while the levels for chords near the separatrix remain nearly constant. This is consistent with a narrowing of the annulus of the broadband edge fluctuations. Note that the broadband fluctuations are peaked in a region where there is little change in density or temperature gradient during the *H* mode.

The microwave scattering measurements have a spatial resolution smaller than the minor radius of the plasma and can monitor fluctuation levels in the plasma interior. On the average, the broadband fluctuation amplitude $\tilde{n}$ observed in the plasma interior remains nearly constant after the *H*-mode transition. Since the local density in the plasma interior increases appreciably after the transition, the fluctuation level $\tilde{n}/n$ decreases by a factor of 1.5 to 3. The levels measured by microwave scattering are a factor of 20 to 50 lower than those at the plasma edge measured with the CO_2 laser interferometer. The narrowing of the annular distribution observed in the CO_2 laser results and the decreased levels observed by microwave scattering are consistent, since the two diagnostics predominantly measure separate regions of the plasma.

The fluctuation levels associated with the QCF can be estimated from the spatial models discussed earlier in this paper and the observed scattering levels. This yields $\tilde{n}/n$ for the QCF in the range from 0.02 to 0.1 if an annular Gaussian radial distribution for the QCF is assumed. This value is somewhat lower than the broadband fluctuation amplitudes at the plasma edge which are estimated to be in the range of $\tilde{n}/n$ from 0.1 to 0.3. It should be remembered that the density fluctuation levels cannot be directly related to transport, since the transport involves both the amplitude of the fluctuating potential and its phase relative to that of $\tilde{n}$.

The basic mode associated with the QCF has not been identified. The fact that the QCF is observed in a narrow region in minor radius near the separatrix tends to rule out the possibility that it is a magnetohydrodynamic (MHD) oscillation for two reasons: First, the large shear near the separatrix tends to stabilize MHD modes; in addition, the narrow radial structure is not characteristic of MHD activity. Thus it is more likely that the QCF is electrostatic in character with a magnetic component due to finite β effects. Finally, it is interesting to note that the QCF occurs in a region of the plasma that is marginally collisional before *H* mode and is more nearly collisionless during the *H* mode.

In summary, a new kind of quasicoherent fluctuation (QCF) has been observed at the edge of plasmas in the PDX tokamak during *H*-mode operation. The QCF's occur in bursts of 10 to 20 cycles, with each burst being well defined in frequency ($\Delta\omega/\omega \sim 0.1$). The QCF is located in the same region of the plasma where large increases in density and temperature develop during the *H* mode. The bursts are correlated with decreases in vuv emission, indicating that the QCF may be associated with an instability that limits the local density and temperatures or their gradients. The one-to-one correspondence between the QCF and the *H*-mode regime indicates that these fluctuations may well play an important role in the dynamics of this new and important regime of tokamak operation.

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