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By

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NEW FLUCTUATION PHENOMENA
IN THE H-MODE REGIME OF PDX TOKAMAK PLASMAS

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ABSTRACT

A new kind of quasi-coherent fluctuation is observed near the edge of plasmas in the PDX tokamak during "H-mode" operation. (The H-mode occurs in neutral beam heated divertor plasmas and is characterized by improved energy containment as well as large density and temperature gradients near the plasma edge.) These fluctuations are evidenced as VUV and density fluctuation bursts at well-defined frequencies ($\Delta\omega/\omega \lesssim 0.1$) in the frequency range between 50 and 180 kHz. They affect the edge temperature-density product, and therefore they may be important for understanding the relationship between the large edge density and temperature gradients and the improved energy confinement.

The transport processes near the edge 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 twisted magnetic field. Scattering and probe measurements[1-3] have shown that there are density fluctuations in tokamak plasmas whether the plasmas are bounded by a limiter or magnetic divertor. These fluctuations peak in amplitude near the plasma edge where the level $\tilde{n}/n$ is nearly as large as possible; with $\tilde{n}/n$ in the range from 0.1 to 0.5, where n is the local density and $\tilde{n}$ is the local fluctuating density integrated over the broad bands of observed frequencies [mean frequencies $\omega/2\pi$ are near 50 kHz for plasmas in PDX (Poloidal Divertor Experiment tokamak)] and wavevectors (mean wavevectors $\bar{k}$ are near 3 cm^{-1} for PDX). In small tokamaks (where probe measurements can be made),[3] these large fluctuations have been shown to cause the "anomalous" transport observed near the plasma edge. The time-averaged edge fluctuation spectra and levels are similar from discharge to discharge in all tokamaks. Even during intense neutral beam heating and high beta conditions, the edge and interior fluctuations do not change by more than a factor of two in level, and the frequency and wavevector spectra remain broad.

A new kind of "quasi-coherent" fluctuation (QCF) has been observed in PDX plasmas which is characterized by a surprisingly sharp frequency spectrum. The QCF always begins within a few milliseconds after the abrupt transition to the "H-mode," a regime of magnetic divertor plasmas which is characterized by improved energy confinement.[4,5] Density fluctuations associated with the QCF are observed by both a CO_2 laser interferometer intersecting the outer edge of the plasma in a vertical chord 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 broad-band density fluctuations and the QCF during the H-mode are shown in Fig. 1 as measured with the 2-mm microwave 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 co-injected beams is in the range between 50 and 100 kHz, considerably below the range from 100 to 180 kHz observed for counter-injected beams (as 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 co- and counter-injected 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 plasma rotation (poloidal and/or toroidal). Plasma rotation effects may explain some of the QCF frequency differences between co- and counter-injected neutral beams. The wavevector corresponding to the scattering angle for the data in Fig. 1 is K_θ 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 QCFs are also observed on a VUV/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 electron volts. 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, which is consistent with the lower range of m numbers deduced from the microwave scattering results.

The spatial distribution of the QCF is determined by analyzing the amplitude of the CO_2 laser interferometer signal as a function of the major radius of the interferometer chord. These data 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 $W_F = 0.5$ cm and $r_F = 38$ cm. The separatrix at the outside edge of the plasma is near a minor radius of 40 cm and a major radius of 180 cm. Thus the QCF fills an annulus ∿ 1 cm wide, which is located just inside the separatrix. Note that this annulus overlaps the region where large increases (up to a factor of three) in the density and temperature gradient develop after the H-mode transition [(Figs. 2(a) and (b)].

Another important parameter is the magnetic field fluctuation $\tilde{B}$ associated with the QCF. QCF fluctuations are observed only on sensing coils closest to the plasma, located 12 cm above the plasma and 10 cm out in major radius from the "x" point of the magnetic separatrix. The m numbers in the range from 15 to 30 estimated from the VUV data imply a high order multipole field which decreases rapidly with the distance of the coil from the annulus of the QCF. For a QCF annulus at a 38cm radius, the multipole field decreases from the QCF annulus to the coil by 10^{-2} for an m value of 30. Using this model for $\tilde{B}$, the measured amplitudes at the coil of 10^{-4} below the $\tilde{B}$ for a typical m = 2 mode imply a magnetic field fluctuation at the QCF annulus in the range from 1% to 10% of the fields associated with an m = 2 instability ($\tilde{B}/B$ 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 (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 (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 ∿ 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, the VUV emission signal is proportional to a positive power of local density and temperature. This indicates that the QCF affects transport in the edge region. It allows the possibility of 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. The H_α emission also decreases during a QCF burst but the connection to local density and temperature is less obvious.

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 in the timing or phase of the QCF and the H_α spikes. In contrast to the H_α spikes, which typically begin 10 to 30 ms after the H-mode, the QCF bursts begin between 2 and 10 ms after the time of the H-mode transition.

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 fit to an annular Gaussian model with a width W_F = 5 cm and a peak several centimeters outside the separatrix radius at r_F = 43 cm. This is consistent with the CO_2 laser crossed beam correlation scans at the top of the plasma where the fluctuation level peaks nearly 5 cm above the separatrix.[6] 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.

Microwave scattering measurements have a spatial resolution better 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 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 model 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 from $\tilde{n}/n$ of 0.1 to 0.3. It should be remembered that fluctuation levels cannot be directly related to transport, since the amplitude of the fluctuating potential and its phase relative to that of $\tilde{n}$ are required.

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 an 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. 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. The frequency of the QCF decreases after the initial H-mode transition, a trend which is opposite to that expected for the simplest model for drift waves with a constant wave-vector, since both the density gradient and the local temperature are increasing functions of time. However, the measured toroidal rotation in the H-mode would tend to downshift the QCF frequency and might produce the net downshift which is observed.

In summary, a new kind of quasi-coherent fluctuation has been observed at the edge of plasmas in the PDX tokamak during H-mode operation. The QCFs 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 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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FIGURE CAPTIONS

Fig. 1. The time record and spectra of microwave scattering from density fluctuations during a PDX H-mode discharge are shown in (a) and (b), respectively. Nearly coherent QCF bursts are seen in (a) at 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. Heterodyne detection allows the direction of propagation (or rotation) of the fluctuations to be determined from the sign of the frequency shifts.

Fig. 2. 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 data 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.

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 (a), (b), and (c), respectively, for a 4ms 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.

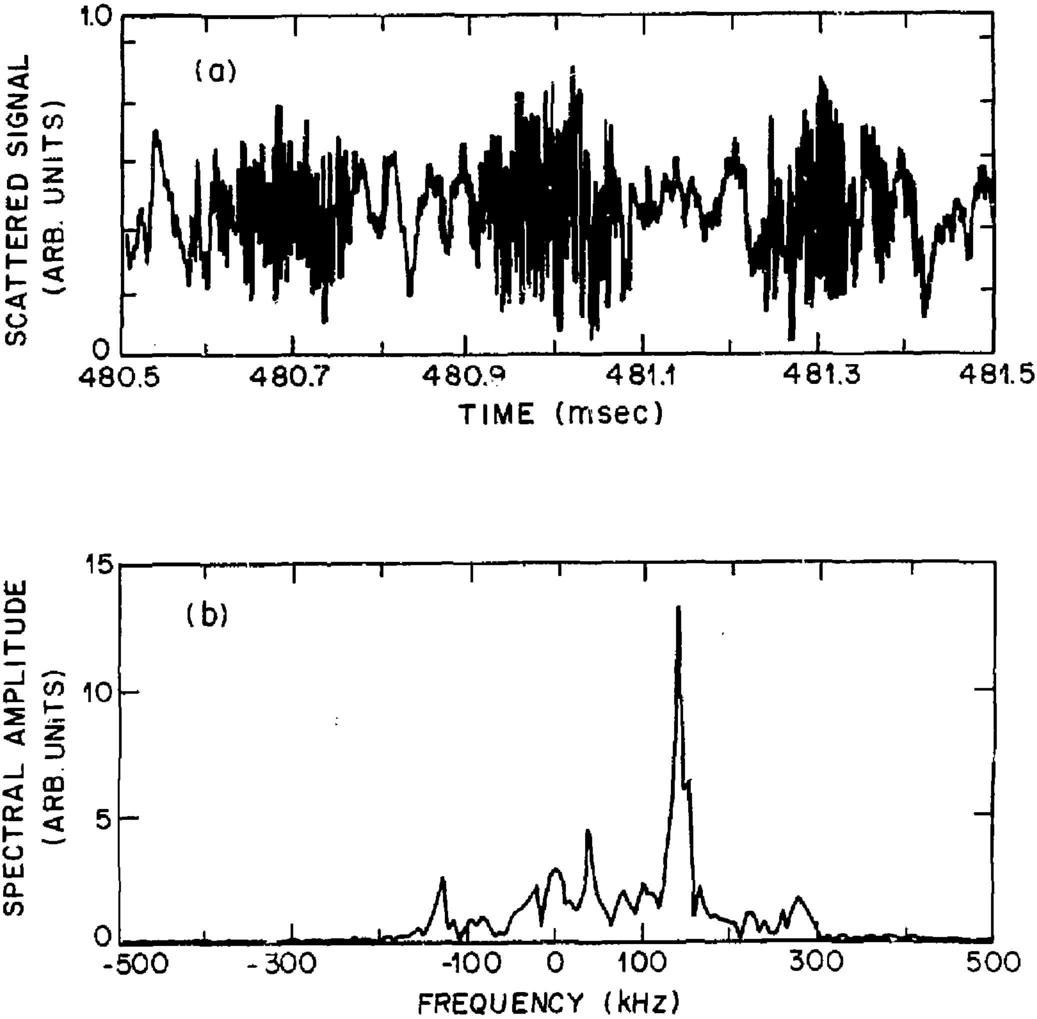
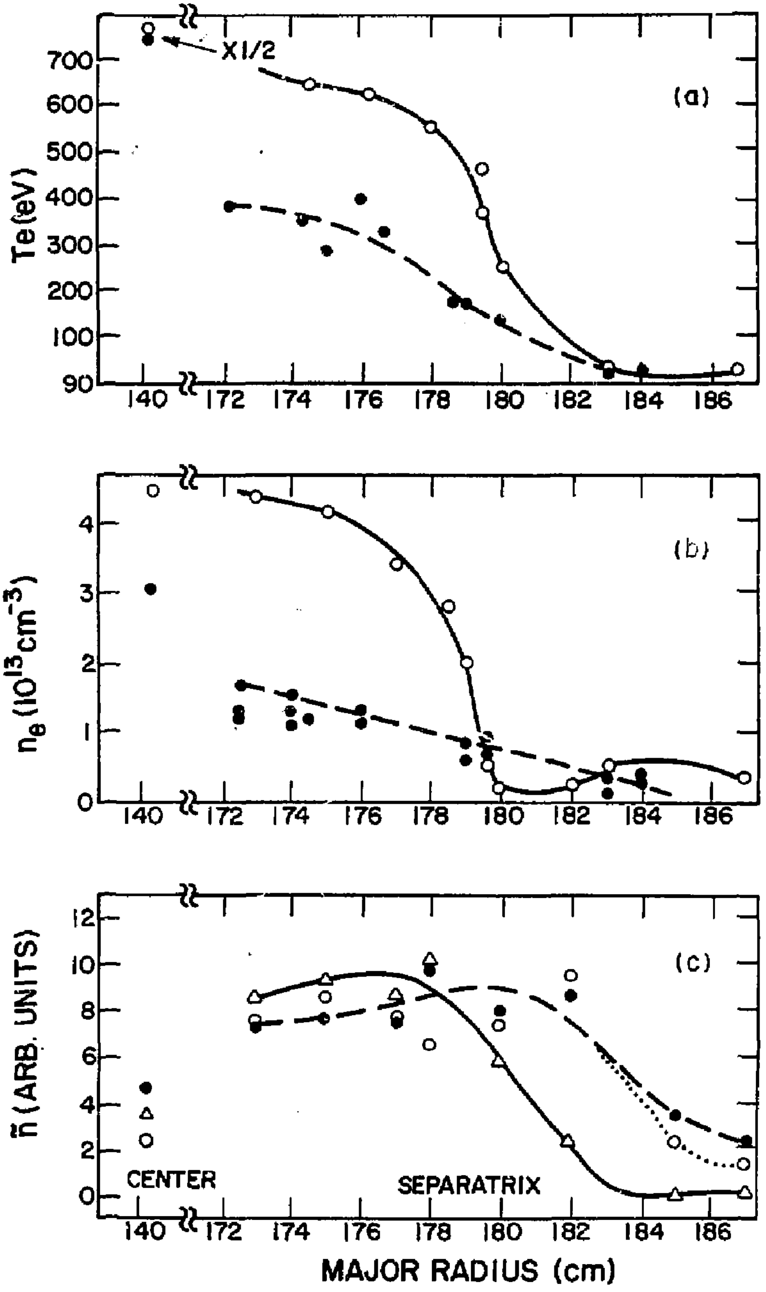

1.0
(a)
SCATTERED SIGNAL
(ARB. UNITS)
0
480.5
480.7
480.9
481.1
481.3
481.5
TIME (msec)
15
(b)
SPECTRAL AMPLITUDE
(ARB. UNITS)
10
5
0
-500
-300
-100
0
100
300
500
FREQUENCY (kHz)

FIG.1



X1/2
(a)
Te(eV)
700
600
500
400
300
200
100
90
140
172
174
176
178
180
182
184
186
(b)
n_e (10^{13}cm^{-3})
4
3
2
1
0
(c)
$\tilde{n}$ (ARB. UNITS)
12
10
8
6
4
2
0
CENTER
SEPARATRIX
MAJOR RADIUS (cm)

FIG. 2

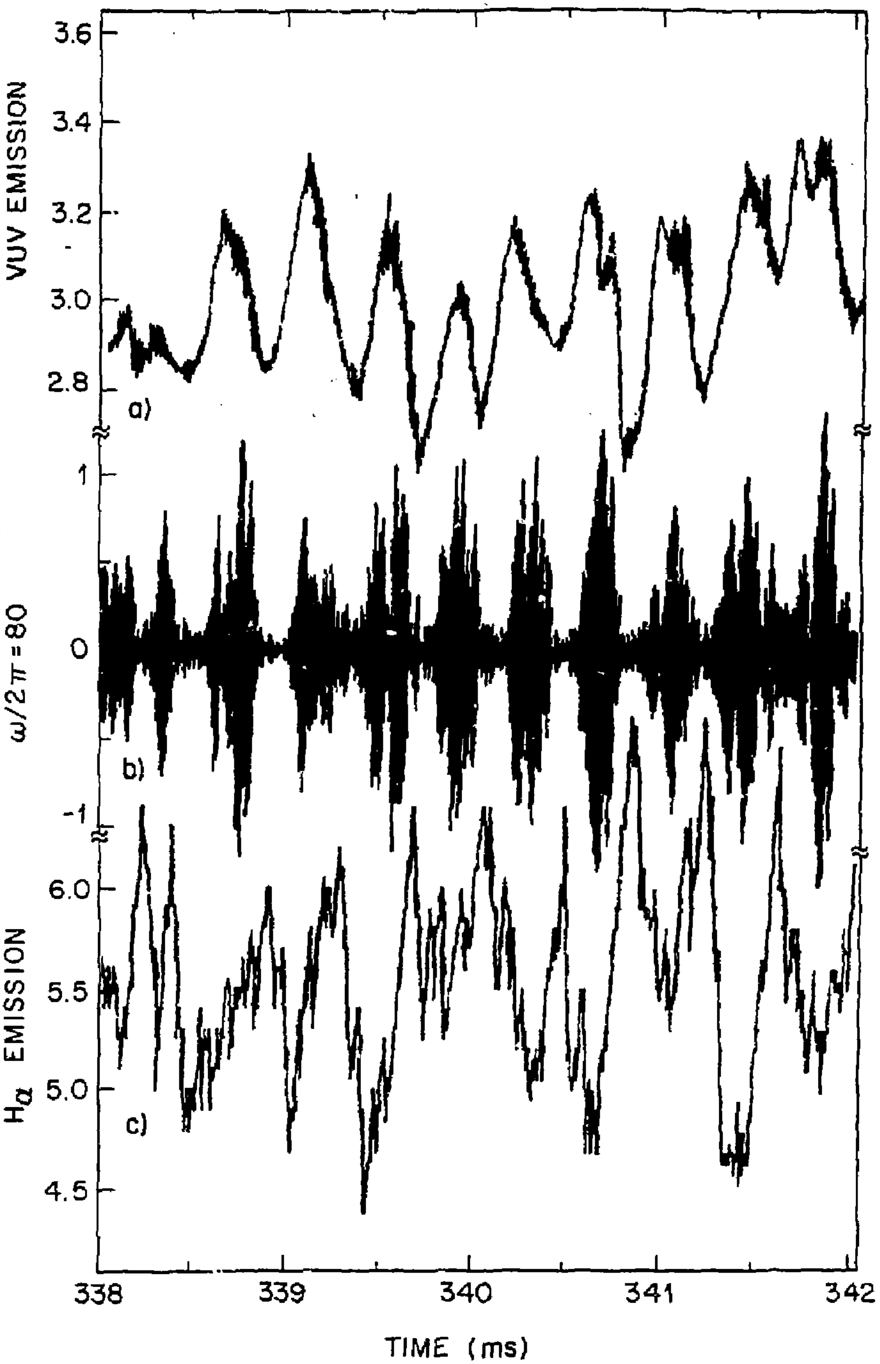

3.6
3.4
3.2
3.0
2.8
VUV EMISSION
a)
1
0
-1
$\sum_{\omega/2\pi=80}^{120} \tilde{n}(\omega)$
b)
6.0
5.5
5.0
4.5
H_α EMISSION
c)
338
339
340
341
342
TIME (ms)

FIG. 3

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