Characteristics of high-frequency precursors to edge-localized activity in the PBX-M tokamak

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Abstract

High β_{pol} H-mode plasmas in the PBX-M tokamak often exhibit periods of Edge Localized Mode (ELM) activity, with each ELM preceded by a short duration ($\leq 350 \mu\text{sec}$) burst of high frequency (200 to 250 kHz) magnetic activity. The burst grows on a time scale of $10 \mu\text{sec}$, and disappears just prior to the rapid increase in the D_α emission that is characteristic of the ELM. The burst of activity is observed at all poloidal locations, with the largest amplitudes seen on the coils on the inner major radius side, indicating that the mode is not outward ballooning in character. Stability calculations indicate that a likely candidate for this high frequency ELM precursor is the pressure-driven ideal kink.

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H-mode, or high-confinement mode, operation in tokamaks is often characterized by energy confinement times a factor of two times that in the more standard L-, or low-confinement, mode plasmas. A common repetitive feature of H-mode plasmas are ELMs (Edge Localized Modes). Each ELM is identified by an increase in the D_α emission, denoting an increase in edge recycling, and is associated with a loss of plasma energy and density. In this sense the term ELM is a misnomer, as the energy loss can extend into the core of the plasma and, in some cases, can be coupled to internal activity.¹ Since the ELM may, in fact, be a transient return to the L-mode confinement state,² it follows that controlling ELMs may lead to improved operational control of plasma confinement.

The control or suppression of ELMs requires an understanding of the underlying physical process causing this phenomenon. It was suggested by Chyabu et al.³ that the relatively high amplitude edge magnetic fluctuations seen during the L-mode and during ELMs in DIII-D could be due to microtearing modes. A subsequent stability analysis of DIII-D profile data near the plasma edge indicated that "Giant" ELMs may be triggered by the ideal MHD ballooning instability.⁴ This conclusion was supported by the poloidal mode structure determined from the sometimes observed magnetic precursors.⁵

In this report we present data from a poloidal array of Mirnov coils on the PBX-M tokamak. These data also exhibit magnetic precursor oscillations to ELMs; however, unlike those seen on DIII-D, the precursor oscillations are at higher frequency (≥ 200 kHz) and are not outward ballooning in character. Stability analyses based on measured kinetic profiles indicate that the near-edge plasma is stable to both microtearing and to ideal ballooning. However, the analysis indicates that the pressure-driven ideal kink is unstable, and is, therefore, a possible candidate for the ELM precursor oscillations observed on PBX-M.

The objective of the PBX-M tokamak is exploration of regimes of enhanced plasma confinement and stability. Stability control is effected through the use of strong plasma shaping to produce a plasma whose poloidal cross-section is bean-shaped, through the use of a set of close-fitting passive stabilizer plates, and through profile

control. Details of the PBX-M hardware and experiment can be found in Okabayashi et al.,⁶ and a recent overview of experimental results is found in Bell et al.⁷ The magnetic data to be shown in this report come from a poloidal array of 20 Mirnov coils as close as several cm from the plasma surface. The data to be shown were obtained at a sampling rate of 0.5 MHz.

H-mode transitions were usually observed in high-power PBX-M plasmas run at the relatively low Troyon-Sykes parameter of $I/aB \simeq 0.8-1.0 \text{ MA/m-T}$. Typical parameters for such plasmas were: $I_p = 330 \text{ kA}$, $B_t = 1.3 \text{ T}$, $\bar{n}_e = 5-6 \times 10^{13} \text{ cm}^{-3}$, $\kappa = 1.9$, $\text{indentation} = 0.15$, and up to 5 MW of co- D^0 injection into D^+ plasmas, yielding β_{pol} values of up to 2.2. These plasmas were close to the ideal β -limit, as reflected by the $\langle \beta_t \rangle / \frac{I}{aB}$ parameter value of up to 4.5. Here, β_{pol} and β_t refer to the ratios of plasma pressure to poloidal and toroidal magnetic pressures respectively.

In these high- β_{pol} discharges, various types of MHD activity during the H-phase were observed. This activity included sawteeth, low-(m,n) continuous modes, and ELMs. Giant ELMs, which sometimes occurred during periods of continuous mode activity, accounted for an instantaneous energy loss of up to 15%. Giant ELMs were observed in PBX-M only in discharges near the β -limit. Figure 1 shows an example of a 3 msec period containing a giant ELM in a discharge with $\beta_{pol} = 2.0$ and $\langle \beta_t \rangle / \frac{I}{aB} = 4$. Shown in the figure from the top are two chord-integrated soft X-ray (SXR) traces from the horizontally viewing array (one view near the plasma edge, and one view intersecting the vertical through R_0 approximately halfway up from the midplane), raw signals from Mirnov coils situated on the outer midplane, near the top of the plasma, on the inside major radius, and the D_α emission on the midplane. In this particular example, the ELM at 497.6 msec occurred during a period of continuous mode activity seen in both the Mirnov and SXR data. The continuous mode activity here consisted of a 13 kHz $m=3/n=1$ and a 23 kHz $m=3/n=2$ component. Here, m and n represent the poloidal and toroidal mode numbers respectively.

The rapid increase in D_α signal starts at 497.6 msec, and lasts for a duration of approximately 0.4 msec. In this example, the near-edge SXR signal exhibits a several cycle, low frequency ($\approx 5 \text{ kHz}$) mode growth just prior to the ELM. In other cases, a

higher frequency mode (20 to 50 kHz) is sometimes observed by this diode. However, these modes are not seen in every case, and do not always grow even when they are seen. The earliest decrease in SXR emissivity occurs at 497.45 msec in a channel several cm inside the plasma edge. The $Z = 21$ cm SXR emissivity starts to decrease at 497.5 msec, prior to the decrease in the near-edge channel. This is typical for each ELM; the energy and/or density loss, as observed on the SXR array, starts several cm inside the edge prior to the rapid rise in D_α , and propagates from this region towards both the edge and the center.

Seen also in Fig. 1 prior to the rapid rise in D_α is a change in appearance of each of the Mirnov coil traces; this is contained within the shaded region in the figure. This period contains the high frequency mode that is the main topic of this paper, and that will be discussed in more detail. As can be seen in the figure, the high frequency mode begins at ≈ 497.25 msec, prior to the drop in any of the SXR signals, although the mode starts in conjunction with the start of the low frequency growing mode in the near-edge SXR channel. Again, the low frequency mode is not always observed, but the high frequency precursor mode was always observed when the data was sampled at 0.5 MHz. The high frequency precursor is not observed in any of the SXR signals, nor is it typically associated with any decrease in neutron flux. Drops in neutron flux have previously been associated with instabilities in the core region of the plasma.^{8,9} These observations indicate that the mode is more prominent near the plasma edge.

A 1 msec expanded view of the period of time that includes the ELM is shown in Fig. 2. The top trace in the figure is, again, the raw Mirnov signal from a coil near the outer midplane, the middle trace is the D_α signal, and the bottom trace is the Mirnov signal filtered in the frequency range from 200 to 240 kHz. The high frequency component is seen in both the unfiltered and the filtered traces. The filtered trace clearly shows the high frequency mode amplitude growing on a 1 to 10 μ sec time scale. The high frequency burst persists for approximately 350 μ sec, during which there is a slight increase in the slope of the D_α signal, and it disappears just prior to the rapid increase in the D_α signal. Spectral analysis of the full complement of Mirnov coils

in the poloidal and toroidal directions indicate little coherence between the signals during the time of the high frequency mode; thus, no poloidal or toroidal mode information could be extracted. One practical reason making mode identification difficult is that the mode frequency is close to the Nyquist frequency of the time trace (250 kHz).

To test whether the high frequency precursor is ballooning in character, we have examined the poloidal variation of the amplitude of this mode. Ballooning mode theory indicates that a strong poloidal variation should exist, with the largest amplitudes on the outer major radius side since this is the region of bad curvature and is where the zero shear surface is most likely to be. Figure 3 shows the mode amplitudes as a function of distance (closest approach) from the plasma. Encircled in the figure are data from groups of coils in the inner and outer major radius sides. The uncircled points are from coils near the top and bottom of the plasma. What is clear in Fig. 3 is that even at comparable distances from the plasma, the inner major radius points exhibit higher amplitudes than those on the outer major radius side. Thus, we can conclude that these high frequency ELM precursors are not outward ballooning in character.

In the preceding discussion, the ELM was identified as the rapid rise in D_α emissivity, and, therefore, the high frequency burst is naturally identified as a precursor. Although the time sequence of the two suggest a causal relationship, this cannot be concluded unambiguously. Nevertheless, it is tempting to suggest that the precursor mode reflects some instability that modifies its own driving forces (e.g., current or pressure gradient) and, thus, the good edge confinement characteristic of the H-mode. The several hundred μsec time delay between the onset of the instability and the rapid rise in the D_α signal is consistent with a transport diffusivity of $> 5 \times 10^4 \text{ cm}^2/\text{sec}$ across several cm (from the location at which the mode and ELM originate to the edge). This diffusivity value is characteristic of L-mode values, and it is greater than those deduced during H-phases by a factor of five to ten. The L-mode-like diffusivity estimated in this fashion is consistent with the suggestion that the ELM is a transient return to the L-mode.

To attempt to determine the source of the high frequency mode, we studied the stability of the edge plasma using the following profile information: $T_e(r)$ and $n_e(r)$ from Thomson Scattering, $T_i(r)$ from Charge Exchange Recombination Spectroscopy, $Z_{eff}(r)$ from visible bremsstrahlung, and $P_{rad}(r)$ from bolometers. The data were analyzed using the TRANSP¹⁰ transport code to produce equilibrium pressure and current profiles from a solution of the Grad-Shafranov equation inside the plasma with a fixed outer plasma boundary as determined from external flux loop measurements. The measured and calculated profiles were used to study the edge plasma stability to three types of MHD modes: microtearing, ideal ballooning, and ideal kink. Because of low edge collisionality, the plasma was found to be stable to microtearing. Additionally, the plasma was found to be stable to ideal ballooning, with the measured pressure gradient values in the plasma only 60% of those required to drive a ballooning mode unstable. However, since detailed profile information at the plasma edge was not available on PBX-M, ballooning cannot be entirely ruled out. Within experimental error, it is possible to adjust the plasma pressure profile so that a marginal ballooning unstable state in the vicinity of, but not right at, the edge is achieved. For this case, however, the ballooning modes are unstable only for $n \geq 25$, where it is believed that finite Larmor radius effects would stabilize the mode. This, coupled with the observed non-outward-ballooning character of the mode, makes ideal ballooning an unlikely candidate for our case.

Calculations using the PEST¹¹ equilibrium and stability code indicate that $n = 1$ to 3 ideal kink modes are unstable with no conducting wall present. The $n = 1$ mode is stabilized by a closed ideal conducting shell at $r_{wall}/a \leq 1.45$. These calculations reveal a mixed poloidal mode structure for each unstable toroidal mode, but with the characteristic that the net mode amplitude peaks near or at the plasma edge. The mixed poloidal mode structure would lead to difficulty in identifying even the toroidal structure, irrespective of the proximity of the mode frequency to the Nyquist frequency. The growth time of the mode is predicted to be on the time scale of the poloidal Alfvén time (μsec), and is consistent with the observed growth time.

The presence of the passive stabilizer plates in PBX-M might appear to present a

major difficulty with the interpretation of this instability as an external kink mode. This difficulty can be resolved by recognizing that the original design of the plates was for particular plasma parameters and geometry. The discharges described in this report are at a lower plasma current. Consequently, the plasma is shifted inward and is farther away from the stabilizer plates. This, along with the effect that the plasma profiles have on critical wall position, effectively brings the plasma closer to marginal stability. Additionally, the kink mode at high-beta is not driven solely by the current, but also, in part, by the pressure. This has the effect of coupling the dominant poloidal mode at the edge with many interior modes. If a conducting shell is brought close to the plasma, its principal effect would be to lower the amplitude of the edge modes. However, the pressure-driven interior modes are relatively unaffected. The net result is an instability which is peaked towards the plasma edge but which falls off less slowly towards the interior. These results are illustrated by Figs. 4a and b which show the Fourier decomposition of the radial displacement vector, χ_ϕ , along the outer midplane of the plasma. The large mode near the axis is the $m = 1$, while the largest mode at the plasma edge is the $m = 5$. Although not evident from Fig. 4b, we note that the total plasma displacement near the plasma edge due to this pressure-driven kink is calculated to be largest on the inner major radius side, consistent with the results shown in Fig. 3. We also note that when the same stability analysis was performed on profiles measured two msec after an ELM (at similar β_{pol}), the ballooning stability characteristics were the same as in the pre-ELM case. However, the pressure-driven kink mode was determined to be more stable in that the mode could be stabilized by a conducting wall farther from the plasma (by almost a factor of two) than in the pre-ELM case.

In summary, characteristics of a high frequency magnetic precursor oscillation to ELMs have been presented. High frequency precursor modes have also been reported on TFTR,¹² but, unlike those, the ones observed on PBX-M are not axisymmetric and appear to be more prominent near the edge. Stability calculations indicate that the pressure-driven ideal kink is a likely candidate for this high frequency precursor. This result does not necessarily contradict the ideal ballooning result of DIII-D; the

different conclusions suggest that the period of rapid rise in D_a during the ELM may be merely the result of some process that destroys the edge particle and thermal barriers established at the L-H transition. That process, however, does not appear to be unique.

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Figures

FIG. 1. Time traces of horizontally viewing soft X-ray chords, raw Mirnov coils, and midplane D_α around the time of an ELM. One of the soft X-ray views shown is near the plasma edge while the other is approximately halfway up off the midplane. The Mirnov traces are taken from coils on the outer midplane, near the top of the plasma, and on the pusher coil. The time during which the high frequency precursor exists is highlighted by the shaded region.

FIG. 2. Time expanded view of the ELM shown in Fig. 1. Shown is the raw trace from the outer midplane Mirnov coil, the midplane D_α and the Mirnov signal filtered from 200 to 240 kHz. The time during which the high frequency precursor exists is highlighted by the shaded region.

FIG. 3. Amplitudes of the high frequency precursor as a function of distance of closest approach to the plasma. Omitted from (b) are the data from coils farthest from the plasma, near the bean tips.

FIG. 4. Eigenmode structure of the pressure driven kink mode computed from PEST for (a) no conducting wall, (b) $r_{wall}/a = 1.5$, where a is the midplane halfwidth.

Figure 1

Figure 2

Figure 3

Figure 4

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