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Interaction of ELMs with the core transport barrier in CH-mode in PBX-M

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Abstract. An addition of ion Bernstein wave power of only a tenth of the neutral beam power into an H-mode causes the formation of a core transport barrier. At the location of the barrier, reduced ELM losses in the soft x-ray profile are observed. During the IBW-modified ELM, one can observe enhanced fluctuations in the soft x-ray fluctuation profile over the whole of the observed frequency range. In the region of the core transport barrier, the enhancement of fluctuations seems to be strongly reduced. The ELM loss propagates to the core with a velocity greater than that which would be consistent with a normal energy diffusion process.

1. Introduction

One of the signatures of the H-mode is a periodic loss of energy and particles near the edge of the plasma [1–4]. These events, named edge-localized modes (ELMs), reduce the global energy confinement time. They could be beneficial, however, because they allow a steady-state H-mode to be achieved and regulate density and impurities [5].

In this paper, we describe a new type of ELM, where the loss profile of the ELM is modified in the core of the plasma by a core transport barrier, created by a small addition of ion Bernstein wave (IBW) heating into an H-mode discharge in PBX-M. The ELM loss and the fluctuation data have been obtained from a midplane soft x-ray diode array and from the poloidal and toroidal Mirnov probe arrays [6, 7]. We shall discuss the decrease in the energy loss due to ELMs in the region across the core transport barrier and the enhancement of fluctuations over most of the plasma cross section during the ELM.

2. CH-mode

The addition of 200 kW of IBW power into an ELM-free H-mode plasma with only 1.7 MW of neutral beam power causes the edge H-mode to make a gradual transition into a core high confinement mode (CH-mode) [8]. A transport barrier is formed in the core of the plasma, but the H-mode barrier at the edge erodes into the L-mode. This transport barrier is characterized by a strong density peaking, large ion temperature and density gradients, and a strong toroidal velocity shear at the location of the peak of the IBW power deposition. This barrier is situated between $r_{\rm mid}/a = 0.2$ and 0.5.

The transport barrier is not created immediately after the IBW injection; the ELM-free H-mode first evolves into an ELMy H-mode. Although the ELMs are phenomena triggered at the edge, they penetrate rapidly to the plasma core. This permits the ELMs to interact

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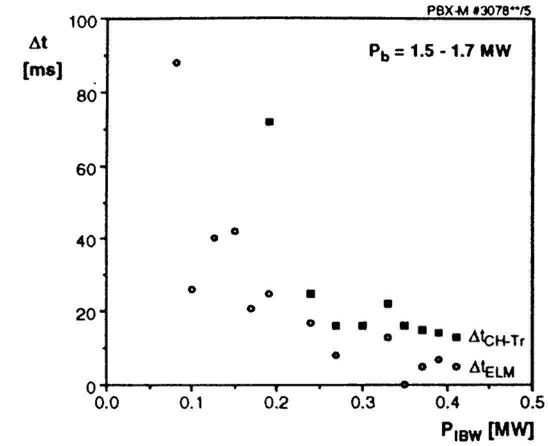

Figure 1. Delay between the onset of the full IBW power and the first ELM, $\Delta t_{\rm ELM}$ and the onset of the CH-mode transition, $\Delta t_{\rm CH\text{-}tr}$, as a function of the IBW power but for a constant low neutral beam power of 1.5 to 1.7 MW.

with the core transport barrier and weaken it. With the high ELM repetition rate of 1 kHz, the core transport barrier cannot develop during this ELMy phase.

The delay between the start of the IBW power and the ELMy H-mode phase, $\Delta t_{\rm ELM}$, is inversely proportional to the IBW power (figure 1). The delay between the start of the IBW power and the CH-mode transition, $\Delta t_{\rm CH\text{-}tr}$, also decreases with increasing IBW power. The transition to the CH-mode, characterized by a fully-developed transport barrier, is not possible at low neutral beam power ($\approx$ 1.7 MW), until the ELMs destroy the edge H-mode barrier and the edge makes a transition into the L-mode.

If the neutral beam power is increased from 1.7 MW to 2.7–3.3 MW, the ELM repetition rate decreases from 1 kHz (for $P_{\rm b} = 1.7$ MW) to below 200 Hz. This increase in time between two successive ELMs allows the core barrier to develop, although it is still partially weakened by the ELMs. This is reflected in somewhat decreased density and velocity gradients. Therefore, for the higher neutral beam powers and an IBW power of 300 kW, the discharge develops into a weakened stationary CH-mode in the core and retains an H-mode profile at the edge.

3. IBW-modified ELMs

The interaction between the ELMs and the core barrier manifests itself in a modification of the soft x-ray ELM loss profile. We define the soft x-ray ELM loss as $\Delta I_{\rm x} = I_{\rm x}(t) - I_{\rm x}(t_0)$, where $I_{\rm x}(t)$ is the soft x-ray signal at any time during the ELM and $I_{\rm x}(t_0)$ is the signal immediately before the ELM. In a normal (NBI only) H-mode, the $\Delta I_{\rm x}$ profile typically shows a maximum loss halfway to the magnetic axis. In IBW-modified ELMs, a soft x-ray loss minimum also appears at the core transport barrier location.

A comparison of the ELM loss profile without and with IBW is shown in figure 2. In the normal H-mode, the losses penetrate to the core of the plasma. Most of the losses occur during the first 600 μs. In all PBX-M ELMs, we consistently see a loss inversion radius approximately two centimetres inside the edge of the plasma, even after the Abel inversion of the soft x-ray intensity profile.

Both with and without IBW, there is a relatively slow radial propagation of the maximum ELM loss from the inversion location towards the core region. For the IBW-modified ELM, we observe a strong decrease in loss in the region of the core transport barrier

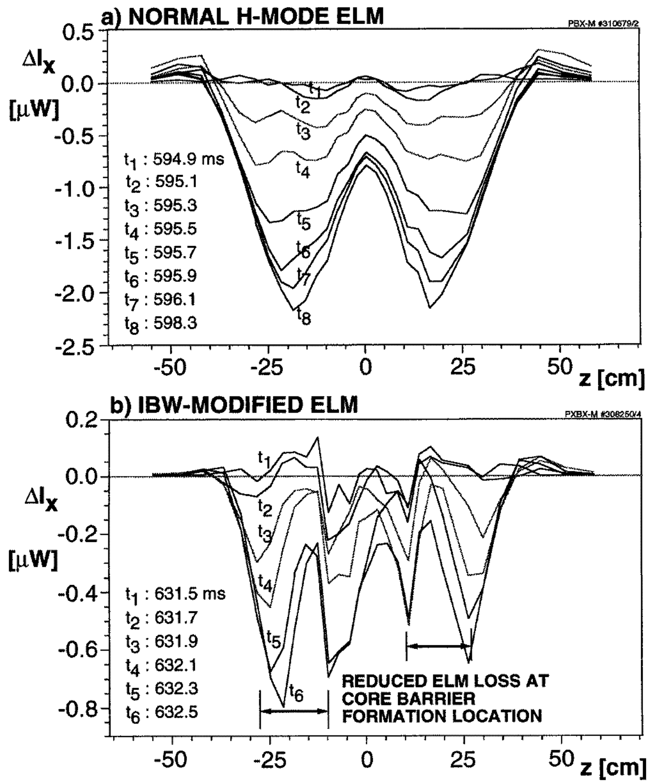

Figure 2. Time evolution of the ELM profile loss in the soft x-ray intensity, ΔI_x for (*a*) normal H-mode ELM and (*b*) IBW-modified ELM. z is defined as the vertical height from the midplane to the intersection between the diode line of sight and the vertical line at $R = 165$ cm.

($10 < z < 27$ cm). Since the soft x-ray intensity profile is peaked, the signal varies rapidly from diode to diode. Therefore, the Abel-inverted ELM loss profile is very similar to the intensity loss profile, particularly because the ELM losses are small. The loss profile is depicted in figure 2(*b*).

These ELMs have characteristics very similar to those of type III ELMs in ASDEX and DIII-D [4]. However, we do not often observe the MHD precursors; the growth rate of the precursor appears to be faster than the inverse of the precursor frequency. In some cases, the precursor was found to be an $n = -3$ mode.

During the ELMing phase of the $P_b = 1.7$ MW discharge, the strength of the core barrier quickly saturates to a low level, which is why the CH-mode is not achieved at that time. The soft x-ray ELM loss profile shows this as a weak loss minimum in the core barrier region. Increasing the neutral beam power to 3.3 MW and the IBW power to 300 kW reduces the ELM repetition rate to less than 200 Hz. In this case, the core barrier between two successive ELMs can be more robust and continue to develop, even during the subsequent ELMs (figure 3).

4. Enhanced turbulence during ELMs

Increased fluctuation levels during the ELM, between 2 and 500 kHz, have been measured in the soft x-ray and the Mirnov probe signals. The fluctuation amplitude (power spectrum) profiles in two frequency bandwidths during the ELM, the quiet phase between two ELMS, and the calculated photon noise values (Ph) are shown in figure 4. Low-frequency

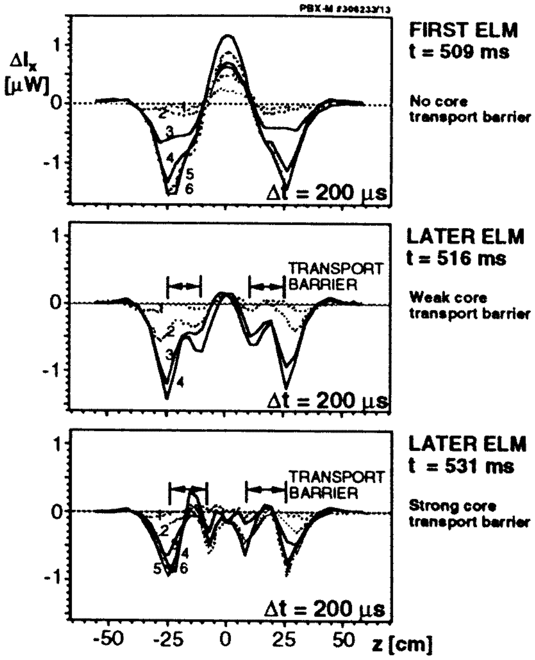

Figure 3. Evolution of the transport barrier strength, as observed in successive ELM loss profiles.

fluctuations between 4 and 6 kHz during the ELM increased strongly over the whole plasma cross section. The maxima and minima in the profile indicate that at low frequencies, there is a strong coherence between fluctuations measured at various diodes, where this coherence extends to at least $z = 25$ cm. A part of this enhancement could stem from a low-frequency MHD perturbation triggered by the ELM.

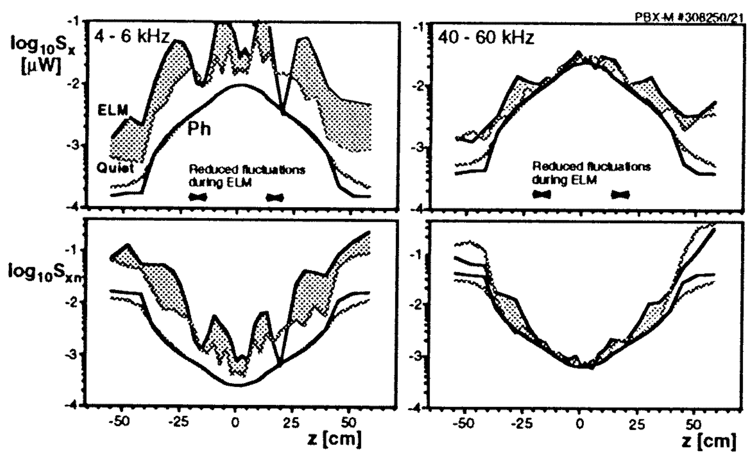

Figure 4. Enhancement of the fluctuation amplitude, S_x and the normalized fluctuation amplitude, S_{xn}, during ELM in two frequency bandwidths: 4 to 6 kHz and 40 to 60 kHz. 'ELM' denotes the profile during ELM, 'quiet' during the quiet phase and 'Ph' the calculated photon noise. The shaded areas represent the fluctuation enhancement.

The lower figures represent the normalized fluctuation amplitude, $S_{xn} = S_x/S_0$, where S_x is the measured fluctuation amplitude in the given frequency bandwidth and S_0 is the DC signal of the diode. They show that the relative fluctuation level is increasing towards the edge of the plasma and that it reaches a value of 10% or higher at the edge.

At higher frequencies, the enhancement of the fluctuation amplitude during the ELM over the level in the quiet phase appears to become smaller with increasing frequency. However, this may not actually be the case, because the measured fluctuations during the quiet phase are within the photon noise at frequencies above $\sim$ 30–50 kHz. We always observe an apparent enhancement of the fluctuation amplitude of about 10% during the ELM, even at frequencies up to 300 kHz; this enhancement may be higher in reality.

A decrease in fluctuation enhancement is seen at all frequencies in the region $z \sim$ 10–20 cm, which coincides with the core transport barrier. More studies are needed to determine whether the reduced fluctuation enhancement might actually be a consequence of the transport barrier.

5. Discussion and conclusions

The ELM losses penetrate deep into the plasma. This is supported by the observation that the ELM can trigger simultaneous MHD perturbations on the $q = 2$ and $q = 1$ magnetic surfaces: an $m/n = 2/1$ low-frequency (2.5 kHz) perturbation on the $q = 2$ surface and an $m/n = 1/1$ high-frequency (20 kHz) perturbation on the $q = 1$ surface. Both of these perturbations decay after the ELM: the 2/1 mode in 3 to 6 ms and 1/1 mode in about 500 μs. It should also be noted that the 1/1 mode, which is decaying more quickly, is located in the region of the core transport barrier. The core transport barrier is typically localized between the $q = 1$ and 1.5 surfaces.

The ELM loss starts almost simultaneously over the whole plasma cross section; thus, the fast penetration of the ELM loss into the plasma core region appears to be non-diffusive. There must, therefore, be some other mechanism, possibly involving radial propagation of turbulence, that should be invoked to explain this fast penetration. One possibility is a combination of toroidal coupling and nonlinear three-wave coupling of higher m and n modes in the plasma [9]. It is also possible that the ELM may consist of many poloidally and toroidally localized turbulent events, which are coupled together somehow. An indication of this is the observation that during an ELM, we observe several weak, poloidally localized sawtooth-like events in the soft x-ray signals, occurring at different radial locations. In the case of the IBW-modified ELMs, the turbulence, enhanced by the ELMs, seems to tunnel through the core transport barrier, affecting the core barrier only slightly, but subsequently causing an increased loss on the other side of the core barrier. This 'tunnelling' effect is a further indication that the ELM losses inside the barrier cannot be diffusive, but must be caused by an enhanced turbulence, propagating radially. The change in the pressure gradient at the barrier during the ELM is very small, which would result, if the enhanced losses were purely diffusive, in a small change of pressure gradient inside the barrier and, therefore, in rather small change in the diffusive losses inside the barrier. This is not, however, what we observe inside the barrier: the ELM losses are large. This means that the ELM turbulence, coming all the way from the edge and propagating radially, is allowed to penetrate through the barrier and cause an increased loss on the other side of the barrier.

More work is required in the future to develop a complete understanding of the ELM loss mechanism and to study the core barrier/ELM interaction.

Acknowledgment

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