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PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76-CHO-3073

PPPL-2961
UC-420,426

PPPL-2961

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FEBRUARY, 1994

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Periods of Enhanced Transport During H-Mode in PBX-M

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Abstract. In PBX-M, periods of enhanced transport are often observed in high β_{pol} H-mode discharges. They can reduce the energy confinement time by a factor of two. Their duration is typically between 2 to 20 ms. They are followed by periods of normal transport of a similar duration. These periods of enhanced transport consist of a series of turbulent m =even MHD events, starting several cm inside the plasma edge. They propagate into the confinement region in 600 μ s, causing a progressive erosion of the profile. Each m =even event can also cause an energy loss of 1% or less, mainly from the confinement region. These m =even events are reminiscent of grassy ELMs.

1. Introduction

Supplementary heating, either neutral beam or wave heating, has been shown to produce a deterioration in energy and particle confinement in present day tokamaks. Many studies have been made of the enhanced transport during this phase and especially at high toroidal and poloidal betas. The saturation and the collapse of β_{tor} or β_{pol} can be caused by different physical mechanisms involving the plasma core and the edge of the plasma, but they mainly affect the confinement region. In this paper we will concern ourselves with losses originating at the plasma edge and then propagating into the confinement region.

Closely associated with the enhanced transport events described in this paper are ELMs, and especially grassy ELMs. The main differences between the ELMs and the MHD events described in this paper are that the latter originate several cm inside the edge, while the ELMs, in ASDEX, DIII-D and other experiments originate near the separatrix. The other difference is that the PBX-M Enhanced Transport Period (ETP) event propagates into the confinement

region more slowly. The different edge behavior relative to ASDEX and DIII-D is possibly due to the effect of the stabilizing plates near the plasma edge ($\Delta r/a \approx 0.2$) in PBX-M. The first descriptions of ELMs can be found in the earliest reports on the H-mode in ASDEX, PDX and DIII-D experiments [1, 2, 3, 4]. Since then many papers described various aspects of ELMs.

The MHD events described in this paper that cause a transient enhancement in transport have been observed exclusively in H-mode discharges during the β -rise, β -saturation or β -collapse [5,6]. For these plasmas, the plasma current was varied between 200 and 350 kA and neutral beam injection between 2 and 5 MW. The toroidal field was approximately 1.3 T, average densities were above $3 \times 10^{13} \text{ cm}^{-3}$, electron and ion temperatures above 1 and 2 keV respectively, elongation between 1.5 and 1.9, indentation was 15%-18%, and triangularity was 0.3. The toroidal beta varied between 0.8 to 3.5 %. The poloidal beta was rather high and in the range of 0.8 to 2.5.

The principal diagnostics used to obtain data on the transient enhancement of the transport were the soft x-ray diode array and the poloidal and toroidal magnetic probe arrays. The lines-of-sight of the soft x-ray diode array superimposed on the flux surfaces are shown in Fig. 1. The distance between the midplane and the intersection of the line-of-sight and a vertical axis at $R_0 = 165 \text{ cm}$ defines the radial profile dimension z used in the paper.

Section 2 is devoted to the description of this MHD phenomenon and Sec. 3 describes the difference in fluctuations during the periods of enhanced transport as relative to the quiet periods. In Sec. 4, the turbulent activity at the edge of the plasma, caused by these MHD events, is described. Section 5 closes this paper with a discussion of these transient enhanced transport events.

2. Description of Periods of Enhanced Energy Loss

Approaching a Troyon parameter of 4, one can first observe a reduction of the rate of increase of β , and then a β -saturation. Sawteeth are observed during the period in which the rate of β -increase decreases, but the β -saturation is better correlated with the edge perturbations, which in the H-alpha edge radiation look like the grassy ELM's. More discussion on these ELM-like perturbations will be given later. As the β -saturation sets in, more violent edge perturbations penetrate with increased depth into the confinement region. Occasionally one can observe a correlated decrease in β , but this drop can be spread over a shorter or longer time period. One such case is shown in Fig. 2, where the time evolution of β , together with the soft x-ray diode signals at the center ($z = 0 \text{ cm}$), in the confinement region ($z = 23 \text{ cm}$), and at the edge ($z = 49 \text{ cm}$), and the beam power are shown. Note that the gradual drop in β around 480 ms, correlated with a drop of over 10 % of the total energy, follows closely the drop in the signal of the SX diode at $z = 23 \text{ cm}$, localized in the vicinity of the center of the confinement region. Neither the central nor the edge diodes show this drop. This period of enhanced transport (ETP), from 460 to 480 ms, is followed in time by a period of normal transport (Normal

Transport Period or NTP). Such strong and violent events are rather rare; more often one observes weaker ETP events of shorter duration (few ms), that might only slow down the rate of β increase or, more often, cause the β saturation. The ETP's are correlated in time with an increased edge perturbation, resembling "grassy" ELM activity. The question of whether or not these are the "grassy" ELM's observed in other devices will be discussed later. During the NTP periods this edge activity almost disappears.

Of particular interest is an estimate of the losses during the ETP. One can estimate the change in the confinement time due to the ETP by comparing the rate of rise or fall of β during the NTP or ETP. The instantaneous energy confinement time can be written $\tau_E = \beta / [(\beta P_T)/W_T - (d\beta/dt)]$, where P_T is the total input power and W_T the total plasma energy. The incremental energy confinement time during the NTP is estimated to be 61 ms, and during the ETP it falls by factor of two to 31 ms.

The evolution of the soft x-ray intensity loss during the ETP of Fig. 2 is shown in Fig. 3 for four time steps of 4 ms duration each. Here $(I_x - I_{x0})/I_{x0}$ is the normalized intensity loss, where I_{x0} is the soft x-ray intensity at the start of the ETP and I_x is the intensity at any other time during the ETP. The main loss in soft x-ray intensity occurs in the confinement region between $z=15$ and 30 to 40 cm. The core of the plasma, roughly the region with $q < 1$, and the edge region are not affected by the ETP. The evolution of the ETP in time seems to indicate that the ETP is initially localized in a smaller region, and that in time it propagates mainly outward. Integrating the soft x-ray intensity loss over minor radius and assuming that the soft x-ray emissivity is roughly proportional to the square of the plasma pressure (electron pressure) one finds the total loss of plasma energy during the ETP of Figs. 2 and 3 to be about 20% of the initial plasma energy. This is in good agreement with magnetic measurements which show a loss of 20%.

The ETP of Figs. 2 and 3 is followed by an NTP of 20 ms duration. During the NTP a large enhancement (between 20 to 30%) in the soft x-ray intensity occurs precisely in the same region where the losses during the ETP were the largest, indicating the replenishment of the lost energy in the confinement region.

3. Fluctuations during ETP and NTP

A large change in the heat and/or particle transport in the confinement region (roughly outside $q = 1$ surface and inside the region dominated by edge effects) is seen during the onset of the ETP. To help understand this sudden onset of poor confinement, extensive studies were made of both the soft x-ray and edge magnetic fluctuations during both the ETP and NTP periods, and highlights of these studies will be described below.

The fluctuation measurements in the core region show that there is no enhancement of fluctuations in the region for roughly $q < 1$. However, both the confinement and the edge

regions show a large increase in fluctuations during the ETP period. An example of such a fluctuation enhancement during an ETP is shown in Fig. 4, where two spectral power profiles in the frequency band between 30 and 34 kHz are displayed for the ETP and NTP periods, respectively. Similar profiles are obtained for the lower and the higher frequencies, except that the enhancement factor in the confinement region is higher for the lower frequencies (larger than 5 at 5 kHz), and lower for the higher frequencies (enhancement of only 20% at 100 kHz). The studies also show that the very low fluctuation frequencies are associated mainly with the edge region of the plasma. The very last points in the profiles of Fig. 4 ($z \geq 60$ cm) show that in the separatrix region (outside), there is no enhancement in the fluctuations during the ETP. In most cases, the photon noise prevents fluctuation measurements above 100 kHz. The relative fluctuation levels vary, depending on frequency, from 0.1% at 30 kHz in the center to 20% at 5 kHz at the edge.

A similar picture of edge magnetic fluctuations and their spectra is observed when the fluctuations in the magnetic probes separated poloidally near the plasma edge are investigated. There is a large change in the signature of the magnetic probe signals between the small and large major radius sides. The inside probe shows an ETP enhancement over the whole frequency range of at least a factor of three. The outer probe shows a stronger ETP enhancement for lower frequencies up to 20 kHz (a factor of two), but a very weak enhancement for higher frequencies. The comparison of spectra on the inside and outside probes during either the ETP or NTP shows that the fluctuation levels at the outer side of the plasma is higher, especially at higher frequencies (>10 kHz), indicating a possible ballooning character for these quasi-turbulent perturbations.

4. MHD and Turbulent Activity in Edge Region

The PBX-M data show that the edge region during a high- β discharge is very turbulent. At the very early stage of the β -saturation, weak, low frequency, solitary edge perturbations, reminiscent of grassy ELMs, with a low repetition rate of less than 1 kHz, are observed (Fig. 5). The structure of these perturbations, measured by the horizontal soft x-ray array, resembles an m =even mode. Initially, no precursor to this perturbation is observed, but later these solitary perturbations show a precursor of typically 20 to 50 kHz. This earlier perturbation seems to originate around $z = 43$ cm; the perturbation seems to propagate inward in about 600 μ s and is up/down symmetric. In the edge region from ($z = 56$ to $z = 32$ cm) the amplitude of this perturbation can increase inward by a factor of 30, but between $z=20$ and 19 cm the perturbation does not increase much. Each of these m =even events appear to cause a loss in energy of less than 1%. They are similar to grassy ELMs observed on DIII-D and ASDEX, but they are most probably a different edge phenomenon because of their apparent radial propagation inward. They also originate farther away from the separatrix and inside the plasma, whereas the grassy ELMs in ASDEX and DIII-D seem to originate just inside the

separatrix. As the β -value increases, this perturbation becomes gradually stronger and more complex and chaotic.

Later in the discharge, especially during the β -saturation and collapse and during the ETP periods, a more violent type of edge turbulence is observed (Fig. 6). This violent type of edge and confinement region turbulence evolves slowly from the more benign, solitary m =even events. This evolution from benign to turbulent perturbations, which may indicate an evolution of the controlling physics as well, is also observed in the magnetics. From Fig. 6, one can distinguish several features in the diode signals. The most obvious is the low frequency perturbation and crashes. These soft x-ray low frequency perturbations and crashes are often initiated by a growing 30 to 50 kHz precursor. The precursor is localized poloidally (observed either in the "up" or "down" diodes, but not both) and radially (between $z=40$ and 55 cm). The precursor mode often ends in an inverted-sawtooth-like crash seen in the edge diodes. The inverted sawtooth-like crash is observed almost simultaneously at the edge and in some of the confinement region diodes. This is unlike the 600 μ s propagation time of the solitary m =even events. These events create a heat pulse which is observed in both the edge diodes and the H-alpha emission. They do not exhibit an inversion radius. These violent perturbations and accompanying H-alpha spikes also resemble irregular grassy ELM's. The precursor crash is accompanied by a high-frequency burst in the Mirnov coils. The high-frequency burst is on the order of 200 kHz, with a clear coherent oscillatory structure. The duration of this high frequency burst in the Mirnov coil is short: between 50 to 100 μ s. It is important to stress that the ETP is just a collection of violent m =even events with a high degree of turbulence, showing up in the edge and in part of the confinement region.

As was mentioned ETPs can cause either β -saturation or β -collapse. Also observed to cause a β -collapse is a continuous $n=1$ mode, interspersed with giant ELMs. In fact, the latter activity is observed in most of the high- β_{pol} , β -collapse cases. We note, however, that the ETP and the $n=1$ /ELM activity are mutually exclusive.

The ETPs can occur also in the medium- β H-mode with a delay of a few ms after the sawtooth. This ETP is triggered by the sawtooth, lasts for about 10 ms, and seems to carry the energy, accumulated after the sawtooth crash outside the $q=1$ surface, to the edge of the plasma. After this excess energy has been transported to the edge, a quiet NTP period follows, lasting 5 to 10 ms for the rest of the sawtooth period. With the new sawtooth, the ETP/NTP sequence begins anew. This kind of sawtooth/ETP/NTP sequenced activity causes a repeated deterioration of the profile with a gradual loss in total plasma energy and, therefore, a β -collapse.

Often correlated with ETPs are a delayed saturation or even a decrease in the neutron rate, indicating that the ETPs also affect the thermal and fast ions in the core of the plasma. This is probably due to an increased diffusion due to the modification of gradients in the confinement region.

5. Discussion

We have established the correlation between the ETPs, the turbulent m -even events, the enhanced low-frequency turbulent fluctuations, and the degradation of the energy confinement. The low-frequency turbulence is composed of turbulent m -even events, and is possibly the trigger for the confinement degradation. On the other hand, the observations show that the strongest relative (normalized) turbulence does not reside in the confinement region, where the losses are the highest, but in the edge region of the plasma. This would indicate that this observed low frequency turbulence is not the cause for the ETP, but most probably its effect, seen most strongly at the edge of the plasma. We can now propose a possible scenario for ETP-induced enhanced losses. The ETPs, causing a strong profile erosion in the confinement region, carry the energy to the region a few cm from the edge of the plasma, where this surge of energy triggers a violent m -even event. The turbulent m -even event carries the energy to the separatrix region. On the other hand, the turbulent m -even event, also propagating inward, causes a further profile erosion in the confinement region, and the cycle begins anew.

Obviously the key for understanding the ETP is to resolve the questions of what physical mechanism triggers the edge m -even event and how can this edge phenomenon propagate deep into the confinement region, causing a large soft x-ray profile erosion. It has been shown for similar PBX-M discharges that the ballooning modes are stable in the edge region, but that the external kink modes are unstable [5, 6, 7]. Therefore, the trigger for the m -even could even be an external kink mode. The question of enhanced erosion in the confinement region, triggered by the m -even event, is not resolved. This process is not diffusive and it is possible that the m -even event at the edge of the plasma causes some instability to propagate inward. It is obvious that the picture of a turbulent m -even event is not a simple one and that during the ETP, we are encountering more than one physical process. However, this problem is not unique to the turbulent m -even events and the ETPs; the same process occurs with giant ELMs, which in PBX-M also originate a few cm inside the separatrix and then propagate inward into the confinement region on an even shorter time scale.

Acknowledgments:

This work was supported by the United States Department of Energy Contract No. DE-AC02-76-CHO3073.

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Figure Captions:

Fig. 1. Equilibrium magnetic surfaces for a high β_{pol} discharge. The lines-of-sight of the soft x-ray diode array with the definition of the diode position, z , is also shown.

Fig. 2. Time evolution of β_{tor} , average line density, $\langle n_e \rangle$, soft x-ray diode signal, I_x , edge H-alpha radiation, I_H , and beam power, P_b . A large ETP is observed between 465 and 490 ms.

Fig. 3. Consecutive profiles of normalized intensity loss, $(I_x - I_{x0})/I_{x0}$, during ETP of Fig. 1. Profiles are separated by 4 ms. The largest normalized losses are observed in the region between $z=20$ and 40 cm.

Fig. 4. Profiles of fluctuation power in the frequency band between 30 to 34 kHz. Curve *a* represents the fluctuations during an ETP, curve *b* during the following NTP, and *c* is the equivalent photon noise.

Fig. 5. Two solitary m =even events observed with soft x-ray diode array of Fig. 1. The m =even events originate at the edge of the plasma and propagate inward in about 0.6 ms.

Fig. 6. Signals of a Mirnov probe, I_M , central soft x-ray diode and edge diodes, I_x , showing a turbulent behavior in the edge diodes during an ETP. Turbulence is caused by a series of violent m =even events.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

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