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CLASSIFICATION OF DISRUPTIONS IN PBX

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ABSTRACT

Disruptions in beam-heated plasmas on PBX were studied by classifying precursor oscillations detected by a soft x-ray imaging system and Mirnov coils. A data base consisting of 80 discharges was constructed. In low $\dot{I}_p$ operation, attainable β_T values are limited by disruptions preceded by $m = 1$ activity at the center and coupled an $m/n = \text{even}/1$ mode. In high $\dot{I}_p$ and high β_T operation with high indentation, the sawtooth activity disappears. At these disruptions the plasma loses vertical position or distorts on a relatively fast time scale (< 100 microseconds).

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1. INTRODUCTION

Recently, beam-heated high-beta plasmas have been obtained in several tokamak experiments [1-5]. These results have motivated theoretical calculations of high-beta stability to external kink modes and ballooning modes [6-9]. These calculations are sensitive to various geometrical and physical parameters, but assembled results from different tokamak experiments show that a simple beta limit $\beta_T/\beta_N = 2.8$ [where $\beta_N = \mu_0 I_p / (aB_T)$] has not been exceeded [10]. High- β_T plasmas have been obtained by noncircular shaped plasmas that can carry more current than circular plasmas [4,5]. In addition, "bean" (i.e., indented) shaping is predicted to improve the MHD stability property of minimum-B configurations and may provide direct access to the region of second stability [11]. PBX (the Princeton Beta Experiment) has a bean-shaped plasma to investigate access to the second stability region. The PBX results to date are limited by disruptions at the first stability region [12,13], so a better understanding of finite-beta effects on disruptions is a crucial part of the present PBX program.

2. OBSERVATION OF DIFFERENT TYPES OF DISRUPTIONS

2.1 Diagnostics

In this study we used a poloidal array of 12 Mirnov coils and a toroidal array of 4 coils, two on the inside and two on the outside wall, respectively (see Fig. 1). The soft X-ray system consists of 56 horizontally viewing diodes and 30 vertical diodes. The data acquisition system records data from about 35 diodes, usually configured with 28 horizontal and 7 vertical diodes. In this study only the horizontal array was used. The location and orientation of Mirnov coils and soft X-ray detectors are shown in Fig. 1 and Fig. 2.

2.2 Disruption Data Base

With up to 5.5 MW of neutral beam power, PBK has operated circular, dee-shaped and indented plasmas and has attained $T_e < 2$ keV, $T_i < 4$ keV, $n_e < 1 \times 10^{14}$ cm⁻³. The experimentally attainable β_T value is limited by disruptions to $\beta_T/\beta_N = 2.8$ in the first stability region as shown in Fig. 3. To characterize MHD activity at the time of disruption, we have constructed a data base from a wide parameter range of beam-heated discharges. It is necessary to divide the data base into two groups based on the available data from the soft X-ray array and the Mirnov coils. Both Mirnov probe data (with a sampling rate of 40 kHz) and soft X-ray data (with a sampling rate of 50 kHz to 500 kHz) are available for GROUP A, whereas GROUP B consists of discharges for which Mirnov probe data only are available.

All plasma parameters were taken from the output of the SURFAS MHD equilibrium code [15], which computes the shape and the beta value of the plasma using measured magnetic data as boundary conditions.

2.3 Classification of Discharges

We divide the disruption period into two phases by the behavior seen on soft X-ray and Mirnov probe signals. During the first stage called phase I, precursor oscillations may be observed on the soft X-ray and/or Mirnov probe signals, but the soft X-ray emissivity profile does not decay. The MHD instability or other effects which are initiated in phase I cause the decay of the thermal energy, and the soft X-ray emissivity profile starts to deform at the beginning of phase II. During the early period of phase II, we can usually still observe a mode structure on the soft X-ray and Mirnov probe signals. At the final stage in phase II when the soft X-ray profile has

strongly deformed and decayed, it is difficult to identify the mode, and a deformation and an $n = 0$ motion of the plasma column is dominant on the poloidal magnetic signals.

Because of the strong deformation of the flux surfaces in bean-shaped plasmas, a poloidal mode identification based on an angular coordinate system is difficult, and here we only state whether the poloidal mode is even or odd.

Discharges are classified into four types by the behavior in the disruption phases. Because a clear contrast is seen between type 1 and 4, they are discussed first below.

2.3.1 Type-1 Discharges

In type-1 discharges, an $m = 1$ precursor oscillation (< 7 kHz) and coupled $m = \text{even}$ modes grow up during phase I. The plasma loses thermal energy as a result of the growth of the mode in phase II. The spatial extent of the $m = 1$ oscillation beyond the $q = 1$ surface (located at $b = 16 \pm 3$ cm, where b is the height of the chord measured from the horizontal center at $R = 150$ cm) is observed on soft X-ray emissivities in the typical discharge shown in Fig. 4 and Fig. 5. On magnetic probes, an $m/n = \text{even}/1$ mode is observed at the same frequency. Figure 4(a) shows the time history of poloidal magnetic fields at the Mirnov coil positions during phase I and phase II. Phase I starts after the last sawtooth oscillation when perturbations at 3 kHz appear on both X-ray and Mirnov probe signals. At $t = 504$ msec the frequency switches to 7 kHz. The $m = 1$ oscillation is clearly observed by soft X-ray chords inside $b = 36$ cm. The oscillation slows down gradually to ~ 1 kHz when the amplitude of magnetic fields at the coil positions start to change. Analysis of magnetic signals indicates that the plasma column shifts inward, stops and then deforms, and eventually position control is lost.

Figure 4(c) shows a slow $m = 1$ perturbation on a soft X-ray emissivity profile during the inward shift of the plasma column.

Figure 5 shows the ratio of fluctuations of soft X-ray emissivities on the chords viewing inside $b = 36$ cm before and after the switching of the mode frequency. Before the switch the $m = 1$ oscillation at low frequency (~ 3 kHz) has relatively small amplitude at the center region of the plasma. But just before the frequency switches, the fluctuation level at $b = 20$ cm starts to grow up. After the switch to the fast frequency (~ 7 kHz), the $m = 1$ oscillation grows up in the center region.

There is a great variety in the behavior of magnetic signals during phase I among type-1 discharges. There are cases in which the mode frequency switches or stops many times and cases in which the mode simply grows up and slows down. So more than two modes may relate to this activity, but a common feature is $m = 1$ activity that grows up in the center region of the plasma and slows down at the end of the phase I.

2.3.2 Type-4 Discharges

Type-4 discharges have the characteristic that sawtooth activity is suppressed for a time longer than the usual repetition time before the major disruption. During this time fishbones are also suppressed. At the disruption, magnetic probes at the top or the bottom indicate a sudden jump of the magnetic fields, indicating that the plasma loses vertical position or deforms on a fast time scale. For the discharge displayed in Fig. 6, after the last sawtooth at $t = 535$ msec no sawtooth or fishbone activity is observed for 95 msec until the disruption. Although the beam power decreases during this discharge, β_T is still increasing. A fast growing $m = 1$ (8 kHz) mode coupled with the poloidal field is only observed on the chords near center

just before the disruption. At the disruption, soft X-ray emissivities indicate the loss of thermal energy on a fast time scale (several tens of μ secs), which is a common feature of type-4 discharges.

2.3.3 Type-2 Discharges

In type-2 discharges, the MHD activity (usually an $m = \text{even}$ mode or, very rarely, an $m = \text{odd}$ mode) is detected on the magnetic signals during phase I and phase II, even though $m = 1$ oscillations are not observable on soft X-ray signals.

An example of a type-2 discharge, displayed in Fig. 7, shows an unusual MHD structure on the Mirnov probe and soft X-ray signals which is different from the MHD activity in type-1 discharges. During phase I, a small amplitude $m/n = \text{even}/1$ magnetic oscillation is observed. The amplitude is particularly lower at the probe located at the outer wall (10% of B_θ/B_0 in the example described in Sec. 2.3.1), but comparable (50% of the example described in Sec. 2.3.1) at the inner wall. A closer examination of soft X-ray signals shows a small $m = \text{even}$ fluctuation on the chord where $b = \pm 36$ cm (around the $q = 2$ surface as calculated by equilibrium code) at the same frequency as the magnetic oscillation, but in the center of the plasma the fluctuation is not detectable. So, this mode does not seem to be coupled to the center of the plasma, and 3.2 msec after the initiation of phase I the soft X-ray emissivities start to erode from the edge toward the center. When soft X-ray emission at the edge has almost totally decayed, the amplitude of magnetic fields at the top and bottom indicate that the plasma starts to deform. So, this MHD activity seems to be responsible for the erosion and the subsequent transport of the thermal energy.

2.3.4 Type-3 Discharges

For this type of discharge no obvious oscillations are observed in phase I and II, and the disruption seems to be triggered by a sawtooth. At the last sawtooth the plasma column moves inward more than at the previous sawteeth and disrupts within about 5 msec. After the last sawtooth drop, the plasma doesn't recover to its previous position and the flattened soft X-ray emissivity profile doesn't recover. These observations indicate that the plasma does not reheat effectively after the last sawtooth. In a few cases described in Sec. 2.4, the peak of the soft X-ray emissivity profile starts to shift up or down slowly without decaying in amplitude.

2.4 Position Control During the Disruption Phase

An $n = 0$ instability, due to the negative magnetic-field-decay index, is stabilized with conducting walls assisted by an active feedback system in PBX. But at the disruption, there are two types of vertical motions observed on the horizontally viewing soft X-ray signals, which are classified by the decay of the soft X-ray emissivities.

For the first type, no large MHD activity is observed when the peak of the emissivity profile starts to move. The peak shifts up to 20 cm in several milliseconds without decaying in amplitude. This seems to be an $n = 0$ instability caused by the failure of the active feedback system.

For the other type, the soft X-ray emissivity profile decays vertically and quenches rapidly within 100 - 300 μ secs. For several cases of type-3 disruptions, this type of instability took place after the plasma column had apparently moved too far inward (as the result of a large decrease in the internal inductance at a sawtooth). This vertical motion may be due to the fact that the plasma moved into a region of more negative field-decay

index. Another example is shown in the last stage of the discharge described in Fig. 4(c). This vertical motion, observed on the soft X-ray array, seems to be induced by the growth of MHD activity.

3. COMPARISON OF DISRUPTIONS

We have observed a definite trend in that type-1 discharges are most often observed when β_T/β_N is close to the beta boundary and $\dot{I}_p$ is low or zero. On the other hand, type-4 discharges are obtained when $\dot{I}_p$ is high, during neutral beam injection.

We have used our data base to examine correlations of the discharge types with plasma parameters. The discharge types are plotted in the β_T vs β_p plane as shown in Fig. 8(a). Type-1 discharges statistically localize around the region of high β_p , high q_0 , and lower indentation. Most of the type-1 discharges take place under the condition that $\beta_p > 0.9$, $q_0 > 4.0$, and indentation $< 17\%$, as shown in Figs. 8(b) and 8(c). We have included a small number of disruptions from circular and dee-shaped plasmas in the data base, and we have found that they have type-1 characteristics. When the plasma reaches a high- β_p state, $m = 1$ activity and coupled $m = \text{even}$ modes appear to be triggered by several plasma conditions. There are a lot of cases in which soft X-ray emission profiles do not recover and disrupt with the $m = 1$ mode and the coupled $m/n = \text{even}/1$ mode after the last sawtooth. Changes in temperature and current profiles or other effects caused by sawteeth may trigger type-1 disruptions. Furthermore, the mechanism which triggers $m/n = 1/1$ activity associated with the disruption is unresolved.

Type-2 discharges have transitional features between high β_p with low $\dot{I}_p$ to low β_p with high $\dot{I}_p$ discharges. Although type-2 discharges extend from low β_p to high β_p , type-2 discharges don't have similar features such as

type-1 discharges at high β_p . Actually, in type-2 discharges with high β_p , $m = 1$ activity coupled with an $m/n = \text{even}/1$ mode is observed. But in these discharges the $m = 1$ mode does not grow up and does not cause the disruption directly.

We can only obtain type-4 discharges with high $\dot{I}_p$ and indentation higher than 17%, so type-4 discharges tend to have lower β_p and low q_ψ . In low- q ($q_\psi \lesssim 3$) discharges with high indentation, the plasma must carry more current near the edge if the radius of the $q = 1$ does not change when the current is increasing. A flat current profile of this nature seems to be obtained in type-4 discharges with the help of the skin current during high $\dot{I}_p$ (< 1.5 MA/sec). The small radius ($b = 16$ cm) of the $m = 1$ precursor oscillations, in spite of high $\dot{I}_p$ in the discharge shown in Fig. 6, supports this assumption. Suppression of fishbone activity may be explained by a flat current profile where q_0 is not much lower than unity. Figure 9 shows discharges which have the same β_T/β_N and perpendicular beam power. Both discharges are expected to have same amplitude of fishbone activity [14], but in the type-4 discharge, fishbone activity is suppressed, demonstrating that the current profile may be flat.

Since the characteristics of type-1 and type-4 discharges are not mutually exclusive, we observe a discharge with attributes of both types, as shown in Fig. 10. The example (classified as type-1 discharge) has a slowly growing, higher frequency (15 kHz) mode appearing first; then an $m/n = \text{even}/1$, lower frequency mode overlaps with this mode before the disruption. This slow-growing high-frequency oscillation is also observed in the high β_T type-4 discharges.

4. SUMMARY

Disruptions in beam-heated plasmas with a wide range of parameters were classified and characterized. In low $\dot{I}_p$ operation, disruptions around the beta boundary take place after the $m = 1$ fluctuation in the center of the plasma and coupled $m = \text{even}$ modes grow up. In high $\dot{I}_p$ operation with high indentation, we can reach the low- β_p /high- β_T region at $q_p \sim 3$. In these discharges sawteeth disappear, and the plasma losses vertical position or distorts, losing the thermal energy on a fast time scale ($< 100 \mu\text{secs}$) at the disruption.

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FIGURE CAPTIONS

- FIG. 1. Mirnov probe system in PBX which consists of 16 coils located inside the vacuum vessel.
- FIG. 2. Chords of horizontally viewing soft X-ray array with 28 detectors.
- FIG. 3. Disruption data base points plotted in β_T vs $\mu_0 I_p / (aB_T)$ space (240 kA $< I_p < 520$ kA, 6.7 kG $< B_T < 11.2$ kG. Geometrical parameters are defined in Ref. [11].) $\beta_N / \beta_T = 2.8$ is the experimental limit deduced from other tokamak experiments.
- FIG. 4. (a) and (b) Time history of poloidal magnetic fields in phase I and phase II of a typical type-1 discharge ($B_T = 8.9$ kG, $\beta_T = 2.8\%$, $\beta_p = 1.15$). (c) Soft X-ray emissivity profile in phase II. Movement of the peak shows the $m = 1$ mode during the inward shift of the plasma column at $t \approx 510$ msec.
- FIG. 5. (a) Fluctuation of soft X-ray emissivities in phase I. The $m = 1$ oscillation extends beyond the $q = 1$ surface ($b = 16 \pm 3$ cm). Note the peaks at $b = \pm 20$ cm which grow up before the switching of the frequency. (b) The relative soft X-ray emissivity fluctuation profile before and after the switching of the frequency.
- FIG. 6. Type-4 discharge ($B_T = 10.2$ kG, $\beta_T = 3.6\%$, $\beta_p = 0.75$). After the last sawtooth, no sawteeth or fishbone activities are observed for 95 msec until the disruption.

FIG. 7. MHD activity during the disruption phase in the type-2 discharge ($B_T = 9.6$ kG, $\beta_T = 2.5\%$, $\beta_P = 0.8$). When soft X-ray emissivities have almost decayed at the edge of the plasma, the plasma column starts to deform and position control is lost.

FIG. 8. (a) Data in β_P vs β_T space for bean-shaped plasmas. The beta boundary is deduced from the assumption of cylindrical plasma with $\kappa = 1.6$. (b) Data in β_P vs indentation space. Since highly indented plasmas tend to be obtained during high $\dot{I}_P$ the β_P value is small. [The ellipticity (κ) is ~ 1.4 for dee-shaped plasmas, 1.5-1.8 for bean-shaped plasmas.] (c) Data in q_ψ vs q^* space. The q^* is a cylindrical safety factor, which give a measure of the average current density.

FIG. 9. Fishbone activities in (a) type-4 discharge and (b) other type discharge. Both discharges have almost the same perpendicular beam power and β_T/β_N , but type-4 discharge has no fishbones after the last sawtooth.

FIG. 10. Typical transitional discharge between type-1 and type-4 discharges ($B_T = 10.1$ kG, $\beta_T = 3.9\%$, $\beta_P = 1.1$, $q_\psi = 3.6$). After the last sawtooth, at $t = 574$ msec, a slow growing, higher frequency (15 kHz) mode appears first and a lower frequency (3 kHz) mode overlaps before the disruption.

Fig. 1

#85X0815

CHORDS OF THE HORIZONTALLY
VIEWING SOFT X-RAY ARRAY IN PBX

Fig. 2

Fig. 4(a)

Fig. 4(b,c)

#85X0806

Fig. 5(a,b)

Fig. 6

Fig. 7

Fig. 8(a)

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Fig. 8(b,c)

Fig. 9(a,b)

Fig. 10

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