LOSS OF CONFINEMENT FOLLOWING A SAWTOOTH INTERNAL DISRUPTION IN PBX TOKAMAK

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Some bean-shaped plasmas heated by neutral beam injection lose a large amount of energy ($\delta\beta_{p\perp}/\beta_{p\perp} \leq 20\%$) within a short period (0.3-6ms) following a sawtooth internal disruption, indicating a momentary worsening of the confinement. The most severe ($\delta\beta_{p\perp}/\beta_{p\perp} > 20\%$) events lead to discharge termination. The internal disruptions in the PBX plasmas often have an unusually large inversion radius, up to 75% of the plasma half-width.

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In most tokamak discharges, a repetitive process known as sawtooth oscillations¹ has been observed, each cycle of which is composed of a period of gradual increase in T_e (electron temperature) followed by an internal disruption. Mechanisms that lead to the internal disruption have recently received an intense interest. Detailed measurements using advanced diagnostic techniques^{2,3} have become available, and theoretical models,^{4,5} radically different from the widely accepted one,⁶ have been proposed. Sawteeth with a very large change in the electron temperature,² or in the SXR (soft X-radiation) signal⁷ have also been reported. The profile modification due to the sawtooth oscillations has recently been reported⁸ as an important element in determining whether a fusion plasma can be brought to ignition. The internal disruption expels an amount of energy in the plasma core inside the so-called inversion point into the outer region. The inversion point is believed to lie somewhat beyond the surface where the safety factor, q , is unity. The traditional view holds that the internal disruption causes mostly redistribution of energy within the plasma, rather than the loss from it, and the excess energy given to the outer region diffuses out at a rate commensurate with τ_{EG} (global energy confinement time). Events following the internal disruption, however, have received scant attention in comparison, in spite of a body of evidence⁹ that the energy and particle transport, not only in the core, but also in the outer region may be adversely affected by the internal disruption.

We report in this article observations (1) that the energy can be promptly lost from the plasma, rather than being simply redistributed within it, (2) that the size and/or the rate of the loss can be great, and (3) that there exist internal disruptions with an unusually large inversion radius. These observations, made in neutral-beam-injection (NBI)-heated, bean-shaped plasmas in the PBX tokamak,¹⁰ provide new information for modeling of tokamak discharges with sawteeth⁸ and a clue for studies of the sawtooth mechanism. A high resolution diamagnetic loop and compensation loops, all mounted inside the vacuum vessel, are used to determine the size and rate of change of $\Delta\Phi_t$ (toroidal flux displaced by the plasma-'diamagnetic' flux). The measurement is free from shielding effects of the vessel eddy currents and has a fast time response needed to follow the internal disruption. Results from the diamagnetic and other magnetic diagnostics are used to determine changes in $\beta_{p\perp}$ (poloidal β associated with the perpendicular energy, $W_{\perp}$). In order to quantify approximately the rate of additional energy loss due to the sawtooth crash, we define an instantaneous confinement time as $\tau_E \equiv W_{\perp}/(P - \dot{W}_{\perp})$, where P is the total (injected NBI and ohmic) power, and compare it with τ_{EG} . The τ_{EG} is the moving average of τ_E determined over a period (17ms) long compared to the period of momentary confinement change. Following an internal disruption there is a slight rise in the plasma current (mostly $\delta I_p/I_p < 2\%$) and a change in the S_1 factor,¹¹ both of which contribute to the change in $\beta_{p\perp}$. The rate of change in these quantities is, however, smaller than that of the toroidal flux. Neglecting these contributions and under an assumption that $\tau_{EG} \simeq W_{\perp}/P$ over the averaging period, the ratio of the global

to momentary confinement times can be approximated in terms of the rate of change in $\Delta\Phi_t$ alone,

$$\frac{\tau_{EG}}{\tau_E} \simeq 1 - \frac{\tau_{EG}}{\beta_{p\perp}} \frac{\Delta\dot{\Phi}_t}{\Phi_p}. \quad (1)$$

Here, $\Phi_p \equiv (\mu_0 I_p)^2 / 8\pi B_{\phi 0}$ is the paramagnetic flux, where $B_{\phi 0}$ is the toroidal field at the plasma geometrical center. The approximations introduced here generally result in an underestimate of the confinement ratio, especially for slow events. The ratio is, however, taken only as an approximate yardstick for the momentary confinement degradation. The evolution of sawteeth is shown in Fig. 1 for a hydrogen discharge heated by 1.9 MW of two co-perpendicular deuterium beams. Sawteeth are evident on the SXR signal (Fig. 1(c)) beginning at about 390 ms during the ohmic heating phase and throughout the NBI heating that begins at 450 ms. No oscillations are discernible on the $\Delta\Phi_t$ signal during the ohmic and early NBI phases to the scale shown in Fig. 1(b). Oscillations in $\Delta\Phi_t$, coincident with those in the SXR signal, appear about 60 ms into the NBI phase. The I_p is little affected by the oscillations (Fig. 1(a)). During the early NBI heating phase, in many discharges the internal disruptions cause only a small $\Delta\Phi_t$ drop (corresponding typically to $\delta\beta_{p\perp}/\beta_{p\perp} < 2\%$) over a relatively long (~ 5 ms) period, which is a major fraction of τ_{EG} (10–40 ms). As the NBI heating progresses, the $\Delta\Phi_t$ drop can become larger and steeper.

The $\Delta\Phi_t$ change of a large ($\delta\beta_{p\perp}/\beta_{p\perp} \sim 8\%$) event with a short drop time ($\tau_d \sim 0.5$ ms) in a hydrogen plasma heated by three deuterium beams, two co-perpendicular (at 2.7 MW) and one co-tangential (at 1.3 MW) beams, is shown in Fig. 2(a). The discharge parameters at 490 ms are: $B_{\phi 0} \simeq -0.9$ T, $I_p \simeq 370$ kA, $\Phi_p \simeq -9.1$ mWb, $R_g \simeq 1.43$ m (geometrical center radius), $a_{mid} \simeq 0.33$ m (plasma half-width at midplane), $\kappa \simeq 1.7$ (elongation), $\iota \simeq 0.17$ (indentation), $q_{edge} \simeq 4.2$ (edge safety factor), $\langle\beta_t\rangle \simeq 3.0\%$ (volume-averaged toroidal β), and $\beta_{p\perp} \simeq 1.0$. The CX (charge exchange) analyzer,¹² which intercepts fast neutrals escaping radially outward from the plasma at a near perpendicular angle (in direction counter to I_p) in the horizontal midplane, registers no large change in its mean level before and after the internal disruption (Fig. 2(c)), indicating the absence of any significant change in the fast ion loss in this direction at the sawtooth crash. The signal from the CX analyzer which detects fast neutrals that are lost co-tangentially (Fig. 2(d)) in the horizontal midplane exhibits a large, but short burst just after the sawtooth crash. The neutron emission falls a total of about 20% after the crash, but the decline in emission coincident with the CX burst is small (Fig. 2(b)). From these observations we infer that the fast ion loss is probably small in this event and that the drop in $\Delta\Phi_t$ represents, for the most part, the loss of energy from thermal ions (rather than the loss of beam ions). The decrease in the neutron emission is probably caused, in part, by a stronger slowing-down process due to the lowered central T_e and the fast ion transport into a region of lower T_e , and, in part, by a lower emission rate due to the fast ion transport to the lower deuterium density region. In other discharges a large drop

in the central ion temperature and toroidal rotation speed due to the sawtooth internal disruption¹³ has been detected by charge exchange recombination spectroscopy and CX analysis. The central T_e typically drops by 15% due to the sawtooth. Important to note here is the fact that the steep drop in perpendicular energy is arrested within a short time, perhaps suggesting that unfavorable conditions causing the drop have been 'healed': τ_d is then also the healing time constant. Some sawteeth found in PBX are unusual in terms of either the large size, the rapidity, or both, of the energy loss. They will be simply referred to as the 'large-loss' sawteeth. They may be different from the so-called giant sawteeth⁷ that cause mostly redistribution of a large amount of energy within the plasma.

The precursor activity and the location of the inversion radius have been investigated using SXR cameras in an attempt to differentiate between sawteeth with a large, fast energy loss and normal sawteeth with a small, gradual loss. Figure 3(a) illustrates the internal fluctuations before a large-loss sawtooth ($\delta\beta_{p\perp}/\beta_{p\perp} \approx 4\%$ and $\tau_d \approx 0.5ms$) in a hydrogen discharge heated by two co-perpendicular deuterium beams at about 2.6MW. The discharge parameters are: $B_{\phi 0} \approx -1.0T$, $I_p \approx 330kA$, $R_0 \approx 1.44m$, $a_{mid} \approx 0.29m$, $\kappa \approx 1.8$, $\nu \approx 0.16$, $q_{edge} \approx 4.5$, $(\beta_t) \approx 2\%$, and $\beta_{p\perp} \approx 0.8$. The abscissa of Fig. 3(b) is the horizontal radius of the flux surface tangent to each line of sight, deduced from an MHD equilibrium. Note the abrupt fall in the amplitude between 12 and 15cm, presumably corresponding to the $q = 1$ radius where the $m = 1$ component falls rapidly. The phase plot in Fig. 3(c) shows the mode to be $m = 1$ in the core. The phase changes outside $q = 1$ indicate coupling to other helicities, as suggested by the nonzero fluctuation amplitude in this region. Normal sawteeth on PBX have the inversion point (r_{inv}) close to the peak in perturbation amplitude whereas all large-loss sawteeth examined have r_{inv} significantly outside the $q = 1$ surface and r_{inv} is often very large (typically 60%, but ranging up to 150% of a_{mid}). Comparing mode structures for successive normal and large-loss sawteeth reveals little if any difference: both have $m = 1$ peaks in the same place and both show coupling to the outer regions. There are also intermediate cases in which the sawtooth has r_{inv} considerably greater than the $q = 1$ radius, but show no significant energy loss. Thus, while all large-loss sawteeth have r_{inv} much greater than the $q = 1$ radius, not all events with r_{inv} greater than the $q = 1$ radius result in the rapid global energy loss. Comparison of the large-loss and intermediate events again reveals no major change in mode structure, but r_{inv} and the mode amplitude are larger still for the large-loss sawteeth. The data thus show no clear signature of the precursor peculiar to the large-loss sawtooth. It is also found that r_{inv} can vary substantially in successive sawteeth.

The large-loss sawteeth are often observed in the regime, $q_{edge} < 5$ and $\beta_{p\perp} < 1.2$. In a typical discharge a series of large ($\delta\beta_{p\perp}/\beta_{p\perp} \sim 8\%$), fast ($\tau_d \sim 0.5ms$) drops may occur at intervals comparable to τ_{EG} (10-40ms). In general, however, the large-loss

sawteeth can have widely varying magnitudes and drop times during a period when most macroscopic discharge parameters are steady, and can also occur as isolated events among normal sawteeth. This may indicate that their occurrence and effects on the confinement depend on the details of the equilibrium (e.g., local gradient of the current or temperature profile). The magnitude and the drop time of the sawteeth taken from many discharges vary over the range: $0.02 < \delta\Phi_t(mWb) < 1.5$ and $0.3 < \tau_d(ms) < 6$, or in normalized forms, $3 \cdot 10^{-3} < \delta\beta_{p\perp}/\beta_{p\perp} < 0.2$ and $10^{-2} < \tau_d/\tau_{EG} < 0.4$. The energy confinement degradation defined by Eq. (1), in which the average rate of change, $\delta\Phi_t/\tau_d$, is used instead of instantaneous $\Delta\Phi_t$, is plotted against the total heating power in Fig. 4. The maximum degradation at each power level (dashed line) that can be tolerated without causing a disruption increases with the heating power. However, at each power level, degradation of all degrees is observed. The most severe events can cause a very large energy loss ($0.2 \leq \delta\beta_{p\perp}/\beta_{p\perp} < 1.0$) over a short period ($\tau_d < 3ms$), affect the current significantly ($\delta I_p/I_p > 2\%$), and can lead to a minor disruption or to a complete termination of the discharge with only a short delay period. These events are not included in Fig. 4.

In summary, we have shown that the energy expelled from the core by a sawtooth internal disruption in NBI-heated, bean-shaped plasmas in PBX can be rapidly transported through the outer region and lost from the plasma, indicating a momentary loss of confinement. We have also shown that the sawtooth events in the bean-shaped PBX plasmas often have unusually large inversion radius. Rapid energy loss after each sawtooth crash would affect the initial conditions of each cycle of sawtooth oscillations in fusion plasma modeling. We may speculate on several possible explanations for the rapid transport. Nonlinear enhancement of the transport⁸ caused by a massive energy input from a large-volume core into the small-volume outer region, and generation of turbulence⁴ both in the core and outer regions are possible mechanisms. A picture based upon the stochastic field generated through mode coupling¹⁴ across the plasma cross section immediately after the internal disruption and subsequent rapid recovery of good magnetic surfaces could qualitatively explain some features of the momentary confinement degradation and 'healing.' The unusually large inversion radius could be consistent with a picture of a global instability where the interaction between rational q surfaces increases rapidly at some mode amplitude that depends on the fine scale details of the equilibrium.

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Figures

FIG. 1. The evolution of (a) I_p , (b) the displaced toroidal flux, $\Delta\Phi_t$, and (c) central chord SXR in an NBI-heated bean-shaped plasma.

FIG. 2. The evolution of (a) $\Delta\Phi_t$, (b) neutron flux, (c) fast neutral flux at 35keV escaping from the plasma in a counter-perpendicular direction, and (d) fast neutral flux at 35keV escaping from the plasma in a co-tangential direction, all through a large sawtooth internal disruption. The drop period, τ_d , is defined as the time required to complete 90% of the total sawtooth $\Delta\Phi_t$ drop, $\delta\Phi_t$ (see (a)).

FIG. 3. (a) Waveform from an SXR detector viewing 6cm off axis; (b) relative fluctuation amplitude ($f=6.1\text{kHz}$) as a function of flux surface radius. The $q = 1$ surface lies within the shaded areas and the arrows indicate the inversion point of crash; (c) Phase plot as a function of flux surface radius.

FIG. 4. The ratio of the global to instantaneous confinement time, τ_{EG}/τ_E (Eq. 1), is plotted against the total heating power.

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Fig. 1

Fig. 2

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Fig. 3

Fig. 4

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