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SAWTOOTH OSCILLATIONS IN THE FLUX OF RUNAWAY ELECTRONS
TO THE PLT LIMITER

BY

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SAWTOOTH OSCILLATIONS IN THE FLUX OF RUNAWAY ELECTRONS TO THE PLT LIMITER

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ABSTRACT

Increased fluxes of runaway electrons at the PLT limiter are observed in the few milliseconds following internal disruptions. These fluxes have an inverted (outside) sawtooth character. The time for the flux to reach a maximum after the disruption has been studied as a function of the plasma parameters for thousands of PLT discharges. One interpretation is that this delay represents the time for a perturbation to the runaway electron population to travel from the $q = 1$ region to the plasma boundary. These times are $\sim 10^{-1}$ of the electron thermal confinement times and increase with the plasma electron density.

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INTRODUCTION

Runaway electrons in a tokamak are electrons which have been accelerated to high enough velocity that they are decoupled from collisional interaction with the thermal electron and ion species. The transport of runaway electrons is due to physical processes which also affect the collisionless transport of thermal electrons, and which may create the observed anomalously high thermal electron conductivity. A new measure of the runaway electron confinement is from the observation of increases in thick target hard X-ray bremsstrahlung emission due to runaway electrons, striking the tokamak limiter following sawtooth internal disruptions[1] (Fig. 1).

The hard X-ray sawtooth event can be useful in transport measurements due to its interior origin and distinct start time. In this paper, we report the scaling of the time to peak emission with different plasma parameters, and we propose its interpretation as a measurement of the runaway electron confinement. The dominant scaling is a linear increase with plasma density in the range of 1 to $5 \times 10^{13} \text{ cm}^{-3}$. At lower densities ($< 3 \times 10^{13} \text{ cm}^{-3}$) the time to peak increases with stronger toroidal field. It has a weak dependence on plasma current and none on auxiliary heating power. In the energy range of 0.2 to 1 MeV, there is no significant variation in the delay time with electron energy. The delay time was not significantly changed by a small ($\sqrt{2}$) change in the limiter radius.

Observations of hard X-ray sawtooth oscillations have been reported from Pulsator [2,3] as short bursts of hard X rays peaking ~ 0.2 msec after a large internal disruption. The PLT delay time is longer than the Pulsator delay time by approximately the square of the ratio of their minor radii. For both PLT and Pulsator, the ratio of the delay time to the thermal electron energy confinement time is $\sim 10^{-1}$, which is about the ratio of the electron thermal velocity to the runaway electron parallel velocity.

Attempts to explain the phenomena have considered the influence of a presumed current redistribution by the internal disruption upon runaway electron drift surfaces [4]. Our observation of the fast rise and slow fall of the hard X-ray signal (Fig. 1) is consistent with the diffusive propagation of electrons from near the $q = 1$ surface at the time of the disruption to the limiter, similar to the propagation of the temperature heat pulse seen with soft X rays [5]. The confinement time would then be proportional to the delay time of the hard X-ray sawtooth event. If this were the case, then the scaling of the transport could be studied by observing the events in a wide variety of plasma discharges. Our measurements would then be evidence that parallel transport along perturbed magnetic field lines [6] was causing the transport of both runaway electrons and thermal electron energy by a diffusive process.

The hard X-ray sawtooth oscillations have been observed on a wide variety of PLT discharges [7] including those heated ohmically [8], by ICRF [9], and by neutral beams [10]. So far, 10^4 separate sawtooth oscillations have been monitored, typically with $R = 135$ cm, $a = 28$ or 40 cm, $I_p = 200 \rightarrow 600$ kA, $B_T = 15 \rightarrow 32$ KG, carbon limiters and titanium gettered vacuum walls. The discharges are typical of clean PLT operation with low runaway electron levels. The hard X-ray events are well-correlated to, and peak after, the sawtooth disruptions, (Fig. 1) and are distinct from the $5 \rightarrow 10$ times faster hard X-ray bursts which occur at "external" disruptions.

The runaway electrons leave the PLT plasma by impacting the limiter producing thick-target bremsstrahlung hard X rays. The hard X rays are detected in the forward radiation cone from the limiter using large NaI, NE213, or NE102A scintillators. Characteristic time scales in the detection process are: (a) the depletion time of runaway electrons on a drift surface

which interacts the limiter ($\sim 10^{-6}$ sec); (b) hard X-ray transport times from the limiter to the detector ($\sim 10^{-8}$ sec); and (c) scintillation time constants ($\sim 10^{-6}$ sec for NaI, $\sim 10^{-7}$ sec for NE213, $\sim 10^{-9}$ sec for NE102A). These time constants are all much shorter than the observed sawtooth modulation ($\sim 10^{-3}$ sec).

The application of external heating (either ICRF or neutral beam heating) often causes the sawtooth period to be longer and the amplitude of the soft x-ray modulation to be larger (Fig. 2). The effect of increasing the heating power on the hard X-ray modulation is to increase the percentage fluctuation while the average time to peak of the hard X-ray sawtooth remains constant. Soft X-ray chord measurements indicate that the location of the $q = 1$ surface is unchanged during this scan. Most of the hard X-ray sawtooth data comes from discharges with external heating since the increased sawtooth amplitude tends to bring the hard X-ray signals out of the statistical noise.

From shot to shot, and even within each shot, the time to the peak of the hard X-ray emission varies. For nearly constant plasma parameters the time is normally distributed about some average value (Fig. 3). The mean hard X-ray delay time can vary between the various heating modes, and for similar conditions can also vary significantly from one run day to the next. This means that care must be taken in finding the dependence of the delay time with the plasma parameters so that one either forms very large statistical samples or scans with a fixed heating regime within a single run. This is similar to the problems of determining scaling of other plasma quantities such as the electron energy confinement time τ_{E_e} , and the ion heating quality, $\Delta T_i \bar{n}_e / P_{\text{ext}}$, which vary considerably between run sequences [11]. Fortunately, over ten individual sawtooth events can often be monitored in one shot during the steady-state portion of the heating, improving the statistics.

The principal scaling of the hard X-ray delay time is with plasma electron density (Fig. 4). The delay time increases linearly with plasma density in the range from 1 to $5 \times 10^{13} \text{ cm}^{-3}$. This scaling is apparent for all toroidal fields, plasma currents, and heating methods. The measured time to peak is slightly but significantly longer in ICRF heated discharges than in neutral beam heated ones.

A toroidal field scan was done with neutral beams with the density held nearly constant between 1.2 and $2 \times 10^{13} \text{ cm}^{-3}$. Varying the field from 22 to 32 kG changed the average time to peak for each discharge by an amount consistent with a linear dependence on B_T . Similar scaling with the toroidal field was observed at densities below $2.5 \times 10^{13} \text{ cm}^{-3}$ with ICRF heating, although changing the field from 12.5 to 25 kG involved different ICRF heating regimes [9]. A small decrease in the measured time to peak can be seen as the current is increased and the q at the limiter decreased [7].

Attempts were made to see an explicit energy dependence in the delay time for different energy runaway electrons by energy resolving the hard X rays. In one method, the signal from an unshielded NE102A scintillator was compared to the simultaneous signal from a NaI scintillator shielded by 5 cm of lead. Consideration of the X-ray attenuation and absorption coefficients for the two detectors meant that the NE102A scintillator was recording signals from runaway electrons with energies greater than $\sim 200 \rightarrow 300 \text{ keV}$, while the NaI scintillator was recording signals from runaway electrons with energies greater than $\sim 1.0 \text{ MeV}$. For most discharges, there was no appreciable difference in the hard X-ray delay time between these two signals. On two daily runs the harder X-ray delay time was consistently $10 \rightarrow 15\%$ shorter, perhaps because generally softer X-ray spectra on these days made an energy difference observable. A second method involved pulse height resolution of an

NE102A scintillator with 10 MHz frequency response allowing 10 kHz time resolution of hard X rays from 0.3 $\rightarrow$ 1 MeV. No statistically significant difference in the time evolution was observed.

Attempts were made to see an explicit minor radius dependence on the hard X-ray sawtooth by comparing $a = 28$ cm and $a = 40$ cm plasmas (a^2 changing by a factor-of-two). These discharges were run sequentially with the sawtooth disruptions enhanced by neutral beam injection (Co only, H⁺) and the $a = 28$ cm plasma was obtained by moving in the top and bottom limiters. The inverted hard X-ray sawtooth delay did not significantly change by the reduction in minor radius. Coincidentally, the electron energy confinement time, τ_{E_e} , was also unchanged in the ohmically heated plasma for these discharges.

One logical interpretation of the hard X-ray sawtooth oscillations is that of a transit time for the runaway electrons to travel from the $q = 1$ surface to the limiter. The internal disruption could cause a perturbation of the steady-state runaway electron population, either in the form of creating and accelerating some interior runaway electrons, or spatial redistributing the existing runaway electron population. Although we feel that the transport interpretation of the phenomena is consistent with all the available data, we point out several other possibilities. The hard X-ray sawtooth could result from:

(a) An expansion of the plasma minor radius in the few milliseconds following the internal disruption. Countering this possibility is the observation that the thermal heat pulses propagate more slowly than the runaway electron pulses. Also the hard X-ray event is not correlated with in-out major radius motion of the plasma column.

(b) Changes in the current profile that shift the drift orbit displacement of the runaway electrons at the edge of the plasma [4]. Several

factors make this explanation unlikely, including the observation of sawteeth in a = 28 cm plasmas far removed from the outside limiter, the question of how the edge runaway electrons could get continuously replenished, and the small calculated magnitude of this effect in PLT.

(c) A time evolving change of the total confinement in the few milliseconds following the internal disruption.

Of particular interest is that the ratio of the runaway electron confinement time to the electron energy confinement time, is about the ratio of the parallel velocities ($\tau_R/\tau_{E_e} \sim v_e/Rc$). The runaway electron confinement time has the same principal scaling as τ_{E_e} , i.e., proportional to density, and weakly dependent on $q(a)$. We note that factor-of-two variations in τ_R are possible between run sequences much in the manner of τ_{E_e} variations although not as yet directly correlated due to the lack of overlapping data.

A consistent explicit dependence of τ_R upon runaway electron energy was not found in the range $E_R = 0.3 \rightarrow 1.5$ MeV, but since $v_{||}$ varies by only 10% over this range, such a dependence would be hard to observe. However, $\tau_R \sim 50 \rightarrow 100$ msec has been measured in the energy range $10 \rightarrow 20$ MeV on PLT by analysis of limiter activation [12]. First, we note that the activation results are averaged over many discharges and so may characterize different discharges than the one reported here. Second, as the drift orbit displacement of runaway electrons becomes larger than the perpendicular scale length of the transport process, some enhancement in runaway electron confinement can occur [13]. The fact that no enhancement is seen in the range of $0.3 \rightarrow 1.5$ MeV can indicate that drift-orbit displacements $\sim 0.3 \rightarrow 1.0$ cm are not much larger than the perpendicular scale lengths of the transport process. By comparison, the ion Larmor radius on PLT is in the range $\sim 0.05 \rightarrow 0.2$ cm across the PLT minor radius while a 5 msec runaway electron

confinement time implies that the runaway electrons undergo a 0.07 cm minor radial step per transit of the torus.

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REFERENCES

- [1] S. Von Goeler et al. Phys. Rev. Lett. 33 (1974) 1201.
- [2] G. Fussmann et al. "Plasma Physics and Controlled Nuclear Fusion Research" I, 401 (1978).
- [3] Similar observations were briefly noted on ORMAK by S.J. Zweben ORNL/TM-6030 (1977), and on TFR by TFR Group, Proc. Eighth Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research (Brussels, 1980).
- [4] H.P. Zehrfeld et al. Plasma Phys. 23 (1981) 473.
- [5] J.D. Callen and G.L. Jahne, Phys. Rev. Lett 38 (1977), 491; M. Soler and J.D. Callen, Nuc. Fusion 19, (1979), 703.
- [6] J.D. Callen, Phys. Rev. Lett. 39 (1977) 1540; J.D. Strachan and R.L. Dewar "Plasma Phys. and Contr. Nucl. Fus. Research, Tokoyo, Japan, 1974" I, 171; T. Stix, Nucl. Fus. 18, (1978) 353; A.B. Rechester and M.N. Rosenbluth, Phys. Rev. Lett. 40, (1978) 38.
- [7] C. W. Barnes, Ph.D Thesis, Princeton University, 1981.
- [8] K. Bol et al. "Plasma Physics and Controlled Nuclear Fusion Research" I (1979), 11.
- [9] J. Hosea et al. Proceeding Eighth International Conference on Plasma Phys. & Controlled Nuclear Fusion Research (Brussels, 1980).
- [10] H. Eubank et al. "Plasma Physics and Controlled Nuclear Fusion Research" I (1979) 167.
- [11] W. Stodiek et al. Proc. Eighth Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research (Brussels, 1980).
- [12] C. Barnes et al. PPPL-1794 (1981). To be published (Nucl. Fusion).
- [13] H. Mynick & J.D. Strachan, Phys. Fluids 24, (1981) 695.

FIGURE CAPTIONS

Fig. 1. Sawtooth oscillations on the hard X rays, central soft X rays, and line-averaged density. The sawtooth period is ~ 12 msec.

Fig. 2 Soft X-ray and hard X-ray characteristics of sawtooth oscillations as a function of ICRF power.

- a) Soft X-ray modulation amplitude,
- b) sawtooth period,
- c) percentage of hard X-ray fluctuation,
- d) delay time to the hard X-ray peak.

Fig. 3 Frequency histogram of the hard X-ray delay time for five run sequences

- a) Second harmonic, 42 MHz ICRF,
- b) hydrogen minority, 25 MHz ICRF,
- c) ^3He minority, 25 MHz ICRF (Aug. 28, 1980),
- d) ^3He minority, 25 MHz ICRF (Aug. 22, 1980),
- e) hydrogen neutral beam injection.

Fig. 4 Hard X-ray delay time as a function of density for ^3He minority ICRF heated discharges (O), H 0 neutral beam heated discharges ([●]), and two very low density ohmic heated discharges (Δ).

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Fig. 1

Fig. 2

Fig. 3

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Fig. 4