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ELECTRONS TO THE PLT LIMITER

by

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Measurements of Fluctuations in the Flux of Runaway Electrons at the PLT Limiter

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ABSTRACT

Fluctuations in the flux of runaway electrons to the limiter have been measured during many PLT discharges. Oscillations at 60, 120, and 720 Hz are driven by variations in the vertical magnetic field which moves the plasma major radius. Fluctuations are seen in the range of $2 - 20$ kHz due to MHD magnetic islands which extend to the plasma surface. A continuous spectrum of fluctuations is observed up to 200 kHz which correlates with drift-wave turbulence. The magnitude of the driven fluctuations can be used to measure transport properties of the runaway electrons. The amplitude of electron motion due to the MHD and drift-wave oscillations, and hence a measure of the radial size of the instability, can be determined as a function of frequency. The slope of the frequency power spectrum of the drift-wave-induced fluctuations steepens with increasing runaway electron drift orbit displacement during the current drop at the end of the discharge, and as the power in the MHD oscillations increases. A magnetic probe was used to confirm the presence of oscillating magnetic fields capable of perturbing the electron orbits.

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40

I. INTRODUCTION

This paper attempts to determine the physical mechanisms responsible for runaway electron transport in tokamaks by measurements of the oscillations in the flux of runaway electrons leaving the plasma.¹⁻⁴ The principal motivation of this work is the possible relationship between the confinement of runaway electrons and the anomalous confinement of electron thermal energy.⁵ Such a relationship might exist since the runaway electrons are sensitive to the microscopic (turbulent) structure of electric and magnetic fields and insensitive to particle collisions within the plasma. The results of this paper are consistent with the concept that the runaway electrons are lost by parallel transport along magnetic field lines that have radial components due to drift wave turbulence.⁶

We have examined the Fourier spectrum of fluctuations in the flux of runaway electrons to the Princeton Large Torus (PLT) limiter as observed by hard X-ray measurements. This spectrum relates the motion of runaway electrons onto orbits which intersect the limiter, and thus describes the local transport of these particles. We observe three classes of oscillations: (1) machine induced coherent⁷ oscillations due to the vertical magnetic field of the tokamak (at harmonics of 60 Hz); (2) plasma induced oscillations due to coherent⁷ MHD magnetic island structures ($2 + 20$ kHz); and (3) plasma induced oscillations due to incoherent drift waves (up to 200 kHz).

Since the machine induced oscillations are caused by a measurable plasma position shift in major radius, the magnitude of these oscillations can be interpreted in terms of local runaway electron transport. The confinement increases for runaway electrons of a specific energy as the plasma current decreases. This is expected since drift orbit averaging of the runaway electron response to the electro-magnetic turbulence should increase as the drift orbit

displacement of the runaway electrons becomes larger when the plasma current is decreased.^{5,8} As the current is decreased the drift-wave spectrum becomes steeper and the higher frequency components are less pronounced. At the same time the power in the MHD modes increases.

II. EXPERIMENT

The transit frequency of a runaway electron around PLT is $f_{\text{transit}} \sim \beta c / 2\pi R \approx 35$ MHz. Electrons on drift orbit surfaces which intersect the limiter will strike it within several transits of the torus, depleting the entire runaway electron population on that surface in a few microseconds. Since the creation and acceleration of runaway electrons to the energies we detect require several milliseconds, the runaway electrons cannot be created on orbits which initially intersect the limiter. If the runaway electrons are created on orbits near the limiter there would be a change in the average energy of the observed electron population on each orbit depending on how long since that orbit had been in contact with the limiter. Such a spectral energy change is not seen when 60 Hz oscillations are observed simultaneously at four different average energies. This means that oscillations in the runaway electron flux to the limiter occur due to the transport of runaway electrons onto limiter intersecting orbits, rather than by runaway electron creation on those orbits.

For the discharges considered here, PLT was run with top-bottom carbon limiters at 40 cm, in-out carbon limiters at 43 cm, 135 cm major radius, toroidal magnetic field of 25 ± 32 kG, plasma current of less than 600 kA, (typically 400 kA during the flattop and decreasing at a rate of $\sim 1-4$ kA msec⁻¹ during the end of the discharge), and moderately low runaway electron levels.

The runaway electron population was sufficiently dilute to create no runaway electron instabilities or to carry no appreciable current.

The runaway electron flux was measured by observing the thick target hard X-ray bremsstrahlung from the limiter. The detectors used were: (a) A large NE213 liquid scintillator which generated an output current proportional to the photon flux.¹ The data were digitized at up to 0.5 MHz sampling rates. Count rates of greater than 10^8 photons per second were necessary to prevent statistical fluctuations from dominating the frequency response below a few hundred kHz. (b) A large NE102A plastic scintillator with a fast photomultiplier and electronics allowing energy resolved pulse height photon counting at up to 10 MHz rates.³ Statistics in the count rate limited the time response to 10 kHz with less than a few percent noise. The power spectrum (the complex square of the fast Fourier transform) was calculated from the data of each system.

III. DRIVEN OSCILLATIONS AT 60, 120, and 720 Hz.

In PLT the plasma major radius position is maintained by a vertical magnetic field generated by currents in external coils, which are controlled by a feedback system based upon sensing the plasma position. The PLT power supplies and the feedback circuit have 60 Hz ripple (with 12 phase rectification causing a 720 Hz component), which creates corresponding variations in the plasma position. The 60 Hz ripple is approximately independent of the total current magnitude so that the fractional ripple is larger at lower currents. Skin depth effects in the metal vacuum vessel reduce the size of the magnetic field variation; however, there still occur up to few millimeter variations in

the major radius plasma position at various harmonic multiples of 60 Hz, with the magnitude approximately inversely proportional to the plasma current.

Figure 1 shows the plasma position and the resulting variations in the hard X-ray emission. The in-out position is measured with magnetic loops that determine the major radius of an equivalent line current, and hence the position of the outermost magnetic surface. The magnitude of the position oscillation was calibrated by observing the central plasma movement (observed by soft X-ray chord emission) when the feedback gain was changed. The hard X-ray emission is a direct measure of the modulation of the runaway electron flux to the limiter. There are 120 Hz and 720 Hz frequency components in both signals, with a phase difference of about 90° - 135° . The magnitude of the plasma current is dropping from 200 to 170 kA during this time.

Since electron orbits tend to follow the local magnetic field lines, as those lines move radially, the electrons follow, and they may be transported sufficiently outward to strike the limiter. Variations in the radial magnetic field can thus lead to variations in the runaway electron flux to the limiter. However, as long as the fluctuations due to the drift surface motion are less than the background flux, the transport of electrons onto the limiter may be treated as being dominated by diffusion along a radial density gradient with the radial motion of the drift surfaces treated as a convective perturbation to the transport.

One expects that the fluctuating flux will be proportional to the magnitude of the velocity driving the fluctuations. On the other hand, a larger diffusion coefficient flattens the gradient and provides less variation in density over a given distance, while a higher frequency for the same velocity means a smaller amplitude of motion, and hence, less of this gradient is sampled. These lead to inverse dependences for the fluctuation magnitude.

The continuity equation can be solved in a slab geometry, assuming the convective terms are small perturbations, and the resulting fractional fluctuation of the flux to the limiter is

$$\frac{\tilde{\Gamma}_1}{\Gamma_0} \Big|_{\text{limiter}} = \frac{\delta \omega^{1/2}}{D^{1/2}} e^{i\pi/4} e^{i\omega t}. \quad (1)$$

The outward positive velocity, v , results in an outward displacement of $\delta = v/i\omega$, with ω the frequency of oscillation and D the diffusion coefficient. The phase shift is due to the diffusion providing a damping on the forced oscillations driven by the velocity.³ This model predicts the maximum of the flux should occur just after the maximum outward velocity is achieved and just before the maximum outward displacement. This is due to the compression of the density and resulting steepening of the gradient by the outward radial motion. However, the predicted 45° phase shift does not agree with the measured 90° - 135° phase shift (Figure 1). Careful checking of the experimental signal timings has not removed this discrepancy. This might be because convection, not diffusion, is dominating the transport, thus causing the peak X-ray signal to occur at the time of maximum outward velocity.

Variation of the oscillation magnitude (δ) was obtained at the end of the discharge as the plasma current was slowly reduced. The vertical field was also reduced, keeping the overall plasma position approximately constant, but the variations in the vertical field got relatively larger, and the in-out position amplitude became larger. The time varying signals during overlapping 50 msec periods were Fourier transformed to obtain power spectra and to allow identification of particular frequency components in the signals. The square roots of the power at the different frequency peaks were normalized to the mean

X-ray signal to estimate the fluctuating flux. Figure 2 shows a plot of $\bar{\Gamma}_1/\Gamma_0$ versus $\delta \omega^{1/2}$ obtained in one shot as δ was varied in time between 0.1 cm and 1 cm. Almost all the power in the data was at 120 or 720 Hz, with small amounts at 60 Hz. Note how the data from the different frequencies overlap (the $\omega^{1/2}$ dependence). The fractional fluctuation ($\bar{\Gamma}_1/\Gamma_0$) increases with δ at a given frequency. Data taken at a constant diffusion coefficient D would be expected to fall on the straight lines as shown. Due to finite sampling and random fluctuations in the count rates (1-8 MHz in these experiments), purely statistical variation is expected in the background of the power spectrum at all frequencies. This reduces the measurable amount of coherent power in the 120 or 720 Hz peaks that can be identified above the background at low fluctuating levels. The curvature of the data might also be due to a change in the runaway electron transport caused by the diffusion coefficient decreasing by a factor of 10 during the decrease in the plasma current. With this interpretation, the estimated diffusion coefficient at flat-top plasma current (and smallest fluctuation amplitude) is comparable to other measurements.^{3,9} When the current is dropping, the confinement time is increased. That is, the amplitude of the fluctuation is large for the small distance of the plasma motion, implying steep gradients and thus small D 's. Using this technique the average diffusion coefficient at the limiter can be measured as a function of plasma parameters. Figure 3 shows the measured D , from a linear fit of data as in Figure 1, versus toroidal magnetic field, all other plasma conditions held approximately constant. The data are consistent with a $1/B_T$ dependence.

The power supplies driving the Ohmic heating current also oscillate at harmonics of 60 Hz, and thus the edge loop voltage oscillates, causing changes in the source rate and acceleration of the runaway electrons near the limiter. Such source and acceleration oscillations are a potential complication to the

interpretation of the X-ray fluctuations as a transport process. Observations arguing against these complications are:

1) The energy of the observed runaway electrons is sufficiently high (>0.4 MeV) that the actual oscillating voltages cannot create measurable runaway electrons on limiter intersecting drift orbits in one period.

2) No change in the oscillation percentage is observed when the X rays are resolved in energy (0.4-1.0 MeV). Thus the oscillations do not depend on the duration of any acceleration.

3) The magnitude of the runaway electron source rate at the plasma edge with this oscillating voltage is too small to account for the measured runaway electron fluxes. For typical PLT plasmas, the source rate¹⁰ is $10^6 + 10^{12}$ times larger in the plasma center.³

4) The energy spectrum of the X rays is the same for the fluctuating and background components. This indicates that the source and acceleration of the oscillating component are not significantly different from the background part.

5) When the voltage fluctuations are turned off by turning off the current in the Ohmic heating primary windings, the hard X-ray oscillations persist. Putting the primary current to zero allows only the in-out plasma position oscillations to exist while the plasma current decays.

Finally, another complication with the use of these oscillations to deduce local transport coefficients is the possible existence of a steeper than expected scrape-off layer of electrons due to interaction of the outside drift orbits with the top and bottom limiters. This would tend to cause an underestimation of the diffusion coefficient determining the electron gradient.

IV. MHD OSCILLATIONS

In Figure 4 are examples of the time evolution of the signals digitized at 0.5 MHz. The main oscillation that can be seen is again the 720 Hz component due to motion of the plasma driven by the vertical field (Section III). Expanding the time scales [Figures 4(a) through (e)] allows one to see coherent oscillations due to m=2 magnetic islands. The fluctuation spectra of these data (Figure 5) show the presence and acceleration of the MHD island with time, as detected by its effect on the runaway electron drift orbits intersecting the limiter. Similar effects of MHD modes on the runaway electron flux to the limiter have been previously reported.^{2,11,12} This paper adds to the published information by additionally making the following two observations. First, the driven oscillations at 120 Hz and 720 Hz can be used to calibrate the radial gradient of the runaway electron distribution at the PLT limiter. This can be accomplished since the driven oscillations have a measurable amplitude and percentage hard X-ray fluctuation amplitude, and by Equation 1 can provide a diffusion coefficient D. Assuming this transport coefficient is the same, then the radial extent of the MHD induced drift orbit islands can be measured from the amplitude of the MHD perturbations

$$\Delta_{\text{MHD}} = \frac{\bar{\Gamma}_{\text{MHD}}}{\Gamma_0} \left(\frac{D_{720}}{\omega_{\text{MHD}}} \right)^{1/2} . \quad (2)$$

Figure 6 shows measurements of Δ_{MHD} (assuming $D_{720} = 5 \times 10^3 \text{ cm}^2 \text{ sec}^{-1}$) due to a large m=1 island (600 Hz), the m=2 island of Figures 4 and 5 (7.5 to 9.1 kHz), and the drift wave like spectra (50 kHz; see next section). The radial extent of the MHD induced drift orbit island (Δ_{MHD}) at the PLT limiter acting on the

runaway electron flux appears to decrease as ω_{MHD}^{-1} or $\omega_{\text{MHD}}^{-3/2}$, and has a fairly small amplitude (~ 1 cm). This amplitude is still far greater than the distance the runaway electron drift orbit can be moved due to acceleration in one oscillation period.

Second, an interesting runaway electron energy dependence has been observed on $m=2$ MHD modes which are slowing down. Figure 7 shows two $m=2$ events, each seen simultaneously by an unshielded plastic NE102A scintillator ($E_{\text{X-ray}} \geq 0.2$ MeV) and by a NaI scintillator in 5 cm of lead ($E_{\text{X-ray}} \geq 1.0$ MeV). The actual mode number cannot be determined from these X-ray data alone, but the conditions under which these oscilloscope traces were taken are almost always indicative of large $m=2$ magnetic oscillations. The bottom trace in the figure is the soft X-ray emission from the central chord through the plasma. The mode can be seen to be increasing in size as it slows down in frequency, finally stopping almost completely. Note that the times of minima of the hard X-ray signals are exactly in phase, but the maxima of the plastic NE102A signals occur prior to the signals from the NaI. This difference in the time of the maximum signal might be explained by a difference in the diffusion coefficient and hence the gradient scale length for the relative electron energy populations. The peak in the X-ray emission versus time occurs when the velocity (with respect to the limiter) of the magnetic drift surfaces times the density gradient is greatest. If there is a small gradient increasing the background density away from the limiter into the plasma, the time of the maxima will be slightly later than the time of greatest velocity as the increase in the magnitude of the density makes up for the slowing of the velocity. The steeper the gradient, and thus the lower the diffusion coefficient, the later the maximum occurs. This would then imply that the higher energy detector, the NaI

in lead, whose peak is later, is observing a component of the runaway electrons whose average diffusion coefficient near the limiter is lower.

V. DRIFT WAVE FLUCTUATIONS

The observation of a drift-wave type fluctuation spectrum on the flux of runaway electrons to the PLT limiter has been reported previously.¹ For this paper, the form of the data acquisition was changed from an analog heterodyne system to a computer digitized system. Use of the digitized FFT spectrum analysis method has allowed a more detailed investigation of the characteristics of the power spectra of the hard X-ray fluctuations. There appear to be two limits on the type of spectra observed, with measured spectra lying between those limits. Figures 8 and 9 indicate two limiting examples of the higher frequency oscillations which have a drift-wave-like fluctuation spectra, and which have quite different amounts of coherent MHD oscillations. Spectra approaching both these limits can appear in the same discharge at different times.

There is a correlation between the power level in the MHD frequency range and the power in the higher "drift-wave" frequencies. A series of about 50 discharges was studied on a day not long after a vacuum opening, at a time when the vacuum vessel was not fully conditioned and the runaway electron levels were modestly high, thus providing good, statistically significant counting rates for frequency analysis up to 100 kHz. The hard X-ray emission would gradually increase in time during each discharge until reaching a maximum near the end of the shot, generally as the current was dropping at its fastest rate. Power spectra were obtained at the high count rates during the current and density

drop. Again, due to the fixed magnitude perturbations on the vertical magnetic field, the 60 Hz and 720 Hz oscillations became large as the current decreased.

The spectra below 2 kHz were dominated by the 60 Hz harmonics, the spectra between 2 kHz and 20 kHz were often but not always dominated by the MHD peaks, and the spectra above about 20 kHz were continuous, monotonically decreasing, and representative of the drift-wave-type spectra.¹³ The total integrated power between 20 and 100 kHz increased as the current and density decreased and the total signal level went up. Much of the fluctuating power was below 1 kHz in the 60 Hz harmonics. The power in the spectrum above 1 kHz uniformly increased as the current dropped [Figure 10(a)]. The power in any MHD peaks [Figure 10(b)] also increased as the power above 20 kHz increased.

Simultaneously there appeared a consistent change in the shape of the spectra between 20-100 kHz. As the integrated power increased with increasing signal level, the spectra tended to get relatively steeper; that is, the power at 100 kHz increased considerably less than the power at 20 kHz. Figure 10(c) shows a plot of the power law spectral index of a linear regression fit of log power versus log frequency, against the power between 20 and 100 kHz for up to 6 time intervals for each shot in this sequence. At low powers the spectra are very flat (e.g., like Figure 8). At high powers, the spectra are quite steep (e.g., like Figure 9). These types of spectra occurred on other days under similar conditions. Due to the direct correlation of "MHD" power with 20-100 kHz power, there is a corresponding correlation of spectral slope and MHD activity. Note if the $\text{Power} = f^{-\alpha}$, then since the fluctuation percentage $\propto (\text{Power})^{1/2}$, by equation 2, $\delta_{\text{drift}} = f^{-(\alpha+1)/2}$. If $\alpha \sim 2$ then $\delta \propto f^{-3/2}$ which compares favorably to the data from Figure 6.

Recently Chu¹⁴ published a theory predicting the shape of the high frequency magnetic field spectrum. Based on statistical arguments the theory results in a Planck-like spectrum characterized by a frequency ω_T ,

$$B^2(\omega) d\omega = \frac{(\omega/\omega_T)}{\exp[(\omega/\omega_T)^{1/2}] - 1} d\omega \quad (3)$$

Since the power in the hard X-ray signal is proportional to the power in the runaway electron flux, which is itself assumed to be driven by the magnitude of the fluctuating magnetic fields, the hard X-ray spectrum should have a shape given by Equation 3. A characteristic frequency $\omega_T = 0.7 - 1.7$ kHz well fits the data for $10 < \omega < 100$ kHz such as in Figures 8 and 9. The fitted ω_T decrease as the observed spectra steepen. This occurs as the plasma current decreases and the confinement gets better; that is, ω_T is inversely related to confinement time, as expected by Chu from saturated turbulence arguments, $\omega_T \approx D k_T^2 / 2 \approx 3 k_{Ta}^2 / 2 \tau_e$, with $k_{Ta} \sim 0(1)$. The confinement time τ_e needed to fit the data is about 1 millisecond, a factor of 10-30 less than the thermal confinement time but within factors of 2 of the runaway electron confinement time seen at 0.4-1.0 MeV energies. Since the hard X-ray spectrum represents the runaway electron response to the magnetic field spectrum, the $B^2(\omega)$ spectrum may remain constant as the current drops, but the runaway electrons transport less.

VI. MAGNETIC PROBE

A magnetic probe was used in PLT to directly observe the types of magnetic oscillations seen on other tokamaks.^{11,12,15} Due to probe damage by plasma induced heat fluxes that would result if such a probe were operated beyond the minor radius of the limiter, this probe was only used in the scrape-off region behind the limiter of the tokamak (7 cm beyond the plasma edge). The plane of the loop was oriented so that it responded to both toroidal and radial components.

The probe showed bursts of magnetic fluctuations at the beginning and end of the discharge, with generally constant, "quiet" behavior in the steady-state portion of the discharge. Power spectral analysis of the dB/dt probe data revealed a spectrum that was generally flat or slightly falling with frequency. Removing the frequency dependence of the signal, the spectrum generally dropped as $1/f$ or $1/f^2$ with a signal above the noise up to a hundred kHz. Magnetic oscillations due to MHD magnetic islands could be clearly seen in the 2-10 kHz frequency range. These observations confirm the presence of magnetic fields capable of perturbing the runaway electron orbits near the limiter. A correlation to hard X-ray fluctuation spectra was not obtained due to the low runaway levels for the shots when the magnetic probe was inserted. However, there did appear to be a correlation between the MHD magnetic islands observed near the limiter and increased microwave scattering signals¹⁶ from within the plasma. This occurred during the current rise of the discharge as integral safety factors were obtained on the plasma surface and energetic runaway electrons began to reach the limiter.³

VII. DISCUSSION

The flux of runaway electrons to the PLT limiter has been Fourier analyzed to deduce characteristic fluctuations. For frequencies less than 1 MHz, these fluctuations represent variations in the flux of runaway electrons onto limiter intersecting drift orbits, and thus the fluctuations characterize runaway electron transport in the region radially near the limiter.

The fluctuation spectrum is composed of three sections: (1) in the region below 2 kHz, machine induced oscillations at 60 Hz and its harmonics dominate; (2) in the region between 2 kHz and 20 kHz, coherent MHD induced oscillations often dominate ($m=2, 3$ modes); (3) in the region between 20 kHz and 200 kHz, the spectrum decreases continuously much like the drift wave spectrum observed with density fluctuations.

The driven oscillations below 1 kHz provide a useful measurement of the local runaway electron transport since the magnitude of the in-out position shift can be measured. In this respect, the measurement is similar to drift orbit displacement measurements of runaway electron confinement and is essentially an oscillating analogue to those single shift experiments.^{11,17,18} The local transport of runaway electrons is reduced if the toroidal magnetic field is increased or if the plasma current is decreased. One possible explanation of the plasma current dependence would be an increasing drift orbit displacement for the runaways (whose energy spectrum is observed to remain constant) which displace the runaways from the modes that are causing the turbulence.⁵

Using the driven oscillations to calibrate the effect of MHD modes on the runaway electron drift surfaces indicates that the amplitude, Δ , is approximately inversely proportional to the mode frequency. Also, observation

of detector response during $m=2$ events implies more energetic (and therefore higher drift orbit displacement) runaway electrons undergo less local transport. In PLT 0.5-1.0 MeV electrons will be displaced 0.4-0.7 cm in a 400 kA plasma current, increasing to 0.8-1.4 cm at 200 kA. This perhaps provides some measure of the turbulence scale size.

The fluctuation spectrum in the drift wave region changes its spectral shape when the plasma current is reduced. The fluctuations fall more rapidly with frequency when the plasma current is lower and thus coincidentally when the runaway electron confinement is higher (as deduced by the forced oscillations). This might be taken as evidence that the higher frequency components are related to the runaway electron transport.

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FIGURE CAPTIONS

Figure 1: The hard X-ray count rate, divided by its mean value, and the in-out position of the plasma measured by magnetic loops. Note both the slow 120 Hz and faster 720 Hz variations in the signals, and the relative phase shift.

Figure 2: The measured fluctuation amplitude of the hard X-ray emission at a given frequency, versus the amplitude of the in-out radial motion times the square root of the frequency. The straight lines are the expectations (Eq. 1) for different diffusion coefficients.

Figure 3: Variation with toroidal field of the measured diffusion coefficient from the $\delta \omega^{1/2}$ oscillations. The open circles, $\circ$, are from fits to the fluctuation amplitude data only for $\bar{\Gamma}_1/\Gamma_0 > 8\%$, (see Figure 2), while the closed circles, $\bullet$, are for amplitudes greater than 1.7%.

Figure 4: Time dependence of a typical hard X-ray signal. Multiplicative factors in the expanded time scale plots are for the vertical amplitude.

Figure 5: Frequency power spectra of the same signal as in Figure 4. The spectra are calculated from the square of the Fast Fourier Transform, performed over the indicated 10 msec intervals. The multiplicative factors are again for the vertical scale.

Figure 6: Estimated amplitude of drift orbit motion versus frequency of the observed fluctuation, from Equation 2 using an assumed constant diffusion coefficient of $5 \times 10^3 \text{ cm}^2\text{sec}^{-1}$.

Figure 7: Photographs of $m=2$ oscillations observed with hard X-ray detectors. The top trace is a plastic NE102A detector, the second a NaI in 5 cm of lead, and the bottom trace is the soft X-ray signal. The hard X-ray signals go down when they increase. Time is 10 msec per division.

Figure 8: The time domain signal and power spectrum of the hard X-ray emission from a PLT discharge, both shown also with expanded scales. The spectrum was calculated using the entire time interval shown.

Figure 9: The time domain signal and power spectrum of the hard X-ray emission from another PLT discharge.

Figure 10: Computed quantities from analysis of the power spectra of the hard X-ray signal versus the integrated power between 20 and 100 kHz. The individual data points are 10 msec averages, about 4 to 6 per discharge, for a sequential series of about 30 shots. Generally, as time in the discharge increased, the plasma current decreased and the power in the spectrum increased.

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Figure 1: The hard X-ray count rate, divided by its mean value, and the in-out position of the plasma measured by magnetic loops. Note both the slow 120 Hz and faster 720 Hz variations in the signals, and the relative phase shift.

#81X0738

Figure 2: The measured fluctuation amplitude of the hard X-ray emission at a given frequency, versus the amplitude of the in-out radial motion times the square root of the frequency. The straight lines are the expectations (Eq. 1) for different diffusion coefficients.

Figure 3: Variation with toroidal field of the measured diffusion coefficient from the $5 m^{1/2}$ oscillations. The open circles, o, are from fits to the fluctuation amplitude data only for $\Gamma_1/\Gamma_0 > 8\%$, (see Fig. 2), while the closed circles, •, are for amplitudes greater than 1.7%.

#81X0052

Figure 4: Time dependence of a typical hard X-ray signal. Multiplicative factors in the expanded time scale plots are for the vertical amplitude.

81X 0049

Figure 5: Frequency power spectra of the same signal as in Figure 4. The spectra are calculated from the square of the Fast Fourier Transform, performed over the indicated 10 msec intervals. The multiplicative factors are again for the vertical scale.

#82X0180

Figure 6: Estimated amplitude of drift orbit motion versus frequency of the observed fluctuation, from Equation 2 using an assumed constant diffusion coefficient of $5 \times 10^3 \text{ cm}^2 \text{ sec}^{-1}$.

Figure 7: Photographs of $m=2$ oscillations observed with hard X-ray detectors. The top trace is a plastic NE102A detector, the second a NaI in 5 cm of lead, and the bottom

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Figure 8: The time domain signal and power spectrum of the hard X-ray emission from a PLT discharge, both shown also with expanded scales. The spectrum was calculated using the entire time interval shown.

81X0050

Figure 9: The time domain signal and power spectrum of the hard X-ray emission from another PLT discharge.

82 X 0354

Figure 10: Computed quantities from analysis of the power spectra of the hard X-ray signal versus the integrated power between 20 and 100 kHz. The individual data points are 10 msec averages, about 4 to 6 per discharge, for a sequential series of about 30 shots. Generally, as time in the discharge increased, the plasma current decreased and the power in the spectrum increased.