**CHARACTERIZATION OF DISRUPTIONS
IN THE
MICROWAVE TOKAMAK EXPERIMENT, MTX
ITER R&D CONTRIBUTION
TASK PH07**

**E. B. HOOPER and M. A. MAKOWSKI
LAWRENCE LIVERMORE NATIONAL LABORATORY**

March 30, 1990

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CHARACTERIZATION OF DISRUPTIONS IN THE MICROWAVE TOKAMAK EXPERIMENT, MTX

E. B. Hooper and M. A. Makowski⁺

Lawrence Livermore National Laboratory

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INTRODUCTION

The Microwave Tokamak Experiment (MTX) has a substantial number of fast diagnostics, especially for electrons, as part of its mission for pulsed, high-power electron cyclotron heating. As part of its contribution to ITER R&D, these diagnostics are being used to characterize disruptions in MTX.

This report is the first of two, with the second planned for submittal in September, 1990 at the end of the ITER conceptual design activity. Here, we analyze the characteristics of disruptions during normal operation of MTX, discuss some new data pertaining to the "Granetz limit", and describe preliminary data on ramped density shots which will be used for fast measurements on density limit disruptions. The final report will discuss measurements using the fast diagnostics to characterize the disruption.

DISRUPTIONS IN MTX

Appendix A describes and analyzes disruptions that occur during normal operation of MTX. As the discharges during which these occurred were not designed to test the density limits, the parameters were generally far from operational boundaries. Except for disruptions occurring during current rampup, there was little or no MHD activity associated with most of the events. For some shots, there is evidence of heavy metal bursts, which plausibly triggered the disruption. Discussion of the discharge parameters, time history, etc, can be found in the appendix.

GRANETZ LIMIT

Granetz published evidence for a density limit at which MHD activity occurred when the tokamak was operated as Alcator C. At about 40% higher density, the discharge would disrupt. In Appendix B we present new data indicating that the activity occurs on the inside major radius of the discharge. This new data is contrary to expectations for normal MHD events.

⁺Permanent address: TRW, One Space Park, Redondo Beach, CA.

DENSITY RAMPING TO THE HUGILL LIMIT

In preparation for study of the fast characteristics of disruptions at the density limit, we have begun experiments using slow density ramping during discharges. In the initial experiments we have reached the Hugill limit at the end of the ohmic discharge, but have not attempted to exceed it significantly. We see signs of the limit on MHD loops, soft xrays, and several other diagnostics, but have not yet triggered a disruption. Near-term experiments will increase gas puffing to reach and exceed the limit earlier in the discharge. Several of the fast diagnostics are now installed and will be used in studying the resulting phenomena.

ACKNOWLEDGEMENT

*This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Appendix A. Disruptions in MTX

E. B. Hooper
January 4, 1990

SUMMARY

A disruption data base for MTX operation to date demonstrates that most of the disruptions occur away from the boundaries for the density limit or for large internal inductance, l_i . Many of the disruptions occur early in the discharge, either during buildup or in the transition between the two ohmic current-drive power supplies. An additional set occurs near the end of the discharge during the "ramp-down".

However, even when the early and late disruptions are removed from the data base, there are still a substantial number which occur for conditions which are nominally not subject to a problem. Data is presented which indicates that brief bursts of metallic impurities are the cause of some of the disruptions. It is plausible that a substantial number of them are due to impurities presumedly arising from sparks or other effects on the limiters.

The data is examined for "density limit disruptions". There are only a few candidates, and only a handful appear due to the classical behavior. Note, however, that the data analyzed here was for operation which attempted to avoid disruptions.

The status of the information on the "Granetz" limit is reviewed. The MHD activity which Granetz observed in Alcator C may well be a precursor of MARFES, contrary to Granetz' conclusions.

More details can be found in Ref. [1].

DISRUPTION DATA BASE

Moller has established a data base for shots which disrupt, either partially or fully. The shots are automatically identified by a rapid decrease in ohmic current. In addition, the shots are eliminated from the data base unless density data is available to permit classification on a Hugill diagram.

The full set is shown on a Hugill plot in Fig. 1. Note that few of the disruptions occur near the boundaries. A small number are near the Hugill limit [2], $\bar{n} = 1.6 B / qR \times 10^{20} \text{ m}^{-3}$ with R in m and B in T . We will examine these later.

Many of the disruptions occur early in the discharge. For classification purposes, this is defined as before 120 ms (after time zero); examination of the internal inductance will indicate that the current profile is in near steady state at this time. Also, examination of the behavior of the (few) shots that disrupted near this boundary shows that transients in current, density, etc., have died out, further suggesting that 120 ms is a

reasonable determinant. The early disruptions are plotted in Fig. 2. Many of these discharges are attempts to buildup the current too rapidly, but others occur close to the time of transition between the two ohmic power supplies. This is consistent with observations by those operating the tokamak that this transition must be done carefully to yield a good discharge. These early discharges will not be discussed further here.

Several disruptive shots occur late in the discharge when the current is ramping down. For classification, this is defined as after 320 ms; shots which disrupted near this time were examined and the choice appears reasonable. The data is plotted in Fig. 3. Input power to the discharge drops off significantly after this time, and thus the discharge is particularly sensitive to cooling. In addition, the current profile is evolving as the current drops. Consequently, any analysis would be difficult, so these are excluded from further consideration here.

The remaining discharges are plotted in Fig. 4. These discharges are in equilibrium or evolving slowly and thus candidates for analysis. It is notable that most of the disruptions occur far from the boundaries of the Hugill plot. Of particular interest are density-limit disruptions which occur near the Greenwald/Hugill limit. There are only a few candidates in the operation to date.

INTERNAL INDUCTANCE BEFORE DISRUPTION

In addition to the Hugill plot, it is useful to plot the internal inductance l_i of the discharge versus the safety factor, q . [3,4] The internal inductance can be calculated in two ways:

- The current density can be assumed to be in equilibrium with the resistivity as calculated from the electron temperature profile measured by ECE. Figure 5 shows a Hugill plot and a l_i - q plot for the time history of a discharge, the latter assuming Spitzer conductivity and equilibrium. Early and late in the discharge this is a poor assumption, but it should be good in the steady-state part.
- The saddle and cosine loops can be used to determine $l_i + b_p/2$. As b_p is small in these discharges, this is a good approximation to l_i ; the result confirms the result of Figure 5 during the central time of the discharge. Early and late the loops do not give a good result, apparently because of an instrumental "drift" in the loops. Consequently, we will use the temperature method to characterize disruptions.

Two further general points need to be made. First, on the temperature-determined plot, the symbols (x) are spaced by about 15 ms. We see that the evolution of l_i slows significantly after 90-100 ms. Thus, the choice of 120 ms to separate early disruptions from the data base is consistent with internal equilibrium.

Second, discharge parameters at disruption are far from the boundaries where MHD problems are anticipated. We find this generally to be true for our data base. Furthermore, Makowski has noted that there is rarely MHD precursor activity (e.g. $m=2$ oscillations) before disruptions in the steady-state part of the discharge, although it is often

observed during buildup. Accordingly, we postulate that the cause is not the "classical" current profile narrowing leading to MHD instability and eventual disruption.

EVIDENCE FOR HEAVY METAL "BURSTS"

There is evidence that some, at least, of the disruptions in the steady-state part of the discharge are due to bursts of heavy metals, especially molybdenum. The bursts presumably arise from sparks or flakes from the limiters or from the walls of the vacuum chamber. Although many disruptions do not show the direct evidence discussed below, it is plausible that the bulk of disruptions in the middle of parameter space arise from this mechanism.

Two types of discharges are described as evidence for metals. In the first, there is a burst of soft x-rays and metal line radiation. This is sometimes accompanied by a small increase in visible bremsstrahlung. In these discharges, there is no perturbation to the current or other discharge parameters, and the discharge recovers uneffected.

In the second, a subset of the disruptive discharges, the current collapse is preceded by a soft x-ray burst. Metal line radiation is observed, but as it is acquired on a slow time base, its precise timing is uncertain relative to the disruption. Light impurity radiation always accompanies the disruption, presumably due to the plasma cooling and/or hitting the wall. It is likely that a metal "burst" preceded the disruption and triggered it.

Discharges showing these behaviors are listed in Table 1. Examples of impurities without disruption are Shots 7075 and 7265. In the first example, there is an x-ray burst and small increase in Z_{eff} (visible bremsstrahlung) and in the bolometer signal. Metal line radiation is followed (in this case) by a small increase in low Z radiation. This discharge was at fairly large I_i but did not disrupt. The various loops show no indication of plasma movement or change. Shot 7265 shows x-rays, metal impurity lines, and little else; in particular, there was no decrease in electron temperature.

From Z_{eff} , we can estimate the amount of metal which enters the discharge. As the density and temperature are unchanged,

$$\Delta Z_{eff} / Z_{eff} = \Delta V_{brem} / V_{brem} \approx 0.1$$

But, $\Delta Z_{eff} = n_Z Z^2 (L/a) / n_e$ with $L/a \approx 0.5$ the fractional chord length over which the high ionization states occur. Choosing $Z \approx 15$, we estimate $n_Z \approx 10^{-3} n_e$. For $n_e = 1.3 \times 10^{14} \text{ cm}^{-3}$ and a volume of $3 \times 10^5 \text{ cm}^3$, this is 4×10^{16} atoms, corresponding to about 10^{-3} mm^3 of molybdenum, a rather small droplet or chip.

Disruptive behavior is illustrated by Shots 7037 and 7090. Shot 7037 shows both metal impurities and low Z impurities, suggesting that the low Z material is generated when the discharge hits the wall. (The precise timings are uncertain and cannot be determined from the data.) The visible bremsstrahlung also undergoes its primary increase at the time of disruption. In 7090 we cannot also determine the relative timing of the metal and low-Z impurities; however, the fast ECE indicates that the central

Table 1. Shots showing evidence of metal bursts

<u>SHOT</u>	<u>TIME(S)</u> ms	<u>DESCRIPTION</u>
<u>Non-disruptive discharges</u>		
5785	150,180	2 large xray bursts. The density drops throughout the shot; disruption at 290 ms
6983	200,210	2 x-ray bursts. Weak vis. brems. No current change or magnetic loop activity.
7069	120,260	2 x-ray bursts. No line radiation at first; metals at second. Weak vis. brems. and bolometer spike at second.
7075	260	X-ray, bolometer and vis. brems. spikes. Metal lines followed by light impurity radiation.
7077	190	Small x-ray burst and metal lines. No other effects.
7180	210	Initial minor disruption at 110 ms preceded by x-ray increase. Second x-ray spike during slow current decay at 210 ms without disruption.
7233	300	X-ray spike w/o disruption.
7265	150	X-ray and small vis. brems. spikes. No bolometer or fast ECE (Te) changes.
<u>Disruptive discharges.</u>		
6545	270	Xrays precede disruption.
7037	200	X-ray metal impurity radiation, and bolometer increase and light metal radiation. Precise timing uncertain.
7190	316	Soft xrays precede disruption; electron temperature drops at time of disruption.
7191	140	Soft xrays precede disruption.

electron temperature does not drop until approximately the time of the current disruption.

MHD ACTIVITY

The disruptive shots generally show no significant MHD activity before the disruption. In particular, there is no increase in the level of activity as the discharge approaches disruption at 316 ms. The lack of activity is consistent with a model in which a metallic impurity burst causes such a rapid loss of equilibrium that coherent activity is not observed. Alternatively, it is possible that locked modes exist so that a

weak perturbation is enough to make the discharge disrupt.

Three shots show MHD activity before the disruption. They meet the criteria for density limit disruptions and are discussed in the next section.

Granetz [5] observed MHD activity in Alcator C at a density $0.79 B^2$, often followed by a disruption at a density about 40% higher. His identification of the modes used an analogue circuit to separate the various m-numbers, and he found that $m=2$ to 4 or above were simultaneously observed. Makowski has found that this activity only occurs on the inside of the major radius of the discharge. This makes it unlikely that the observed activity is primarily MHD in nature. As it comes at a somewhat lower density than MARFEs, which also occur on the inside of the tokamak, it may be a precursor to them. At any event, these disruptions are not usually observed in other tokamaks.

DISRUPTIONS NEAR THE DENSITY LIMIT

Only a few discharges disrupted near the Greenwald/Hugill density limit. The 4 closest in Fig. 4 (discharges which disrupt between 120 and 320 ms) are Shots 4965, 4969, 4970, and 7190.

In 7190 there is no evidence of MHD activity building up to the disruption. In addition, there is a soft x-ray burst just before the disruption, suggesting a metal impurity problem. This disruption is thus unlikely to be due to the density limit.

The other three, however, do show MHD activity before the disruption. They did not have a soft x-ray peak preceeding the disruption, so there is no evidence of a metal impurity "burst". (No spectroscopic data is available for these shots.) All three occurred very close to the Hugill/Greenwald limit. We conclude, therefore, that they satisfy the criteria for density limit disruptions. Some parameters are listed in Table 2. The shots were all similar.

Makowski has analyzed the relative phases of the oscillations and concluded that they are an odd-numbered m at a frequency of 6 - 9 kHz. There is no indication in the data of an $m=2$ mode. A plausible interpretation is that we are seeing the $m=3, n=2$ mode, but there is no data to confirm this.

Table 2. Density limit disruptions

SHOT	DISR TIME	$M=nR/B$	M_{limit}	COMMENTS
	(ms)	(m ² /T)	(m ² /T)	
4965	294	3.2	3.1	m =odd MHD activity for 20
	ms before disr; MARFE			
4969	283	2.9	3.0	same
4970	279	3.2	3.15	same

In these three shots, the visible bremsstrahlung from the inside wall increased about 50 ms before the disruption, indicating a MARFE. This differs from JET [4], for example, where MARFEs were observed immediately following the onset of large (100% of ohmic) radiation; here, they are simultaneous as nearly as can be seen.

These appear to be the only viable candidates for density limit disruptions in the operation of MTX to date.

DISRUPTION PROCESS

We can estimate some of the times and plasma parameters for the disruption from the existing data.

Thermal quench time. The thermal quench time can be estimated from the fast ECE (Fabry Perot interferometers), although the power supply noise pickup in these initial experiments was large enough to make the result inaccurate. Lasnier has supplied several cases; the electron temperature decay time is roughly 500 μ s. The pickup should be greatly reduced in future experiments, thus leading to a much better measurement of the temperature time history. Also, fast neutron measurements in deuterium may permit a determination of the ion temperature decay.

Current decay. The current typically decays in two steps. This was also seen on JET [4] and was attributed to the generation of runaway electrons. They argue that, when the electron resistance drops rapidly, a large ohmic resistance and electric field develop, leading to runaway generation. This is consistent with the double x-ray peak often seen on soft x-ray emission and occasional emission on the hard x-ray diagnostic, but the numbers don't appear to work for MTX. The induced electric field due to Spitzer conductivity is

$$E = 3.4 \times 10^{-4} I_{kA} / T_{keV}^{3/2} \text{ volt/m}$$

and the runaway energy in a plasma of density $n(m^{-3})$ is

$$E_c = (Z+2)(n/4.5 \times 10^{18}) / E \text{ keV}$$

If we assume an electron temperature (appropriately averaged over the discharge cross section) of 0.01 keV and $Z=1$, we find $E_c = 450$ keV at a density of 2×10^{20} . This energy will be reduced by the increase in Z due to impurity influx and by the fact that the density is lower in the edge region where T_e is low, but it is hard to see how this could be reduced much below 100 keV.

The hard x-rays thus are probably not due to run-away electrons in MTX; in support of this conclusion, the x-rays in Shot 7180 occur before the fast ECE shows significant temperature drop. Indeed, in this shot the hard x-rays occur at the beginning of a slower increase in soft x-rays, and may thus be related to the generation of metal impurities.

Perhaps a second soft x-ray peak, which is commonly observed, is due to the plasma hitting the wall and releasing impurities.

We see from the data for disrupting discharges that the discharge current drops to zero in about 10 ms; the final 1/e time is roughly 5 ms. This data permits us to estimate the electron temperature from the L/R time for the tokamak:

$$t_{L/R} = \mu_0 [\ln(8R/a) - 2 + l_i/2] T_e^{3/2} a^2 / (3.3 \times 10^{-9} \ln \Lambda [Z N(Z)]) \text{ sec}$$

with T_e in keV and $N(Z)$ the Spitzer-Härm correction for finite Z . Approximating $ZN(Z)=5$ and $l_i=1$, we estimate $T_e \approx 0.07$ keV during the current collapse. This low temperature is consistent with the strong radiation observed during the collapse.

It is unclear whether the plasma is lost by being driven to the tokamak wall or by flowing along magnetic field lines opened by MHD activity. If the latter, the loss will be at the speed of sound, 10^7 cm/s at 70 eV. Direct loss across the minor radius of 16 cm would occur in 2×10^{-6} s; a loss time of 5 ms implies that field lines wind about the torus 2500 times before reaching the wall if this description is correct.

If electron energy loss were by free streaming along these field lines, T_e would decay about $(M_i/m_e)^{1/2} = 43$ times faster, divided by a factor for the higher T_e at the time of the thermal quench. The quench would thus occur in less than 100 μ s, rather faster than the 500 μ s observed. The difference probably lies in collisional processes, including friction and energy coupling with the ions.

ACKNOWLEDGEMENTS

Data utilized in this report was collected and analyzed by members of the MTX experimental group. In addition, comments and ideas were contributed by Tom Casper, interferometer (density); Charles Lasnier, ECE (electron temperature); Mike Makowski, loops (MHD activity); Jeff Moller, disruption data base and analysis; Brad Rice, visible bremsstrahlung (Z_{eff}); Reg Wood, spectroscopy (impurities)

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Fig. 1. **DISRUPTIONS** in MTX

Fig. 2 **EARLY DISRUPTIONS IN MTX**
 $t < 120$ ms

Fig. 3. **LATE DISRUPTIONS in MTX**
 $t > 320$ ms

Fig. 4. **DISRUPTIONS in MTX**
120 ms < t < 320 ms

Fig. 5, Hugill plot, shot 7190

Appendix B. Granetz Limit on MTX

M.A. Makowski
30 March 1990

Introduction

The Granetz limit^[1] is an experimentally determined density limit for the onset of MHD-like activity. The density limit is a function of the toroidal magnetic field, B_T , and scales as B_T^2 . As the density is increased beyond the critical density the magnetic fluctuation amplitude increases until, at high enough densities, a disruption occurs. As measured with the m -spectrum analyzer, the fluctuations consisted of a combination of $m = 2, 3, 4$, and 5 modes.

Data was examined in an effort to verify the Granetz operational limit. What has been found confirms the existence of the limit but the magnetic loop data indicates a static poloidal structure highly localized to the inside of the machine rather than a mix of several poloidal modes. Other experimental details of the fluctuation coincide with those found by Granetz, but the data base extends over only a very limited extent in B_T as yet. The difference in characterization of the poloidal field structure may be attributed to the workings of the m -spectrum analyzer which would Fourier decompose a static field structure into a combination of rotating modes while the present method of analysis examines each raw loop signal independently.

Observations

Magnetic loops are used to measure the MHD activity in the plasma. A set of 12 loops equally spaced in the poloidal direction at each of two toroidal locations (separated by 120°) measures the magnetic fluctuations in the plasma column. Presently, eight loops are active, four at each toroidal location: top, bottom, inboard, and outboard. The signals are digitized at a rate of 20 kHz. Analysis consists of dividing the data record into 128 point segments, computing the Fourier transform and integrated power spectrum of each of the segments, and displaying the transform and integrated power spectrum as a function of time. In addition, there are also routines available for extracting poloidal and toroidal mode numbers.

Two classes of shots are found to have the same general characteristics. The characteristics common to both classes of shots are a coherent oscillation, a frequency which decreases with time, and a static poloidal structure highly localized to the inboard side of the machine. The classes are differentiated by the apparent mechanism responsible for triggering the fluctuations, in one case by exceeding a critical density and in the other by a burst of $m = 4$ Mirnov activity.

The first class is that initially reported by Granetz. The only difference between the present and previous observations is in the nature of poloidal structure, here found to be static but previously reported as a combination of rotating modes. A typical shot is shown in Figs. 1-4. Figures 1a,b show the inboard loop signal and its integrated power spectrum (cut off at 1 kHz to eliminate the 360 Hz loop pickup) as a function of time. Turn on of the fluctuations is defined as the point at which the integrated spectral power exceeds 10 a.u. which occurs for this shot at 130 ms. Figure 2 displays a contour plot of the Fourier transform of the loop signal as a function of time. The fluctuation is discernible at 150 ms and decreases in frequency as the shot evolves. Figure 3 is 3-D plot of Fig. 2. The shot trajectory is displayed on a Hugill diagram in Fig. 4. The vertical dashed line, corresponding to the Granetz density limit for the onset of MHD activity, is crossed at 110 ms which is in good agreement with the turn on time deduced from Fig. 1b. Figure 5 shows the outboard loop signal for the same shot: nothing but noise is observed throughout the discharge. Loops at the top and bottom show fluctuation levels below that of the inboard loop indicating that the fluctuation is localized to the inboard side of the plasma column.

The disparity in loop signals does not appear to be due to differences in sensitivity. All loops are identical. Other data shows Mirnov oscillations of greater amplitude on the outboard probe than on the inboard probe.

The second class of shots is very similar to the above but is distinguished by an apparent association with $m = 4$ Mirnov oscillations. In this case, the fluctuations appear to be triggered by $m = 4$ Mirnov oscillation appearing just as $m = 4$ burst decays. The spectral power is more erratic as a function of time

and in general does not grow beyond several times the noise level. Such a shot is displayed in Figs. 6-9. Figures 6ab shows the inboard loop signal and its integrated spectral power as a function of time. A strong burst of fluctuations is observed at 115 ms into the shot which corresponds to the time the $q = 4$ surface reaches the edge of the plasma (see Hugill plot Fig. 9). Once the burst decays the fluctuation level grows. This is particularly evident in Figs. 7 and 8 which show contour and 3-D version of the Fourier transform of the loop signal versus time. Figure 9 shows the plot trajectory on a Hugill diagram. The trajectory crosses the $q = 4$ line at 125 ms and low level fluctuations are observed past this time even though the Granetz density limit has not been exceeded. Figure 10 shows the outboard loop signal. The $m = 4$ Mirnov burst is present but at a much lower amplitude than on the inboard side. No other fluctuations are observed after this indicating that the fluctuations are localized to the inboard side of the plasma column.

Shots are observed in which both behaviours are present. A $m = 4$ burst can occur early in time giving rise to low amplitude magnetic fluctuations which decay away while the density remains well below the Granetz limit. If later in time the density has increased to near the Granetz limit the fluctuations may reappear.

Results

All the shots for which the integrated spectral power exceeds 10 a.u. have been entered into a data base. When peak spectral power is plotted as a function peak plasma density, peak plasma current, plasma density at the spectral maximum, or plasma current at the time the integrated spectral power reaches a maximum (Figs. 11abcd) the only apparent trend is that the scatter in spectral power increases as the parameter it is plotted against is increased regardless of the parameter. The majority of shots are bounded by a peak spectral power of 25 a.u. and have little to no dependence on current or density. Plots of plasma density and plasma current at turn for each shot in the data base are shown in Figs. 12ab. It reveals that for most shots the fluctuations begin at $I_p = 250$ kA ($B_T = 4.6$ T for all of the data shown) which closely corresponds to $q_{edge} = 4$.

Figures 13abcd and 14ab show the same set of plots as above but restricted to shots in which magnetic fluctuations occurred after a Mirnov burst. The peak spectral power is uniformly low and does not depend in any significant way on any the parameters which it is plotted against. The density at turn on is low (1.14 ± 0.16 in units of $10^{20}/m^3$) while the plasma current at turn on is very nearly constant (250 ± 11 kA). These features reflect the fact the fluctuations initiate early in time when the density is still relatively low and coincide with the $m = 4$ Mirnov burst corresponding to $q_{edge} = 4$ at $I_p = 250$ kA as mentioned above.

Figures 15abcd and 16ab show the basic set of plots restricted to data for which no Mirnov oscillations were discernable. There is still wide scatter in the spectral power vs peak current and current at the time of the spectral maximum. However, the spectral power vs peak plasma density and plasma density at the time of the spectral maximum show marked differences (particularly the latter) above and below $\bar{n} = 2.0$. There is still wide scatter in the density at turn on (Fig. 16a) which yields an average of $\bar{n}_{eo} = 1.54 \pm 0.34$, however, this value is only 10% lower than that reported by Granetz. The current at turn on is 257 ± 12 kA and is still quite close to the time $q_{edge} = 4$.

Discussion

The results are consistent with the observation of the Granetz density limit for the onset of magnetic activity. A critical density is found within 10% of that reported by Granetz. In contrast though the fluctuations are found to be highly localized to the inboard side of the plasma column. In addition a second related class of shots has been found in which the magnetic fluctuations appear to be triggered by a $m = 4$ Mirnov burst at densities well below the Granetz limit later in time. These fluctuations do not grow much above the noise level unless the density approaches the Granetz limit. At this point the fact that the Granetz shots turn on at a current slightly above that yielding $q_{edge} = 4$ (Fig. 16b) appears to be a coincidence but cannot be entirely ruled out due to the limited range of B_T examined so far. The shots may also be precursors to MARFE's as they are localized to the inboard side but at this time there is no evidence for this one way or the other.

References

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MTX SHOT 5267

Figure 1

Figure 2

Figure 3

Hugill plot, shot 5267

Figure 4

Figure 5

MTX SHOT 5227

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16