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OBSERVATIONS OF SEVERAL DISRUPTIONS
IN PLT USING SOFT AND ULTRA-SOFT
X-RAY RADIATION

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Observations of Several Disruptions in PLT Using
Soft and Ultra-Soft X-Ray Radiation

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ABSTRACT

The evolution of ultra-soft x-ray radiation (USX, $h\nu \geq 100$ eV) is compared to that of the soft x-ray radiation (SX, $h\nu \geq 1000$ eV) during several disruptions in PLT. Spatial resolution is obtained in both cases by arrays of silicon surface barrier detectors viewing along different chords. During some disruptions the USX behaves quite differently from the SX, and a classification is made based on the USX behavior. Different interpretations of the data are discussed, along with the possibility that these measurements may distinguish between the roles of temperature and impurity density changes during disruptions.

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I. INTRODUCTION

Disruptive instabilities in tokamaks have previously been observed using soft x-ray radiation (SX, $h\nu \geq 1000$ eV),¹⁻⁴ and the fluctuations have been ascribed primarily to temperature changes. Since ultra-soft x-ray radiation (USX, $h\nu \geq 100$ eV) should be less sensitive to temperature and more dependent on impurity densities, it becomes more attractive to simultaneously monitor the SX and USX and to attribute differences to either temperature or impurity density changes.

Hollow temperature profiles in PLT motivated a search for a source of radiation from the center to explain their evolution, so a two channel USX detector was constructed to investigate the ultra-soft x-ray region.⁵ USX was expected because carbon, oxygen, iron, and tungsten were elements in PLT which could radiate in that region, and computer calculations with the average ion model⁶ had predicted that a small amount of tungsten should produce copious amounts of USX.⁷ In addition, Isler had identified USX from tungsten in ORMAK.⁸ Comparison with vacuum ultraviolet data⁹ showed that tungsten radiation was the largest component of the USX when a tungsten limiter was present.⁵ Subsequently, in order to achieve spatial resolution, a vacuum array of 19 USX detectors similar in geometry to the SX array⁴ was constructed.

II. EXPERIMENTAL APPARATUS

A diagram of the USX array is shown in Fig. 1. Nineteen silicon surface barrier detectors in vacuum view different chords of the plasma yielding profile information. The output from any detector is roughly proportional to the instantaneous x-ray power flux above 100 eV incident upon it. The SX array is practically identical to the USX array, except that it operates in a Helium atmosphere and views through a slot window consisting of a 0.5 mil Beryllium foil, making it most sensitive to radiation above 1000 eV. The outputs from 10 detectors of each array were sampled at 100 kHz, using PTR-7010 transient recorders. The data was then transferred to a PDP-10 computer for analysis. Even these 10 μ sec time steps proved to be too slow to capture some aspects of the disruption. Spatial resolution is also rather coarse due to the finite number of detectors. None of the figures shows Abel-inverted data, so that they display line-integral rather than local profiles.

The tangent radius for each detector is listed in Table I. For all of these measurements PLT was fitted with four tungsten limiters - top, bottom, inside, outside, and a carbon limiter at the bottom mounted at a different toroidal position.

III. A CLASSIFICATION OF DISRUPTIONS

The USX data indicated that there are three distinctly different types of disruptions, which we have labeled as the "asymmetric," "explosive," and "implosive" disruptions. The

division is based on the gross spatial evolution of the USX. For each type the SX decreases inside some radius and increases outside that radius.¹⁻⁴

During an asymmetric disruption the USX increases at an edge disproportionately compared to the rest of the cross section (Fig. 2). Any large asymmetry is difficult to analyze, and in this case the plasma may simply be interacting with the limiter rather than exhibiting some internal instability. Because of this possibility, the asymmetric disruption will not be described in detail.

In an explosive disruption the USX follows the pattern of the SX, decreasing near the center and increasing at larger radii (Figs. 3 and 4). The interpretation for the SX has been a transport of energy away from the center. Since the USX behaves similarly, we have labeled it "explosive" to imply the outgoing aspect. The ordinates of the figures show the tangent minor radius of each chord marked by a "star", which also indicates the minimum of the corresponding signal. The signals have been normalized to the same size with the left bar proportional to the maximum minus the minimum, the right proportional to the offset, and the middle proportional to the ratio of the left and right bars.

The implosive disruption is grossly different from the explosive, with the USX increasing over the entire cross section at the same time that the SX is decreasing in the center (Figs. 5 and 6). The increase of USX at the center suggests a movement in that direction, and "implosive" was chosen to imply this,

even though the presence of transport is not certain. Explosive and implosive disruptions are described more fully in the next sections.

IV. EXPLOSIVE DISRUPTION

In an explosive disruption both the SX and USX decrease at the center and increase at outer radii. The behavior of the SX has been described previously,¹⁻⁴ but will be presented again here in order to contrast it with the USX.

Figure 7 shows the USX during a discharge in which there was an explosive disruption at $t = 305$ msec. The bottom, tungsten limiter was set at 40 cm radius, and the carbon and other tungsten limiters were at 45 cm. The same disruption is shown in Fig. 8 with an expanded time scale. All the USX signals are combined in Fig. 3, and the corresponding SX traces are given in Fig. 4.

Table II lists the important events for the USX and SX during an explosive disruption, and the entries are described more fully below.

Before the beginning of the explosive disruption both the SX and USX are symmetric about the center of the vacuum vessel. Precursor oscillations (Fig. 3) appear before the disruption, and an analysis similar to Reference 4 suggests that they are $m=2$ tearing modes with a 2 kHz frequency. The oscillations on the central trace of the USX lag those of the SX by roughly 62°, which is to be expected for an $m=2$, $n=1$ oscillation with mode rotation in the electron diamagnetic direction since the two

arrays are separated toroidally by 67.7° . A 180° evolution of one of these oscillations is shown in Fig. 9. There may be a high frequency component on the USX, primarily at ± 21 cm (Figs. 10 and 11), with a frequency slightly less than half the sample rate of 100 kHz, although the possibility of aliasing cannot be excluded.

A central odd- m mode of 15 kHz begins to grow and becomes clearly visible on the SX traces from 305.09 to 305.15 msec (Figs. 12 and 13). The USX seems to lag somewhat behind the SX, but an odd component can be seen in Figure 14.

After the growth of the odd modes an asymmetrical decrease in emissivity occurs^{2,4} and leaves the SX very peaked (Fig. 15, 305.15 to 305.20 msec). The USX goes through a slightly different narrowing process, but its profile also becomes peaked (Fig. 16).

Following the peaking, the central traces of the SX and USX finally decrease. The SX goes through an initial period of narrowing and moderate decrease (Fig. 17) and develops a depression on the downward, ion VB side. This is followed by a period of rapid decrease which exhibits an odd- m aspect (Fig. 18) and a gradual filling in of the depression. The USX experiences a more rapid decrease (Fig. 19) and does not have an odd- m part.

After the disruption the profiles of the SX and USX are somewhat broader, but are symmetric. The $m=2$, $n=1$ oscillation which was present before the disruption still persists, its phase relationship intact, interrupted only briefly by the disruption itself.

V. IMPLOSIVE DISRUPTION

The implosive disruption is distinguished by a sudden increase in the USX and the usual simultaneous decrease of the SX.

The example disruption (Fig. 20) occurred at 514 msec, which was at the end of the discharge. The carbon limiter was at 40 cm radius, and the four tungsten limiters were at 45 cm. The central trace of the USX with an expanded time scale is given in Fig. 21, which shows the rise in 50 μ sec, and the composite pictures for the SX and USX are in Figs. 6 and 22.

Details of the evolution of the implosive disruption are presented in Table III and described more fully below.

Before the implosive disruption the USX is symmetric about the center of the vacuum vessel. The SX is symmetric, but contrary to normal conditions, it is shifted upward by 2 cm. The precursor oscillations are again $m=2$, $n=1$ tearing modes.

The first phase (513.91 to 513.98 msec) of the implosive disruption begins with a growing $m=2$, $n=1$ oscillation on the SX (Fig. 23) and a slight increase of the USX in the center, coupled with an odd- m oscillation (Fig. 24). The asymmetrical SX decrease^{2,4} accompanies an increase at larger radii (Fig. 25). Throughout this interval the USX continues to rise in the central region, but broadens somewhat when the SX decreases.

The second phase (513.98 to 514.01 msec) begins with the most dramatic event of the phenomenon. During the first 10 μ sec there is a large flash of SX primarily at the upper edge (Fig. 26). Subsequently, the profile, which has become extremely asymmetrical during the flash, rapidly relaxes to a normal shape which is

broader than before the flash. During the same 10 μ sec interval in which the SX flash occurs the USX doubles in the center (Fig. 27), and the relative increase for the wings is even larger. The rise becomes increasingly asymmetrical until the centroid of the USX is at 7 cm by the end of phase 2 (Fig. 27).

The third phase begins with a considerable broadening of the USX profile (Fig. 28). The SX continues its decrease and develops a hole on the downward side (Fig. 29) at a time which varies from case to case. The depression becomes quite pronounced and persists for about 40 μ sec.

After the disruption the USX slowly relaxes and falls to half its peak value in 400 μ sec, while slightly decreasing in breadth. The depression in the SX profile disappears, and the magnitude of the SX remains constant.

VI. DISCUSSION

The size and speed of the decreases seen in the SX and USX during an explosive disruption need to be explained. Similarly, for the implosive disruption we need to account for the doubling of USX in 10 μ sec accompanied by the large SX flash at the upper edge. Our search for an explanation in both cases has not been entirely satisfactory. Several factors which certainly must be considered are:

- 1) changes in electron temperature;
- 2) changes in impurity or electron density; and
- 3) runaway electrons.

A. Temperature Changes

Theoretically, the SX consists of bremsstrahlung, recombination, and line radiation, and therefore is primarily sensitive to T_e due to the foil cutoff. The decrease of SX in the center and increase at larger radii during a disruption have often been interpreted as a transport of energy away from the center. This suggests that there are fast T_e changes. However, the USX should be relatively insensitive to T_e since thermal electrons can efficiently excite USX transitions. Theory^{6,7} predicts that in steady state tungsten radiation will be only weakly dependent on T_e , with a broad maximum at $T_e = 1$ keV (Fig. 30). Non-equilibrium calculations have also been performed by Hulse, Jensen, and Post which show the effect of an instantaneous change in T_e . A positive or negative T_e step is introduced, and the time dependence of the tungsten radiation is predicted. The results (Fig. 30) are plotted as line segments superimposed on the equilibrium curve, showing the tungsten radiation immediately after various T_e steps. Hulse has subsequently used a more detailed atomic physics model to calculate the dependence of tungsten radiation on temperature, and he has seen that the dependence is even slightly weaker for the equilibrium case than that shown in Figure 30.

For the explosive disruption the decrease of SX in the center could be explained by a temperature drop, but the USX would not be affected similarly. It is possible that the asymmetric SX flash during the implosive disruption could be accounted for by T_e changes, but they could not explain the large USX increase.

B. Impurity or Electron Density Changes

A rapid transport of impurities might explain our observations. The problem is their transport in tens of microseconds. If the magnetic field were braided, transport would be enhanced because of the wandering field lines and the free streaming of particles along the lines. However, the time to travel the large parallel distances predicted by this theory is probably greater than is experimentally observed. For example, it would take a 500 eV tungsten ion 300 μ sec to travel once around toroidally.

Another possibility is a rapid change of electron density. Electrons move parallel to the field more easily than impurity ions, and a 500 eV electron can make 20 toroidal transits in 10 μ sec. During an explosive disruption the density through the center decreases by 16% as sampled on a slow time scale. The USX and SX drop by 31% and 37%, respectively. Of course, n_e in the center could actually decrease by a much greater amount since the line density also samples larger radii. If most of the USX decrease is due to an n_e decrease, then the larger drop of the SX might be due to its greater temperature sensitivity. This explanation suffers from the difficulty that the transport of electrons would establish a confining electric field.

Electron transport is not so promising for explaining the implosive disruption. The electron density has not been seen to increase, and if it did, this would tend to raise the SX unless the T_e drop were significant.

We have assumed in this discussion that impurity densities are constant along field lines. However, with our present geometry

we are unable to exclude the possibility that a cloud of impurities may have moved into our plane of sight. This could be the result of a violent interaction of the plasma with the limiters.

If the USX increase had been caused by a cloud from the limiter moving into the USX array's plane of sight, then the cloud would have to have been created by a disturbance at the limiter at least 100 μ sec earlier, due to its transit delay. There are two reasons that this is an unlikely situation. First, if the SX response were due to a cloud from the limiter, one would not expect the cloud to reach the two arrays at the same time since the SX array is 180° from the limiter in the toroidal direction, and the USX array is 112° away. Second, if the disturbance which the SX array sees were not due to an impurity cloud, then it would be fortuitous for the SX and USX responses to occur at the same time, assuming the USX increase were due to a cloud which originated 100 μ sec earlier. It is, therefore, improbable that an impurity cloud from the limiter is the cause of the USX increase. A more plausible possibility is that both the SX and USX responses are due to a disturbance which has little toroidal dependence or propagates very rapidly in the toroidal direction.

C. Runaway Electrons

It was suggested¹⁰ that runaways might cause enhanced USX. Since runaways may be produced in the center due to strong electric fields, this purportedly might explain the increase of USX at the center during an implosive disruption before it increases at the edges. However, since USX represents 100 to 1000 eV radiation,

runaways should be no better at exciting transitions than thermal electrons. It would take a complete slide-away of the electron distribution to bring low energy electrons up to sufficient excitation energies, but this should be no different than a temperature step which has little effect.

VII. SUMMARY

Two arrays of silicon surface barrier detectors have been used to measure x-rays in the soft and ultra-soft regions of the spectrum during disruptive instabilities. The SX array should be primarily sensitive to temperature, while the USX array should be sensitive to impurity densities, so that a general description of temperature and impurity density behavior during a disruption might be possible.

A classification into the asymmetric, explosive, and implosive disruptions has been made, based on the spatial evolution of the USX. During an asymmetric disruption, the USX increases at an edge disproportionately to changes over the rest of the cross section. In the explosive disruption the USX follows the pattern of the SX, decreasing at the center and increasing at larger radii. The implosive disruption is characterized by an increase of the USX over the entire cross section, while the SX is decreasing in the center.

There is the possibility that a rapid drop in electron density could account for the drop in the USX during an explosive disruption. The SX drop would then be a combination of the electron density decrease and a temperature decrease.

Perhaps the most interesting new feature has been observed during the implosive disruption. The SX can develop a strong asymmetry which lasts for 10-20 μ sec. At the same time the USX doubles over the entire cross section and subsequently increases more slowly for 50 μ sec. Several factors which could influence the USX have been examined, but preliminary considerations of temperature and density changes were unable to account for this rapid rise.

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TABLE 1DETECTOR TANGENT RADII

<u>USX Array</u>	<u>SX Array</u>
Top	Top
31 cm	16 cm
28	12
21	8
14	4
7	0
0	-4
-4	-8
-14	-12
-21	-16
-31	-24
Bottom	Bottom

"Top" is in the direction of the
electron $\overrightarrow{VB}$ drift

TABLE II

EXPLOSIVE DISRUPTION

	USX		SX	
	Events	Fig.	Events	Fig.
Prior to disruption	-14 to +14 cm 2kHz $m=2, n=1$ USX lags	F3, F9	-12 to +12 cm 2kHz $m=2, n=1$ SX leads	F4
Growth of odd m	odd m at ± 21 cm	F10, F11	-4 cm increases	F12
			+4 cm increases	F13
Asymmetric narrowing	-4 cm increases & +7 cm decreases	F14	Asymmetrical drop	F15
	1. -4 cm decreases 2. +7 cm decreases peaked profile	F16	1. -4 cm decreases 2. 0 & 4 cm increase 3. 4 cm decreases peaked profile	
Explosive decrease	rapid decrease no odd m	F19	narrowing and central decrease, depression develops on downward side	
			fast decrease with odd m	F18
After disruption	$m=2, n=1$ continues with phase intact profiles broader, but still symmetric			

305.09
msecs

305.12

305.15

305.17

305.19

305.20

305.23

305.25

305.29

TABLE III

IMPLOSIVE DISRUPTION

	USX		SX	
	Events	Fig.	Events	Fig.
Prior to disruption	-14 to +14 cm symmetric centroid at 0 cm m=2,n=1 mode	F22	-4 to +8 cm symmetric centroid at 2 cm m=2,n=1 mode	F6
Phase 1	1. small central increase 2. alternating growth at 0 & 7 cm odd m	F24	growing m=2,n=1	F23
	growth continues in central region	F24	Mirnov's asymmetrical drop	F25
	broadening at -7 & 14 cm simultaneous with SX decrease		1. 0 cm drops precipitously 2. similarly at 4 cm broadening & shift of centroid	
Phase 2	doubles in center even more in wings	F27	hugh flash at upper side	F26
	increase continues centroid shifts	F27	asymmetry begins to relax	F26
	-18 to +20 cm centroid at 7 cm	F27	asymmetry gone profile broader	F26
Phase 3	profile broadens considerably	F28	1. continues decrease 2. hole develops on downward side 3. depression pronounced	F29
	at end USX extends from -24 to +26 cm		persists until end of phase 3	
After disruption	relaxes to half peak value in 400 μ secs		depression disappears, magnitude roughly constant	

513.91
msecs

513.94

513.98

513.99

514.00

514.01

514.05

FIGURE CAPTIONS

- Fig. 1 Schematic of the ultra-soft x-ray array shown viewing a vertical cross section of PLT.
- Fig. 2 Evolution of the USX profile during an asymmetric disruption. The 31 cm signal saturates at later times.
- Fig. 3 Composite of the USX signals versus time during an explosive disruption. (cf. section 3 for a discussion of the display)
- Fig. 4 Composite of the SX signals versus time during an explosive disruption.
- Fig. 5 Evolution of the USX profile during an implosive disruption.
- Fig. 6 Composite of the SX signals during an implosive disruption.
- Fig. 7 Central signal of the USX for an entire discharge in which an explosive disruption occurs at $t = 305$ msec.
- Fig. 8 Expanded view of the central signal of the USX for an explosive disruption.
- Fig. 9 180° evolution of an $m = 2$, $n = 1$ oscillation in the USX prior to an explosive disruption.

- Fig. 10 USX signals at ± 21 cm prior to an explosive disruption. The oscillations are out of phase from 304.9 to 305.0 msec.
- Fig. 11 Odd-m change in the USX profile before an explosive disruption.
- Fig. 12 First half of an odd-m growth of the SX prior to an explosive disruption.
- Fig. 13 Second half of an odd-m growth of the SX prior to an explosive disruption.
- Fig. 14 Odd-m growth of the USX prior to an explosive disruption.
- Fig. 15 Peaking of the SX profile during an explosive disruption.
- Fig. 16 Peaking of the USX profile during an explosive disruption.
- Fig. 17 Moderate decrease of the SX during an explosive disruption.
- Fig. 18 Rapid decrease of the SX during an explosive disruption.
- Fig. 19 Sharp decrease of the USX during an explosive disruption.
- Fig. 20 Evolution of the central signal of the USX for a dis-

charge in which there was an implosive disruption at $t = 514$ msec.

- Fig. 21 Expanded view of the central signal of the USX during an implosive disruption.
- Fig. 22 Composite of the USX signals during an implosive disruption.
- Fig. 23 Growing $m = 2$, $n = 1$ oscillation on the central signal of the SX during an implosive disruption.
- Fig. 24 Phase 1 growth of the USX during an implosive disruption. Note the odd- m growth at the center followed by a broadening of the profile.
- Fig. 25 Asymmetrical decrease of the SX followed by a broadening during an implosive disruption.
- Fig. 26 Extremely asymmetrical flash of SX at the upper edge during an implosive disruption.
- Fig. 27 Doubling of the USX in 10 μ secs and simultaneous broadening of the profile during an implosive disruption.
- Fig. 28 Phase 3 broadening of the USX profile during an implosive disruption.
- Fig. 29 Development of a hole in the SX profile during an implosive disruption.

Fig. 30 The curve shows the temperature dependence of the steady state radiation from tungsten. The line segments show the radiation immediately after the temperature change shown.

Fig. 1. 776080

Fig. 2. 783999

Fig. 3. 793052

Fig. 4. 793050

= I =
 = I =
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 = I =
 = I =
 = I =

Fig. 5. 793048

Fig. 6. 793053

-

- = -

- = -

= I -

= I =

I = I

I = I

I = I

I = I

= I -

= I -

Fig. 7. 735006

Fig. 8. 786007

FIG. 9. 786012

Fig. 10. 786005

Fig. 11. 786003

Fig. 12. 786009

Fig. 13. 786001

Fig. 14. 793056

Fig. 15. 786010

Fig. 16. 786019

Fig. 17. 786016

Fig. 18. 786014

Fig. 19. 786018

Fig. 20. 786013

Fig. 21. 786002

Fig. 22. 793049

SX CENTRAL TRACE

Fig. 23. 786017

Fig. 24. 786004

Fig. 25. 793070

Fig. 26. 793054

Fig. 27. 793051

Fig. 28. 786011

Fig. 29. 786008

Fig. 30. 793057