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PHENOMENOLOGY OF HIGH ENSITY DISRUPTIONS IN THE TFTR TOKAMAK

BY

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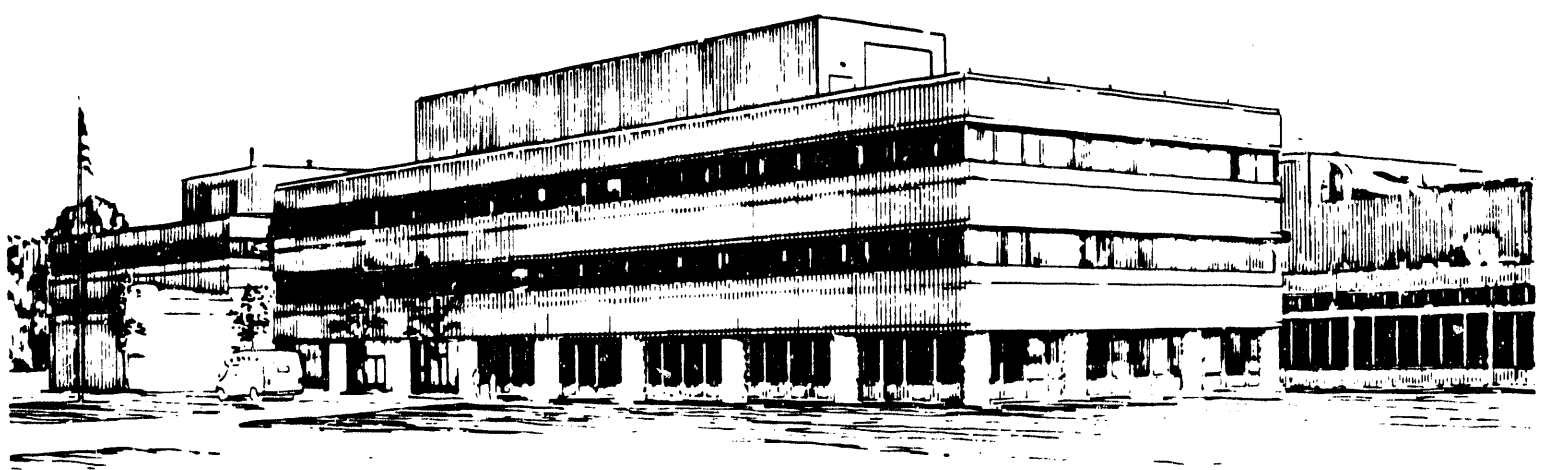

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Phenomenology of High Density Disruptions in the TFTR Tokamak

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Abstract

Recent studies on TFTR of high density disruptions have made significant advances in closing the gap between theoretical models of disruptions and the experimental data. For the first time, an (m,n) = (1,1) 'cold bubble' precursor to the high density disruptions has been experimentally observed. The precursor resembles the 'vacuum bubble' model of disruptions first proposed by Kadomtsev and Pogutse.

MASTER

Disruption control or avoidance is an important engineering issue for the present generation of tokamaks (JET, TFTR, and JT-60) and presents even more stringent design constraints for the next generation of tokamaks, *i.e.*, ITER. To compound the problem, the next generation of tokamaks will also have to operate near the present empirically determined density and β disruption limits to achieve their operational goals. Understanding the disruption mechanism is of vital importance to the future of the fusion energy program. For the first time, the presence of an (m,n) = (1,1) 'vacuum bubble' precursor[1] to the major disruption at high density has been observed experimentally. This kink instability has been proposed by Kadomtsev and Pogutse as a possible mechanism for the major disruption. The instability requires a very low shear region within the q=1 surface for the kink to be unstable.[2-4]

Disruptions at high density occurring both during normal plasma operation and during limiter conditioning have been studied in the TFTR tokamak. The pre-disruptive phase of disruptions at high density on TFTR follow the now well known characteristic pattern which has been observed previously on other machines.[5,6] The disruptions are preceeded by the collapse of the

edge electron temperature accompanied by multiple partial and minor disruptions. Sawteeth may be present during this period; if so the sawtooth inversion radius increases, consistent with the model[3,5,6] that the current profile is contracting. A previously unreported feature is that concurrent with the edge collapse, the electron temperature within the q=1 surface becomes very flat and remains so throughout this phase. An example of the edge temperature collapse and central flattening of the electron temperature during the predisruptive phase is shown in Fig. 1.

Three distinct types of disruptions have been identified[5] (excluding the internal disruption or sawtooth). All are marked by abrupt changes in the shape of the electron temperature profile. The first type is the partial or off-axis disruption, a number of which may be observed in the traces of electron temperature vs. time between 4.55 and 4.65 sec in Fig. 1. One of these partial disruptions is shown in more detail in Fig. 2. As can be seen, the partial disruption flattens the electron temperature in an anular ring, affecting the central electron temperature only on a diffusive timescale. In the partial disruptions studied to date, the flattening has occurred near the location of the q=2 surface.

For detailed examples of minor and major disruptions, we will look at a high density ohmic plasma. This discharge is near the Greenwald density limit[7] [which for circular plasmas can be written as $< n > / < J > \approx 10^{20}$ (MA m)$^{-1}$] (Fig. 3). At about 0.8 sec the plasma became detached[8] from the limiter and remained detached until the disruption. The predisruptive phase begins at 3 sec with the onset of partial and minor disruptions and a further collapse of the edge electron temperature. This phase has sawteeth and partial disruptions as well as a minor disruption at 3.332 sec (Fig. 3). The electron temperature profile over the central region of the plasma was determined from the electron cyclotron emission (ECE) measured with the Grating Polychromator (GPC)[9] at 200 μsec intervals. The GPC was cross calibrated to the ECE radiometer.[10]

The minor disruption in Fig. 3 begins with a growing hollowness of the electron temperature profile on the midplane (Fig. 4). It is found that this hollowness is due to an (m,n)=(1,1) 'cold bubble' moving into the plasma core. The precursor continues to grow until the disruption takes place which flattens the electron temperature across the center of the plasma. This event resembles a sawtooth crash, but the inversion and mixing radii are much

larger. For the example shown in Fig. 4, the inversion radius is 0.28 m (near q=1.5) and the mixing radius extends nearly to the q=3 surface at r=0.49 m. The internal inductance, as determined from the measurement of Λ ($\equiv \beta_{pol}^{equil} + l_i/2$) remains unchanged (Fig. 3). Following the disruption, the edge temperature drops and the profile peaks up to a shape similar to that before the disruption, including the flattened region within the q=1 surface (profile 'd'). The sawtooth inversion radius and the region of flatness in the central T_e profile following the minor disruption are only slightly reduced compared to that before the disruption. Thus, although the electron temperature is flattened out to the q=3 surface, there is no evidence for a similar redistribution of the plasma current.

The major disruption begins in much the same way as the minor disruption, with the rapid growth of a 'cold bubble' m=1 mode (Figs. 3 and 5). Fast data from the horizontally viewing X-ray camera is available at the time of this major disruption, and it shows a vertically asymmetric collapse of the soft X-ray emissivity profile, supporting the model of the cold bubble shape for the precursor. The growth of the precursor is about 5 times faster for the major disruption ($\gamma \approx 5 \times 10^3 s^{-1}$) than for the minor disruption

($\gamma \approx 1 \times 10^3 s^{-1}$). While the central electron temperature is even hotter at the time of the major disruption, the temperature beyond the q=1.5 surface is lower.

At the end of the crash phase the Λ is seen to decrease sharply (Fig. 3), suggesting a redistribution of plasma current.[11,12] (In this figure, the relative timing between the temperature and magnetics diagnostics was determined from comparison of the synchronized fast soft x-ray camera and Mirnov coil data.) The change in Λ from 1.15 to 0.85 is consistent with a flattening of the current profile to the $q \approx 3$ radius (the β_{pol} is ≈ 0.1 at this time). This suggests that in this case either the m=1 mode, or modes excited during the crash, led to a reconnection or a destruction of the magnetic flux surfaces and a broadening of the current profile. The central electron temperature remains about 1 keV for several msec following the major disruption; then the temperature abruptly drops to less than 100 eV and the current quench phase begins. It is not known at this time what is responsible for this final temperature drop.

The internal (m,n)=(1,1) cold bubble precursor structure has also been seen in disruptions at moderate density and low q(a) (≈ 2.5). The density

for this case is well below the Greenwald limit, but the phenomenology of the disruption appears similar to those studied above. Again, the edge electron temperature had collapsed and the central electron temperature profile was very flat, implying very rapid thermal transport (and possibly low shear) within the q=1 radius. With the fast ECE data from the grating polychromator and the soft X-ray data it was possible to observe a cold bubble moving downward (at this toroidal location) into the core of the plasma at a speed of 2×10^6 m/s (Figs. 6a and 6b). The growth rate of the precursor mode, inferred from this measurement, is $\gamma \approx 1 \times 10^4 s^{-1}$.

While (m,n) = (2,1) and (3,1) precursors have been observed before some disruptions on TFTR, direct evidence for them is often lacking, as it is in the present examples. We cannot exclude the possibility that such modes commonly exist in a locked state prior to disruptions; however, that would suggest that the mode retain an amplitude larger than the locking threshold amplitude[13,14] through partial and minor disruptions.

Thus, in both high density and high current discharges on TFTR the temperature profile evolves to a 'tophat' configuration. In such temperature profiles the close proximity of the q=1 surface and the cold edge plasma

allows the (1,1) mode to reconnect in the cold plasma region and inject this cold plasma into the center of the plasma column. The possible nature of the instability and why it may lead to major or minor disruptions are discussed below.

A cold plasma bubble can be injected into the plasma column by either the external[1-4] or internal[15] (1,1) kink if the central q profile is close to unity and q falls below unity off axis. The details of the q profile in the these experiments are unknown. With neoclassical resistivity the flat T_e profiles measured in the experiment should actually produce a peaked $J(r)$ profile, unless the mechanism which maintains the flat central $T_e(r)$ also flattens $J(r)$. As a working hypothesis, we assume that $q(r)$ is flat and that the bubble is produced by the magnetic reconnection over an annular ring of width δr located at a radius r_s (with $\delta r \ll r_s$). An estimate of δr can be obtained from the radius r_b of the cold bubble, $\delta r = r_b^2/2r_s$. Taking r_b as the radius of the bubble at the half depth and r_s the radius of the cold plasma shoulder on the T_e profile, we find that for the minor disruption (Fig. 4) $\delta r \sim 0.037m$ while for the major disruption $\delta r \sim 0.021m$. Thus, the reconnection layers are quite narrow.

There is a continuous transition between the external and internal (1,1) kink based on the resistivity of the plasma at the q=1 surface. When the resistivity is small, the plasma dynamics at the q=1 surface limit the rate of growth of the bubble to the Sweet-Parker rate.[16] The 'frozen-in' condition which is valid everywhere except in a narrow layer around the rational surface guarantees that q will be equal to 1.0 within the bubble after reconnection is complete.[16] When the resistivity is very large, the plasma in the vicinity of the rational surface acts as a vacuum and no longer controls the rate of reconnection. The instability is essentially an external kink. The 'vacuum bubble' injected into the plasma as a result of the instability carries little or no current and thus q will be greater than 1.0 within the bubble.[1,3,4,17] The transition of the (1,1) kink from an internal to an external mode depends on the formation time of the bubble τ_b compared with the flux diffusion rate across the reconnection zone $\tau_R = 4\pi(\delta r)^2/\eta c^2$. For the minor disruption in Fig. 4, $\tau_b \approx 0.8$ msec while $\tau_R \approx 3.3$ msec (based on the 200 eV edge temperature). Thus, since $\tau_R \gg \tau_b$, the mode in this case must be categorized as an internal kink. The internal kink produces a q profile which is flat and close to unity. This conclusion is also consistent with the absence of a large change in the Λ, which would change significantly as a result of the

modification of the current profile by the external kink.[1,4,17]

For the major disruption, $\tau_b \approx 0.2$ msec and $\tau_R \approx 0.34$ msec so that $\tau_r \sim \tau_b$. Thus, the formation of the bubble in the case of the major disruption is driven by a quasi-external kink. The external kink produces a non-monotonic q profile in which $q(0)$ can be significantly greater than unity. Such a profile is unstable to a range of modes with $m \geq 2$ and leads to significant broadening and disruption of the current in a recent 3-D resistive MHD simulation of the density limit.[3]

Summary

The phenomenology of disruptions at high density has been studied on TFTR. While the global features of the pre-disruption phase on TFTR are found to be similar to what has been previously reported, a more detailed picture of the disruption mechanism has emerged from the fast electron temperature profile data. Previous work had suggested that the (m,n)=(1,1) internal kink had played a role in the final disruption.[5,6] The data from TFTR indicates that while the minor disruption may be caused by the internal kink driven cold plasma bubble, the major disruption may be triggered by a 'vac-

uum bubble' as originally predicted by Kadomtsev and Pogutse.[1] The rapid growth rate ($\gamma \geq 10^3 sec^{-1}$) and the (m,n) = (1,1) character of the mode are extremely unfavorable to traditional external feedback methods.[18–20] However, maintenance of a sufficiently high edge temperature ($> 200eV$) should prevent the external kink from developing and therefore inhibit the major disruption.

Acknowledgments

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Fig. 1. Electron temperature profiles at selected times during the predisruptive phase of a high density disruption showing the collapse of the edge electron temperature. [Other parameters for this shot were $q(a) = 5$, $< n_e > \approx 8x10^{19}/m^3$,a = 0.9 m, R = 2.55 m, $I_P = 1.7MA$ and $B_T = 4.6$ Tesla.]

Fig. 2. Detail of a partial disruption during the predisruptive phase of the plasma in Fig. 1.

Fig. 3. Global waveforms showing the plasma current, central electron temperature, line integrated electron density and internal inductance for an ohmic high density disruption. [Other parameters for this shot were $q(a) \approx 9$, $< n_e > \sim 2.5x10^{19}/m^3$, a = 0.8 m, R = 2.45 m, $I_P = 0.7MA$ and $B_T = 4.0$ Tesla.]

Fig. 4. Electron temperature vs. time and major radius through the minor disruption of the shot in Fig. 3.

Fig. 5. Electron temperature vs. time and major radius through the major disruption of the shot in Fig. 3.

Fig. 6a. Profiles of the electron temperature just prior to the major

disruption of a low q(a) shot. [Other parameters for this shot were $q(a) = 2.5$, a = 0.8 m, $< n_e > \sim 4.5x10^{19}/m^3$, R = 2.45 m, $I_P \sim 2.5MA$ and $B_T = 5.2$ Tesla.]

Fig. 6b. Profiles of the chord integrated soft x-ray emissivity.

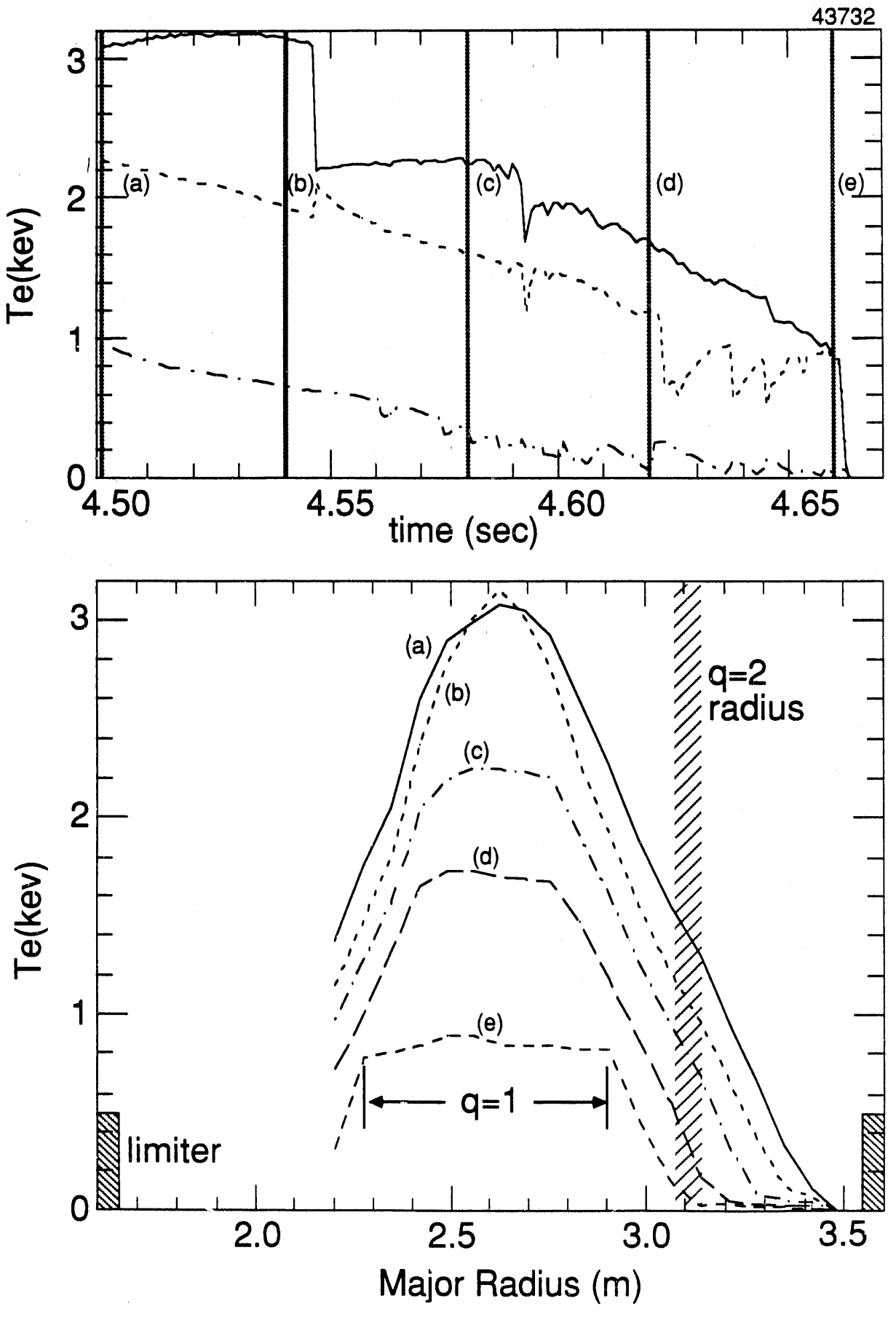

43732
Te(kev)
time (sec)
(a)
(b)
(c)
(d)
(e)
4.50
4.55
4.60
4.65
0
1
2
3
Te(kev)
Major Radius (m)
q=2
radius
q=1
limiter
2.0
2.5
3.0
3.5

Fig. 1

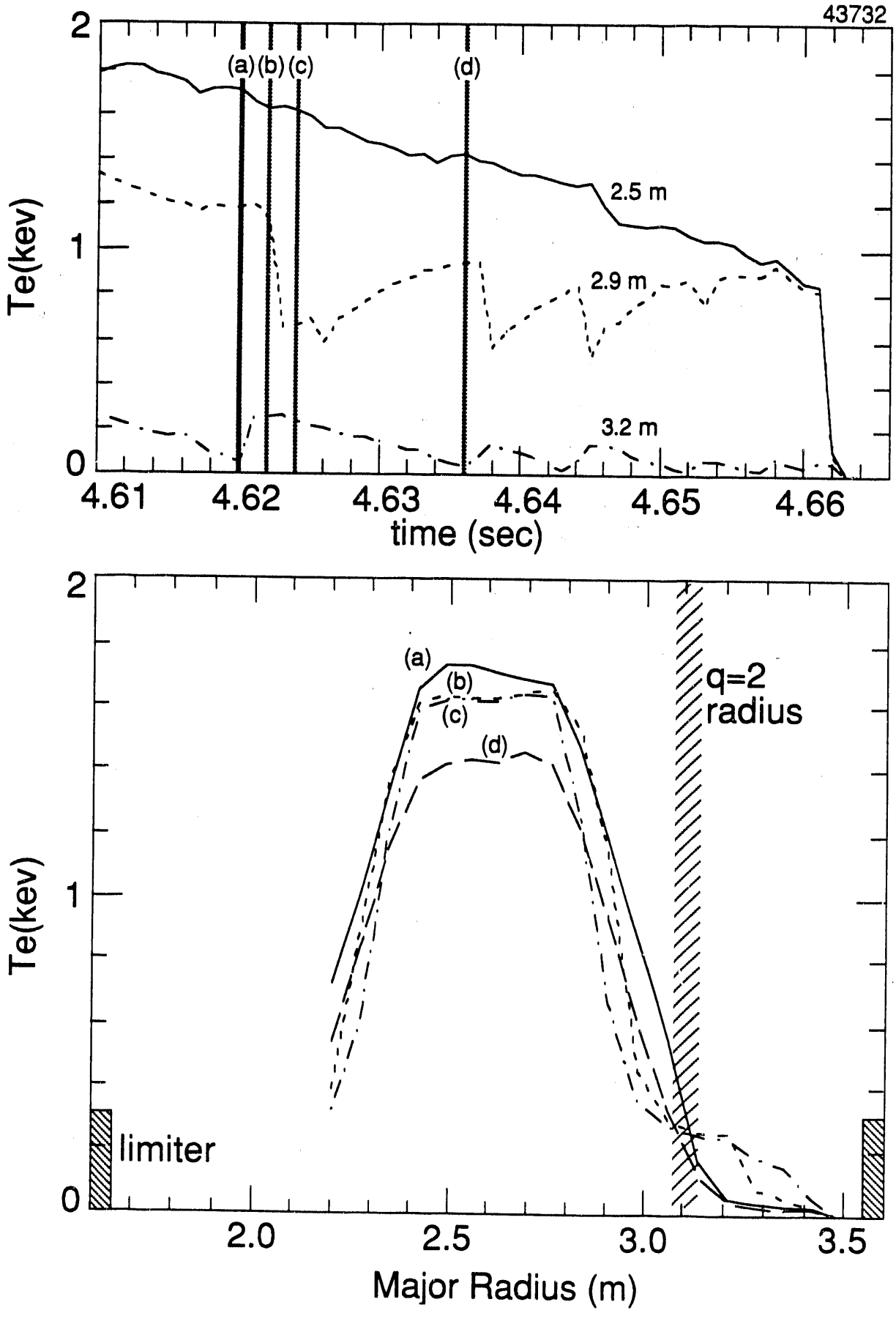

43732
(a)
(b)
(c)
(d)
2.5 m
2.9 m
3.2 m
Te(kev)
time (sec)
4.61
4.62
4.63
4.64
4.65
4.66
q=2
radius
limiter
Major Radius (m)
2.0
2.5
3.0
3.5

Fig. 2

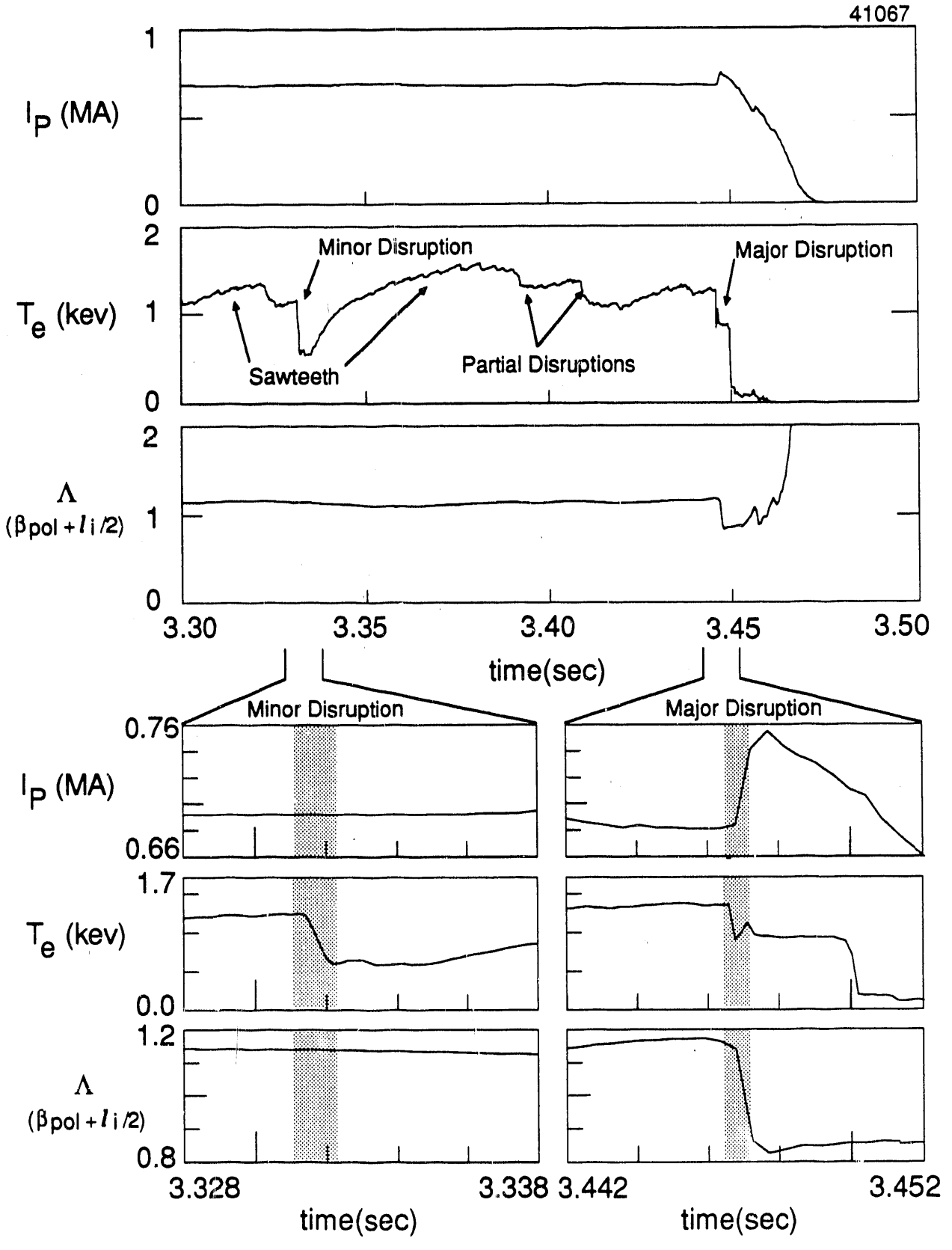

41067
I_P (MA)
1
0
T_e (kev)
2
1
0
Minor Disruption
Major Disruption
Sawteeth
Partial Disruptions
Λ
($\beta_{pol} + l_i/2$)
2
1
0
3.30
3.35
3.40
3.45
3.50
time(sec)
Minor Disruption
Major Disruption
I_P (MA)
0.76
0.66
T_e (kev)
1.7
0.0
Λ
($\beta_{pol} + l_i/2$)
1.2
0.8
3.328
3.338
3.442
3.452
time(sec)
time(sec)

Fig. 3

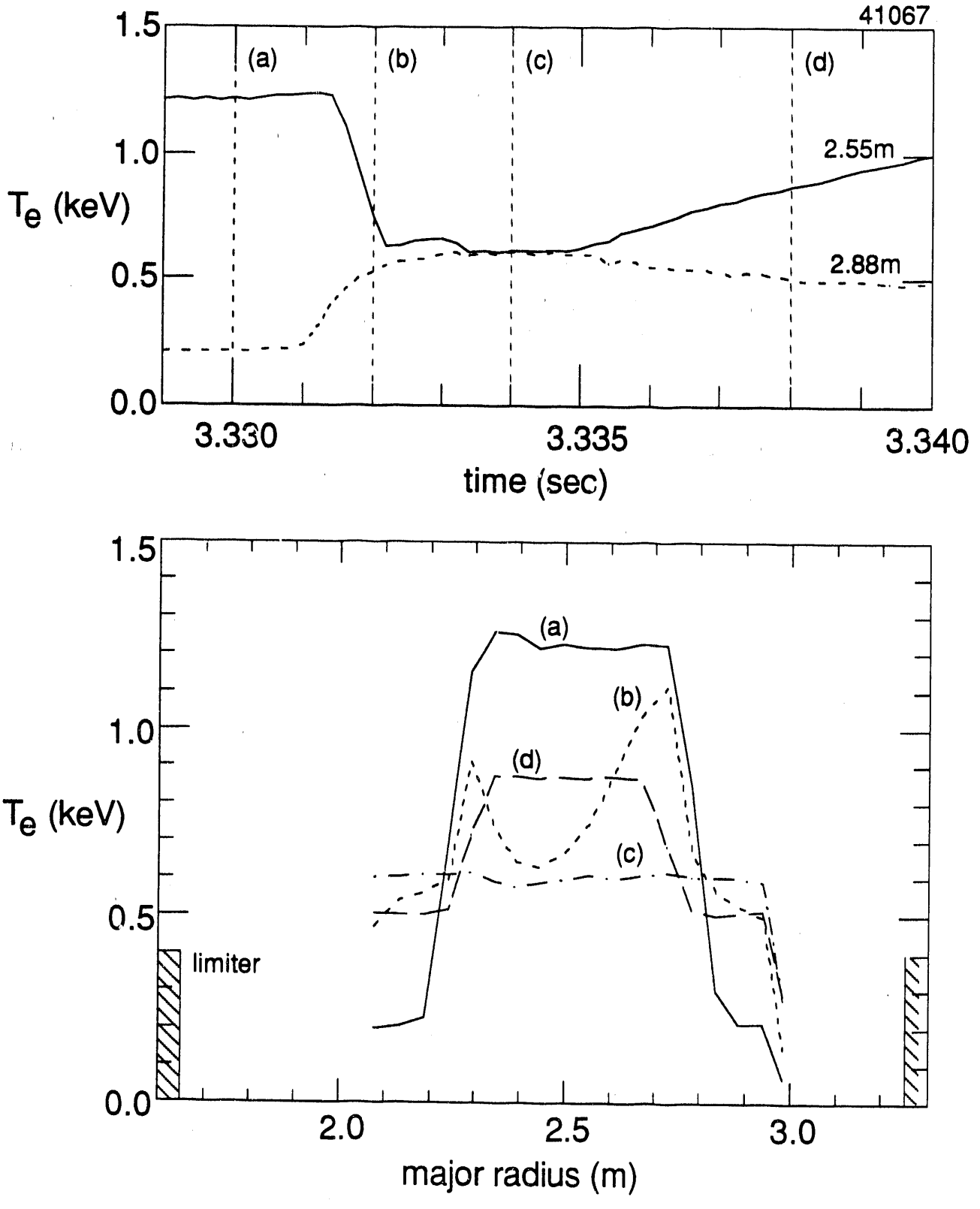
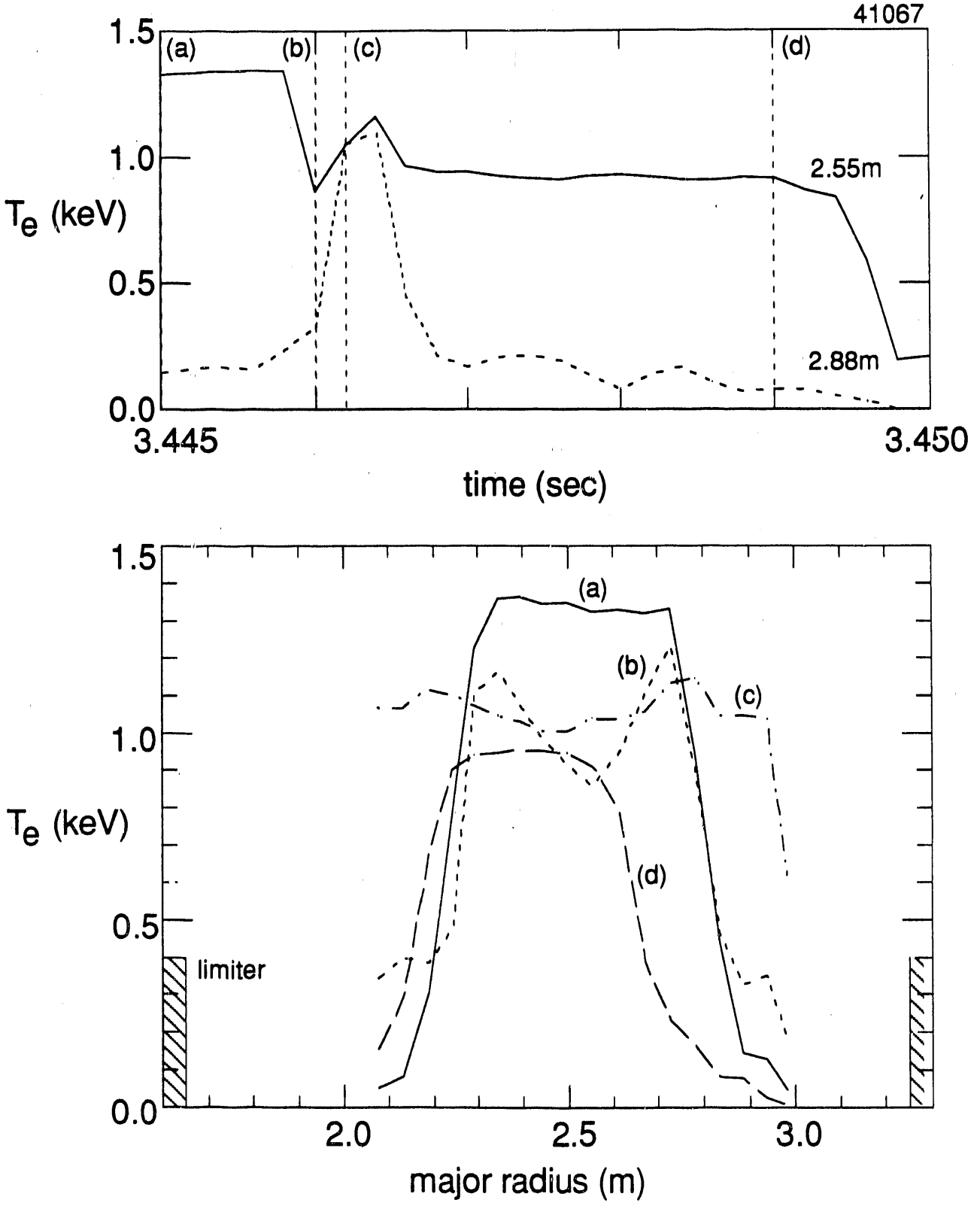

41067
(a)
(b)
(c)
(d)
2.55m
2.88m
1.5
1.0
0.5
0.0
T_e (keV)
3.330
3.335
3.340
time (sec)
(a)
(b)
(c)
(d)
limiter
2.0
2.5
3.0
major radius (m)

Fig. 4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1.5
1.0
0.5
0.0
T_e (keV)
(a)
(b)
(c)
(d)
2.55m
2.88m
3.445
3.450
time (sec)
1.5
1.0
0.5
0.0
T_e (keV)
(a)
(b)
(c)
(d)
limiter
2.0
2.5
3.0
major radius (m)

Fig. 5

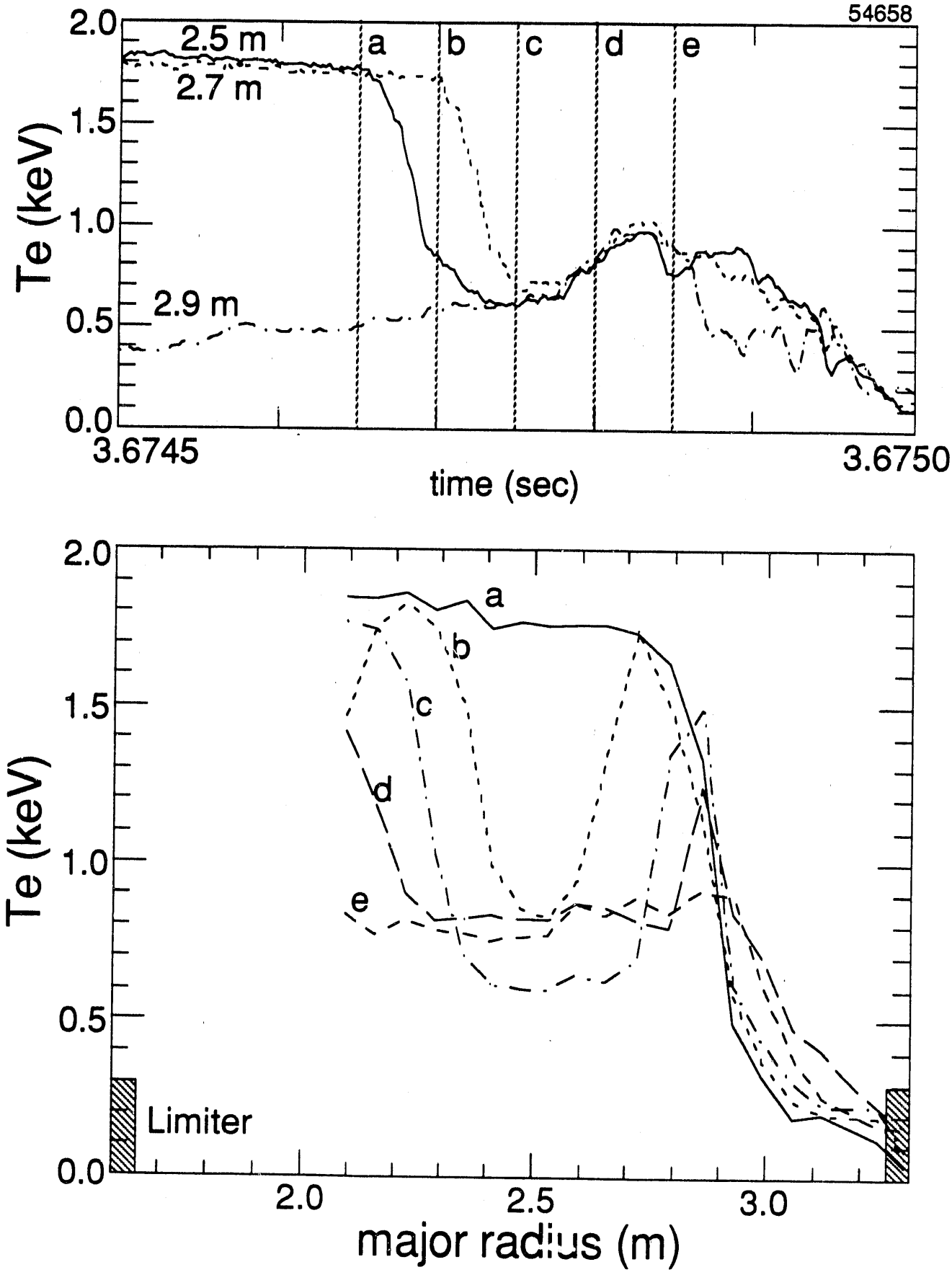
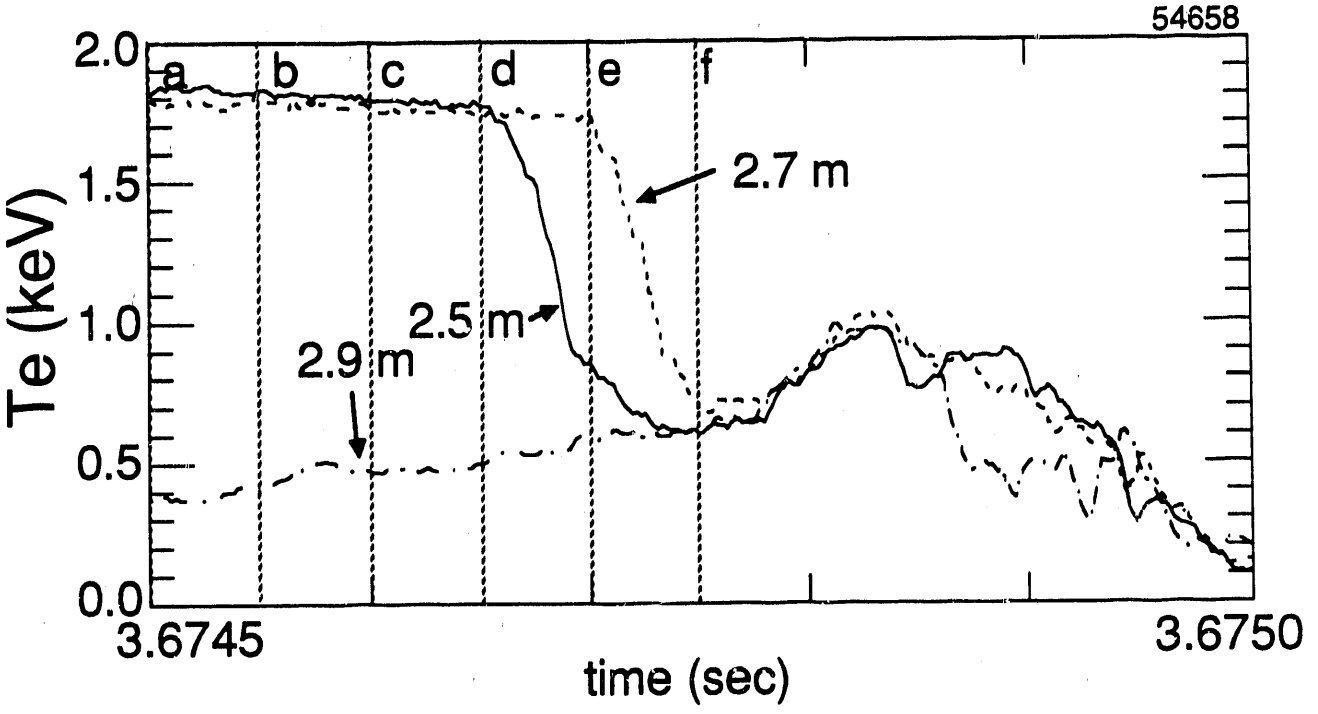

54658
2.5 m
2.7 m
2.9 m
a
b
c
d
e
Te (keV)
2.0
1.5
1.0
0.5
0.0
3.6745
3.6750
time (sec)
Limiter
2.0
2.5
3.0
major radius (m)

Fig. 6a


54658
2.0
1.5
1.0
0.5
0.0
Te (keV)
a
b
c
d
e
f
2.7 m
2.5 m
2.9 m
3.6745
3.6750
time (sec)

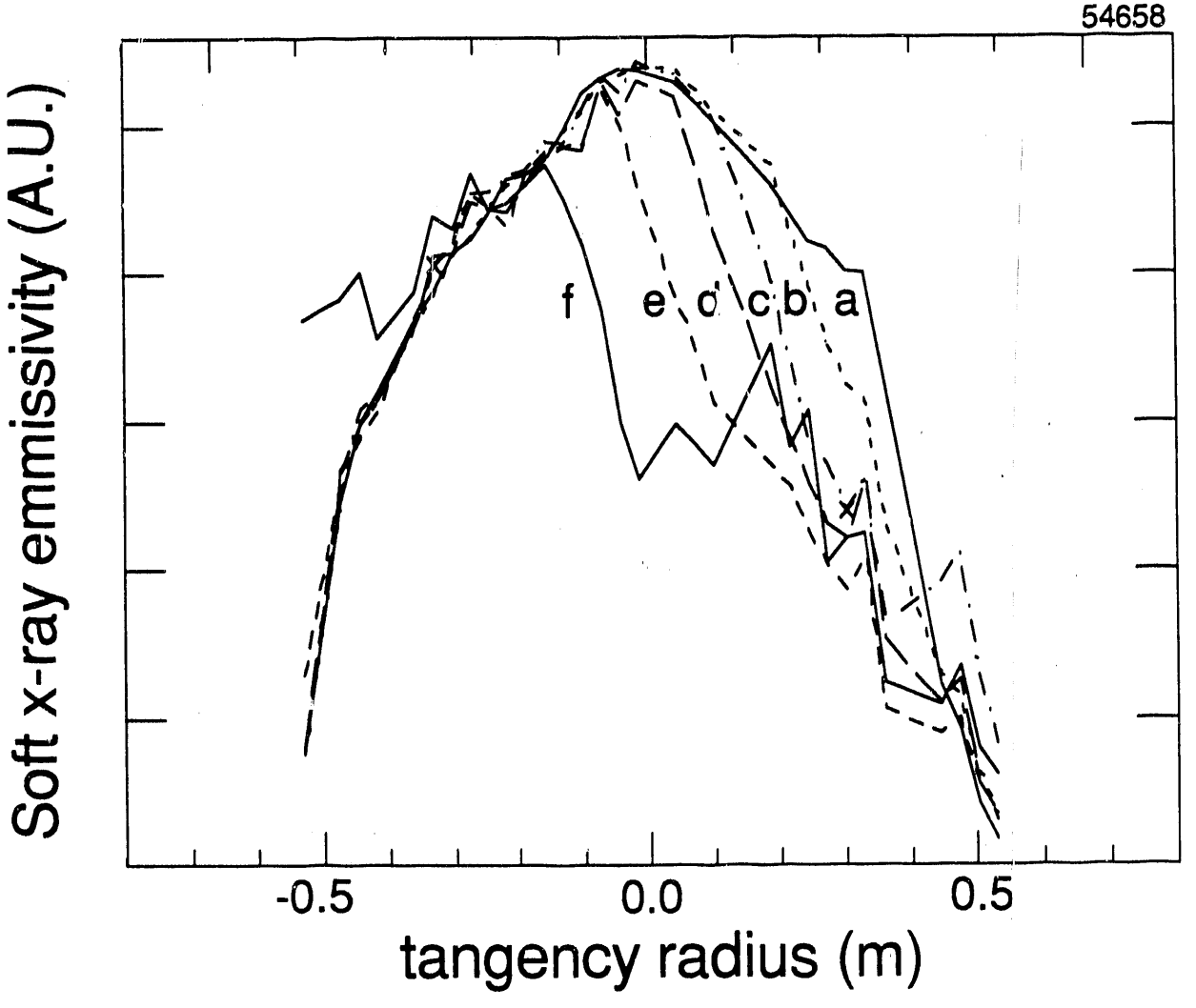

54658
Soft x-ray emmissivity (A.U.)
f
e
d
c
b
a
-0.5
0.0
0.5
tangency radius (m)

Fig. 6b

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