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The high density and high β_{pol} disruption mechanism on TFTR

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Studies of disruptions on TFTR have been extended to include high density disruptions as well as the high β_{pol} disruptions. The data strongly suggests that the (m,n)=(1,1) mode plays an important role in both types of disruptions. Further, for the first time, it is unambiguously shown, using a fast electron cyclotron emission (ECE) instrument for the electron temperature profile measurement, that the (m,n) = (1,1) precursor to the high density disruptions has a 'cold bubble' structure. The precursor to the major disruption at high density resembles the 'vacuum bubble' model of disruptions first proposed by Kadomtsev and Pogutse.

Previous studies of disruptions in hot, high β_{pol} plasmas on TFTR have revealed that the precursor is an (m,n) = (1,1) mode[1]. However, reconstructions of the precursor indicate that it has a kink-like (rather than island-like) structure. This precursor is found to have a very rapid growth rate, often in excess of 10^3/sec. A large, non-thermal burst of electron cyclotron emission lasting 100 - 200 μsec is observed before the thermal transport phase. The thermal transport phase is a rapid (≈200 μsec), structureless collapse of the electron temperature profile.

Studies of disruptions in ohmic plasmas at high density have also found that an (m,n)=(1,1) mode plays an important role. Examples of minor and major disruptions will be discussed below where the precursor has the form of a (1,1) 'cold bubble' or 'vacuum bubble'. Examples of major and minor disruptions in an 0.7MA ohmic plasma are shown in Fig. 1. The minor disruption begins with a growing hollowness of the electron temperature profile measured on the midplane. 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 figure 1, the inversion radius is 0.28m (near q=1.5) and the mixing radius extends nearly to the q=3 surface at r=0.49 m. The measured Λ ($\equiv \beta_{pol}^{equil} + l_i/2$) remains unchanged, suggesting no change in the internal inductance. 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 $q \approx 3$ surface, there is no evidence for a similar re-distribution 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. 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 for the major disruption ($\gamma \approx 5 \times 10^3$ s^{-1}) is about 5 times faster 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. 1), suggesting a redistribution of plasma current. (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 $\approx$ 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 milli-seconds 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 difference between the minor and major disruptions may be understood in the following context: 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 $\delta r << r_s$). 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 $\delta r \approx 0.037$m while for the major disruption $\delta r \approx 0.021$ m. Thus, the reconnection layers are quite narrow. The effective resistive timescale is approximately $\tau_R = 4\pi(\delta r)^2/\eta c^2$. For the minor disruption the bubble growth time, $\tau_b \approx 0.8$ms while $\tau_R \approx 3.3$ms (based on the 200 eV edge temperature). Thus, since $\tau_b << \tau_R$, the mode in this case must be categorized as an internal kink. The internal kink has little effect on the current profile, producing 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 be expected to change significantly as a result of the modification of the current profile by the external kink.

For the major disruption, $\tau_b \approx 0.2$ ms and $\tau_R \approx 0.34$ ms (based on the 100 eV edge temperature) so that $\tau_b \approx \tau_R$. Thus, the formation of the bubble in the case of the major disruption is driven by a quasi-external kink. The external kink can produce 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 led to significant broadening and disruption of the current in a recent 3-D resistive MHD simulation of the density limit[2].

The internal (m,n) = (1,1) cold bubble precursor structure has also been seen in disruptions at moderate density and low q(a) ($\approx$ 2.5) (Fig. 2). 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. In 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 2×10^4 m/s. The growth rate of the precursor mode inferred from this measurement is $\gamma \approx 1 \times 10^4\ s^{-1}$.

These studies of high density and high β_{pol} disruptions on TFTR have shown that, while there are important differences, the disruption precursor in both cases has a large growth rate and an (m,n) = (1,1) structure. While it is not known which type of disruption is more relevant to reactor plasmas, in either case the nature of the instability precludes active external feedback control. The high density disruption studies do suggest that active control of the edge temperature might be used to prevent the major disruption.

Acknowledgements -

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[1]E D Fredrickson, K M McGuire, et al., IAEA, Washington DC, Oct 1990.

[2]R G Kleva and J F Drake, Phys. Fluids B 3 (1991) 372.

Figure 1

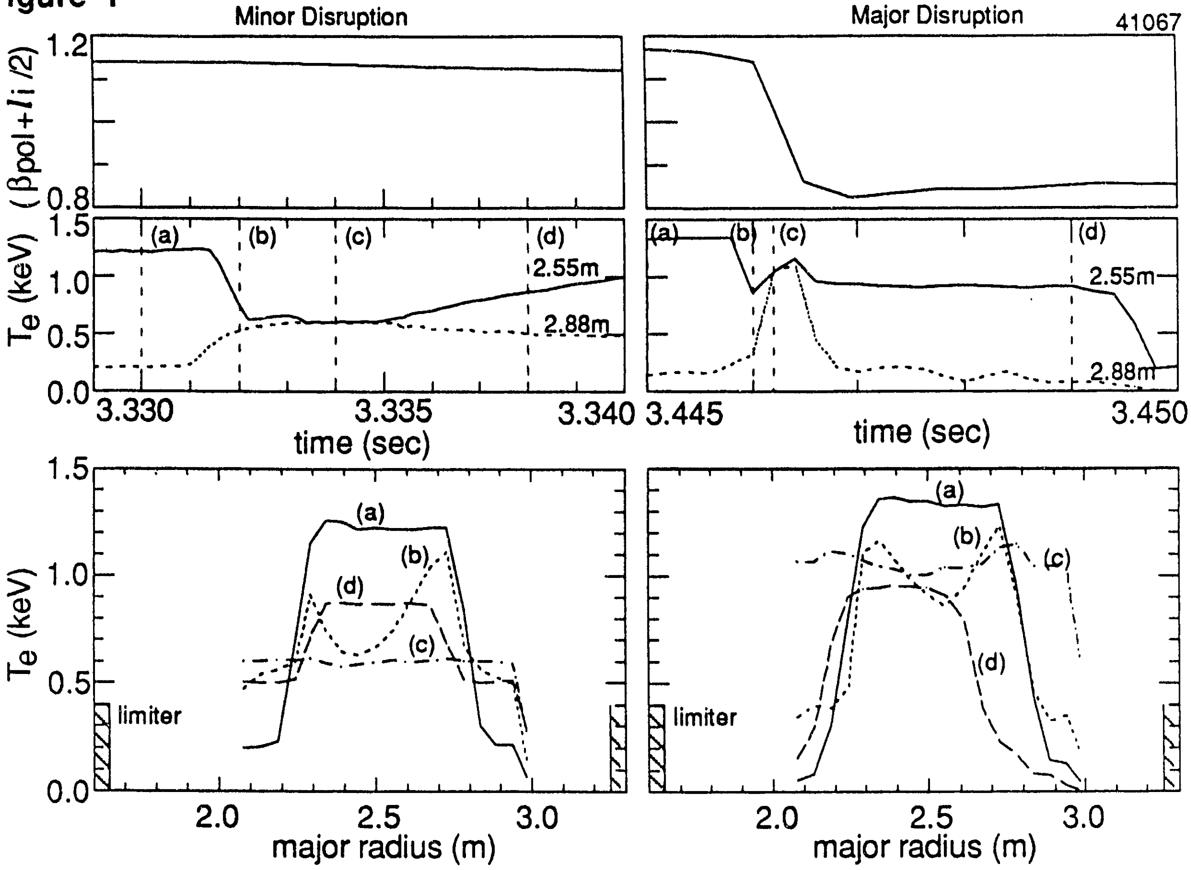
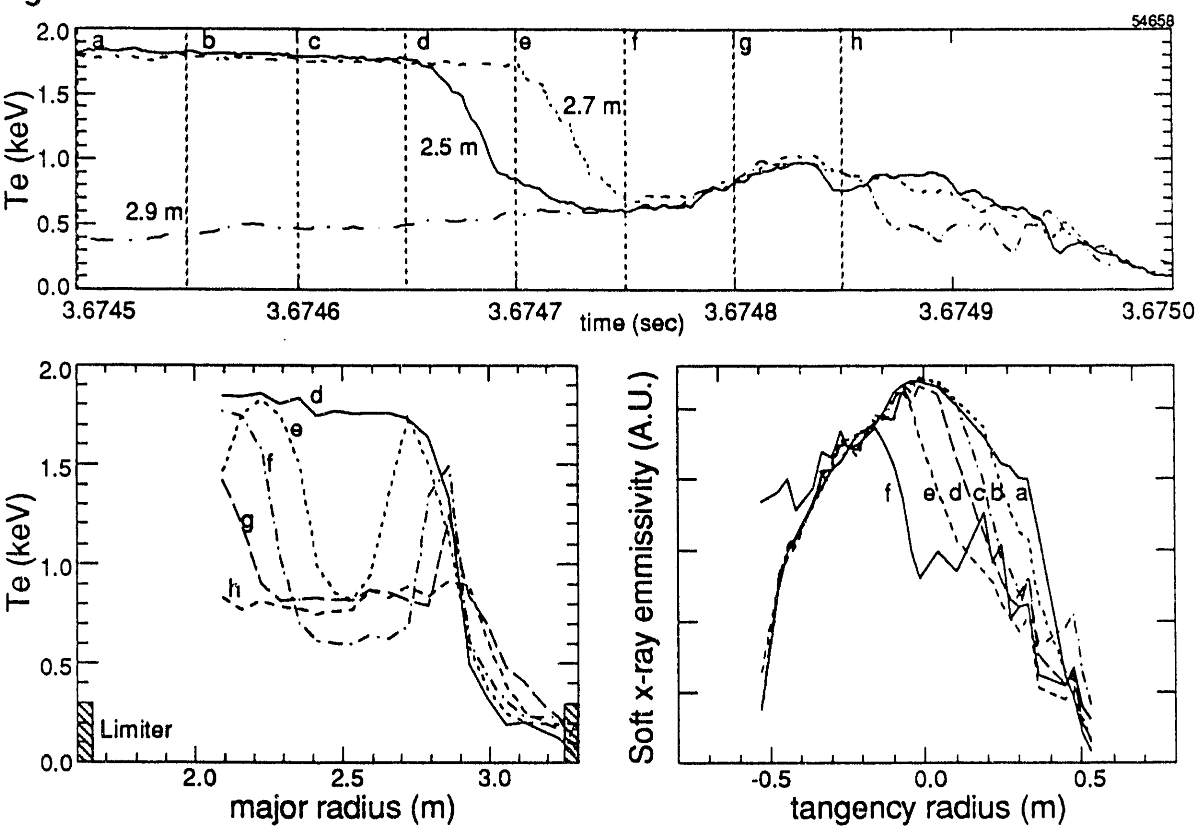


Figure 2



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