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Comparison of Sawtooth Phenomenology on TFTR and DIII-D,

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An experiment to study sawtooth phenomena and to find the threshold for sawtooth stabilization with neutral beam injection heating, as was commonly observed on TFTR, has been done on DIII-D. In the experiments, with co-tangential neutral beam injection at powers of up to 13MW, the sawtooth period was observed to increase to of order 250 msec. Stabilization of the sawteeth for the length of the high power NBI (05.-0.8 sec) was not observed. The sawtooth characteristics were studied with fast electron temperature (ECE) and soft x-ray diagnostics. Fast, 2 msec interval, measurements were made of the ion temperature evolution following the sawtooth to document the ion heat pulse characteristics. These data show that the ion heat pulse does not exhibit the very fast, "ballistic" behavior seen for the electrons. The current profile and other equilibrium profiles were measured on slower time scales. These results are compared to the data from similar studies carried out on TFTR.

Sawtooth Stabilization with Neutral Beam Injection

Stabilization of sawteeth with Neutral Beam Injection was commonly observed on TFTR. The sawtooth stabilization generally occurred only in high performance plasmas (greater than L-mode scaling energy confinement), which were well correlated with low recycling limiters and peaked density profiles[1]. The central q was measured to be well less than unity in these plasmas using a Motional Stark Effect (MSE) diagnostic. This attempt to stabilize the sawteeth on DIII-D failed, perhaps because the density peaking wasn't sufficient or because shaping affects the sawtooth instability. In Fig. 1 is shown the evolution of q(0) at high and low NBI power as measured with the MSE diagnostic

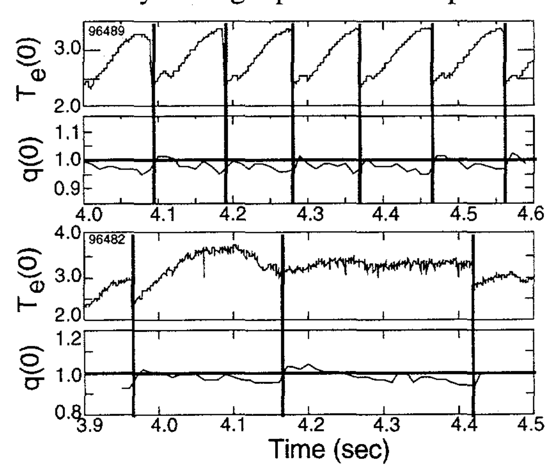

Figure 1. Central electron temperature and q(0) evolution for DIII-D plasmas heated with 7 MW (top) and 11 MW of neutral beams (bottom).

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on DIII-D, with Te(0) also shown to clearly indicate the sawtooth crash times. In the higher power shot the sawtooth period has increased to about 250 msec, however, the q(0) has not dropped to a lower level than in the lower power shot. The most striking difference between sawteeth on DIII-D and TFTR is that q(0) rises to approximately unity during a sawtooth crash on DIII-D, but remains well below one in TFTR[2].

Stabilization of sawteeth on TFTR was found to be easier to achieve with low density target plasmas, although the sawtooth stabilization would persist to a substantial fraction of the Greenwald limit. It was speculated that the stabilization was related to density peaking through ω^* terms. The inability to stabilize sawteeth with NBI on DIII-D might be due to any of many differences between DIII-D and TFTR including less density peaking than on TFTR, plasma shaping, or differences in the NBI injection energy (although the NBI fast ion beta fractions are comparable in TFTR and DIII-D. The fractional contribution of fast ions from Neutral Beam Heating to pressure as calculated with the TRANSP code is comparable in TFTR and DIII-D. For example, with 7 MW of neutral beam heating, TRANSP calculates that 40% of the on-axis pressure is from fast ions in DIII-D.

Sawtooth Precursor Characteristics

Other than the behavior of q(0), many aspects of the sawtooth instability appear similar in TFTR and DIII-D. Both have a "ballooning" m=1 precursor structure, fast growth of an m=1 island towards end of precursor stage, and ballistic heat pulses. A contour plot of the local electron temperature through a typical sawtooth on TFTR as measured with a 2nd harmonic grating polychromator is shown in Figure 2. Temperature contours are drawn every 0.5 keV, the signals are digitized at 500 kHz. As is typical, the precursor is present at nearly constant amplitude for many milliseconds, followed by a period where the island grows rapidly. In this case the growth starts approximately 100 μsecs before the crash. In this example, the precursor oscillations are essentially confined within the q=1 surface until

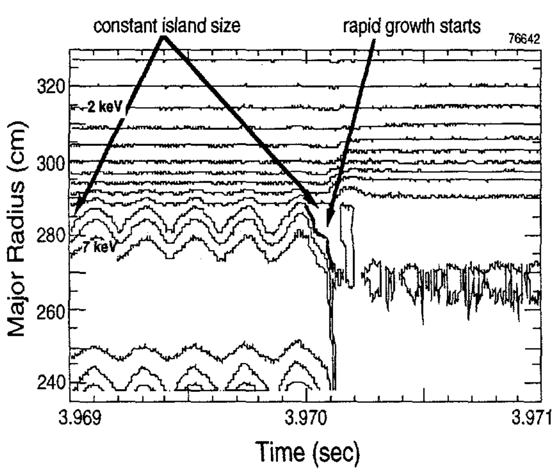

Figure 2. Contour plot of the electron temperature vs. major radius and time showing the m=1, n=1 sawtooth precursor.

the last oscillation, indicating that coupling of the m=1 to higher poloidal harmonics is weak. There is wide variation in this behavior; in a very similar plasma, the sawtooth precursor began to grow 700 μsec prior to the crash and much stronger poloidal coupling was observed (not necessarily correlated).

For comparison, a sawtooth precursor as measured with the heterodyne radiometer on DIII-D is shown in Figure 3. Contours are also shown every 0.5 keV and the digitization rate is 100 kHz. The characteristic precursor frequency (plasma rotation rate) is 15 kHz, vs. the 5 kHz in the TFTR example. The general behavior is very similar with the precursor present for many msec at nearly constant amplitude, followed by a final rapid growth phase. In this case the rapid growth begins 300 μsecs before the sawtooth crash. The coupling to poloidal harmonics is stronger, seemingly a general characteristic of DIII-D sawtooth precursors.

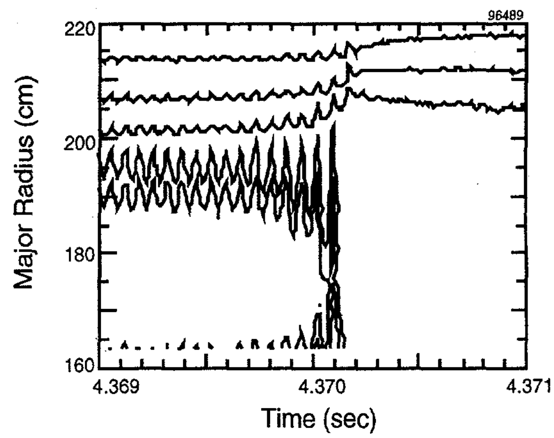

Figure 3. Contour plot similar to Figure 2 for a sawtooth in DIII-D. The poloidal coupling is stronger in this case.

Despite the lower bandwidth and higher characteristic MHD frequencies which preclude very detailed reconstruction of the sawtooth precursor in this data set, it is possible to see that the sawtooth precursors have the classic "cold island" structure typically seen in TFTR sawtooth precursors.

Heat Pulse Propagation Studies

The "ballistic" contribution to the electron heat pulse was strong on DIII-D, similar or stronger than that seen on TFTR[3]. It has been postulated that the "ballistic" effect is the result of a strong enhancement in the thermal diffusivity weakly localized in the region around the q=1 surface. Modeling studies based on TFTR data suggested that the enhancement is present for a short time during and after the sawtooth reconnection. Evidence for this enhancement is seen in Fig. 3 where the temperature is starting to increase outside the reconnection radius even during the sawtooth crash. The effect is summarized in Figure 4 where the measured post-crash temperature profile is compared to a Kadomtsev-like reconnection applied to the pre-crash profile. The simulated post-crash profile is hollow, as expected due to the low central shear and larger shear near the q=1 surface. The experimental post-crash profile is rounded, not hollow, consistent with an enhancement in the thermal diffusivity during the sawtooth crash.

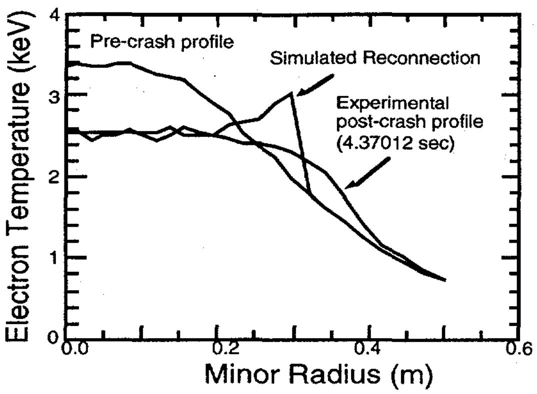

Figure 4. Simulated post-crash temperature profile using measured q(r), precrash Te(r) and Kadomtsev model.

Experiments on TFTR showed that the sawtooth induced density pulse was much slower than the temperature pulse, consistent with a model that the electron heat transport was enhanced by weak magnetic stochasticity generated during the sawtooth crash. The parallel electron heat transport will be much faster than the parallel density transport. The ion heat parallel heat transport should also be slow, thus the ion heat pulse might not be expected to be greatly affected by weak magnetic stochasticity. Further, ion perpendicular heat might be less affected if the scale lengths for the magnetic stochasticity were shorter than the ion larmor radius. Until recently direct measurements of the ion heat pulse were not possible[4]. In this experiment measurements of the ion temperature profile were made at 2 msec intervals using the CER system. The speed and sensitivity was sufficient to have detected a ballistic response in the ion heat transport (Fig. 5). The sawtooth generated heat pulse in the region immediately outside the reconnection radius is weak, however, at larger minor radius, strong, fast heat pulses are observed. It is speculated that they could arise if the electron heat pulses affected, in a nonlinear manner, the ion transport coefficients, but detailed simulations remain to be done. There is also a modulation of the ion and electron temperatures at about the sawtooth period whose origin is not understood at this time.

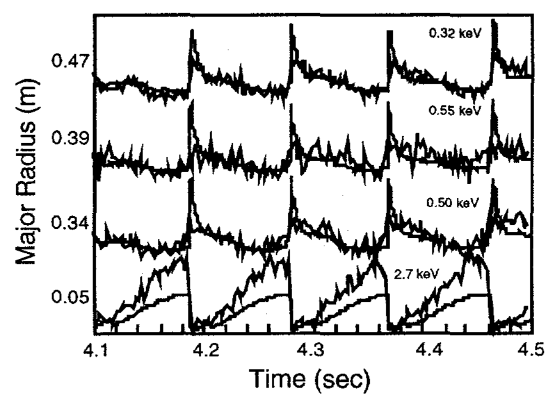

Figure 5. Ti (bold) and Te heat pulses overlayed at several radii.

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