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Correlation between excitation of Alfvén modes and degradation of ICRF heating efficiency in TFTR

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Abstract. Alfvén modes are excited by energetic ions in TFTR during intense minority ICRF heating. There is a clear threshold in rf power above which the modes are destabilized. The net effect of these modes is the increase of the fast ion losses, with an associated saturation of the ion tail energy and of the efficiency of the heating. Typically, several modes are excited with progressive n-numbers, with frequencies in the neighborhood of 200 kHz. Results suggest that Energetic Particle Modes (EPM), mostly unseen by the Mirnov coils, are generated near the center and are responsible for the ion losses. Stronger global TAE modes, which are destabilized by the stream of displaced fast ions, appear responsible only for minor losses.

ICRF MINORITY HEATING

The ICRF experiments in TFTR[1] have been conducted in Deuterium plasmas with either Hydrogen or Helium-3 minority species, with plasma currents between 1.1 and 1.9 MA, central magnetic fields 3.0 to 4.5 T and densities ~3 10^{19} m^{-3}; frequencies used were 43, 47 and 63.6 MHz, never simultaneously, and power up to 11 MW. In all cases, strong electron heating is observed; in general, the total energy of the plasma initially increases linearly with rf power, then at a certain level, the rate of increase diminishes. It is at this power level that MHD activity is detected[2] and simultaneously, probes placed at the edge of the plasma[3] register a sudden increase of lost fast ions.

Figure 1a shows the increase of the total and thermal energy of the plasma as a function of rf power. Three stages are distinguishable: at first, the increase is linear and equal for the total energy and the thermal component. In this regime ion-ion collisions dominate and the ion distribution function does not present asymmetries[4]. As the rf power and the ion energy increase, electron drag begins to dominate and the asymmetric part of the distribution function appears: at the same time low levels of fast ion loss are dectected.

Finally, at higher power (in this case ~4 MW) ion losses increase drastically and the Mirnov coils detect a signal which increases linearly with power. In this regime, confinement is clearly degraded.

The dynamics of the process which culminates in the fast ion losses is clearly visible in the example of figure 2.

The rf power is above the threshold for Alfvén mode destabilization and they appear ≈40 msec after the turn-on.This can be considered the time to form the energetic tail, whose beta and gradient are responsible for the destabilization itself. Because of the ion losses, a saturation is reached, until a "monster" sawtooth takes place. This results in a burst of fast ion loss, and a redistribution of the fast ions and a small change in total ion energy. The fast ion pressure gradient falls below the instability threshold and the mode amplitude drops greatly. As the tail rebuilds, the mechanism repeats itself.

This suggests a possible way to avoid or delay the onset of the instability. Since it is the formation of the gradient of the tail which destabilizes the modes, by either creating the tail in different locations of the plasma (using multiple frequencies, frequency modulating the rf power or by "swinging" the magnetic field), it would be possible in principle to control the fast particles' pressure profile and avoid the Alfven modes destabilization.

ALFVÉN MODES

Typically, the Alfvén spectrum consists of a fundamental mode with toroidal n-number between 4 and 9, and a number of other modes characterized by n+1, n+2... The poloidal number is not uniquely determined, consistent with the fact that an individual Alfvén Eigenmode has a spectrum of m-numbers.

Often, superimposed to this spectrum, a mode with rapidly decreasing frequency is observed. This mode(s) appears to originate near the center of the discharge where the fast ion tail is formed, but it is seen only extremely weakily by the Mirnov coils while localized in the core.As the mode propagates towards the edge, it carries with itself the fast particles, the frequency decreases (whistle) and eventually it is detected more clearly by the Mirnov coils. Such a mode is particularly deleterious, because it transports the fast ions toward the edge, unlike the "stationary" modes (see figure 3) which cause only a shifting back and forth of ions, with consequent low losses.

Confirmation that the "whistling" mode originates near the core has been obtained by measuring the density fluctuations in the core with a microwave reflectometer.[5]

The "stationary" modes display frequencies which are independent of the rf power applied: unlike the "wistling" modes, they do not readily disappear at the monster sawtooth crash, but rather, often they are destabilized at the crash. Figure 4 shows a shot in which after a monster sawtooth, a smaller one takes place. No modes are present immediately before, seemingly because the tail did not have enough time to reform and go above threshold, but a strong burst of "stationary" modes is observed, which lasts ≈40 msec. In spite of the strong signal from the Mirnov coils, the signal from the lost fast ions detector is fairly small.

The "whistling" modes have all the characteristics of Energetic Particle Modes (EPM)[6,7] generated by the fast ion tail near the center, such as the decreasing frequency and the localization, while the "stationary" modes are global TAE modes.

We can therefore postulate the following scenario: ICRF power forms an energetic tail of fast ions near the resonance, in this case inside q=1. As the energy and the gradient of this tail increases above a threshold, core-localized EPMs are excited and as their frequency decreases, a stream of fast ions is expelled. Some are lost, some are displaced in the outer region of the plasma. When this "cloud" of particles is disturbed, either by the EPMs or simply by a sawtooth, it excites in turn a "secondary" TAE modes: losses from this secondary mode appear to be lower. While this scenario is plausible it must be admitted that the difficulty in detecting the core localized EPM does not rule out that in a minority of cases the global TAE exists without the EPM.

CONCLUSIONS.

ICRF minority heating produces an energetic ion tail near the resonance. When the pressure from this tail excedes the threshold for Alfvén wave excitation, an EPM starts plowing fast ions toward the edge of the plasma, causing severe losses. Being a core localized mode, it is detected only with microwave scattering and is seen by Mirnov coils only when it moves toward the outer part of the plasma. During this process of shifting particles, global TAE are excited with well defined frequency which corresponds to a localization near q≈1.5. The global TAE are also destabilized by sawteeth, but the losses associated to them are less severe than for the EPMs.

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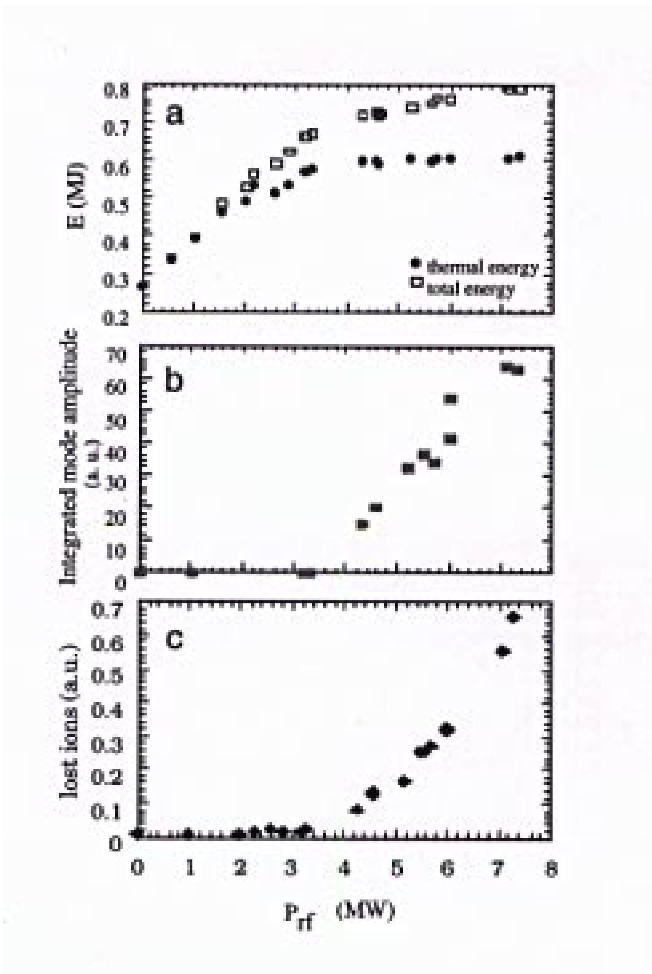

Figure 1 Correlation between onset of MHD instabilities with fast ion losses and energy confinement degradation, versus rf power.

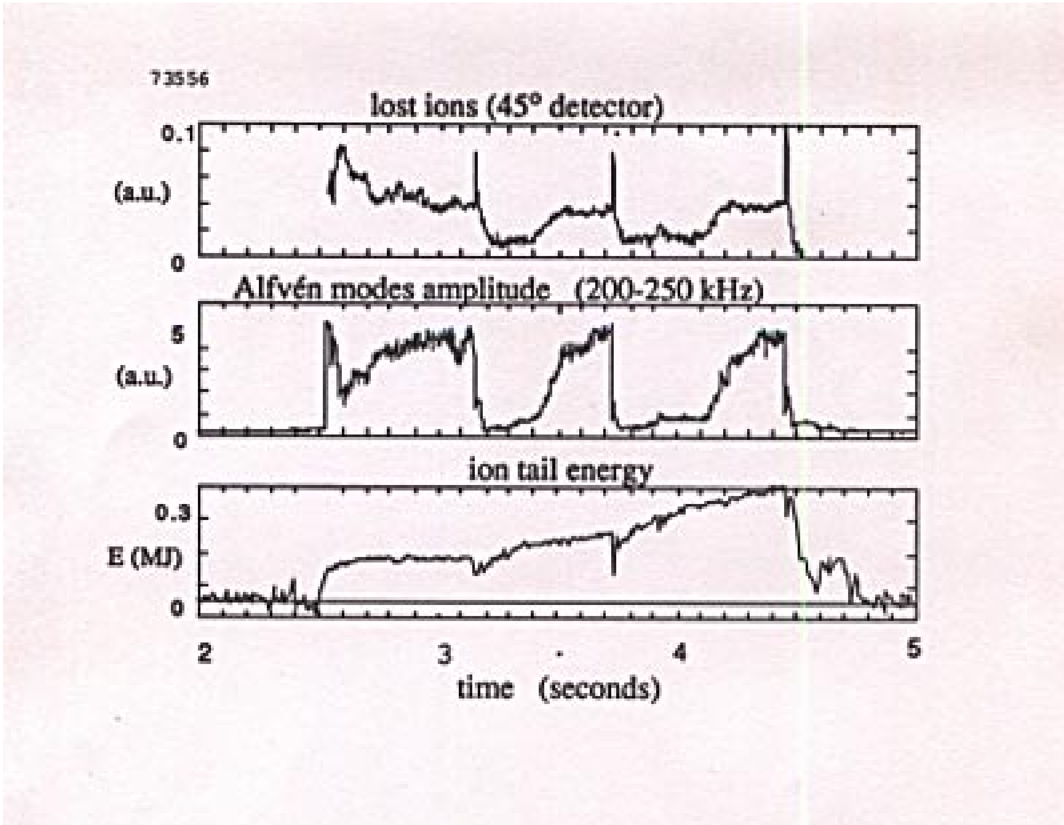

Figure 2 Time evolution of lost particles signal, MHD modes amplitude and tail energy during injection of 4.7 MW of ICRF power between 2.5 and 4.5 seconds. (I_p=1.68 MA, B_o=30 kG, n_e=2.7 10^{13} cm^{-3}, f_o=43 Mhz).

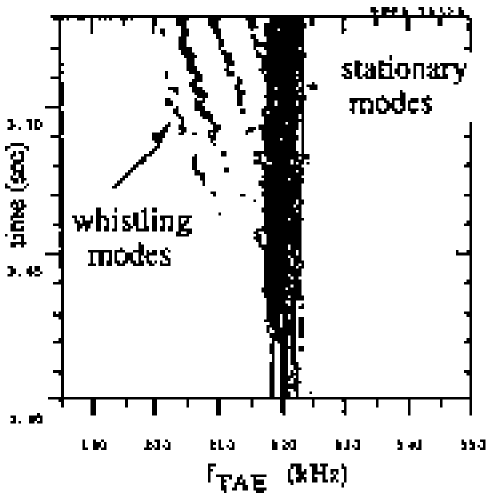

Figure 3 Frequency spectrum versus time showing the frequency-decreasing modes ("whistling") and the "stationary" modes. (same conditions as in Figure 2, with P_{rf}=6.5 MW)

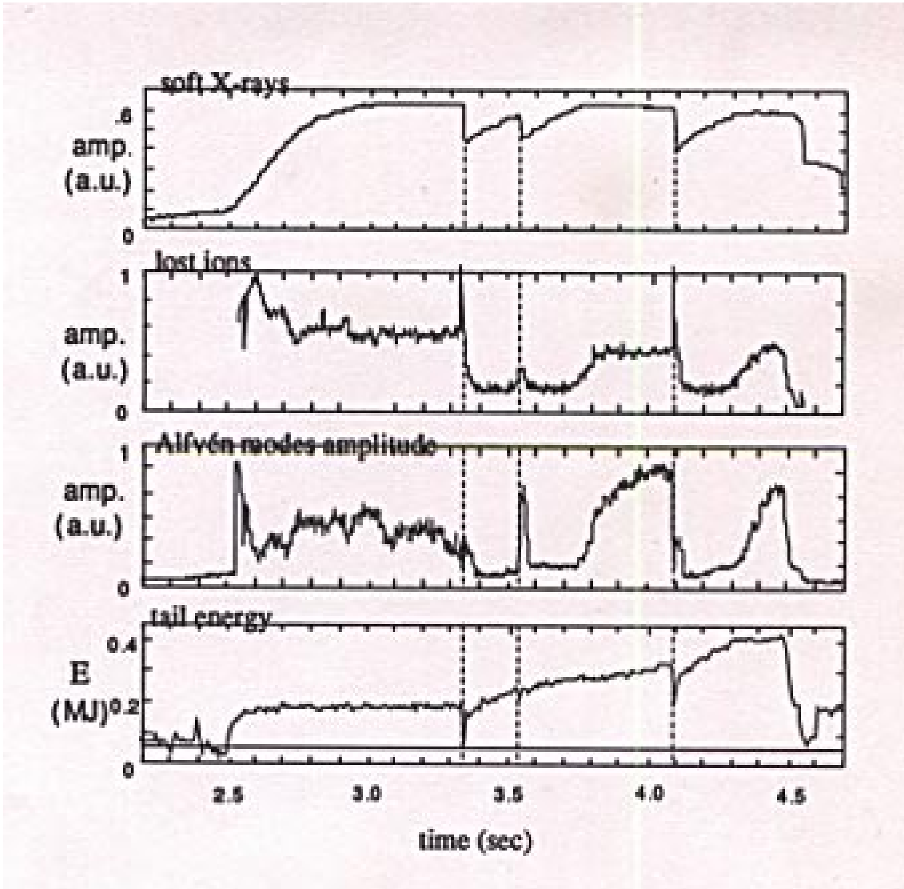

Figure 4 Correlation between soft X-ray, lost particles and TAE modes intensities and tail energy in a TFTR discharge similar to the one in Figure 2, with P_{rf}=4.8 MW.