

Fast Particle Driven Modes in Alcator C-Mod

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Introduction Closely spaced poloidal field pick-up coils mounted to the inner wall and two outboard limiters sampled at 1 – 2 MHz have been used to measure high frequency (150 – 900 kHz) modes during hydrogen minority ICRF heating at $B_T = 5.4$ T in Alcator C-Mod. Such high frequency modes are observed only under two different conditions: with low or reversed shear ($1/q \, dq/dr$) during strong heating in the current rise [1], and in steady-state Enhanced D_α (EDA) H-mode [2]. These modes are not observed in any ohmic plasmas or in ELM-free H-modes. In the low shear current rise cases, there are often multiple modes with frequencies that can increase or decrease very rapidly from 150 – 450 kHz in as short as 15 – 20 ms. In the EDA cases, there is usually only one high frequency mode present with nearly constant frequency between 500 – 900 kHz persisting for up to hundreds of ms. The current rise modes rotate in the ion diamagnetic drift direction with frequencies in the Toroidal Alfvén Eigenmode (TAE) range. The mode frequencies in the EDA H-mode cases are also in the TAE range, but these modes rotate in the electron diamagnetic drift direction.

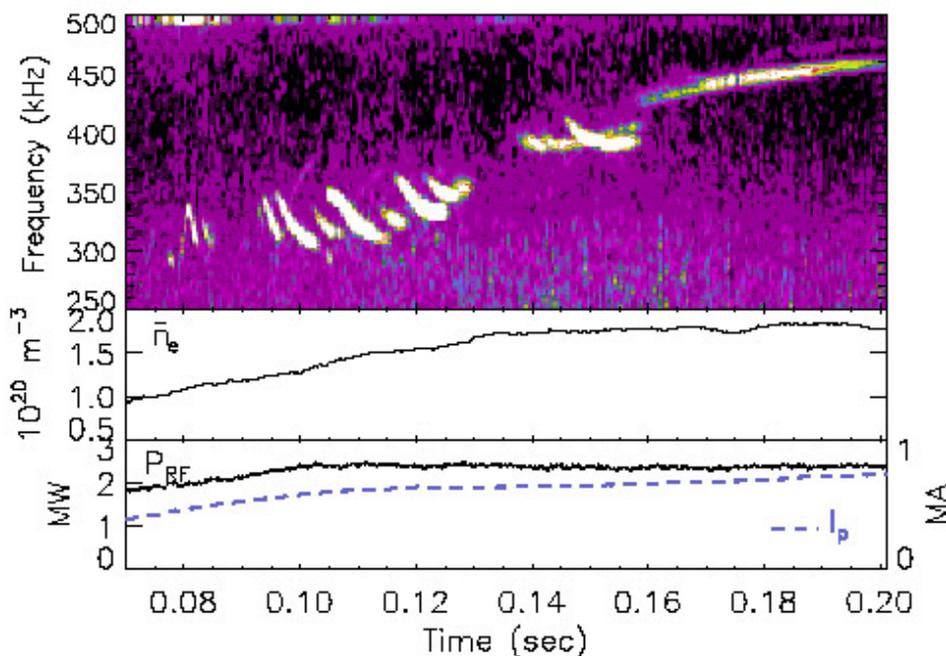


Fig. 1. Fast Fourier Transform showing bursts of multiple coherent high frequency magnetic modes during strong ICRF heating in the current rise. Larger mode amplitude is shown brighter.

Current Rise Heating Attempts to achieve reversed shear through strong ICRF heating in the current rise create multiple high frequency modes as shown in Figure 1. In this case, the

frequency decreases rapidly from say 350 to 300 kHz in less than 10 msec for a series of modes. The ICRF hydrogen minority resonance is on axis, which is expected to drive a fast H ion tail with a centrally peaked fast ion pressure profile. TAE modes are expected to be more unstable at low shear [3]. As the current rises, the central q value drops and the steep gradient region in the fast ion pressure profile should pass through several resonances, which could then explain the multiple modes observed. These modes typically have low n and appear to rotate in the ion diamagnetic drift direction, which is expected for TAE modes. The measured frequencies $\omega = 2\pi f \sim \omega_{\text{TAE}} \approx v_A/(2qR)$ for resonant q values between 1.5 and 2.75. Equilibrium calculations of the q profile indicate that $q(0) > 1$ throughout this time window, which is further confirmed by the onset of sawteeth just after 0.22 sec, consistent with interpreting these modes as TAE's.

Similar current rise discharges have modes with linearly increasing frequency from 150 – 450 kHz in less than 0.015 s. The change in density and the estimated change in q profile are insufficient to explain such rapid frequency changes with linear theory. Nonlinear models of frequency “chirping” [4] may possibly explain these rapid changes in frequency.

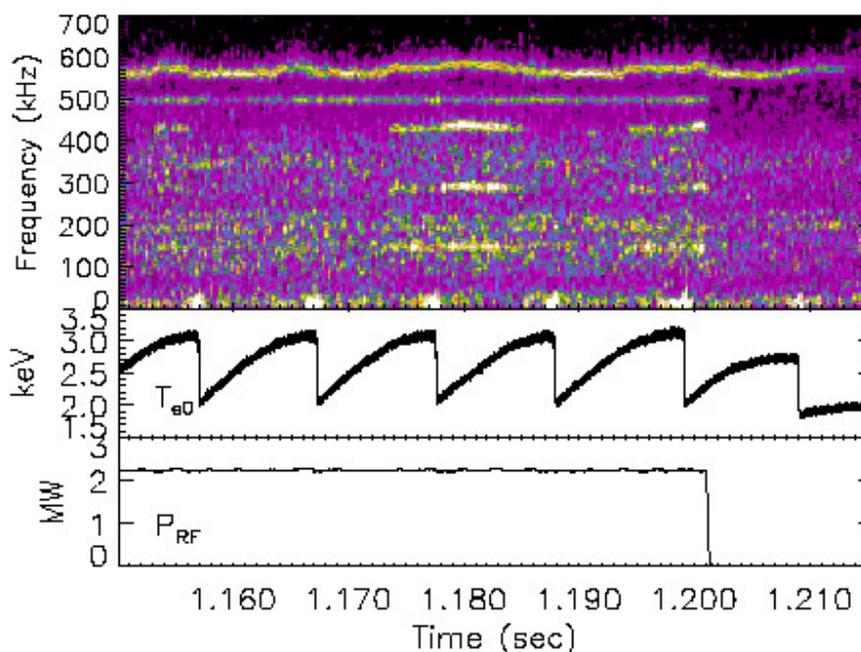


Fig. 2. Fast Fourier Transform showing a high frequency mode near 600 kHz that persists after the ICRF switches off at 1.2 sec together with the central electron temperature and the ICRF power.

Enhanced D_α H-mode In steady-state Enhanced D_α H-mode, high frequency modes are observed with nearly constant frequency, such as the ~ 600 kHz mode shown in Figure 2 that persists for about 12 ms after the RF is switched off. The 500 kHz beat wave between the two ICRF antennas that are driven at 80.0 and 80.5 MHz is also clearly visible together with several other bursting modes at nearly 150, 300, and 450 kHz. The persistence of the high frequency mode after the RF switches off together with its high frequency in the TAE range

suggest that it may be driven by fast particles. Under these conditions ($\bar{n}_e = 2.5 \times 10^{20} \text{ m}^{-3}$, $T_e(0) = 2.5 \text{ keV}$), the slowing down time of a 40 keV fast H ion is about 12 msec. In cases with particularly large sawteeth, the mode frequency is modulated by the sawteeth by about 3 – 5% with the frequency increasing sharply just after the sawtooth collapse then slowly decreasing during the rise of the next sawtooth. Such a change in mode frequency with the sawtooth would be consistent with a TAE mode within the $q = 1$ surface if the central density falls by 6 – 10% at the sawtooth collapse.

In contrast to the current rise modes, these high frequency modes have typical toroidal mode numbers $n = 5 - 7$ and appear to rotate in the electron diamagnetic drift direction. Plasma toroidal rotation, measured by Doppler shift of argon ions in the core, is in the ion diamagnetic drift direction with values of 5 – 25 kHz. In some cases, several simultaneous high frequency modes are observed with increasing frequency and increasing n numbers, such as $n = 5$ (473 kHz), 8 (546 kHz), and 11 (620 kHz), all rotating in the electron diamagnetic drift direction. These data suggest that the multiple n modes are Doppler shifted by a local plasma rotation of about 25 kHz. But, the core plasma rotation is in the opposite direction to the mode rotation, so the n numbers should decrease with increasing frequency if the modes were core localized modes. These data indicate that the high frequency modes in EDA H-mode may come from the steep gradient edge region where the rotation is believed to be in the electron diamagnetic drift direction based on lower frequency $n=1$ magnetic fluctuation measurements [5]. ASDEX has reported edge TAE modes in ohmic plasmas that also rotate in the electron diamagnetic drift direction [6]. In C-Mod, however, these modes are not observed in ohmic plasmas.

Fast Particle Calculations The TRANSP code with FPPRF/Spruce [7] has been used to calculate the fast particle distribution for a current rise ICRF heated discharge in which there was a mode with linearly ramping frequency from 200 – 400 kHz. The calculated parallel and perpendicular fast particle energy profiles and the ICRF power deposition are shown in Figure 3. The perpendicular fast particle energy peaks above 150 keV in this relatively low density case with $\bar{n}_e \approx 1 \times 10^{20} \text{ m}^{-3}$. Although there are large uncertainties in these calculations, the peak energy is certainly sufficient to drive TAE modes under these conditions. A similar calculation for an EDA H-mode case, with $\bar{n}_e \approx 3 \times 10^{20} \text{ m}^{-3}$, including a sawtooth model gave a peaked tail energy of about 30 keV.

Comparison with Theory Calculations of the TAE gap structure were performed with the CSCAS code [8] obtained from JET. Figure 4 shows the gap structure as a function of normalized radius calculated at 0.14 sec for the current rise case of Figure 1 for $n=2$, which was the best estimate of the toroidal mode number from the experiment. The crosshatched

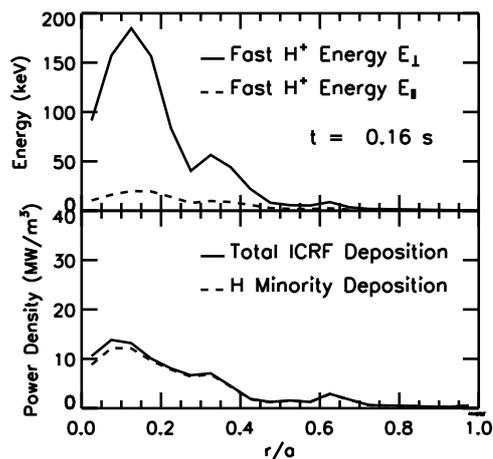


Fig. 3. Perpendicular and parallel fast hydrogen ion energy profiles and the ICRF power deposition profiles calculated for a current rise discharge with a high frequency mode.

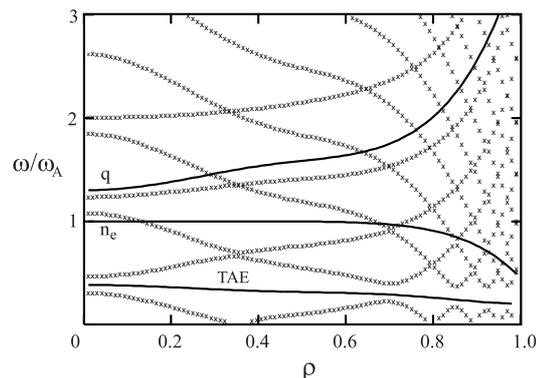


Fig. 4. Calculated TAE gap structure for $n=2$ for the discharge shown in Fig. 1 at 0.14 sec showing a clear TAE gap at $\omega/\omega_A \approx 0.3$.

curves are the continuum frequencies where strong damping of the mode is expected. A clear gap is present centered at $\omega \approx 0.3 \omega_A = 0.3 v_A/(qR)$, which corresponds to about 350 kHz at $q=1.3$, in agreement with the observed mode frequency at this time. There are large uncertainties in the q profile determined from an equilibrium reconstruction constrained by the kinetic pressure measurements. Reasonable fits were obtained for $0.9 < q(0) < 1.5$. Since sawtoothing does not begin until 0.22 sec, $q(0)$ is expected to be significantly larger than unity at this time. So, the agreement with this estimated q profile is reasonable.

Conclusion High frequency modes are observed with hydrogen minority ICRF heating both in the current rise and in steady-state EDA H-mode. Calculations of both the fast particle distribution and the TAE gap structure support the hypothesis that the current rise modes are TAE's. In the EDA H-mode cases, the mode rotation in the electron diamagnetic drift direction with n numbers increasing with frequency suggests that these modes may be edge modes, but fast particles are not expected in the edge, so the driving mechanism is uncertain.

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