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Fast Particle Driven Alfvén Eigenmodes in Alcator C-Mod

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Introduction Through high power H minority ICRF heating (P_{RF} > 4 MW) in Alcator C-Mod at relatively low density ($\bar{n}_e \approx 0.5 - 2 \times 10^{20}$ m^{-3}), multiple fast ion driven unstable Alfvén eigenmodes are excited both in the current rise and in the flattop. In the current rise, low toroidal *n* number modes are observed with frequencies that increase rapidly with time changing from 150 kHz to nearly 400 kHz in about 20 ms. Based on similar results in JT-60U[1] and JET[2], these modes have been identified as Alfvén Cascades (ACs). In the flattop, at densities up to at least 2×10^{20} m^{-3}, moderate |n| = 4 – 10 modes are observed with frequencies in the range of 600 kHz – 800 kHz that decrease with time during the rise of a 'monster'[3] sawtooth. These mode frequencies track the Toroidal Alfvén Eigenmode (TAE) center of the gap frequency ($\omega_{TAE} \approx \mathrm{v}_A/(2qR)$) for q=1. Energetic Particle Modes (EPMs) and TAEs with similar time evolutions have been associated with sawtooth stabilization on JT-60U[4], TFTR[5], and DIII-D[6]. ACs and AEs can be used to precisely constrain the q profile and provide a qualitative measure of the fast particle evolution.

Alfvén Cascades As the q profile evolves with strong ICRF heating in the current rise, Alfvén Cascades are expected when the minimum q value, q_{min}, passes through low order rational values particularly at integers and half-integers. Figure 1 shows an example of such ACs in C-Mod measured with a magnetic pickup coil at the outboard limiter and with Phase Contrast Imaging (PCI)[7] of density fluctuations through the plasma core. The modes visible on the pickup coil at the wall have lower |*n*| = 1 – 3 based on the increasing slope of the frequency with time[2] ($\omega(t) = \left|\frac{m}{q_{\min}(t)} - n\right| \cdot \frac{\mathrm{v}_A}{R_0} + \Delta\omega$) while the core modes measured with PCI have higher |*n*| in the range of 3 to 6. The PCI is more sensitive to higher |*n*| modes in the core while the pickup coil is not as sensitive to higher |*n*| modes because their amplitudes decay rapidly with distance from the mode to the coil.

In a similar discharge to that of Figure 1 but with the ICRF resonance shifted 1.7 cm to the inboard side, through enhanced signal processing, the PCI signal shows a clear 2nd harmonic of the principal AC (Figure 2). The principal mode increases in frequency

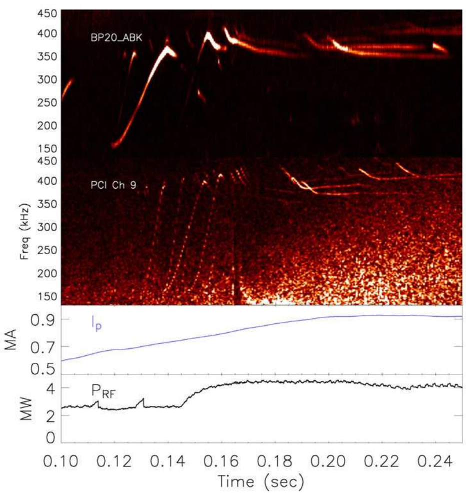

Fig. 1. Alfvén Cascades in the current rise measured with magnetic pickup coils at the wall and Phase Contrast Imaging through the plasma core.

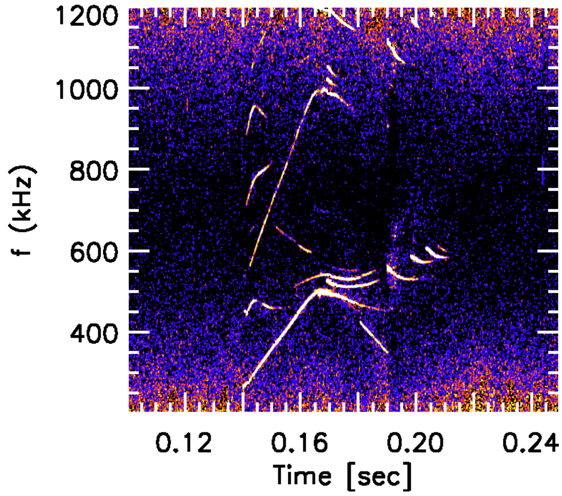

Fig. 2. Alfvén Cascades measured in the core with PCI showing a second harmonic of the principal mode at twice the frequency.

from 275 kHz to 500 kHz from 0.14 s to 0.165 s while the 2nd harmonic is at twice that frequency. The ratio of the amplitude of the 1st to 2nd harmonics is about 10, indicating the nonlinear character of these modes as expected by theory[8,9].

To determine the effect of the ICRF resonance location on the ACs, the toroidal field was varied shot-to-shot from 4.8 T to 5.9 T, which at the ICRF frequencies being used (78 – 80.5 MHz), shifted the H minority resonance location from $-0.3 < r/a < +0.35$. With a central resonance, the ACs and accompanying TAEs were the most unstable, but with the resonance shifted to the outboard side, the modes were nearly as unstable whereas with the resonance on the inboard side, the modes were almost completely stable except for a weak downward chirping mode, which is predicted under some conditions by theory[9]. A downward chirping mode is also visible in Fig. 2 with a resonance at r/a = The increased mode stability may be explained by the fast particle banana orbits, which are calculated to be much fatter for the inboard resonance and so are more likely to be lost to the outboard limiter.

Alfvén Eigenmodes with Monotonic Shear In the flattop during sawtoothing, the q profile is expected to be monotonic with $q_{min} \approx 1$. Both TAEs and EAEs (Ellipticity-induced Alfvén Eigenmodes) have been observed under these conditions in C-Mod during strong ICRF heating in reactor relevant regimes with $T_i \approx T_e$ and densities up to 2×10^{20} m^{-3}. Figure 3 shows an example of TAEs during sawtooth stabilization with frequencies

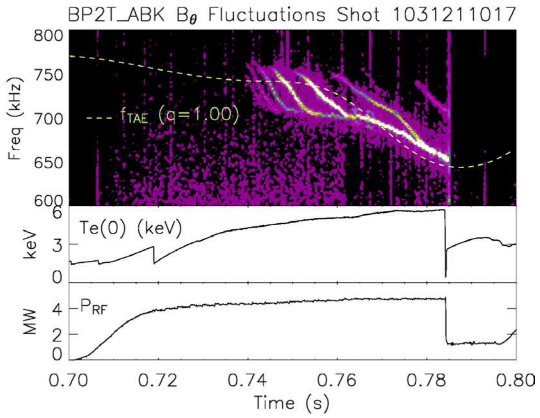

Fig. 3. Core TAEs near q=1 during sawtooth stabilization. The calculated $f_{TAE} = v_A/(4\pi qR)$ for q=1 agrees well with the measured mode frequency.

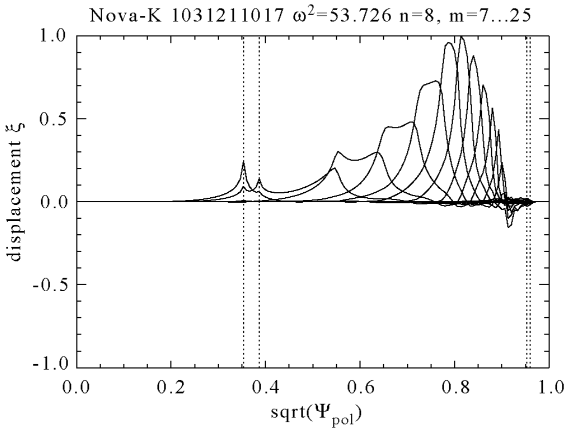

Fig. 4. Nova-K calculated n=8 TAE radial structure with multiple poloidal harmonics from m= 7 – 25. $r_{q=1}$ from EFIT is at r/a ≈ 0.37.

associated with q=1. The toroidal mode numbers begin in the range of |n| = 8 – 10 and then fall to n=4 as the modes coalesce in frequency just before the 'monster' sawtooth collapse at 0.784 s. The fact that the measured mode frequencies so closely track the center of the TAE gap for q=1 indicates that the modes are excited near the q=1 surface. These modes indicate the presence of fast H ions in the core that are believed to stabilize sawteeth[10]. Although no time resolved fast ion loss measurements are available, the loss of the fast ions by the TAEs may be responsible for terminating sawtooth stabilization[4-6]. Under similar conditions, but with only moderate sawtooth stabilization, EAEs have been observed with frequencies tracking very close to $f_{EAE} = v_A/(2\pi qR)$ with q=1 in the frequency range of 1.3 – 1.4 MHz.

Modeling The AEs in the current rise and in the flattop have been modeled with the MISHKA[11] and Nova-K[12] codes, respectively. Using the plasma equilibrium from the discharge in Figure 1, the toroidal mode numbers, and the frequency evolution of the AC's, MISHKA models the time evolution of the minimum q value and estimates the q profile. The calculated gap structure of the modes indicates that as q_0 evolves the character of the modes changes from AC's to TAEs. The calculated q profile at the start of the AC is very flat or possibly slightly reversed in the core with $q_0 \approx 3$ out to r/a ≈ 0.5. At this near integer q_0 value, the n=1 gap is wide allowing the AC frequency to sweep up to the TAE frequency. Then, as q_0 evolves to the half integer value $q_0 \approx 2.5$ the n=1 gap narrows to meet the TAE frequency and the mode changes from an AC to a TAE.

The fast particle distribution for the discharge in Figure 1 was modeled with TRANSP/FPPRF. The calculated ICRF power deposition was centrally peaked with more than 75 MW/m^3 and significant power out to r/a = 0.4. The fast ion distribution was even somewhat more peaked with a maximum H ion energy exceeding 300 keV. This corresponds to a fast H velocity relative to the Alfvén velocity of $v_H / v_A \approx 0.7$ which is more than the value of ~0.55 needed to destabilize TAEs through the bounce resonance[13].

Using the equilibrium from the discharge in Figure 3, the Nova-K code was used to calculate the TAE radial mode structure for n = 5 – 11. TAEs were found in the frequency range of the measured modes with broad multiple m mode structures such as that shown in Figure 4 for n=8, which has m = 7 – 25. Although the modes are excited near the q=1 surface, they are toroidally coupled to multiple harmonics with a broad radial structure that extends out to the plasma edge where they can be observed by magnetic pickup coils.

Conclusions The unstable Alfvén eigenmodes observed in both the current rise and in the flattop provide a qualitative measure of the fast ion evolution and a precise measure of the q profile at the start of the Alfvén Cascades. These results indicate that fast H ions are driven up to energies of at least 200 keV and perhaps more than 300 keV by high power ICRF even in regimes with $\bar{n}_e > 1 \times 10^{20} m^{-3}$ and $T_i \approx T_e$. TAEs near q=1 during 'monster' sawteeth also provide a measure of the time evolution of the fast ions during sawtooth stabilization.

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References

[1] H Kimura *et al* (1998) *Nucl Fus* **38** 1303.
[2] S E Sharapov *et al* (2002) *Phys Plasmas* **9** 2027
[3] D J Campbell *et al* (1988) *Phys Rev Lett* **60** 2148
[4] M Saigusa *et al* (1998) *Plasma Phys Cont Fus* **40** 1647
[5] S Bernabei *et al* (2000) *Phys Rev Lett* **84** 1212
[6] S Bernabei *et al* (2001) *Nucl Fus* **41** 513
[7] A Mazurenko *et al* (2002) *Phys Rev Lett* **89** 225004
[8] H Berk *et al* (2001) *Phys Rev Lett* **87** 185002
[9] F Zonca *et al* (2002) *Phys Plasmas* **9** 4939
[10] Francesco Porcelli (1991) *Plasma Phys Cont Fus* **33** 1601
[11] A B Mikhailovskii, *et al* (1997) *Plasma Phys Rep* **23** 844
[12] C Z Cheng (1992) *Phys Rep* **211** 1
[13] H Biglari, F Zonca, L Chen, (1992) *Phys Fluids B* **4** 2385