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Reversed Shear Alfvén Eigenmodes in Alcator C-Mod During ICRF Minority Heating and relationship to Sawtooth Crash Phenomena

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Recent Alcator C-Mod experiments focusing on Alfvén eigenmodes in the current flattop phase of the discharge have discovered reversed shear Alfvén eigenmodes (RSAEs) between sawtooth crashes [1]. The phase contrast imaging (PCI) diagnostic [2] is the primary tool for these studies. Having high sensitivity to small perturbations of the electron density, having fast time response and simultaneous broad radial coverage, the PCI system on Alcator C-Mod is able to detect core-localized RSAEs even if only weakly excited. The output signal from the PCI system is an image of the line integral of the electron density perturbations along the beam path, decomposed into 32 elements in the coordinate parallel to the major radius. Images from PCI are compared to numerical results from the ideal MHD code NOVA [3] through the use of a "synthetic diagnostic" analysis. The presence of RSAEs near the q=1 surface suggests that a reversed shear q profile (hollow current density profile) exists during sawteeth. This observation has motivated the modeling of current diffusion following a sawtooth crash which has shown the development of a hollow current density profile for certain initial conditions. These results mark an important contribution to the understanding of current relaxation during sawteeth.

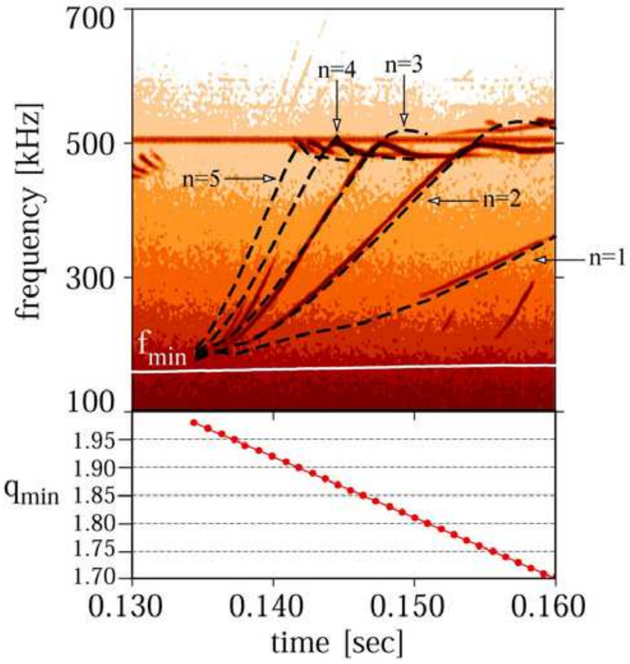

Figure 1: PCI spectrogram from the current ramp phase with NOVA modeling overlaid in black dashed traces. Toroidal mode numbers are inferred from the rate of chirping as described in Eq. (1).

The RSAEs are localized near the minimum of the q profile (q_{min}), where the magnetic shear, s = (r/q) (dq/dr), is small and allows for Alfvénic modes with finite spatial extent to develop. At lower frequencies, the Alfvénic component of the mode is modified by the geodesic acoustic deformation of the Alfvén continuum, resulting in a finite minimum frequency in the plasma reference frame. Discussion of these aspects and derivations of the differential equation describing RSAEs can be found in references [4] and [5]. An approximate dispersion relation [4] is repeated here for reference,

$$\omega = \left[\frac{2T_e}{R_0^2 M_i}\left(1+\frac{7}{4}\frac{T_i}{T_e}\right) + \frac{V_A^2}{R_0^2}\left(\frac{m}{q_{\min}} - n\right)^2 \right]^{1/2} + \omega_\Delta\,, \qquad (1)$$

where R_0 is the tokamak major radius, M_i the majority ion mass, $V_A^2=B^2/\mu_0 n_i M_i$ is the Alfvén velocity, B is the modulus of the magnetic field and n_i ($\approx n_e$) is the ion density, m is the poloidal mode number, n the toroidal mode number, and the ω_Δ term includes corrections for fast ion pressure and finite pressure gradients and can be neglected in the current experiments because these terms are small near the q=1 surface. The first term in brackets in Eq. (1) derives from the geodesic deformation of the Alfvén continuum and provides the minimum frequency offset ($f_{\min}$). The Alfvénic nature of the RSAEs is represented by the second term in brackets, and being inversely proportional to $q_{\min}$ is largely responsible for the frequency sweep as the equilibrium evolves and $q_{\min}$ decreases. It is the Alfvénic term, being inversely proportional to $q_{\min}$ which causes the RSAE frequency to increase as the current diffuses toward the core and $q_{\min}$ decreases. The maximum achievable frequency of the RSAEs is set by the toroidicity-induced Alfvén eigenmode (TAE) frequency, $f_{TAE}=V_A/4\pi q R_0$.

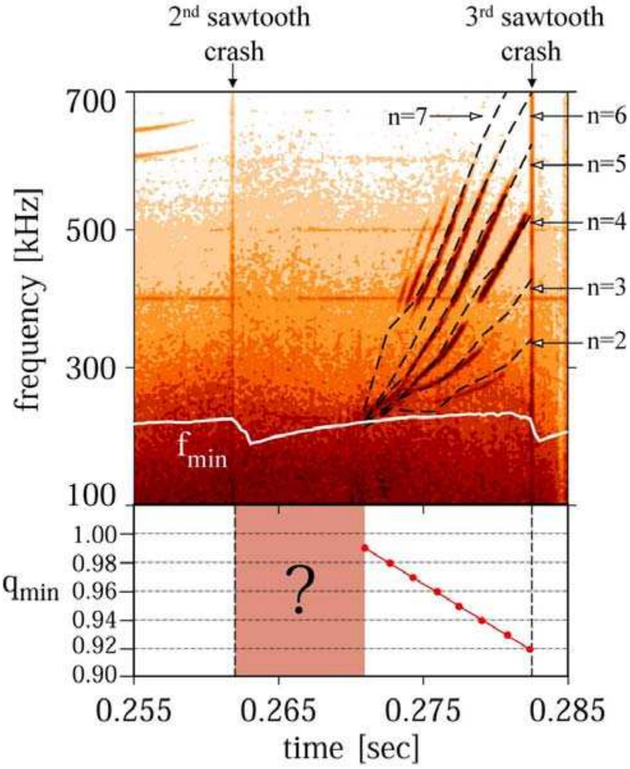

Figure 2: PCI spectrogram showing the modes arising between sawteeth, overlaid in black dashed line is the modeling results from NOVA.

The ideal MHD code NOVA is used to model the RSAEs observed during the current ramp and during sawteeth [1]. The core localized RSAEs often produce weak signals at the edge magnetic probes, requiring that the toroidal mode numbers be inferred from the rates of chirping, expected to scale as $n_j^2 \sim d/dt(f_j^2)$ based on Eq. (1), where n_j is the j^{th} toroidal mode. NOVA modeling results for $q_{min} \leq 2$ using mode numbers identified by the rate of chirping are presented in Fig. 1 where generally good agreement between modeling and experiment is seen. Applied to the sawtooth phase, NOVA finds RSAE solutions for $q_{min} \leq 1$, also in good agreement with experiment, as shown in Fig. 2. Both RSAE and TAE solutions are found numerically, though in experiment only RSAEs are seen in the equilibrium studied here. The TAE solutions from NOVA around f ≈550 kHz exhibit strong interaction with the Alfvén continuum and are expected to be strongly damped. An n=3 solution calculated by NOVA for the sawtoothing equilibrium is presented in Fig. 3. Based on theoretical arguments in [4] (in particular, see eq.14) it was found that for q_{min} below 1 the plasma curvature increases the threshold above which the RSAEs can exist. However, observations of q=1 RSAEs have now been reported in JET [6] and most recently in Alcator C-Mod [1]. Stability calculation with the code NOVA-K [7] shows that the n=3 RSAE solution can be unstable for fast ion distributions with tail temperatures above 100 keV.

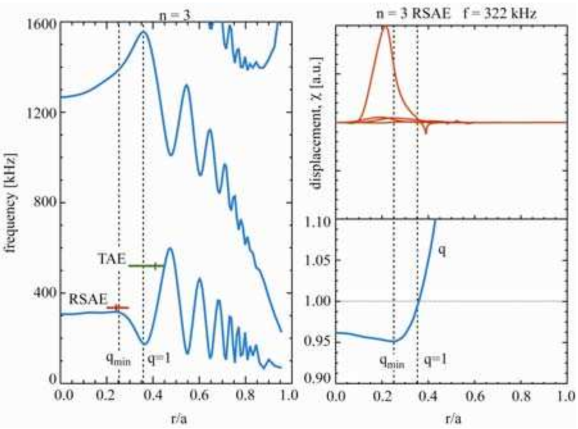

Figure 3: NOVA solutions for an n=3 RSAE in an equilibrium with q_0=0.96 and q_{min}=0.95 at r/a=0.25.

A one dimensional cylindrical model of current diffusion based on the equation $d/dt(j) = \nabla^2 (Dj)$ has been used to model the relaxation of the current following redistribution from the sawtooth crash. The initial q profile is flat out to a mixing radius, defined in terms of the Kadomtsev model of reconnection [8] using a pre-crash q profile with the q=1 surface determined from ECE and soft x-ray measurements to be near 0.35. Results of this current diffusion model are shown in Fig. 4 where it is seen that a reversed shear q profile develops within a few milliseconds and persists until the end of the sawtooth cycle (19 ms). For a temperature profile of the form $T(\rho)=T_0(1- \rho^g)^h$ where ρ=r/a, reversed shear is initially generated when g>2. The core temperature profile immediately following the crash is well modeled with g=2.5 and h=2.6. Other numerical studies have also reported reversed shear profiles [9,10], where the evolution of the temperature profiles was included using heuristic perpendicular thermal conductivity models. Recent experimental results reported by Lazarus *et al.* from the DIII-D tokamak have shown that a reversed shear q profile is generated during the sawteeth in strongly shaped plasmas [11].

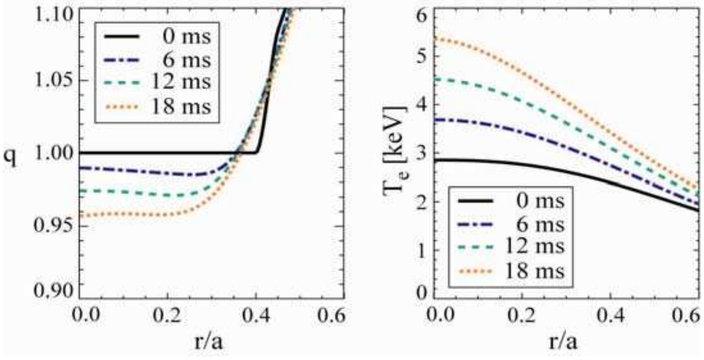

Figure 2: Modeling of resistive diffusion of the current shows reversed shear is generated when the temperature profile is sufficiently flat.

In summary, RSAEs are observed between sawteeth implying the presence of a reversed shear q profile. These are the first convincing demonstrations of reversed shear in the presence of fast ions between sawtooth crashes in standard D-shaped plasmas. Modeling from the code NOVA finds RSAE solutions with $q_{min}<1$ which can be unstable in the presence of an ICRH generated fast ion distribution. Frequency spectra calculated by NOVA are in good agreement with the spectra measured by PCI. Modeling of the current diffusion following a sawtooth crash shows that reversed shear q profiles is created for equilibria with sufficiently flat temperature profiles following the sawtooth crash. It is expected that the amount of reversed shear in an ITER-like device would be significantly larger on account of the higher temperatures. The impact of the RSAEs and the reversed shear on the confinement of fast ion remains an open question for further investigation.

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References

[1] E.M. Edlund *et al.*, *to be published.*
[2] M. Porkolab *et al.*, IEEE Trans. Plasma Sci. 34, 229 (2006).
[3] C.Z. Cheng and M.S. Chance, J. Comp. Phys. 71, 124 (1982).
[4] N G.orelenkov, G. Kramer, and R.Nazikian, Plasma Phys. Cont. Fus. 48, 1255 (2006).
[5] B.N. Breizman, M.S. Pekker and S.E. Sharapov, Phys. Plasmas 12, 1 (2005).
[6] S.E. Sharapov, *private communication to M. Porkolab, IAEA, Chengdu, China (2006).*
[7] C.Z Cheng, Phys. Rep. 1, 1 (1992).
[8] B.B. Kadomtsev, Sov. J. Plasma Phys. 1, 389 (1975).
[9] R.F. Denton, J.F. Drake, R.G. Kleva,and D.A. Boyd, Phys. Rev. Lett. 56, 2477
[10] V.V. Parail and G.V. Pereverzev, J. Sov. Plasma Phys. 6, 14 (1980).
[11] E.A. Lazarus *et al.*, Phys. Plasmas 14, 055701 (2007).