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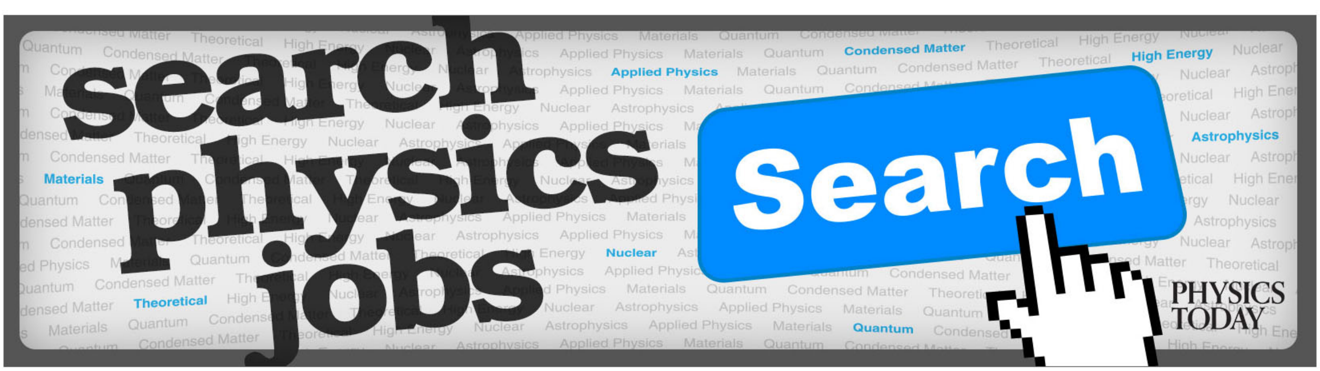

Phase contrast imaging measurements of reversed shear Alfvén eigenmodes during sawteeth in Alcator C-Mod[a)]

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Reversed shear Alfvén eigenmodes (RSAEs) have been observed with the phase contrast imaging diagnostic and Mirnov coils during the sawtooth cycle in Alcator C-mod [M. Greenwald *et al.*, Nucl. Fusion **45**, S109 (2005)] plasmas with minority ion-cyclotron resonance heating. Both down-chirping RSAEs and up-chirping RSAEs have been observed during the sawtooth cycle. Experimental measurements of the spatial structure of the RSAEs are compared to theoretical models based on the code NOVA [C. Z. Cheng and M. S. Chance, J. Comput. Phys. **71**, 124 (1987)] and used to derive constraints on the q profile. It is shown that the observed RSAEs can be understood by assuming a reversed shear q profile (up chirping) or a q profile with a local maximum (down chirping) with $q \approx 1$. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3086869]

I. INTRODUCTION

The sawtooth crash in a tokamak plasma is a process whereby magnetic reconnection modifies the topology of the flux surfaces near the plasma core, inducing rapid energy and particle transport as well as causing redistribution of the current parallel to the magnetic field.[1–3] The sawtooth cycle is characterized by the abrupt crash in the central temperature, caused by the magnetic reconnection, followed by a relaxation and reheat phase during which the temperature increases nearly linearly in time and the parallel current density diffuses toward the core until an instability threshold is reached and another reconnection event occurs. After years of study there remain many questions as to the nature of both the physics of the magnetic reconnection and diffusion during the sawtooth cycle. In particular, there has been much debate over the evolution of the q profile (where $q \approx rB_\phi / R_0 B_\theta$ is the magnetic safety factor, r is the minor radial coordinate, B_ϕ is the toroidal magnetic field, R_0 is the tokamak major radius, and B_θ is the poloidal magnetic field), an important quantity in the stability of kink and interchange modes which may be responsible for initiating the reconnection process. While some studies have found that q_0, that is, q at the magnetic axis, remains well below unity throughout the sawtooth cycle,[3–5] others concluded that q_0 was close to or larger than unity following the crash, implying a complete reconnection process.[6–10] While the central temperature can increase by a factor of 2 or more during the relaxation process and can be readily measured by electron-cyclotron emission (ECE) diagnostics or Thomson scattering, the current density profile may change by only a few percent and is considerably more difficult to measure precisely. However, it is important for understanding the physics of the relaxation and reconnection processes that the evolution of the q profile be measured throughout the sawtooth cycle.

A particular class of Alfvénic instability, the reversed shear Alfvén eigenmode (RSAE, also Alfvén cascade) has proven very useful as a method of "magnetohydrodynamic (MHD) spectroscopy" for inferring the evolution of q in reversed shear equilibria (i.e., negative magnetic shear for some portion of the q profile near the plasma core), where the magnetic shear is defined as $s=(r/q)(dq/dr)$. The RSAE frequency is a strong function of the minimum value of q ($q_{\min}$) in equilibria with reversed shear.[11–13] Reversed shear q profiles are known to be present during the current ramp phase as the Ohmic current diffuses toward the core and is transiently peaked off axis, a fact confirmed by the observation of RSAEs in the presence of energetic ions,[13,14] motional Stark effect (MSE) measurements,[15,16] and numerical modeling.[17] When $q_{\min}$ is near an integer value the RSAEs appear in a characteristic "grand cascade" pattern whereby multiple modes chirp in frequency at rates proportional to their individual toroidal mode number. Comparison of the grand cascade pattern to the dispersion relationship provides a method by which the toroidal mode numbers can be identified and the value of $q_{\min}$ determined unambiguously.

Recent observations of RSAEs during the sawtooth cycle in Alcator C-Mod,[18] and also in the Joint European Torus (JET),[19,20] offer a method by which the evolution of the q profile during the sawtooth cycle can be studied to high precision. While Ref. 20 concluded that the up-chirping modes resembling RSAEs were incompatible with a reversed shear q profile based on analysis of the so-called tornado modes, it did not consider the possibility that a reversed shear q profile may exist transiently following the sawtooth crash in the giant sawteeth that were studied. In Alcator C-Mod the $q=1$ RSAEs are seen in plasmas at International Thermonuclear Experimental Reactor (ITER) relevant densities of $n_{e0} < 1.5 \times 10^{20}$ m^{-3} with ion-cyclotron resonance heating (ICRH) utilizing the on-axis fundamental hydrogen minority heating scheme at 80 MHz and 5.4 T in deuterium majority plasmas ($n_H/n_D \approx 0.05$). Importantly, the ICRH generates an energetic proton component with energies of approximately 100 keV or more, which provides the drive

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[b)]Invited speaker.

