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β suppression of Alfvén Cascade Modes in NSTX

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INTRODUCTION

The coupling of Alfvén Cascade (AC) modes or reversed-shear Alfvén eigenmodes (rsAE) to Geodesic Acoustic Modes (GAM) [1] implies that the range of the AC frequency sweep is reduced as the electron β is increased [2]. This model provides an explanation for the otherwise surprising absence of AC modes in reverse shear NSTX plasmas, given the rich spectrum of beam-driven instabilities typically seen in NSTX. In experiments done at very low β to investigate this prediction, AC modes were seen, and as the β_e was increased from shot to shot, the range of the AC frequency sweep was reduced, in agreement with this theoretical prediction [3].

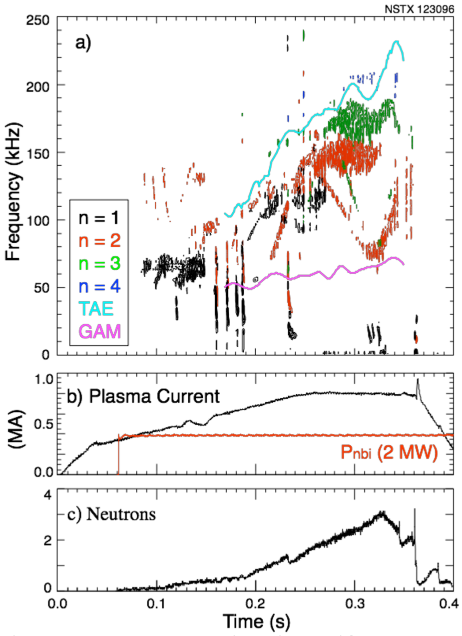

Fig. 1. Spectrogram showing Alfvén Cascade modes. Cyan and magenta curves indicate local TAE gap center and Geodesic Acoustic mode frequencies, respectively

Confirmation of the identification of the modes as Alfvén Cascades requires an independent measurement of the q profile evolution. First to show that the q profile indeed has an off-axis minimum needed for the AC mode, and second that the evolution of the q_{min} agrees with that deduced from the AC mode frequencies. The regime discovered in the initial AC mode experiments has recently been revisited to obtain concurrent measurements of the q-profile evolution with the MSE diagnostic. The q_{min} evolutions as deduced from the MSE diagnostic and data from the AC modes are found to be in good agreement and further, the minimum frequency of the AC modes are in good agreement with estimates of the Geodesic Acoustic Mode frequency.

EXPERIMENTAL RESULTS

The conditions of the original experiment were reproduced, and a spectrum from a very low β shot is shown in Fig. 1a. The AC modes can be seen as the upward chirping modes with black signifying n = 1, red n = 2, green n = 3 and blue n = 4. The local, at q_{min}, estimate for the Geodesic Acoustic mode frequency, $f_{GAM} = C_S(2 + 7T_i/2T_e)^{1/2}/(2\pi R)$ is shown in magenta, and the center frequency of the TAE gap at q_{min}, $f_{TAE} = V_{Alfvén}/(4\pi q_{min}R)$, is shown in cyan. The plasma current, beam heating waveform and neutron rate are shown in Figs. 1b and c.

The clearest of the AC modes in Fig 1a is the n = 2 mode (red contours) with the sinusoidal shape between 210 ms and 350 ms and 75 kHz and 140 kHz. The initial upward sweep between ≈ 210 ms and ≈ 250 ms is likely the m = 3, n = 2 mode following the $q_{min} = 1.5$ crossing. TAE modes, bursting and chirping, persist while the AC mode sweeps back downwards, now as an m = 2, n = 2. The n = 2 AC mode reaches the estimated GAM frequency of ≈ 75 kHz at about 320 ms. Concurrent with the n = 2 downward sweep, at slightly higher frequency can be seen an n = 3 AC mode, also sweeping downward. The confluence of the n = 3 and n = 2 frequency minima at 320 ms suggests that this corresponds to a $q_{min} = 1$ crossing. An n = 4 AC mode was also seen sporadically during this interval, but was too weak to show in the spectrogram. Earlier AC modes are also seen in the spectrogram. For example, between 180 ms and 210 ms there is an n = 1 AC mode and possibly and n = 2 AC mode.

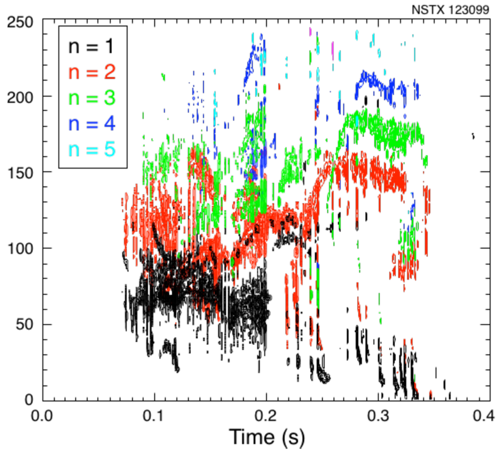

Fig. 2. Spectrogram showing Alfvén Cascade modes.

The AC modes in this example were excited with the innermost neutral beam source, C. The MSE diagnostic requires source A. The tangency radii of the three beam sources on NSTX are 69.4 cm, 59.2 cm and 49.7 cm for sources A through C respectively ($R_0 \approx 0.85$ m). It is typically observed that source A, which is somewhat more co-tangential, excites modes with stronger frequency chirping. A simple substitution of source A for C before 200 ms results in the spectrogram shown in Fig. 2. The strong chirping of the modes obscures, or possibly suppresses the AC modes.

To validate the relevance of the measured q_{min} evolution, a sequence of nine plasmas, including this one, were made. These included discharges where source C was substituted for source A after 200, 230 or 250 ms, and discharges where source A was substituted for source C after 200, 230 and 260 ms, and one shot with only source A. The q_{min} evolutions determined through MSE-constrained equilibrium reconstructions are shown as the black curves in Figs. 3 and 4. The evolution of q_{min} seems relatively unaffected by the choice of neutral beam source for these shots.

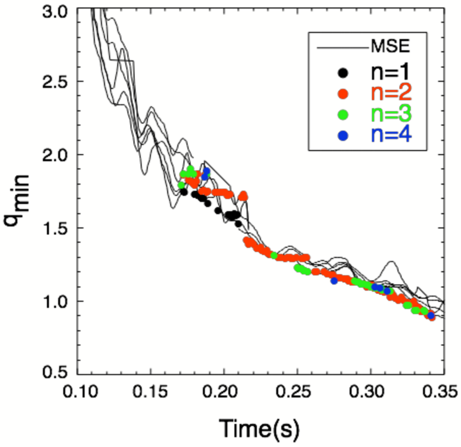

Fig. 3. Evolution of q_{min} deduced from spectrogram in Fig. 1. Black lines indicate q_{min} evolution from MSE in similar shots.

ANALYSIS

The dispersion relation for Alfvén Cascade (AC) modes at low β is very simple

$$\omega = k_{//} V_{Alfvén}, \text{ where } k_{//} = (m-nq)/qR$$

so at resonant surfaces, the AC mode frequency is zero. The theory proposed by Berk, *et al.* [1] finds that the AC modes couple to Geodesic Acoustic Modes (GAM) which sets a lower bound on the onset frequency. For finite beta, the dispersion relation becomes

$$\omega^2 = (k_{//}V_{Alfvén})^2 + 2C_S^2(1 + 7T_i/4T_e)/R^2$$

This modification to the dispersion relation predicts the sinusoidal frequency variation of the n = 2 AC mode frequency sweeps shown in Fig. 1.

The AC mode upward frequency sweep saturates in the TAE gap (as can be seen in Fig. 1). The ratio of the minimum to the maximum of the frequency sweep is then the ratio of the TAE frequency to the GAM frequency. As that ratio approaches one, the Alfvén Cascades will essentially disappear. Thus, a necessary condition for the presence of frequency-sweeping AC modes may be written:

$$\omega^2_{TAE}/\omega^2_{GAM} \approx 4q^2R^2/V^2_{Alfvén}\ 2C^2_S/R^2\ (1+7T_i/4T_e) = 4q^2\beta_e\ (1+7T_i/4T_e) < 1.$$

At the high β's typical for beam heated ST plasmas, AC modes would not be expected.

The AC mode dispersion relation may be used to deduce the q_{min} evolution from the observations of the AC mode frequency sweeping. The first step is to subtract the GAM frequency, in quadrature, from the observed frequency (Doppler corrections have also been made, but are negligible in these low density plasmas). The GAM frequency is approximated by a linear fit to the evolution shown in Fig. 1a (magenta curve), but scaled by 1.1 to match the observed minimum n = 2 AC mode frequency at 250 ms. The results of this analysis are shown in Fig. 3. The black curves are the q_{min} evolutions obtained from MSE-constrained equilibrium reconstructions. The black, red, green and blue circles correspond to analysis of n = 1 through n = 4 modes, respectively. The result of a similar analysis for the AC modes after 200 ms in Fig. 2 is shown in Fig. 4. In both cases the q_{min}^{AC} evolution is in reasonable agreement with that inferred from the equilibrium reconstructions, although the q_{min}^{AC} tends to be slightly lower than q_{min}^{equil} after 250ms.

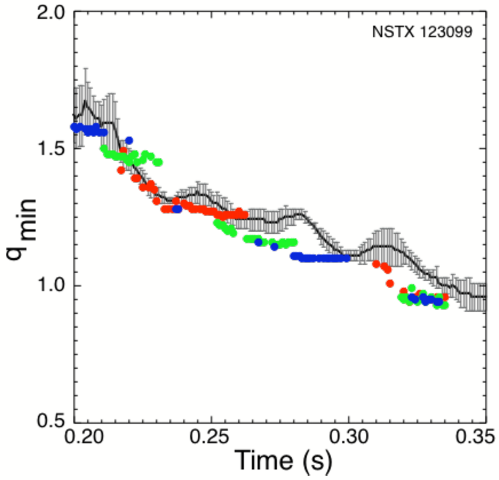

Fig. 4. Evolution of q_{min} deduced from spectrogram in Fig. 2. Black line indicates q_{min} evolution from MSE averaged over similar shots.

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