Frequency Chirping of Core-Localized Toroidicity-Induced Alfvén Eigenmodes and their Coupling to Global Alfvén Eigenmodes

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The fast frequency change or chirping of core-localized toroidicity-induced Alfvén eigenmodes (C-TAE), excited before giant sawteeth during ion cyclotron resonance heating, has been investigated. The chirping can be accounted for by small changes of the central q profile. When the C-TAE crosses the frequency of a global TAE (G-TAE) a small frequency gap was found. These gaps can be attributed to mode coupling between the C-TAE and a G-TAE which is observed for the first time. The coupling and the frequency gaps are consistent with linear TAE mode coupling.

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In large tokamaks heated with energetic ions, toroidicity-induced Alfvén eigenmodes (TAEs) are often observed ([1,2], and references therein). These modes reside in the lowest frequency gap of the shear Alfvén spectrum and are of concern for their potential to induce losses of energetic particles which resonate with the modes [3,4]. Enhanced loss of energetic particles in a fusion reactor can lead to a reduction of plasma heating efficiency and to intense localized heating of plasma facing components.

Experiments have shown the existence of a variety of modes in the TAE range of frequency. One variety of modes chirps down in frequency (up to 10% in 100 ms) prior to a giant sawtooth crash (GST) in ion cyclotron range of frequency (ICRF) heated plasmas [5,6].

In this Letter we show for the first time that chirping modes observed in JT-60U ICRF heated plasmas can be accounted for with linear TAE theory [7]. They are associated with core-localized TAEs (C-TAEs) and reside in the central low shear region of the plasma with two dominant poloidal harmonics [8]. The chirping is caused by small changes of the plasma equilibrium in the core.

During the chirp the C-TAE frequency can cross over the frequency of a global TAE (G-TAE). G-TAEs have a very weak frequency variation during the sawtooth cycle and are usually characterized by a large number of poloidal harmonics concentrated in the increased shear region away from the core [3,8].

A consequence of the linear mode theory is that at the frequency crossing the two modes mix whereby a small gap is created in the frequency chirp. In the JT-60U ICRF experiments we have found that such gaps can be explained as linear mode coupling during frequency crossover between the C-TAE and a G-TAE. The coupling of core and global modes can potentially lead to enhanced losses of energetic particles if the fast particle drive exceeds the additional damping from the global mode.

Experiment.—TAEs can exist in the lowest gap of the shear Alfvén continuum. When the magnetic shear is low TAEs are formed by the coupling of two poloidal harmonics with toroidal mode number n and poloidal mode numbers m and $m + 1$. The TAE frequency, ω, is given for the large aspect ratio tokamaks by $\omega \simeq v_A/2Rq_{\rm TAE}$ with $v_A = B/\sqrt{\mu_0\rho}$ being the Alfvén velocity (B the magnetic field, ρ the mass density), R the major radius, and $q_{\rm TAE} = (2m \pm 1)/2n$. In sawtooth stabilization experiments a low shear region with $q_0 < 1$ is present in the plasma core region. There TAEs can be excited that consist of mainly two significant poloidal harmonics and are called the C-TAEs [8]. The best experimental evidence for the existence of C-TAEs was obtained in Tokamak Fusion Test Reactor (TFTR) where the radial mode structure of α-driven TAEs in weak shear ($d\ln q/d\ln r \ll 1$) plasmas was directly measured with an X-mode reflectometer [9]. In the increased shear region, away from the core, G-TAEs can exist and they are formed by coupling a large number of poloidal harmonics. TAEs can be driven unstable by a sufficient fast particle population in the plasma. An efficient way to create such a population in the plasma core is with ICRF heating.

We have studied the frequency chirping of C-TAEs (Fig. 1) in a ^{4}He discharge in JT-60U in which the fast particle population was created by second harmonic minority hydrogen ICRF heating. Typical parameters for this discharge are toroidal magnetic field, $B_T = 3.3$ T at the magnetic axis, plasma current, $I_p = 2.6$ MA, major radius, $R = 3.47$ m, minor radius, $a = 1.03$ m, ellipticity, $\kappa = 1.4$, internal inductance, $\ell_i = 1.23$, line averaged electron density, $n_{el} = 1.9 \times 10^{19}$ m^{-3}, ICRF power $P_{\rm IC} = 3.8$ MW, and 1.8 MW of neutral beam power (hydrogen beams) for plasma rotation and q-profile measurements.

The TAEs were detected using an array of eight fast sampled Mirnov coils. Toroidal mode numbers were obtained from these measurements. The density profile was measured with the ruby and YAG laser Thomson scattering systems and was found to be constant in the plasma center ($r/a < 0.5$) before the GST when the TAEs were observed (time resolution: 0.1 s). The n_{el} was also constant (see Fig. 1). The q profile was obtained from the 14-channel motional Stark effect (MSE) diagnostic

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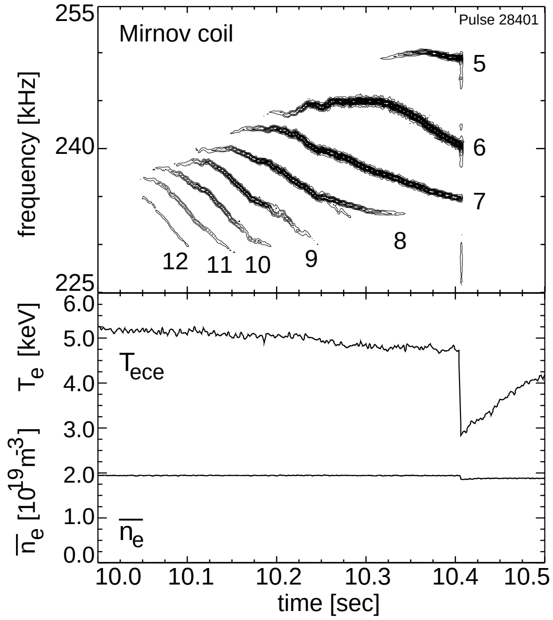

FIG. 1. TAEs, labeled with their toroidal mode number, from the Mirnov coil measurements (top), before a GST and the central electron temperature and line averaged density (bottom).

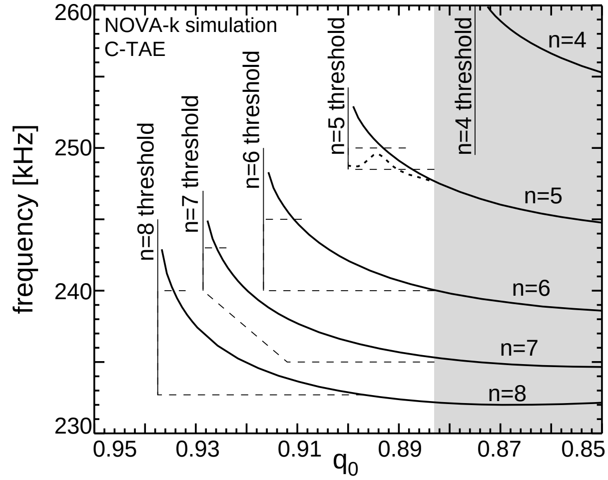

FIG. 2. NOVA-K simulation of the frequency behavior of the C-TAEs with $n = 4$ to 8. The dashed lines indicate the experimentally observed frequency chirp after correction for the Doppler shift (see Fig. 1). The shaded area is not observed experimentally because of the GST.

(time resolution: 0.1 s). It was found that q_0 decreased in the period before the sawtooth. The toroidal rotation velocity of the plasma, which gives a Doppler shift to the measured frequencies, was measured with a charge exchange recombination spectroscopy technique. It was found to be small (<2 kHz) in the central region and it is included in the analysis.

Frequency Chirping of C-TAEs.—To understand the experimental results we have performed a theoretical analysis by employing the nonvariational kinetic-MHD stability code, NOVA-K [7]. From the experimentally measured q, density, and pressure profiles we have calculated the TAE spectra for toroidal mode numbers $n = 4$ to 8 (Fig. 2).

The MSE measurements indicated that q_0 is slowly decreasing from 0.94 ± 0.10 to 0.86 ± 0.10 in the 400 ms before the sawtooth but the time resolution and accuracy were not sufficient to provide the fine details of the evolution of the experimental q profile. Instead, we have chosen to model the q profile in the simulations as $q(r, \varepsilon) = q_{\mathrm{MSE}}(r) + \varepsilon \exp(-r^2/\sigma)$ where $q_{\mathrm{MSE}}(r)$ is the experimental q profile measured at 10.0 s, $\sigma = 0.1$ and ε was varied so that q_0 ranged between 0.95 and 0.85. This procedure is consistent with the MSE measurements which indicate that only the central part of the q profile is evolving before the GST. The density profile was kept constant in the simulations, in accordance with the experimental observations.

The $n = 8$ C-TAE appears in the plasma after q_0 falls below 0.9375, and this mode consists mainly of the $m = 7$ and 8 poloidal harmonics (Fig. 3 top). When q_0 is lowered the resonant surface and hence the mode moves through the region of low shear. The mode frequency decreases during this phase. When the mode reaches the increased shear region near the $q = 1$ surface the effects of coupling to higher-m poloidal harmonics ($m > 8$) outside the $q = 1$ surface become important and the down chirping stops. When q_0 is lowered further the coupling to the higher-m poloidal harmonics becomes so strong that the core-localized character is lost (Fig. 3 bottom). After that the mode frequency starts to chirp up slowly.

In Fig. 2 we show the calculated frequencies of the C-TAEs for $n = 4$ to 8 as a function of q_0, with q_0 decreasing from left to right. This corresponds to the time evolution in the experiment. The change from q_0 variation

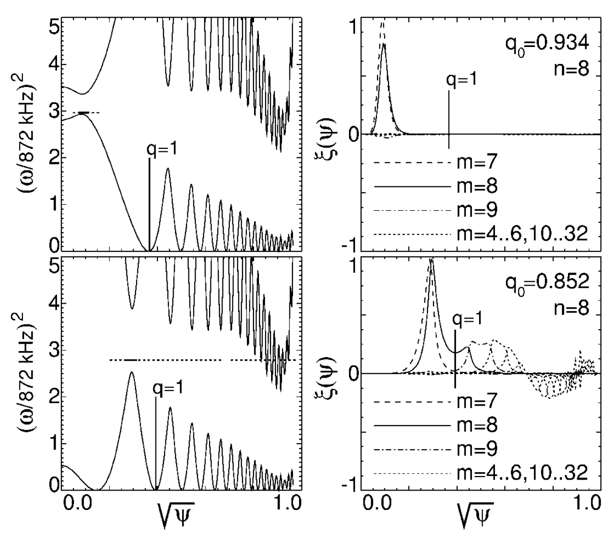

FIG. 3. Alfvén continua (left) and displacements (right) of the $n = 8$ C-TAE at the start (top) and end (bottom) of the chirp as a function of the flux coordinate ($\sqrt{\psi} \approx r/a$). The bars (dotted lines) in the Alfvén continua indicate the mode width at 50% (5%) of the maximum displacement. The displacements are normalized to their peak amplitude.

(in the calculations) to time evolution (in the experiment) is not straightforward. The MSE measurements indicate that q_0 is decreasing with a rate of 0.2 per second which is also supported by the onset time of the different TAEs. Changing the q axis of the simulations to time with this rate gives the same time separation between the onset of the different modes. Moreover, matching the onset times yields $q_0 = 0.88$ at the GST and $q_0 = 0.94$ 0.4 s earlier.

We can draw several conclusions from Fig. 2: (i) The order of appearance of the modes, a cascade from the high to low-n modes which appears at higher frequencies, is in agreement with the experiment. The threshold q for the high-n modes is reached first when q_0 decreases below 1. (ii) The range over which the modes chirp is similar to that observed experimentally (Fig. 2 dashed lines) where it is assumed that the C-TAEs are excited soon after their threshold is passed. (A stability analysis is beyond the scope of this paper.) There is, however, a small problem: in the simulations the mode frequencies start to chirp down immediately after they appear, but experimentally, the frequency is constant or chirps up slightly at the start. This behavior can be attributed to the precise shape of the pressure profile in the core. In the simulations we have used a parabolic profile, $P(r) = P_0(1 - r^{\mu})^{\nu}$, whereby the parameters P_0, μ, and ν were determined via a χ^2 minimizing procedure. We have done similar simulations for the $n = 5$ mode (Fig. 2 dotted line) in which we have used a Chebyshev polynomial expansion for the pressure profile. This expansion gave a 0.5% to 2% steeper pressure gradient inside $r/a < 0.25$ whereas the difference between the two parametrizations is less than 4%, well in the experimental error bar of 10%. (iii) When q_0 decreases sufficiently, the frequency starts to chirp up (see the $n = 8$ in Figs. 1 and 2). As the C-TAE moves out of the low shear region, it obtains a global character (cf. Fig. 3). We note that a similar up chirping has also been observed clearly in TFTR experiments where the frequency chirps up by about 5 kHz in 200 ms [6].

Physically, we can understand the frequency chirping of C-TAEs as follows: When q_0 decreases the resonant q surface of the C-TAE moves outward through the region of low shear in the core. Because the C-TAEs have a ballooning structure, they move to a lower toroidal magnetic field region with a lower Alfvén velocity, resulting in a lower mode frequency.

Frequency crossover of C-TAEs.—With the NOVA-K code we not only found C-TAE solutions but we also found G-TAE solutions with its mode structure localized outside the $q = 1$ surface. Usually, these G-TAEs are not excited in ICRF experiments because the fast particle drive is located in the plasma center, away from where these modes peak. Moreover, these G-TAEs intersect with the Alfvén continuum near the edge and are therefore heavily damped. However, when a C-TAE chirps down and "crosses" the frequency of a G-TAE, the C-TAE is influenced by the G-TAE in the following way (Fig. 4): instead of crossing the G-TAE frequency, the two modes

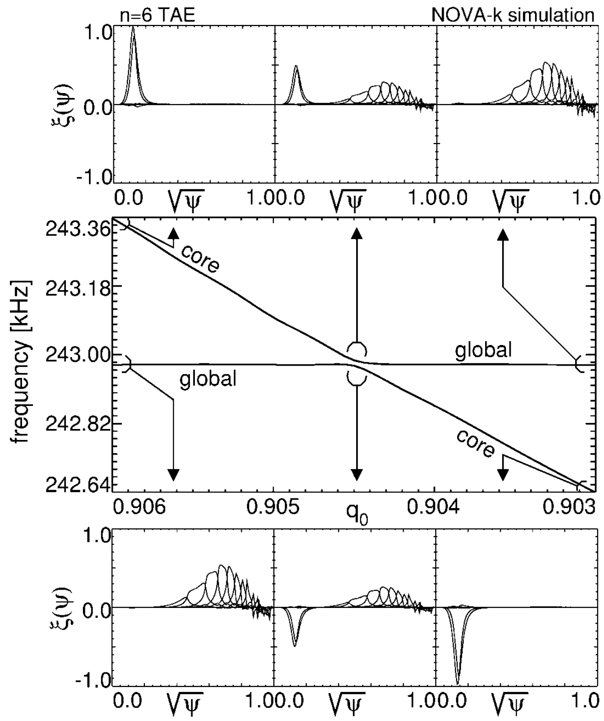

FIG. 4. NOVA-K simulation of the frequency crossing avoidance between C-TAE and G-TAE. The higher (lower) frequency mode starts as the C-TAE (G-TAE), mixes in (out of) phase with the G-TAE (C-TAE) at the closest approach, and finally becomes the G-TAE (C-TAE). Note that after the "crossing" the C-TAE phase is shifted by π. The displacements are normalized to the strongest poloidal harmonic for both modes (C-TAE: $m = 5$; G-TAE: $m = 9$).

mix with each other when the frequency difference becomes small. At the point of closest approach, usually less than 100 Hz in our simulations, the two separate modes still exist but they both have become a mixture of the core and global components (see Fig. 4). The upper frequency mode starts off as the core mode. When q_0 decreases it mixes in phase with the global mode and finally, it becomes the global mode. The lower frequency mode starts as the global mode, mixes out of phase with the core mode, and ends up as the core mode that continues to chirp down. In this way the frequency crossing is avoided. Note that when the C-TAE passes the G-TAE its phase is changed by 180° (Fig. 4). When the C-TAE couples to a G-TAE it is expected that the damping of the C-TAE increases significantly because of the strong damping of the G-TAE part.

In Fig. 5 a frequency gap can be seen at 231 kHz for the $n = 10$ TAE around 10.160 s. This gap can be explained as a frequency "crossing" of the C-TAE and a G-TAE as discussed above. From Fig. 5 it can be seen that the higher frequency mode chirps down and decays after 10.155 s. At the same time the lower frequency mode appears and starts to chirp down. At a number of places in the C-TAE spectra we have seen similar gaps in the frequency chirp that can be explained by the coupling

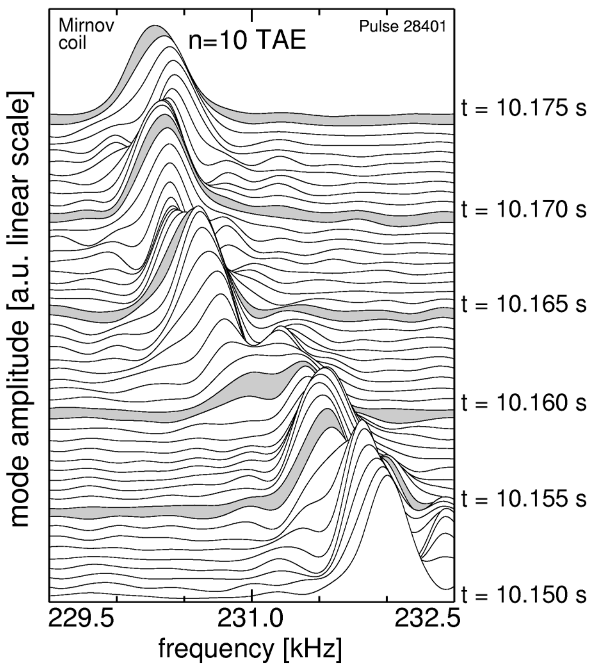

FIG. 5. Spectra of the magnetic fluctuations of the $n = 10$ TAE at 10.15 s. The gap due to frequency crossing avoidance between the C-TAE and G-TAE is clearly visible at 231 kHz. The time of the shaded profiles is indicated on the right.

of the C-TAE and G-TAEs. Four such gaps are shown in Fig. 6 for the $n = 10$ and $n = 9$ modes. At those crossings the mode amplitude decreases as expected.

Discussion and Conclusion.—With the NOVA-K code we have simulated the chirping behavior of C-TAEs that was observed during ICRF sawtooth stabilization experiments. These C-TAEs reside in the very low magnetic shear region in the plasma core. Because of this low shear, a tiny decrease in q_0 shifts the location of the C-TAEs significantly outward where the C-TAEs experience a lower magnetic field and hence the frequency drops. Apart from the q profile, the pressure and density profiles affect the chirping of the C-TAEs as well. We have found that the C-TAE frequency chirping observed before GSTs is mainly caused by small changes of the plasma equilibrium in the core. The nonlinear chirping theory as presented in Ref. [10] is not applicable here because the mode frequency variation is in the order expected from the linear theory. Any nonlinearity in the frequency chirp must be weak compared to the dominant linear mode variation. Moreover, the predicted simultaneous frequency up and down shift as observed elsewhere [11] is not observed here.

We have also found two different ways in which the C-TAEs can affect the plasma in the outer regions: (i) When the frequencies of the C-TAE and a G-TAE are almost the same, mixing between the two modes occurs whereby a frequency crossing is avoided. The two mixed modes consist of a core localized and a global part. (ii) After passing through the very low shear region in the core the C-TAE starts to interact with higher-m poloidal harmonics outside $q = 1$ thereby losing its core-localized nature and becoming a G-TAE.

In our simulations we found that when the C-TAE couples to the higher-m poloidal harmonics in the outer region of the plasma via one of the two above mentioned mechanisms, it started to intersect the Alfvén continuum near the edge. It is expected that continuum damping will play a significant role in stabilizing these mixed C- and G-TAE modes. One of the consequences of the coupling between the C-TAE and G-TAE is that the transport of energetic particles from the core may be enhanced when the drive is so strong that the continuum damping is not sufficient any more to stabilize these modes. Another consequence of the induced fast particle losses by the TAEs is that the GST can be triggered because of a degradation of the fast particle population which stabilizes the GST, but more experimental work is needed on the fast particle loss mechanisms before GSTs.

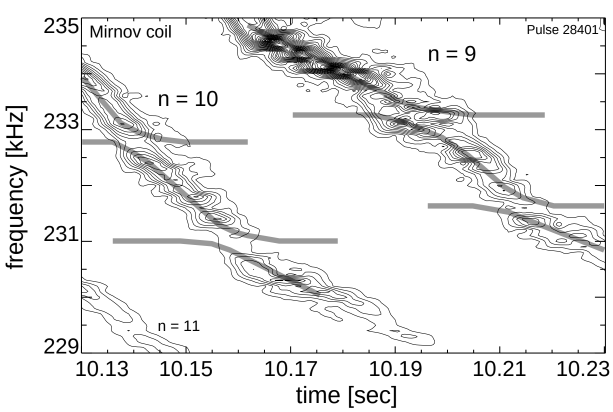

FIG. 6. An expanded view of the $n = 10$ and $n = 9$ contours, showing the reduction in amplitude of the C-TAE which can be explained by the coupling to G-TAEs. The tick gray lines are only to guide the eye at the mode crossings.

[1] C. Z. Cheng and M. S. Chance, Phys. Fluids **29**, 3695 (1986).
[2] K. L. Wong, Plasma Phys. Controlled Fusion **41**, R1 (1999).
[3] C. Z. Cheng, Phys. Fluids B **3**, 2463 (1991).
[4] R. Nazikian *et al.*, Phys. Rev. Lett. **78**, 2976 (1997).
[5] M. Saigusa *et al.*, Plasma Phys. Controlled Fusion **37**, 295 (1995).
[6] E. D. Fredrickson *et al.*, Nucl. Fusion **35**, 1457 (1995); S. Bernabei *et al.*, in *Proceedings of the 17th International Conference at Yokahama* (IAEA, Vienna, 1998) (Report No. IAEA-F1-CN-69/EXP3/8, 1998).
[7] C. Z. Cheng, Phys. Rep. **211**, 1 (1992).
[8] G. Y. Fu *et al.*, Phys. Plasmas **3**, 4036 (1996).
[9] R. Nazikian *et al.*, Phys. Plasmas **5**, 1703 (1998).
[10] H. L. Berk *et al.*, Phys. Lett. A **234**, 213 (1997).
[11] Y. Kusama *et al.*, Nucl. Fusion (to be published).