High-frequency reversed-shear Alfvén eigenmodes in fast-ion experiments on JET

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The three-ion D-(D NBI)-^{3}He ion cyclotron radio frequency (ICRF) scheme was recently successfully applied for plasma heating and fast-ion-physics studies in mixed D- ^{3}He plasmas at JET [1-4] . In this series of experiments, co-passing fast deuterons from Neutral Beam Injection (NBI) with initial energy $E_{\mathrm{NBI}} \approx 100$ keV were accelerated to energies up to ~2 MeV in the plasma center, without significant change in their pitch-angles (specifics of the 3-ion ICRH scheme). A large variety of Alfvén Eigenmodes (AEs) in the frequency range varying from ~80 kHz to ~700 kHz was regularly destabilized by fast ions in these JET experiments. The observed modes include the toroidicity-induced AEs (TAEs), ellipticity-induced AEs (EAEs), as well as reversed-shear AEs (RSAEs), referred to as Alfvén Cascades (Acs) [5,6] throughout this work. Both ICRF-generated energetic deuterons and fusion-born alpha particles can resonate and excite AEs in contrast to the sub-Alfvénic NBI ions causing damping of AEs on JET. Studying the characteristics of AEs in these JET plasmas with strong core electron heating from MeV-range fast ions is also relevant for ITER and future fusion reactors, where similar conditions will be reached with alpha particles.

A substantial modification of the AE spectrum was identified during our experiments due to the changes in the plasma equilibrium. In particular, the observation of ACs implies the reversed-shear equilibrium as the presence of a local minimum of the safety factor, q_{min} is one of the necessary conditions for these modes to be destabilized. Two different types of ACs were regularly observed during the long-period sawtooth phases in this series of JET experiments [5-7]. In addition to the well-known low-frequency ACs with frequencies below the TAE frequency, also ACs with frequencies above the TAE frequency (the high-frequency ACs (HFACs)) were destabilized by energetic ions (See Fig.1). Similar HFACs (also called H-RSAE) were previously observed in reversed-shear plasmas in JT-60U experiments heated with negative-ion-based NBI, injecting a large number of passing ions with energies ~400 keV [5].

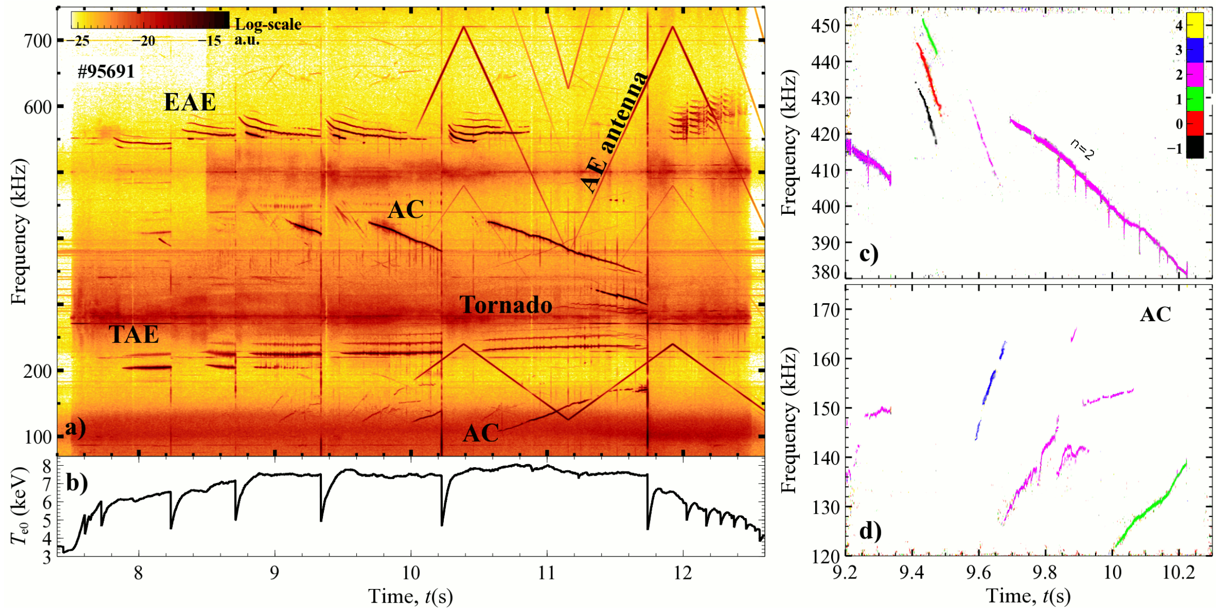

Fig 1. (a) The spectrogram of the Mirnov coil signal in JET pulse #95691 heated with the three-ion D-(D_{NBI})-^{3}He ICRF scenario. . (b) The temporal evolution of the central electron temperature. (c) and (d) The toroidal mode numbers of the high-frequency and low-frequency Alfvén cascades (t = 9.2-10.3 s).

Soft X-ray and interferometer diagnostics are used for estimation of radial location of the modes. Core HFAC localization is expected according to these estimations. The HFAC is localized inside R=3.3m (inside the q=1 surface) according to the scanned frequency microwave reflectometer measurements (See Fig.2).

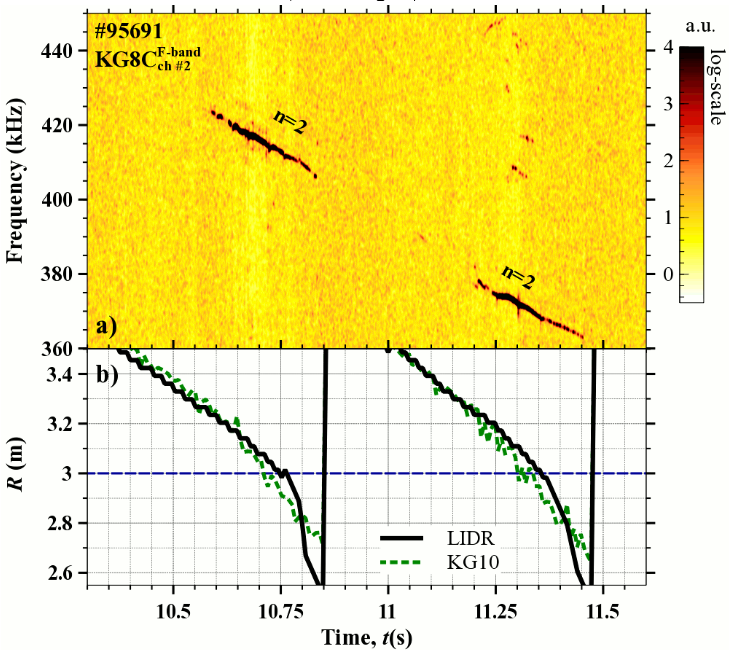

Fig. 2. Localization of high frequency AC modes by reflectometer: a) spectrogram; b) location of cut-off by LIDAR (black) and KG10 (green).

Numerical analysis of HFACs, was carried out using a set of MHD codes HELENA, CSCAS and MISHKA. The largest uncertainties in these calculations are mainly determined by uncertainties in the safety factor, in particular, in the plasma core. The model q-profiles in the central region of the plasma were constructed by the MHD-spectroscopy approach with the use of MHD markers (q_1-q_3) in addition to the q-profile at $t = 9.9$ s inferred from MSE measurements (dashed green line) as it is shown in Fig.3a.

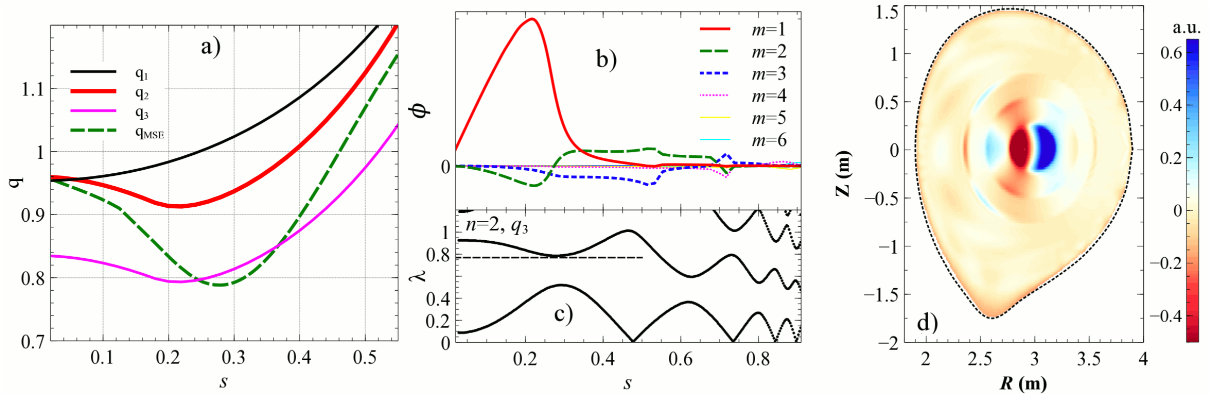

Fig. 3. a) A set of the q-profiles used for MHD analysis of HFACs in JET pulse #95691. The dashed green line illustrates the inverted q-profile at $t = 9.9$ s, as inferred from MSE measurements. MISHKA calculation of HFAC modes: (b) of plasma potential ϕ; (c) Alfvén continuum structures ; (d) poloidal structure of ϕ . n=2 and q_{MSE} profiles are used.

The HFAC and usual AC are localized in the same region, as figure 6 shows. This location corresponds to the q_{min} location of about $s \approx 0.2$-0.3 ($R\approx3.2$m) as it is seen from measurements. The value of q_{min} is deduced from the measured AC mode frequency via our numerical modeling. The q_{min} causes a formation of additional “hill” and “valley” of the continuum. The usual ACs are localized above the “hill” in the continuum, HFAC is localized below the “valley”. Computed by MISHKA eigenmodes of HFAC for q_{MSE} case are shown in Fig.3 b-d.

In order to assess the wave-particle resonant interaction for HFAC, we employ a particle following code HALO [8] which computes full orbits of test energetic particles in toroidal geometry. For the case of the $n = 2$ HFAC with $f = 410$ kHz, we assess for which energetic ions the wave-particle resonance condition $\Omega=\omega-n\omega_{tor}-p\omega_{pol}=0$ is satisfied, where ω, n are the mode frequency and toroidal mode number, ω_{tor} is the toroidal orbit frequency, ω_{pol} is the poloidal orbit frequency, and p is an integer. We plot log $\Omega(E, \lambda)$ and find that the resonance is satisfied for the areas shown in Fig. 4(a).

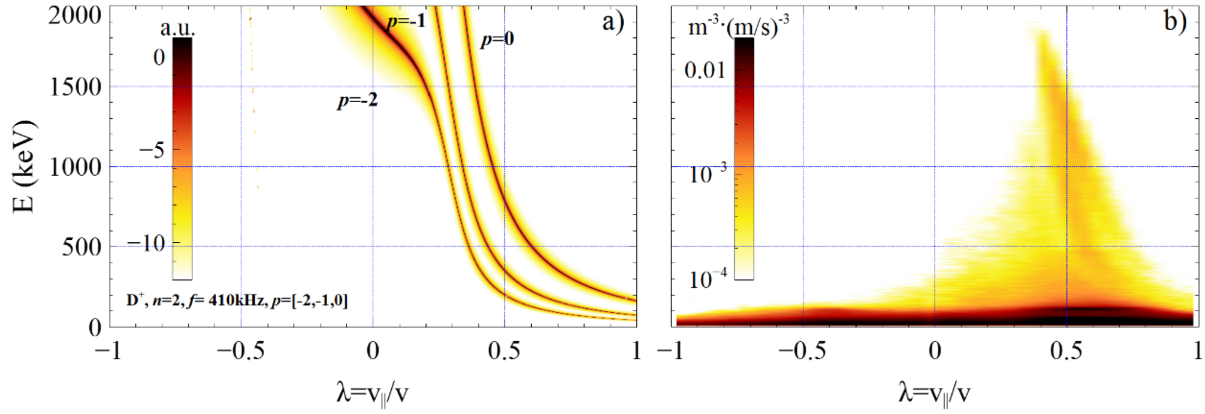

Fig. 4. a) The HALO calculation of the regions in energetic ion phase space where the resonance condition (3) is satisfied for the *n*=2 HFAC mode with frequency 410 kHz. The strongest resonances with integer values of *p*=0, -1, -2 are shown. b) The distribution function of ICRF-accelerated deuterons at the mode location computed with the TRANSP-TORIC code.

Fig.4 shows that the HFAC resonant interaction (and destabilization) could be caused by passing ions with the pitch-angles between 0.5 and 1 at energy of several hundred keV well exceeding the initial NBI energy of 100 keV. This is in agreement with the JT-60U experimental results, which concluded that super-Alfvénic passing ions are necessary to satisfy the resonance condition for HFAC. The resonances (especially the strongest *p*=0) are found to be well within the computed distribution function of energetic deuterons accelerated with ICRH from the NBI seed as Fig. 4(b) shows. The distribution function is calculated for the D-(D_{NBI})-^{3}He ICRH discharge at the radial location of the HFAC mode with the TRANSP-TORIC code [9]. As HFACs resonate with high-energyions, this explains why HFACs were not seen in previous JET experiments with ICRH creating populations of *trapped* energetic ions. In contrast, the low-frequency ACs can be destabilized by both trapped and passing ions. The novel three-ion scenarios at JET have a unique feature of generating a large population of passing fast ions of energy ~0.5 MeV and higher, thereby mimicking the conditions of earlier JT-60U experiments with negative-ion-based NBI. The observed HFACs could also be highly relevant for future ITER and fusion reactor plasmas dominated by fusion-born alpha-particles, including a large population of MeV-range passing fast ions.

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