BAE dynamics in presence of external magnetic field perturbations in AUG, EAST and JET plasmas

L. Piron [a,b], P. Buratti[c], M. Falessi[d], F. Zonca[c], B. Sieglin[e], R. Henriques[g], L. Gil[g], T. C. Hender[f], S. E. Joffrin[i], Y.Q. Liu[j], M. Maraschek[d], R. Paccagnella[b], L.Pigatto[b], G. Pucella[c], G. Szepesi[f], D. Terranova[b], J. Vicente[g], H.H. Wang[k], P. Zanca[b] and ASDEX Upgrade Team* and JET contributors**

(*) See author list of H. Meyer et al 2019 Nucl. Fusion 59 112014 (**) See author list of E. Joffrin et al 2019 Nucl. Fusion 59 112021

[a] Dipartimento di Fisica "G. Galilei", Università degli Studi di Padova, Padova, Italy, [b] Consorzio RFX, Corso Stati Uniti 4, 35127, Padova, Italy, [c] ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Rome, Italy, [d] CREATE, Consorzio CREATE, Via Claudio 21, Napoli, Italy, [e] IPP Garching | Max-Planck-Institut für PlasmaphysikGarching, Germany [f] UKAEA, CCFE, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom, [g] Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001, Lisboa, Portugal, [i]Association EURATOM-CEA sur la Fusion, Cadarache, France, [j]General Atomics, San Diego, US, [k] Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China.

A class of MHD instabilities, named beta-induced Alfvén eigenmodes (BAEs) [1, 2], can be destabilized by energetic particles and can cause the redistribution and loss of such particles. To guarantee in ITER and in future burning plasma reactors good confinement of energetic particles and alpha heating efficiency, investigating the BAEs triggering mechanism and their dynamics in present fusion devices is thus of particular importance. This work presents BAEs behaviour in AUG, EAST and JET Ohmic plasmas, in presence of externally applied magnetic fields. In such a plasma, without an energetic particle population, BAEs are due to the non-linear excitation of Alfvén waves by a locked magnetic island, induced by the external fields. It has been observed that BAEs can disappear from the MHD spectrum, despite the magnetic island being present. Such phenomenon can be explained through a theoretical evaluation of the continuum distortion in the presence of magnetic field perturbations, based on the general fishbone like dispersion relation [3, 4, 5].

Evidence of beta-induced Alfvén eigenmodes in compass scan experiments

To detect the intrinsic error field (EF) sources in fusion devices, the compass scan method [6] is commonly used. It consists in applying a probing magnetic field of known phase and amplitude to reproducible Ohmic plasmas. The EF amplitude and phase are inferred from the

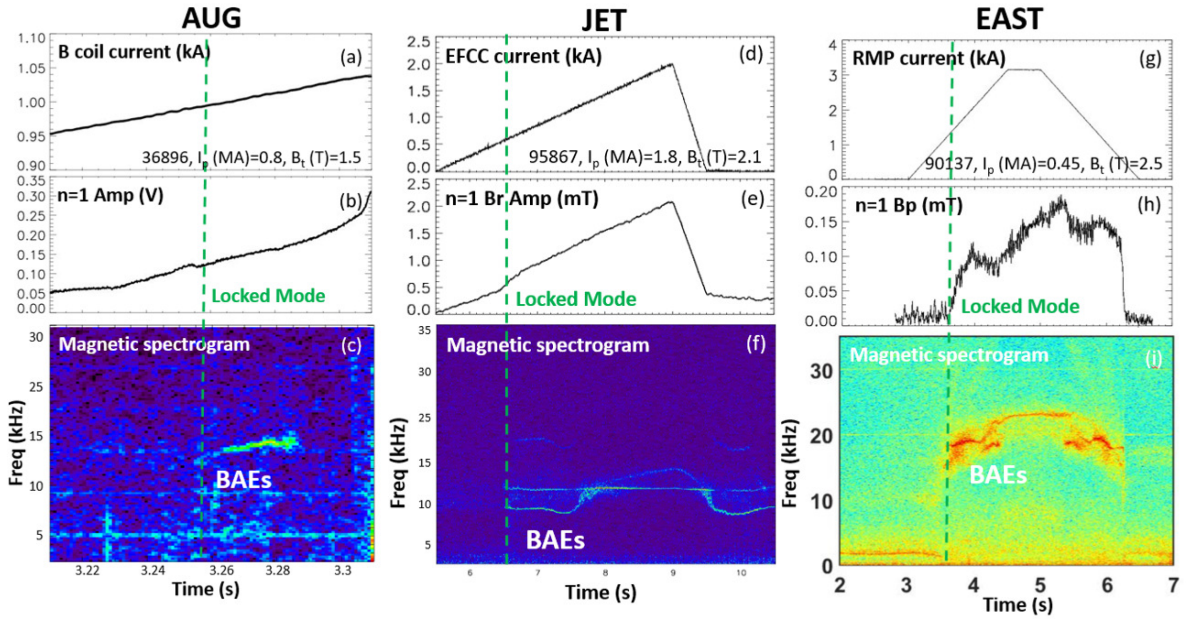

Figure 1: Time evolution of (a-d-g) error field correction coil current, (b-e-h) n=1 magnetic field amplitude and (c,f,i) magnetic spectrogram of a compass scan test performed in AUG (on the left), JET (centre) and EAST (on the right).

possible shift of this circle that is obtained by measuring the locked mode onset, as the probing magnetic field is ramped with several different toroidal phases.

The compass scan method has been applied in AUG, JET and EAST in Ohmic discharges, by applying n=1 external magnetic fields by means of EF correction coils, named B coils, EFCC and RMP coils, respectively.

The time behaviour of these correction coil currents is reported in figures 1(a-d-g). Above a threshold of the EF correction current, when the field penetration process occurs, an n=1 locked mode is induced, whose time behaviour is shown in figures 1(b-e-h). As the locked mode is triggered, beta-induced Alfvén eigenmodes (BAEs) appear in the Mirnov spectrogram, in the frequency range around 8-24 kHz, as reported in figures 1(c-f-i).

These plasmas being in Ohmic regime, thus without an energetic particle population, the BAEs are due to the non-linear excitation of pairs of Alfvén waves counter-propagating in the island frame. In our experiments, since the magnetic island is locked at the probing magnetic field's phase, the two BAE branches degenerate in a single line because of the lack of Doppler effect.

In JET, a complex BAEs dynamics has been observed: BAEs appear in the MHD spectra as two lines with slightly different frequencies, i.e. 9 kHz and 12 kHz, as reported in figure 1(f), in absence of any rotating tearing mode at around 1.5 kHz, as we would expect based on BAEs behaviour in FTU [7]. The MHD activity with initial frequency of 9 kHz has a time evolving frequency, while the MHD mode with initial frequency of 12 kHz has a constant frequency. In this manuscript, we focus the attention on the BAEs branch with appears at 9 kHz. In this case, BAEs are made up of two standing waves with n=-1 and n=1 which are localized at the q=2 surface, as inferred by the BAE signature in the interferometer line of sight data close to the q=2 surface (not reported here).

In the compass scan tests, the BAEs appear above a threshold value of the EFCC field, when the locked magnetic island is sufficiently large to transfer energy to the Alfvén waves overcoming the thermal ion Landau damping. Such a threshold depends on density, as demonstrated in figure 2, which refers to compass scan discharges performed in JET while exploring various density regimes.

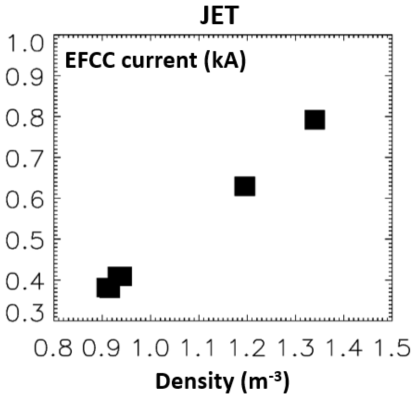

Figure 2: EFCC current as function of plasma density at the time of locked mode and BAEs triggering. Data refers to JET compass scan tests perform in Ohmic Ip=1.8 MA and Bt=2.1 T discharges.

Once triggered, the frequency of BAE depends on the n=1 locked mode amplitude, i.e. island width, which is consistent with theory predictions [8] in the case of toroidal mode number of BAEs equals to the toroidal mode number of the locked mode.

Beta-induced Alfvén eigenmodes close to the continuum accumulation point

In JET and in AUG experiments, it has been observed that BAEs disappear from the Mirnov spectrogram, despite the locked mode being present. This happens when BAEs reach around 15.8 kHz and 18 kHz in JET and in AUG, respectively, as shown in figures 3(a-b).

Similarly to Bragg reflection in a crystal lattice and the electron band gap in conductors, Alfvén Eigenmodes lie in gaps, which arise from finite shear Alfvén wave compressibility via geodesic curvature coupling in the case of BAEs.

To investigate the physical mechanism responsible for BAEs disappearance in the MHD spectrum, the theoretical framework of the general fishbone like dispersion relation (GFLDR) [3], implemented in the FALCON code [4, 5], has been applied in JET and AUG plasmas, utilizing the experimental plasma equilibria and the density profiles of 95871 JET (t=45 s, 47 s, 49 s) and 36906 (t=2.84 s, 2.87 s, 2.90 s) AUG discharges.

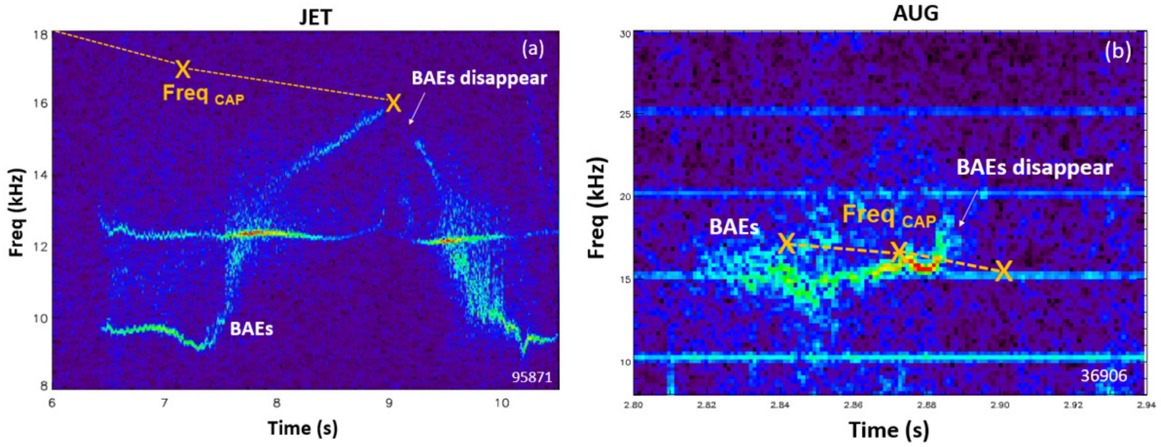

Figure 3: Magnetic spectrogram of compass scan tests performed in JET, on the left, and AUG, on the right, with theoretical evaluation of the continuum accumulation point.

The upper limit of the BAE frequency gap, dubbed continuum accumulation point (CAP), has been evaluated at the q=2 surface, since the BAEs are associated with a 2/1 locked magnetic island. We recall that, consistently with [8], its value does not depend on the external magnetic fields but only on the equilibrium. These theoretical predictions have been reported with orange crosses in figure 3. For the JET case, BAEs are expected to disappear when the frequency of CAP is around 16 kHz, which is in good agreement with the experimental evidence. A similar continuum accumulation point, around 16.05 kHz, is predicted for the AUG case, showing a good agreement with the experimental data, as well.

Discussion

Signature of BAEs, MHD activities which lie in Alfvén continuum gap, associated with beta and geodesic curvature, has been documented in this work during the application of n=1 external magnetic fields used in compass scan tests in AUG, JET and EAST devices. BAEs are sustained by the presence of a locked magnetic island, which is triggered when the external magnetic field penetration occurs. Once triggered, BAEs can disappear from the MHD spectrum if the upper limit of the BAE frequency gap in the Alfvén continuum is reached, as observed in AUG and JET plasmas and as demonstrated by GFLDR theory predictions.

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