Comparison between BAE observations at FTU and theoretical models

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1. Introduction

The beta Alfvén eigenmodes (BAE) are high frequency oscillations (30-70 kHz) in tokamak plasmas, identified in the spectrum of the Alfvenic modes as discrete eingemodes located in the low frequency gap of continuum which is produced by geodesic curvature and finite beta effect. BAEs have been first identified as waves excited by circulating fast ions. However BAEs were also observed in ohmic plasmas (i.e. without any fast ions population) with the simultaneous presence of a large magnetic island, for the first time at FTU [1]. This observation induced to consider new excitation mechanisms for BAE, in particular the most promising non-linear excitation via three-wave coupling with a magnetic island sufficiently large to transfer enough energy to overcome Landau damping [2]. BAE needs to be controlled in tokamak devices, because it can cause energetic loss and reduce the confinement of alpha particles, limiting plasma performance.

2. Experimental observations

We focus our attention on some long BAEs observed at FTU. Fig. 1 shows signals detected by poloidal field pick-up coils located inside the vacuum vessel (lower parts) and relative spectrograms of fast Fourier transformer in some analyzed discharges. This picture is representative of the phenomenology we are investigating. The intense lines from 1 to 5 KHz (middle parts) refer to typical oscillations produced by a large magnetic island. Temporal ranges show the evolution of these tearing modes, which decrease in frequency as the magnetic island amplitudes grow and lock. Other harmonics are also observed at twice the fundamental frequency. BAE oscillations accompany tearing modes at higher frequencies between 30 and 50 KHz (upper parts) and intensities two order of magnitude less than tearing modes. BAE is characterized by two main lines which merge in a single line when the island oscillation frequency becomes very low. Mode analysis pointed out poloidal and toroidal mode numbers |m|=2 n=-1, corresponding to magnetic islands formed around the q=2 surface. The BAE frequency lines have $n = \pm 1$, the higher lines propagate in the same direction with respect to the island, while the lower lines propagate in opposite direction.

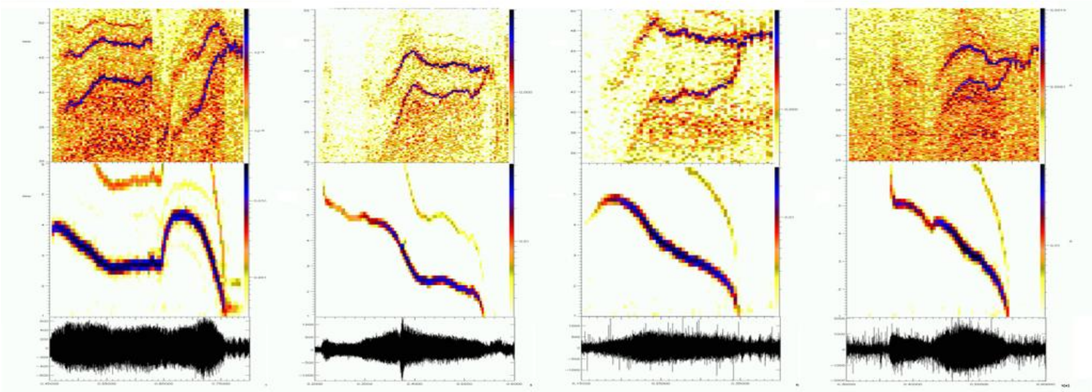

Figure 1. Magnetic signals (lower part) and their FFT spectrogram at both frequencies of tearing mode (medium part) and frequencies of BAE (upper part) for shoots number 23184, 23540, 25877, and 27255.

The difference between the two BAE frequency lines is exactly twice the fundamental frequency of the tearing mode. The frequency difference can be explained as Doppler shift due to island rotation. In this picture, BAE forms a standing wave composed by two waves propagating at opposite velocities in the island rest frame [2], indeed the BAE frequency is the average of the two lines: $f_{BAE} = (f_h + f_l)/2$.

In various discharges, a third mode that accompanies BAE and tearing mode is observed, with frequency comparable to tearing mode, intensity comparable to BAE, and located in a region closer to the centre of the plasma respect to the q = 2 radius.

3. Theoretical results

Different theoretical approaches have been used to investigate the physics of shear Alfven spectrum. The kinetic theory is necessary to construct a realistic theory of BAE modes. In [3] is developed a linear kinetic theory of high toroidal mode number low-frequency Alfvèn waves ($\omega < \omega_A$), including diamagnetic effects and finite core-plasma ion compressibility, and considering the wave interaction with circulating ions. The generalized fishbone-like dispersion relation of the form $i\Lambda = \delta W$ is used to solve both the continuum structure of the spectrum (real solutions of Λ) and the discrete branches (imaginary solutions of Λ), the continuum accumulation point (CAP, i.e. the higher edge of the frequency gap in the Alfven continuum) is found by solving $\Lambda = 0$. In [3] is found that the finite plasma compressibility introduces a gap in the structure of the low-frequency shear Alfven continuous spectrum, the corresponding BAE-CAP at lowest order is analytically expressed by [3]:

$$f_{BAE-CAP} = \frac{1}{2\pi R_0}\sqrt{\frac{2T_i}{m_i}\left(\frac{7}{4}+\frac{T_e}{T_i}\right)} \qquad (1)$$

In [4], the same linear kinetic approach is used including the effect of the trapped particles (banana particles) on the low frequency shear Alfvèn spectrum. Numerical analysis of Λ show a shift of the BAE–CAP frequency in respect of eq.(1) when trapped particles are taken into account, this shift can be upward or downward depending on plasma parameters, and becomes negligible in the limit of high BAE frequencies ($\omega > \omega_{Ti}$).

Previous results are developed in the large aspect ratio tokamak equilibrium geometry. In [5], a modified geometry due to effects of magnetic island is taken into account. The modification of BAE spectrum is calculated in the framework of fluid equation for shear Alfvèn wave in tokamak with quasi static magnetic islands. An upward shift in the continuum accumulation point is found, resulting in a nonlinearly modified BAE-CAP frequency, given by [6]

$$f_{nl\,BAE-CAP} = f_{BAE-CAP}\sqrt{1+\ q\ |s|\frac{\delta B_r}{B_\theta}\left(\frac{f_A}{f_{BAE-CAP}}\right)^2} \qquad (2)$$

where $q,\ s,\ f_A$ and $\delta B_r/B_\theta$ are respectively safety factor, magnetic shear, Alfvèn frequency and field oscillation at the rational surface r_s. Moreover, the modified BAE frequency has a similar form for small magnetic islands [6]:

$$f_{BAE} = f_{BAE,0}\sqrt{1+\ q\ |s|\frac{\delta B_r}{B_\theta}\left(\frac{f_A}{f_{BAE-CAP}}\right)^2} \qquad (3)$$

where $f_{BAE,0}$ is the BAE frequency for vanishing magnetic islands.

4. Comparison between observations and theoretical predictions.

In Fig.2 the calculated BAE-CAP frequency is compared with the observed BAE frequency. The red lines refer to observed frequency, blue lines to BAE-CAP frequency calculated with eq.(1) and green lines include magnetic island correction eq.(2). We have assumed s = 1.0, T_e=T_i and T_e is measured at q=2 radius by ECE. We observe an agreement with the expected situation of BAE frequency just below the BAE-CAP point. The large difference between BAE and BAE-CAP frequency in shot 26644 is related to its higher temperature. We also have observed a strong dependence of BAE-CAP point on magnetic island amplitude. In Fig.3 we compare the theoretical prediction of BAE frequency as a function of magnetic island amplitude with experimental observations.

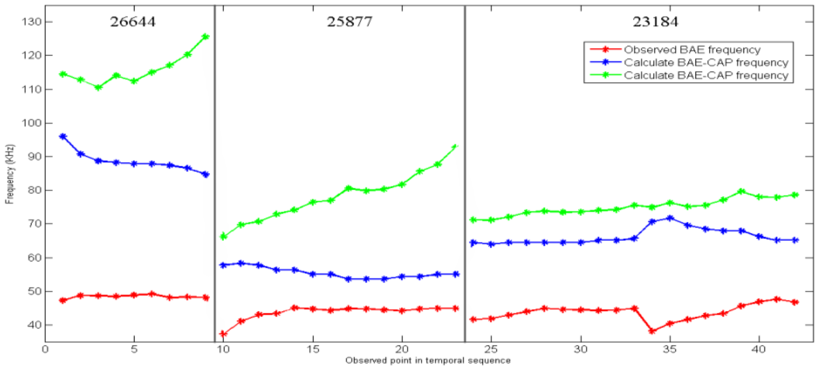

Fig. 2 Observed BAE frequency (red) and calculated BAE-CAP frequency (blue and green) for discharges N. 23184, 25877 and 26644.

We observe that during the first part of island growth, BAE frequency increases roughly linearly, in good agreement with the eq.(3), on the other hand a discrepancy is found for $\delta B_r(r_s)/B_\theta(r_s) > 2 \cdot 10^{-3}$ where BAE frequency remains rather constant. Therefore, we can state the perturbative theory gives consistent results only for low magnetic island amplitudes. This result confirms the interpretation of these oscillations as BAE nonlinearly interacting with the magnetic island.

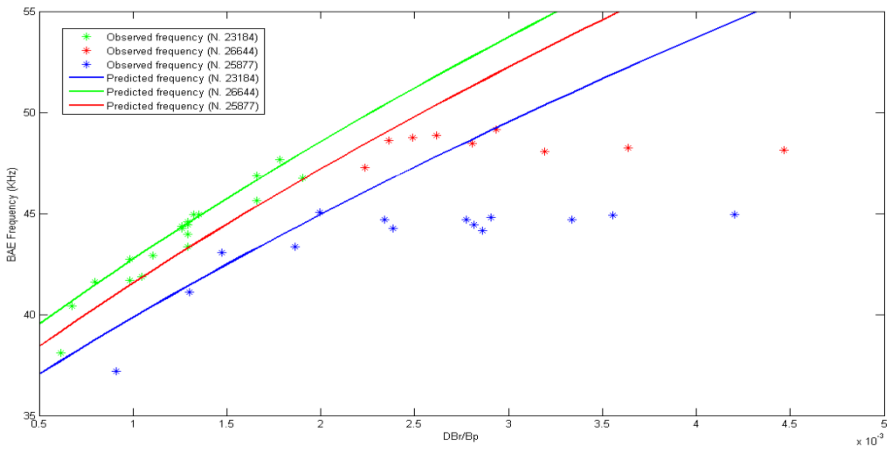

Figure 3. Observed and calculated BAE frequency (eq. 3) as a function of $\boldsymbol{\delta B_r(r_s)/B_\theta(r_s)}$ for discharge N. 23184 (green), 25877 (blue) and 26644 (red).

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