Inter-Machine Scaling of Alfvén-like Modes Excited by Magnetic Islands in FTU and TEXTOR

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1. Introduction

The excitation of high-frequency (HF) waves in the presence of large magnetic islands has been recently discovered in tokamak plasmas [1, 2]. Wave frequencies are well above the island rotation frequency, one order of magnitude below the first toroidal gap in the Alfvén continuum and of the same order of the low frequency gap introduced by finite beta effects. Observation of HF waves in ohmic plasmas, i.e. in the absence of fast ions that could drive Alfvén eigenmodes, calls for the identification of new excitation mechanisms. In order to help such an identification, in this paper we will determine the scaling of wave frequency using experimental data from FTU and TEXTOR.

2. Experimental results from FTU and TEXTOR

HF waves appear as soon as the island formed by a tearing mode exceeds a threshold amplitude [3]. The tearing mode can be either spontaneous or induced by external perturbations [2]. HF modes appear in the spectrograms of magnetic signals as pairs of lines that rotate in opposite directions and are separated by twice the island rotation frequency (figs. 1, 2). If the island frequency decreases to zero due to locking, each pair coalesces into a single line (see fig. 1 at $t = 0.35$ s).

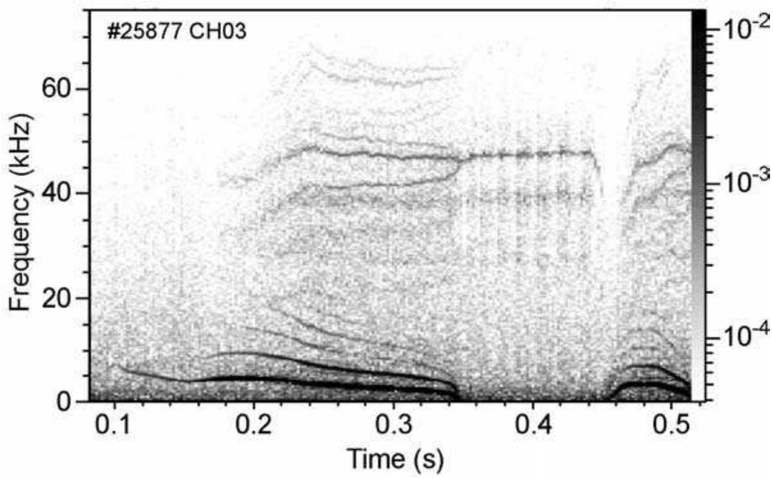

Figure 1. Spectrogram of a Mirnov coil signal in an ohmic FTU pulse. Greyscale gives the relative amplitude of poloidal field oscillations $\delta B_{pol}/B_{pol}$. Lines below 20 kHz correspond to a (-2, -1) tearing mode. The intense HF line near 50 kHz has n=-1, the other just below has n=1.

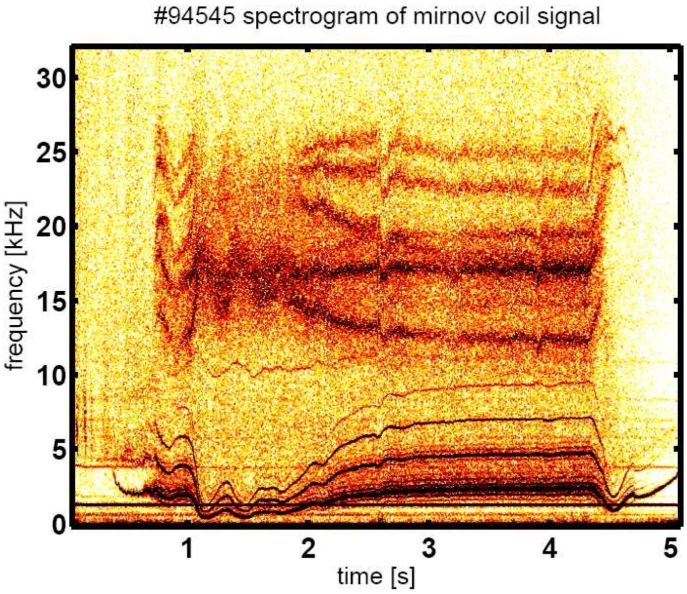

Figure 2. Spectrogram of a Mirnov coil signal in an ohmic TEXTOR pulse. Lines below 10 kHz correspond to a (-2, -1) tearing mode and its harmonics. The HF-modes higher than 12 kHz have alternating positive and negative mode numbers.

Inclusion of data from two tokamaks of different size (major radius $R = 0.95$ m in FTU and $R = 1.75$ m in TEXTOR) gives a wide span of plasma parameters, in particular toroidal magnetic field $1.75 \le B \le 7.5$ T, line-average density $1.4 \le \bar{n}_e \le 7.7\times10^{19}$ m^{-3}, central electron temperature $0.91 \le T_e \le 2.6$ keV. The database includes 95 cases, 53 from TEXTOR and 42 from FTU; for each case, the average frequency of the strongest pair of lines is considered. In all cases the magnetic island had m/n=2 ratio between poloidal and toroidal mode numbers. The influence of island width on HF modes frequency is weak [3] and will be neglected in the following; this will introduce a basic data scatter of ±15% at worst.

3. Comparison with basic Alfvénic scaling

A linear dependence of the measured frequency on Alfvén velocity clearly emerges from the database (fig. 3). Separate linear fits give very similar slopes for both machines, 3.17×10^{-3} m^{-1} in FTU and 3.22×10^{-3} m^{-1} in TEXTOR. This common slope is a severe problem for a simple Alfvénic scaling, in fact the slope gives the parallel wavenumber $k_{\|}/2\pi$, which should scale inversely with machine size; in other words, measured frequencies scale with the Alfvén velocity but they do not scale with the Alfvén frequency $f_A = V_A/(2\pi Rq)$. This implies that a simple picture based on the possible instability of HF modes in the helically distorted equilibrium that is formed by the island cannot explain HF modes excitation, and a more complex scheme of interpretation, like the one presented in the next section, has to be considered.

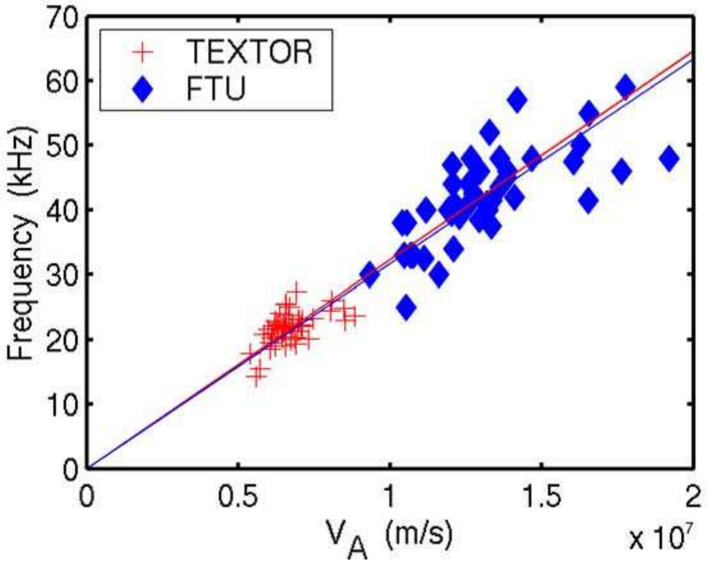

Figure 3. HF modes frequency versus Alfvén velocity calculated with line-average density. Solid red line: slope from a linear fit to TEXTOR data only. Blue line: same for FTU.

4. Scaling based on beta-induced Alfvén eigenmodes

Since HF modes have been observed in ohmic plasmas, in which there are no fast ions that can excite Alfvén waves, the observed perturbations are likely to be due to the non-linear excitation of shear-Alfvén waves by the magnetic island. More precisely, it has been conjectured [3] that modes of the Beta-induced Alfvén Eigenmode (BAE) branch [4] are nearly marginally stable in the case under investigation, and can be nonlinearly excited in the presence of a sufficiently large magnetic island. Pairs of BAEs, with given helicity and localized near the $q=2$ surface, can interact with the (-2,-1) island via three-wave couplings and be nonlinearly excited provided that the energy transfer rate from the island to BAEs is sufficient to overcome the linear mode damping, thereby setting a threshold condition for the island amplitude. For example, a (-4,-2) and (2,1) BAE pair can nonlinearly interact with the (-2,-1) island (negative mode numbers correspond to modes propagating in the electron diamagnetic direction). For each BAE propagating in the electron diamagnetic direction, the model predicts that there will be a twin BAE wave propagating in the ion diamagnetic direction. These twin waves will look like standing waves in the plasma rest frame, the phase coherence being set by the common nonlinear excitation mechanism, i.e. the (-2,-1) island.

The BAE frequency can be estimated by the accumulation point of the low frequency gap introduced in the shear Alfvén continuous spectrum because of finite beta [3]. To lowest order the accumulation point is given by [5]

$$f_{BAE} = \frac{1}{2\pi R}\sqrt{\frac{2T_i}{m_i}\left(\frac{7}{4}+\frac{T_e}{T_i}\right)}, \tag{1}$$

where T_e and T_i are electron and ion temperatures at the $q=2$ radius. This frequency is an upper bound for the expected mode frequencies. The comparison between experimental frequencies and BAE scaling is shown in fig. 4. Again separate linear fits give nearly the same slope (0.38 in TEXTOR, 0.35 in FTU), but this time the dependence on machine size is included in the scaling expression. The scaling frequency in fig. 4 has been estimated using central electron temperature, because ion temperature at the q=2 radius was not available; this justifies at least in part the large data scatter and the small slope (according to the meaning of eq. 1, the slope should be below but not too far from unity). An improved estimate could be obtained using T_e at the $q=2$ radius, but this is left to future work.

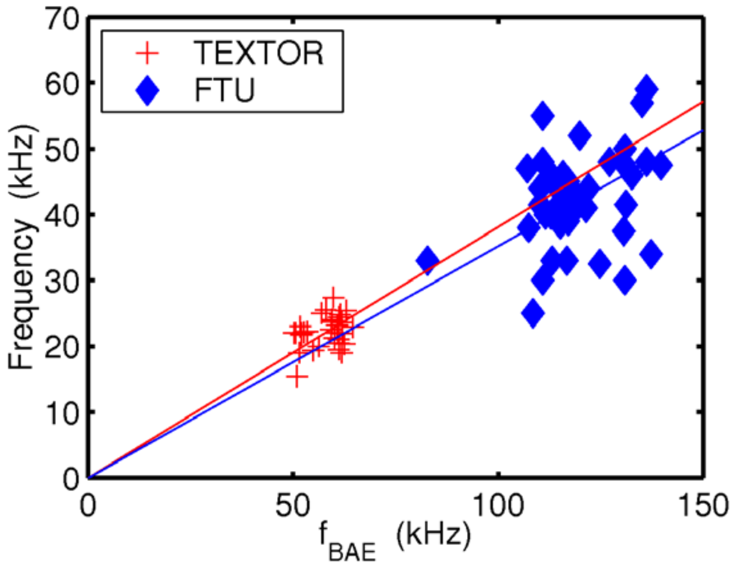

Figure 4. HF modes frequency versus BAE frequency accumulation point calculated with central temperature and $T_e = T_i$. Solid red line: slope from a fit to TEXTOR data only. Blue line: same for FTU.

5. Conclusions

Inter-machine scaling of Alfvén-like modes excited by magnetic islands shows an impressing ordering of frequencies with the Alfvén velocity, but not with the Alfvén frequency in its simplest form. Frequency scaling resulting from non-linear excitation of beta-induced Alfvén eigenmodes by three-wave coupling with the magnetic island is consistent with experimental data.

References

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