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Fast Particle Driven Modes at ASDEX-Upgrade

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Introduction and experimental features

In many ICRF heated discharges (hydrogen minority heating) at ASDEX-Upgrade a variety of fast particle driven modes can be observed. In order to determine their nature and their possible impact on fast particle transport, a broad set of diagnostics is employed: the Mirnov coils show clearly the footprints of all electromagnetic modes with finite perturbation at the plasma edge and allow for a reliable mode number identification. The soft x-ray cameras deliver valuable information about the radial mode position. Finally, the energy and the pitch angle of expelled particles can be directly measured by the fast-ion-loss detector (FILD) diagnostic allowing to reconstruct possible resonance conditions and the mode amplitude evolution.

During an IRCF power ramp, the toroidal Alfvén Eigenmodes (TAE) with typical mode numbers $n = 4...7$ at typically $200-280$ kHz appear first, indicating that they are the least damped modes under these experimental conditions. At higher heating power another electromagnetic mode at about $70-110$kHz is observed, a so-called 'BAE' [1, 2] or 'sierpes' [3] mode. At ASDEX-Upgrade this mode seems to be closely connected with the appearance of a $q = 1$ surface and therefore with sawtooth oscillations (see Fig. 2). Its mode numbers are $n = 4$ with a dominant $m = 4$ component and it is located radially at $\rho_{pol} \approx 0.2-0.4$ (SXR reconstruction with the MHD-IC code [4]). It has been demonstrated that this mode is non-Alfvenic since neither B-field ramps nor density changes influence the mode frequency. Furthermore, the appearance of the 'BAE' mode enhances the FILD-losses induced by the TAE mode [3] suggesting a possible 'channelling' effect between the 'BAE' and the TAE.

As in earlier publications [2], no clear scaling with *only* the ion sound speed or *only* the diamagnetic frequency $\omega_{p*} = \omega_{*n} + \omega_{*T} = m_i/(eB)k_\theta(\nabla n/n)(1+\eta)$ with $\eta = \frac{\nabla T}{T}/\frac{\nabla n}{n}$ or *only* the energetic particle drive can be found. Therefore, it was concluded [2] that this mode is a hybrid mode. This hypothesis is investigated in this paper employing a linear gyrokinetic analysis. In order to identify the fast-particle-drive mechanism and to interpret the FILD signal non-linear simulations are also carried out [11].

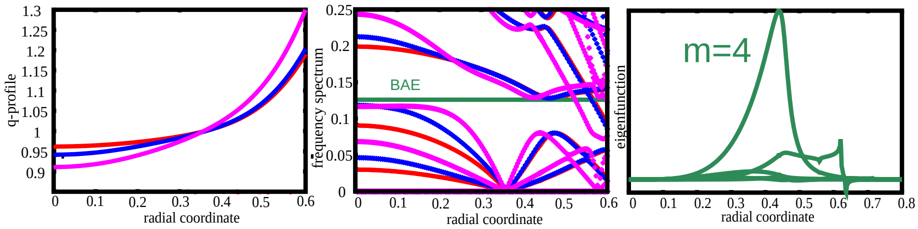

Figure 1: q-profile variation $q_0 = 0.9...0.97$ and corresponding spectra, BAE eigenfunction

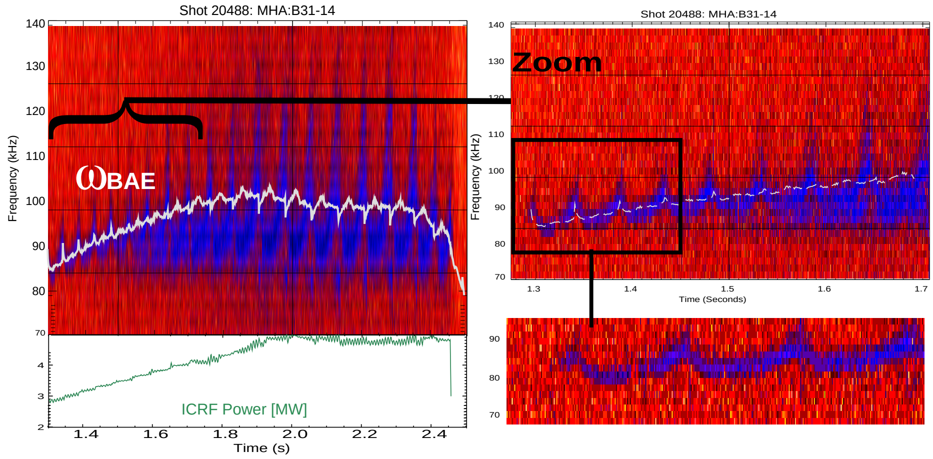

Figure 2: Mirnov coil spectrogram for the ICRF power ramp up phase of #20488. In the beginning, for low power (1.3 to 1.5s), the mode frequency follows roughly formula (1)

Theoretical Model - linear properties

Employing the compressible MHD model implemented in CASTOR [5] shows (Fig. 1) the BAE- gap structure and the BAE eigenfunction at $\omega/\omega_A = 0.126$. Assuming typical plasma rotation values of $\sim$ 4kHz translates to this to the experimentally observed $\sim$ 90kHz. Since the mode peaks close to the $q = 1$ surface, it's q-dependence is very weak, as shown in Fig. 1: for three different equilibia that allow for a change of q_0 due to a sawtooth cycle, but keep the $q = 1$ surface radially fixed, almost no change of the gap structure close to $\rho_{pol} = 0.3..0.4$ and therefore also no change in the mode frequency is found. As a consequence, the variation of q cannot explain the mode's frequency evolution during a sawtooth cycle.

The simplest kinetic dispersion relation for BAE modes [6] is

$$\omega_{BAE}^2 = \frac{v_{thi}^2}{R_0^2}\left[\frac{7}{4} + \tau(1 + \frac{1}{2q^2})\right] \tag{1}$$

where R_0 is major radius, v_{thi} is the thermal speed of the background ions and $\tau = T_e/T_i$. It predicts a mode frequency, that scales with $\sqrt{T_i}$. Fig. 2 shows this dispersion relation, where for T_i the experimental values of an ECE channel close to the $q = 1$ surface were chosen ($T_i = T_e$ assumed). Reasonable agreement is found only before 1.5s where the heating power is relatively low. Furthermore, even in this early phase, the 'dip' (that can be up to 40kHz!) of the mode signal roughly in the middle of a sawtooth cycle cannot be explained with this simple model.

It was pointed out in reference [6] that for $\omega \sim \omega_{ti} \sim \omega_{p*}$ the BAE and the kinetic ballooning branches couple. Furthermore, finite η can lead to unstable continua. Introducing finite Larmor radius and finite orbit width effects discretise these continua leading to unstable so-called Alfven-ion-temperature-gradient-driven (AITG) modes. At long wavelengths ($k_\theta \rho_E \sim 1$) and low frequencies, this branch can be easily excited by energetic ions [7]. The relevant dispersion relation, originally derived in the ballooning formulation [6] is rederived here for the gyrokinetic model [8] underlying the eigenvalue code LIGKA [9]. Applying a Fourier-ansatz in the poloidal coordinate, keeping the $m \pm 1$-sidebands, retaining the geodesic curvature and the sound wave coupling by an appropriate expansion of the propagator integrals, leads to:

$$\omega^2 = 2\frac{v_{thi}^2}{R_0^2}\left(-\left[H(x_{m-1}) + H(x_{m+1})\right] + \tau\left[\frac{N(x_{m-1})^2}{D(x_{m-1})} + \frac{N(x_{m+1})^2}{D(x_{m+1})}\right]\right) \tag{2}$$

with $x_m = \frac{\omega}{k_{\|,m} v_{th}}$, $D(x_m) = \left[1 + \tilde{D}(x_{e,m})\right] + \tau\left[1 + \tilde{D}(x_{i,m})\right]$, $N(x_m) = \tilde{N}(x_{i,m}) - \tilde{N}(x_{e,m})$, $\tilde{D}(x) = (1 - \frac{\omega_*}{\omega})xZ(x) - \frac{\omega_*}{\omega}\eta\left(x^2 + xZ(x)(x^2 - \frac{1}{2})\right)$, $2\tilde{N}(x) = (1 - \frac{\omega_*}{\omega})\left[x^2 + xZ(x)(x^2 + \frac{1}{2})\right] - \frac{\omega_*}{\omega}\eta\left[x^4 + \frac{x^2}{2}) + xZ(x)(\frac{1}{4} + x^4)\right]$, $H(x_m) = \tilde{H}(x_{m,i}) + \tau\tilde{H}(x_{m,e})$, $\tilde{H}(x_m) = \frac{1}{2}\left[(1 - \frac{\omega^*}{\omega})\tilde{F}(x_m) - \eta\frac{\omega^*}{\omega}\tilde{G}(x_m)\right]$, $2\tilde{F}(x) = xZ(x)(\frac{1}{2} + x^2 + x^4) + \frac{3x^2}{2} + x^4$, $2\tilde{G}(x) = xZ(x)(\frac{3}{4} + x^2 + \frac{x^4}{2} + x^6) + 2x + x^4 + x^6$ and $Z(x)$ the plasma dispersion function. Although obtained in a completely different way, eqn 2 is very similar (same coefficients) to the ballooning formulation result. However, this derivation serves as a straightforward way for benchmark purposes and the investigation of geometrical effects.

Solving this equation without expansion by employing a local version of the LIGKA code allows to map the influence of ω_{*p} on the mode frequency and the damping rate. The following parameters are chosen for the time point 1.34s: $k_\theta \approx nq/\rho_{pol}a \approx 23/m$, with $a = 0.5m$ and $\rho_{pol} = 0.35$, $\beta_{local} \approx 0.015$, $\omega_{A0} = 6.7 \cdot 10^5$. Fig 3 shows that for growing ω_{*p} ($\omega_{*n} < 0.05\omega_A$) the mode frequency passes through a minimum - regardless if one keeps η fixed and varies ω_{*n} or one keeps ω_{*n} fixed and varies η. This behaviour can explain the frequency 'dip' (by about 15%) during a sawtooth cycle where experimentally $\omega_{*n} \sim 0.035$ and η changes from 0.2 to 3. Also the deviation from formula 1 at later times $> 1.5s$ (higher heating power - stronger gradients - lower frequency) can be explained. However, for very high heating power the mode character is dominated by the fast particles - as seen in Fig 2 where multiple modes appear just before the sawtooth crash.

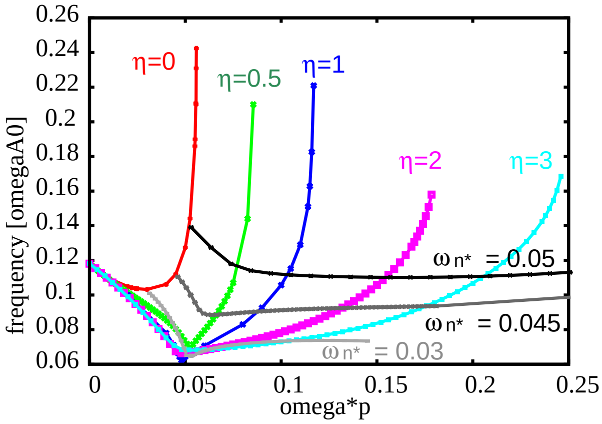

Figure 3: mode frequency of the BAE/KBM branch: ω_{*p} and η dependence

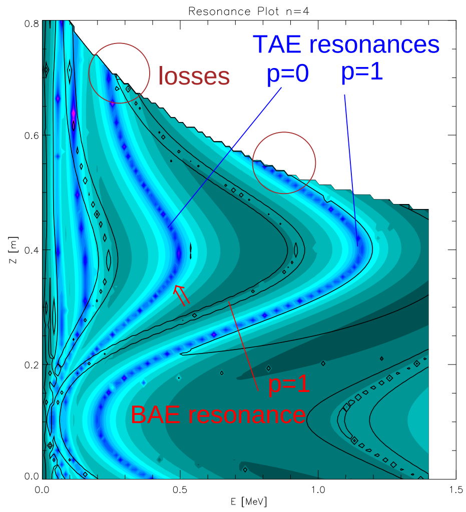

Figure 4: Graphical respresentation of the resonance conditions for the $n = 4$ TAE and the BAE mode [11]

Mode Drive

In order to understand the mode drive, the resonance condition $\omega - \omega_D - p\omega_b$ for the trapped ICRH ions is mapped by employing an extended version (including the vacuum region and gyroradius effects on the loss orbits) of the HAGIS code[10, 11]. Fig 4 shows the resonances in energy and Z-space for the $n = 4$-TAE and the BAE mode. Here Z labels the vertical position of the banana tips at $R = R_{mag}$. Even at low amplitudes the TAE can expell particles via the $p = 0$ and $p = 1$ resonances at ~ 0.25 and $\sim 0.9 - 1.0$ MeV - in agreement with the FILD signal [3]: just a small radial displacement can move resonant particles onto loss-orbits (indicated by circles in fig 4). Furthermore, the BAE mode moves particles via a $p = 1$ resonance radially outwards, enhancing the population of the $p = 0$ resonance for the TAE and thus increasing its amplitude. Fig 4 also shows that $0.8 - 0.9$MeV ions can be expelled by the BAE itself. Further quantitative calculations are on the way.

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