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# AlfvØn Eigenmodes in a Beam-Assisted Ohmic START Discharge

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## 1. Introduction

Observations of magnetic fluctuations in the AlfvØn frequency range during neutral beam heating in the START spherical tokamak have provided an opportunity to test the theory of AlfvØn eigenmodes (AEs) under conditions of extreme magnetic geometry [1]. Towards the end of the last START campaign, such fluctuations were observed during a beam-assisted ohmic discharge in which hydrogen beam injection was applied initially to a mainly deuterium target plasma, then switched off 3ms after plasma formation, before significant beam heating had taken place. Here we present observations and modelling of fast particle instabilities occurring in this discharge.

## 2. Observations

High frequency instabilities were detected on both outboard and inboard Mirnov coils for approximately 1.5ms after neutral beam injection was switched off in START shot #36484. During this time there was a temporary increase in $D_\alpha$ emission, accompanied by an influx of sputtered high Z material from above the midplane. Figures 1 and 2 shows a spectrogram and power spectrum obtained using the outboard coil. Peaks appear at frequencies around 400-500 kHz on both the outboard and inboard power spectra, particularly the latter.

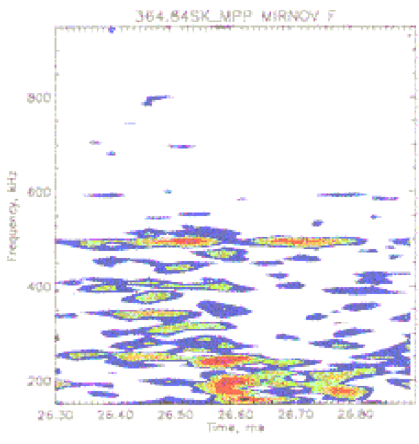


**Fig. 1.** *Spectrogram from START shot #36484, obtained using outer midplane Mirnov coil. Beam injection was switched off at t = 26ms.*

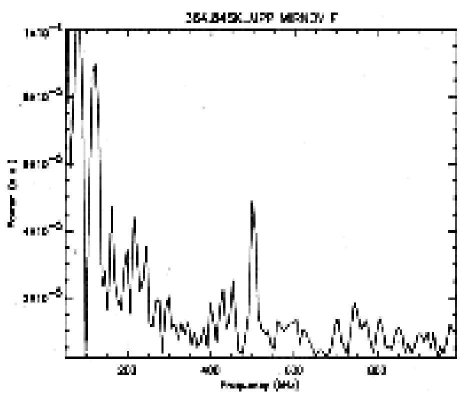


**Fig. 2.** *Outer midplane power spectrum corresponding to spectrogram in Fig. 1.*

At frequencies below 200 kHz, the strongest activity appears on the outer coil signal (Fig. 2). The toroidal plasma beta was approximately 8.8%.

### 3. AlfvØn Continua and Eigenmodes

The plasma equilibrium at the time of beam switch-off in shot #36484 was reconstructed using the EFIT code [2]. The continuous spectrum of shear AlfvØn waves with toroidal mode number n=1, computed using the NOVA code [3], is shown in Fig. 3. The quantity $\psi_p$ is normalised poloidal flux; $\omega$ is mode frequency; and $\omega_A$ is AlfvØn speed in the plasma centre divided by the product of the edge safety factor and the geometric major radius.

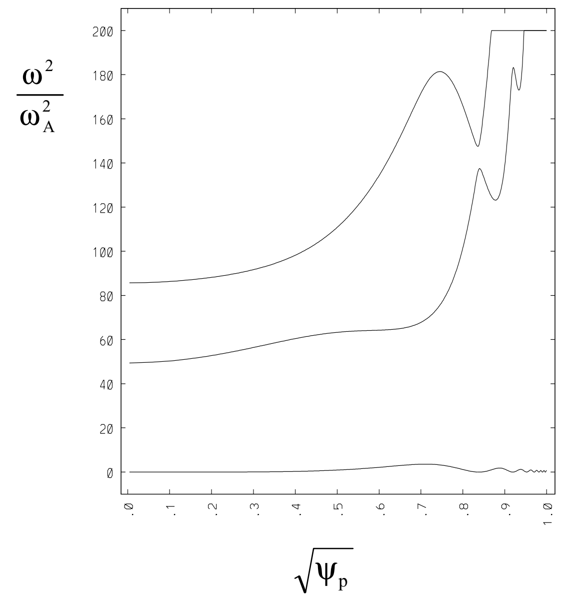

**Fig. 3.** *Shear AlfvØn Continuum for n=1 at t=26ms in shot #36484, computed using NOVA.*

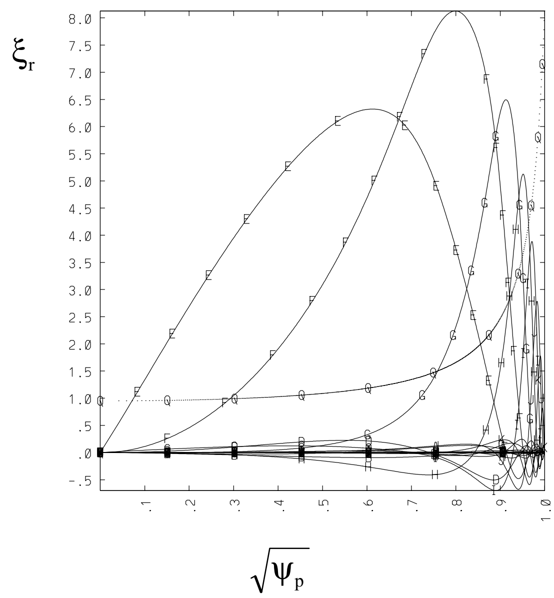

**Fig. 4.** *Toroidal AlfvØn eigenfunction with n=1 and frequency $\nu \approx 126$ kHz.*

Figure 3 indicates the presence of a wide toroidicity-induced gap in the n=1 AlfvØn continuum: as noted in [1], the high gap width is a consequence of tight aspect ratio. Toroidal AlfvØn eigenmodes (TAEs) can exist in this gap. Although there is also an ellipticity-induced gap, at $\omega^2/\omega_A^2 \approx 140$, any mode existing in this gap would be subject to strong continuum damping, and hence is unlikely to be observed.

A single n=1 TAE was found using NOVA in the toroidicity gap of Fig. 3: the plasma displacement eigenfunction is shown in Fig. 4. The curve Q shows the q-profile; the other curves show the contributions of poloidal harmonics, with E corresponding to m=1, F corresponding to m=2, and so on. The mode is global and ballooning in character: the dominant harmonics m=1,2 interfere constructively in the outer midplane, destructively in the inner midplane. The frequency eigenvalue, 126kHz, coincides with a strong peak detected using the outboard Mirnov coil (Fig. 2). Several n=2 modes were also found using NOVA, with frequencies ranging from 83kHz to 166kHz. However, the code did not indicate the existence of any modes with frequencies close to those of the strongest peaks observed on the inboard side (400-500kHz). It is possible that these peaks are due to energetic particle modes, which can exist inside the AlfvØn continuum [4].

## 4. Drive and Damping Rates

The observations described in Sect. 2 are reminiscent of afterglow experiments on TFTR [5] and JET [6], in which TAEs were destabilised by a drop in beam and thermal damping following auxiliary heating. In START, beam ions are injected with speeds greater than the AlfvØn speed $c_A$, and hence provide drive rather than damping. For START shot #36484 we have computed the beam ion distribution $f_b$ at t=26ms, the time of beam switch-off, using the Monte Carlo LOCUST code [7]. Figure 5 shows $f_b$ (in arbitrary units) as a function of toroidal canonical momentum $P_\varphi$ (in m), at fixed particle energy E and magnetic moment $\mu_0$; Fig. 6 shows $f_b$ as a function of E at fixed $P_\varphi$ and $\mu_0$. Beam ions with E = 4.95keV, the energy used to plot Fig. 5, have $v \approx c_A$ at the position of peak amplitude of the mode shown in Fig. 4.

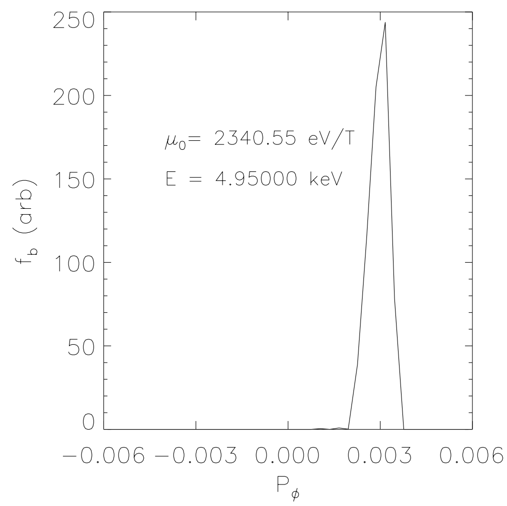


**Fig. 5.** *Distribution in $P_\varphi$ space of beam ions with E=4.95keV and $\mu_0$ = 2.4keVT$^{-1}$ at t=26ms.*

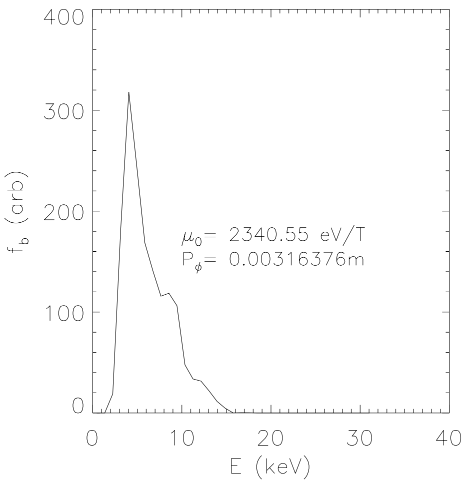


**Fig. 6.** *Distribution in energy space of beam ions with $P_\varphi$=0.0032m and $\mu_0$ = 2.4keVT$^{-1}$ at t=26ms.*

The beam ions invariably have narrow pitch angle distributions, peaking at $\mu_0 \approx 0$: this is due to a combination of tangential beam injection and neutralisation of beam ions born into trapped orbits [1]. Because the ions whose distribution is plotted in Fig. 5 have parallel velocity $v_z \approx v$, they can interact with TAEs via the resonance $v_z = c_A$. Such modes can be driven unstable by energetic particle distributions $f_b$ with $\partial f_b/\partial P_\varphi < 0$ or $\partial f_b/\partial E > 0$ [8]: it is clear from Figs. 5 and 6 that the distributions computed using LOCUST have both of these characteristics. The triggering of instability after beam switch-off is most likely to have been caused by a steepening of $f_b(P_\varphi)$. This could have resulted from a drop in the charge exchange time in the plasma edge ($P_\varphi$ is essentially a radial variable). The influx of sputtered high Z material noted in Sect. 2 was probably also accompanied by cooling, leading to a reduction in the edge slowing down time, and a consequent further steepening in $f_b(P_\varphi)$. Quantitative evaluation of these effects on TAE drive remains to be carried out.

We have used the NOVA-K code [8] to estimate electron collisional damping $\gamma_c$, electron Landau damping $\gamma_e$ and majority bulk ion Landau damping $\gamma_i$ of the mode shown in Fig. 4. These estimates depend on the temperatures and densities of the two species, which are subject to considerable uncertainty, and in any case are likely to have changed significantly in the plasma edge during the period of mode excitation. The profiles of electron temperature $T_e$ and density $n_e$ were estimated using Thomson scattering data from a different, similar discharge; the ion temperature $T_i$, upon which $\gamma_i$ depends critically, was assumed to be equal to $T_e$ (data from comparable START discharges indicate values of $T_i$ between about $0.7T_e$ and $T_e$). These model profiles were used to compute both the mode damping rates and the distribution functions shown in Figs. 5 and 6. The computed values of $\gamma_c$, $\gamma_e$ and $\gamma_i$ are

$$\frac{\gamma_c}{\omega} = -0.0053, \qquad \frac{\gamma_e}{\omega} = -0.0012, \qquad \frac{\gamma_i}{\omega} = -0.0861. \tag{1}$$

The damping is thus dominated by bulk ions. This arises from the fact that the bulk ion thermal speed is comparable to $c_A/3$: ions with $v_z$ equal to this speed can interact strongly with the TAE. It should be stressed that the value given in Eq. (1) for $\gamma_i$ is highly uncertain, because it is exponentially sensitive to the bulk ion plasma beta [9]. Nevertheless, the large value obtained for this quantity suggests that the absence of TAEs from the highest performance START discharges was due to strong ion Landau damping.

## 5. Conclusions

We have employed a set of codes to study the excitation of high frequency instabilities observed immediately after the end of neutral beam injection in a START discharge. Using a plasma equilibrium corresponding to the time of mode excitation, several TAEs have been identified theoretically, with frequencies close to those of the strongest modes observed on the outboard side of the plasma. However, the excitation mechanism of modes observed in a higher frequency range is not yet clear. The TAEs are subject to strong ion Landau damping: their excitation may have resulted from a steepening in the radial profile of the beam ion distribution, arising from changes in the charge exchange and slowing down times at the plasma edge. It is intended that the expertise developed in this analysis will be applied to fast particle instabilities observed in the MAST spherical tokamak [10].

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