

# Toroidal Alfvén Eigenmodes in the Extrap T2 Reversed-Field Pinch

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## 1 Introduction

It was noted in [1,2] that the magnetic fluctuation spectra reported from MST [3] do not follow a power law, and suggested that the frequency regime below the cyclotron regime is not inertial, but contains absorption! This regime corresponds to the Alfvén resonance continuum, or the related continua [4–6] between impurity ion cyclotron resonances. Thus continuum gaps make room for global resonances, which can be excited by the transient tearing modes [1,2]. The tearing modes are aperiodic and transient, but have Fourier spectra reaching all global resonance frequencies.

In order to study effects of the Alfvén wave continuum on the fluctuation spectra in Extrap T2, magnetic probes were set-up in the boundary region [7]. Partially coherent fluctuations were seen at frequencies in the range 100 – 800 kHz, varying with the Alfvén velocity and with a polarisation corresponding to the shear Alfvén wave. The wave numbers were not measured and it was not possible to identify the modes.

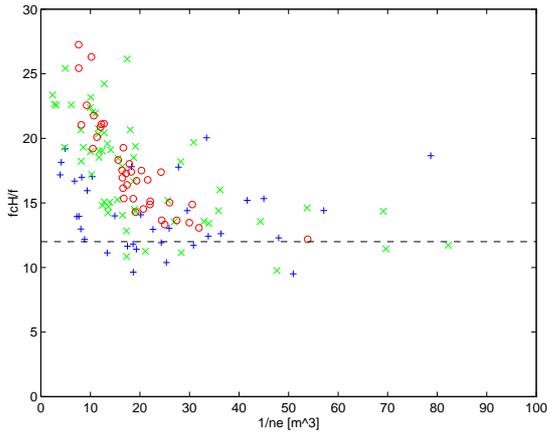
The modes observed motivated additional analysis of data taken with Langmuir probes in the edge region. These measurements were aimed at a study a particle transport by edge electrostatic fluctuations [8]. Using a two-point correlation technique, the toroidal and poloidal mode numbers could be evaluated. The resonance peak dominated the radial particle flux and was found to be correlated with the magnetic fluctuation spectrum [9], indicating that the fluctuations were electromagnetic rather than electrostatic in nature. The probes, however, measured only the curl-free part of the electric field.

For tokamaks the interest in TAE modes stems from the possibility that they can be destabilized by fast ions and enhance fast particle transport. The modes observed in Extrap T2, on the other hand, are not unstable. A short pulse, most likely a transient tearing mode, initiates exponentially decaying oscillations, as expected for a damped eigenmode.

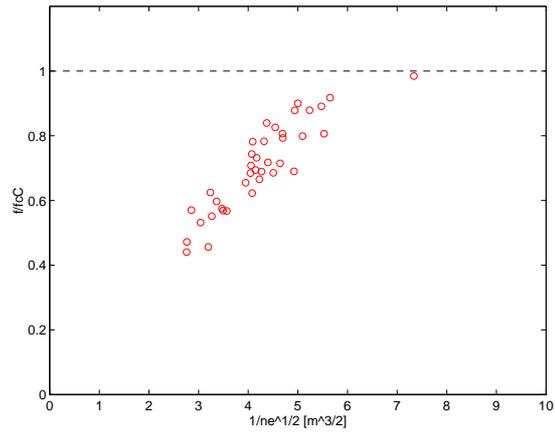
In a tokamak, the TAE modes normally appear below all cyclotron resonances, but in the RFP, impurity cyclotron resonances may appear in the same regime, moving the Alfvén spectrum down below the lowest impurity resonance and introducing the ion cyclotron continua between each impurity ion cyclotron resonance. The strong inhomogeneity of  $\varepsilon_{\perp}$  near cyclotron resonances alters the mode coupling and results in the TAE-like TLE modes [5,6].

## 2 Electrostatic probe results

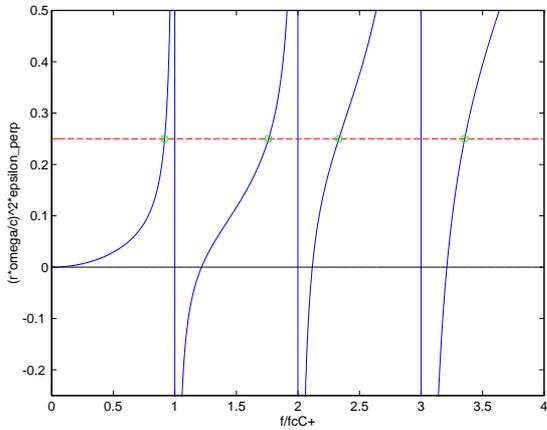
A triple probe technique provided time-resolved measurements of the electron temperature and density and the floating potential. The signals were low-pass filtered at 500 kHz and sampled at 1 MHz, which excludes modes with higher frequencies. The electric field



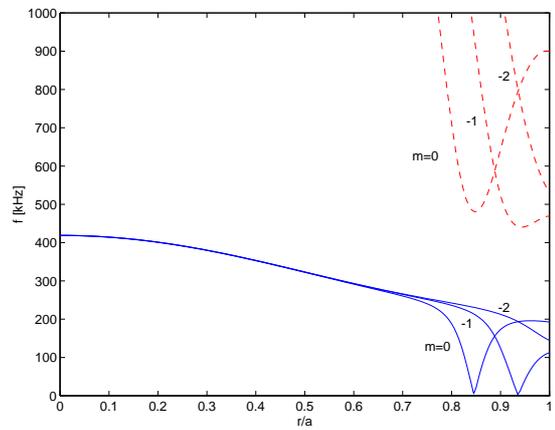
**FIGURE 1.**  $f_{cH}/f$  as a function of the inverse electron density  $1/n_e$  for  $I_\phi = 120$  kA (+), 150 kA (x), and 180 kA (o)



**FIGURE 2.**  $f/f_{cC+}$  as a function of  $n_e^{-1/2}$  for  $I_\phi = 180$  kA



**FIGURE 3.** Mode coupling may occur at frequencies for which  $(r\omega/c)^2\varepsilon_\perp$  (solid) equals  $(m_{1,2} + nq)^2 = 0.25$  (dashed) (H plasma with  $C^+$ ,  $C^{2+}$ , and  $C^{3+}$  impurity ions)



**FIGURE 4.** Alfvén (solid) and two-ion (dashed) wave spectrum for H plasma with  $C^+$  impurity, with  $n = -53$  and  $m = 0, -1$  and  $-2$ .

driven particle transport were shown to be concentrated to the frequency band where the spectrum had a peak, localised in space to the edge region [8].

The frequency of the peak is shown in Fig. 1 for three values of plasma current. It appears to saturate at  $1/12$  of the hydrogen cyclotron resonance at low electron densities and stays below at higher densities. The spread is rather large for the lower plasma currents, probably due to varying carbon content, which is not measured. For 180 kA plasma current the spread is smaller and the frequency varies linearly with the Alfvén velocity for high densities and saturates at the cyclotron resonance of singly ionized carbon (Fig. 2).

The poloidal mode number spectrum extended from  $m = 0$  to  $-4$  and the toroidal mode number  $n$  from  $-30$  to  $-70$  [8]. At the lowest plasma current, 120 kA, the product  $nq(a)$  varied around 1.5, in agreement with the condition for a TAE gap with  $m_1 = -1$  and  $m_2 = -2$  close to the boundary. For higher currents,  $nq(a)$  was smaller and the only possible TAE coupling outside of the reversal surface was between  $m_1 = 0$  and  $m_2 = -1$ .

The condition for degeneration between modes  $m_1$  and  $m_2$  and the formation of a toroidicity induced gap in the Alfvén spectrum, in addition to  $\omega^2 = c^2 k_\parallel^2 \varepsilon_\perp$ , is

$$nq = -\frac{m_1 + m_2}{2} \Rightarrow m_{1,2} + nq = \pm \frac{m_1 - m_2}{2} \quad (1)$$

For the TAE gap  $|m_1 - m_2| = 1$  and the parallel wavenumber at the intersection becomes

$$k_{\parallel 1,2} = (m_{1,2} + nq) \frac{B_\theta}{rB} = \pm \frac{B_\phi}{2qRB} \approx \pm \frac{1}{2r} = \pm \frac{B_\theta}{2rB} \quad (2)$$

where the last expression refers to the edge region of the RFP, where the poloidal magnetic field dominates.

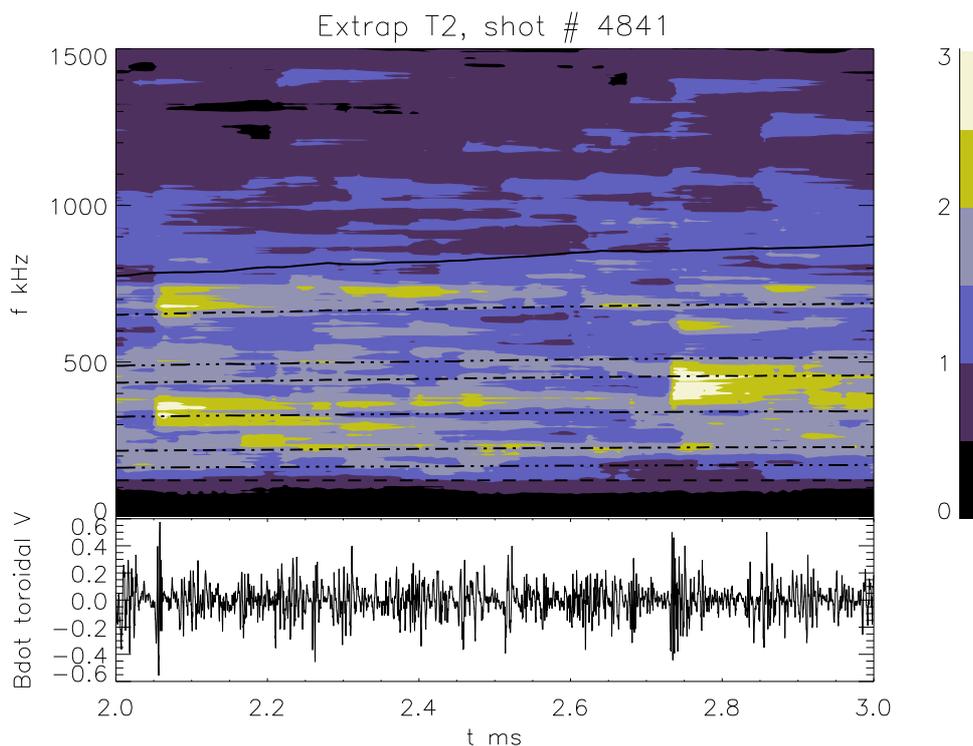
Fig. 3 illustrates the condition for a hydrogen plasma with the first three ionization stages of carbon as impurities. Carbon is of course a significant impurity in the edge region, since the Extrap T2 walls are covered with carbon tiles. Additional ion species introduces other gaps for the same mode numbers, below each ion cyclotron frequency [5, 6]. Ellipticity or, in the ion cyclotron regime, variation of  $\varepsilon_\perp$  can also cause mode coupling between  $m_1 = 0$  and  $m_2 = -2$ , yielding  $(m_{1,2} + nq)^2 = 1$ . Modes in such gaps have frequencies closer to the cyclotron resonances.

Fig. 4 shows the Alfvén wave resonance and the corresponding two-ion resonance versus radius in Extrap T2 for parameters corresponding to shot 4841 but with only one impurity species included, singly ionized carbon, for illustration. In both frequency regimes a gap of the TAE type,  $|m_1 - m_2| = 1$  occurs at  $r/a \approx 0.9$ . The ellipticity is small, but a TLE gap can occur in each regime with  $|m_1 - m_2| = 2$  at  $r/a \approx 0.93$ . For a clear identification, the poloidal mode numbers must be determined with higher resolution than the present  $\pm 1$ . The figure represents only one  $n$  number. The measured  $n$  spectrum contains a group of modes, each with a different  $q$ -value and a different radial position.

### 3 Magnetic probe results

Using a Morlet [10] wavelet transform on the magnetic probe fluctuations, with 8 MHz sampling rate, time and frequency resolved spectra were obtained (Fig. 5). Assuming modes observed are located in the edge region like the electrostatic probe peak, one resonance peak is located in each interval between the main impurity, oxygen and carbon, ion cyclotron resonances up to  $O^{4+}/C^{3+}$ . A peak above this frequency appears to be close to the TAE frequency for pure hydrogen plasma.

Comparison with the time trace below also shows how oscillations at a sequence of frequencies are excited by a perturbation, decay, and are then excited again by a new perturbation. These triggering perturbations appear to be due to intermittent transient tearing modes, thus providing an energy channel from tearing mode fluctuations to thermal energy. The time and frequency resolution is limited and the observed rather broad maxima in the magnetic spectra may consist of more than one resonance peak. The strong variation of  $q$  in the edge region yields gaps for a range of  $n$  numbers. With a different radial position and a different  $\varepsilon_\perp$ , the frequency is shifted. While the electrostatic probe array measures locally in the boundary region, the magnetic probes may detect also internal resonances, with  $m/n < 0$ .



**FIGURE 5.** Wavelet spectrum of the fluctuating magnetic field signal shown below. The electrostatic probe spectrum peak frequency (---), the lowest cyclotron resonances of carbon (- · -) and oxygen (- · · -), and the TAE frequency for H plasma (solid) are also shown.

## 4 Conclusions

The resonant structures observed have frequencies in the Alfvén – impurity ion cyclotron regime. The polarization corresponds to shear Alfvén waves and the frequency varies with the Alfvén velocity. The mode observed below the lowest carbon resonance can be identified as a  $m = 0$  and 1 TAE mode or a  $m = 0$  and 2 TLE mode.

## 5 Acknowledgements

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