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Observation of Modes at Frequencies near the Second Alfvén Gap in TFTR

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Abstract. Modes have been observed near the frequency of the second Alfvén gap during off-axis H-minority heating experiments on TFTR. The observation of these modes is surprising in that the second gap, which is generally opened with ellipticity, is expected to be small, of order $(r/R)^2$, since TFTR plasmas are circular in cross-section. A model is proposed in which the second gap is opened by the fast ion beta, which is shown to be able to introduce mode coupling, much as toroidal effects introduce mode coupling for Toroidal Alfvén Eigenmodes (TAE). The modes are seen with and without accompanying TAE mode activity.

INTRODUCTION

The modes observed near the frequency of the second Alfvén gap are seen predominantly in plasmas with H-minority heating with the resonance off-axis on the high field side. All of the data was collected during ICRF conditioning shots on TFTR. The second gap modes were observed under the following conditions: $I_p = 1.3$ MA, $B_{tor} = 2.5$ T, $f_{ICRF} = 43$ MHz, $R_0 = 2.62$ m, $R_{res}(H) = 2.35$ m, $a_p = 0.97$ m. Approximately 90% of the plasmas with these parameters and ≈ 4 MW of RF power exhibited these "second gap" modes. Previously, extensive RF conditioning and H-minority heating experiments had been done under a wider range of conditions, but predominantly with the resonance near the magnetic axis. In a very few of these experiments, peaks in the magnetic fluctuation spectra were observed at approximately twice the TAE frequency. These peaks were only observed in the presence of strong TAE or EPM activity and are not considered to be strong evidence for the second gap modes, due to the possibility of non-linear response in the Mirnov coil electronics. In the data presented in this paper, the spectral peaks at the second gap frequency are clearly not harmonics of the TAE activity, which in these experiments is often weak or non-existent with very different time behavior.

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The observation of modes at second gap frequencies in the circular TFTR plasmas is surprising since the second gap is generally thought of as the Alfvén gap that is induced primarily by ellipticity. Toroidicity effects on the second gap are negligibly small, of order ϵ^2 , where $\epsilon = r/R_0$ is the inverse aspect ratio. However, it has been predicted that the second Alfvén gap can be opened by the presence of an energetic trapped ion population [1]. Preliminary estimates suggest that there is sufficient fast ion beta in these TFTR plasmas to open the gap and drive the mode.

EXPERIMENTAL OBSERVATIONS

At least three distinct types of mode activity are seen in the second gap [Fig. 1]. The first type is the most common and characteristically shows up as bursts lasting of order 50 msec. It appears to be a single mode. The mode chirps, changing frequency by about 5 kHz in the 30–50 msec that it is present. The second mode type characteristically has a shorter burst, lasting of order 5 msec. This type often shows up as multiple modes separated in frequency by about 1 kHz. It is slightly less common than the Type I modes. The third type is also a short burst, but at a lower frequency. The three types span a frequency range of about 15 kHz, which is $\approx 3.6\%$ of the typical second gap frequency of ≈ 410 kHz. All may be manifestations of one mode.

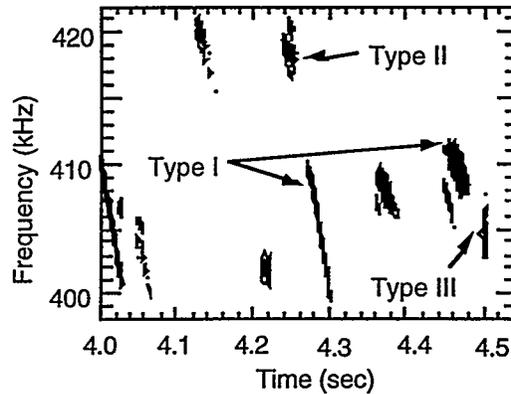


Figure 1. Spectrogram of the second gap modes, showing the three types of behavior.

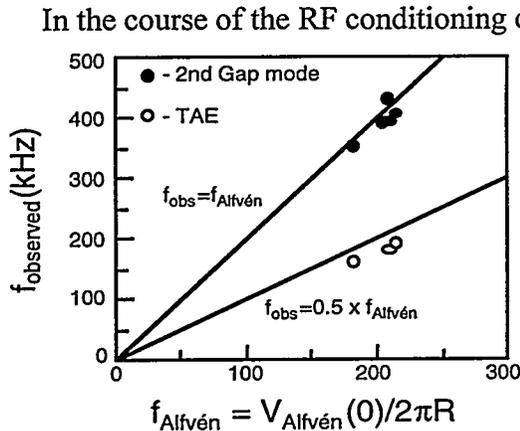


Figure 2. Frequency scaling of second gap modes with central density.

The growth rate of the Type I mode varies from about 0.5 msec to 1.8 msec. Typically the rate is nearly constant over three e-foldings of the mode amplitude, although more complicated growth behavior is also seen. The mode amplitude then

resulted in a range of central plasma densities from $3.2 \times 10^{19} \text{ m}^{-3}$ to $4.2 \times 10^{19} \text{ m}^{-3}$. From this data set it was possible to examine the scaling of the mode frequency with density. The mode frequency is in good agreement with the predicted frequency for the second gap and scales as $n_e(0)^{-1/2}$, consistent with Alfvén-like modes [Fig. 2]. The existing data set has no toroidal field variation from which to derive a magnetic field scaling.

saturates and can remain nearly constant or have a slow drop and then increase. Generally the modes are terminated by a sawtooth crash, which is assumed to flatten the fast ion beta within $q=1$. This suggests that the mode's drive is within $q=1$.

The chirping of the mode frequency is consistent with the time evolution of the central density [Fig. 3]. With off-axis resonance on the high field side, the sawteeth were not stabilized in these plasmas in the range of input power levels (< 5 MW).

The frequency drop coincides with the recovery of density peaking between sawtooth crashes.

The best experimental fits to the 7-coil toroidal array of Mirnov coils give $n=+4$ (in the ω^*_e direction) for the modes. In contrast, the TAE modes and related Energetic Particle Modes propagate in the ω^*_i direction [2]. Even when multiple modes are present simultaneously, the best fit for all of the second gap modes is still $n=4$.

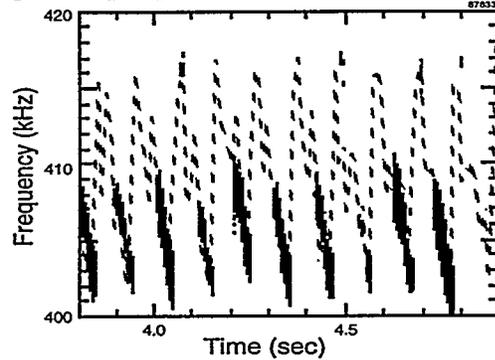


Figure 3. Spectrogram of the second gap modes. Dashed line shows the approximate central Alfvén frequency.

ANALYSIS

The RF heat deposition and tail formation are modeled with the TRANSP code and the SPRUCE RF package. Sawteeth are assumed to affect the fast ion tail population, and this is modeled in TRANSP with a mixing model that assumes a Kadomtsev-type flux reconnection at each sawtooth crash. The RF resonant position is off-axis on the high field side, presumably resulting in few deeply trapped fast ions. The fast ion beta is hollow, peaking off-axis at a minor radius of about 15 cm in a 96 cm minor radius plasma prior to each sawtooth crash [Fig. 4]. The RF power deposition layer is broad; the width depends on assumptions about the fast ion redistribution at each sawtooth crash and the H minority fraction that is assumed. The peak fast ion beta varies from about 0.6% just prior to a sawtooth crash, to about 0.4% after the sawtooth crash mixes the fast ions, flattening the profile. Initial calculations of the fast ion pressure profile show that it is hollow prior to sawtooth crashes—possibly consistent with the “backwards” mode propagation. An alternative explanation is that an inverted energy population at constant magnetic moment can also provide a source of free energy to

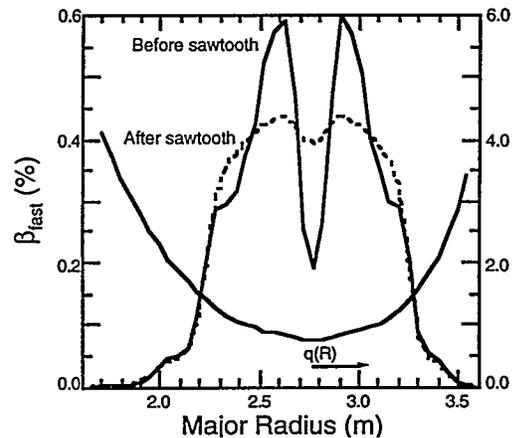


Figure 4. Fast ion beta before and after sawtooth crash. The q -profile is also shown.

drive Alfvénic modes, since in some cases this mechanism can couple strongly to counter-propagating modes [3]. More detailed calculations of the damping and driving terms still need to be done.

The agreement between the frequency evolution and the central density evolution suggest that the modes are most strongly affected by core (within $q=1$) plasma parameters. This would be consistent with the supposition that the “backward” wave propagation is due to the hollow fast ion profile.

SUMMARY

Modes has been observed in the frequency range of the second Alfvénic gap in H-minority ICRF heated plasmas in TFTR. This observation is surprising in that the second gap is generally considered to be small in circular cross section plasmas. The mode is inferred to be a “core” mode, i.e., localized in some sense within the $q=1$ surface. This follows from the observation that the time dependence of the mode frequency is consistent with the changes in the central density, with the appearance of the mode in the latter part of the sawtooth period when the central fast ion beta has peaked up, and with the direction of propagation, the last of these being explained by a hollow fast ion beta profile, which is only present in the core region. The modes are generally not observed during on-axis H-minority heating, but commonly observed during off-axis heating on the high field side (with the resonant layer outside the $q=1$ surface). A model has been proposed that the beta of the fast ions opens the second gap, allowing instability. For TFTR parameters, the model predicts a gap width of approximately 10 kHz, which is 2.5% of the second gap frequency. If the backwards mode propagation is due to a hollow fast ion profile (as indicated in the TRANSP calculations), then instability due to wave-particle resonance at the magnetic curvature precessional frequency can occur only if the precessional frequency is reversed—which can indeed be the case for off-axis heating on the high field side. Thus, trapped fast ion pressure effects seem to explain several of the observed features of these second gap fluctuations.

ACKNOWLEDGEMENTS

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