Alfvén cyclotron instabilities in D and H-D plasmas on MAST

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1. Introduction

Alfvén cyclotron instabilities (ACI) driven by energy gradients of fast ions have been observed as Ion Cyclotron Emission on major conventional tokamaks [1-5], and as Compressional Alfvén Eigenmodes (CAEs) and Global Alfvén Eigenmodes (GAEs) on spherical tokamaks NSTX [6] and MAST [7,8]. These instabilities are of interest for diagnosing fusion products, and they may affect the efficiency of beam current drive by causing pitch-angle scattering higher than Coulomb collisions. In view of deuterium-tritium (DT) operation required for burning plasmas, studies of Alfvén cyclotron instabilities in plasmas with two main bulk ion species are highly relevant. Properties of ACI in the frequency range $\omega_{BT} \le \omega \le \omega_{BD}$ are of particular interest due to the ion-ion resonance at some radius in the plasma core,

$$-\frac{\omega_{pD}^2}{\omega^2-\omega_{BD}^2}-\frac{\omega_{pT}^2}{\omega^2-\omega_{BT}^2}\cong 0\,,$$

where ω_{pi} and ω_{Bi} are ion plasma frequency and ion cyclotron frequencies of ions i. Experimental studies of beam-driven ACI in plasmas consisting of two main ion species, D and H, were performed on MAST mimicking the ACI in D-T plasmas.

2. The MAST H-D experiment and isotopic composition measurements

Alfvén cyclotron instabilities were excited by super-Alfvénic D beam with energy $E_b \approx$ 70-74 *keV* injected into spherical tokamak MAST ($a\approx$ 0.65 m, $R\approx$ 0.85 m) with hydrogen-deuterium (HD) plasmas at low magnetic field, $B_T(0) \approx 0.31T - 0.44T$. All MAST discharges had the same scenario, with H/D concentration being the only parameter varied. Plasmas with range of H/D concentrations from 0% to >60% were produced by puffing H for different time intervals, from the low field side of the machine, at a constant D puff at the high field side as Figure 1 shows. The H/D concentration was diagnosed by using i)

H_α/D_α intensity ratio, ii) fission chamber measuring neutron rate from D-D reactions, and iii) neutron camera with four lines-of-sight at different radial positions. TRANSP analysis was performed showing the effect of H dilution on DD neutron rate so the D:H mix could be estimated accurately [9]. Figure 2 shows the TRANSP results versus fission chamber measurement of DD neutron rate.

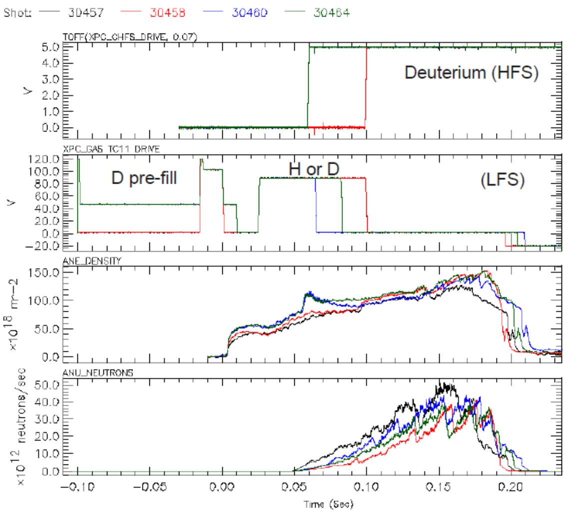

***Figure 1**. From top to bottom: D fuelling rate; H fuelling rate; time evolution of n_e; time evolution of DD neutron rate during NBI*

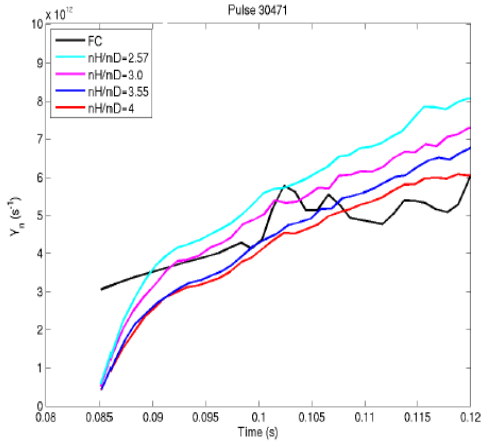

***Figure 2.** Neutron Yield (black) measured with MAST fission chamber against neutron rates computed with TRANSP for different H:D ratios*

For detecting beam-driven ACI, OMAHA coils [7] digitised up to 10 MHz were employed thus covering the whole ion-ion hybrid frequency range, from ~2 .5 MHz to ~ 5 MHz.

3. The mode observations

In pure D plasmas, Alfvén instabilities were excited over a broadband frequency range, up to ~3.5 *MHz*, with two distinct classes of modes (Figure 3): 1) sub-cyclotron modes with frequencies from ~500 *kHz* to ~1 *MHz*, and propagating in counter-NBI, counter-current direction (toroidal mode numbers n<0), and 2) modes with frequencies from ~500 *kHz* to ~3.5 *MHz*, and n>0. The second class of modes has large frequency separation, ~150-230 *kHz*, between modes of different n's, and since the highest frequency of these modes exceeds D cyclotron frequency, the modes are identified as CAEs. It was observed that at increasing H/D concentration, CAEs are suppressed as Figures 4,5 show. The suppression effect on CAE is especially strong (CAE disappear) in the frequency range between cyclotron frequencies of deuterium and hydrogen, $\omega_{BD} \leq \omega \leq \omega_{BH}$, where the ion-ion hybrid resonance could provide a strong damping.

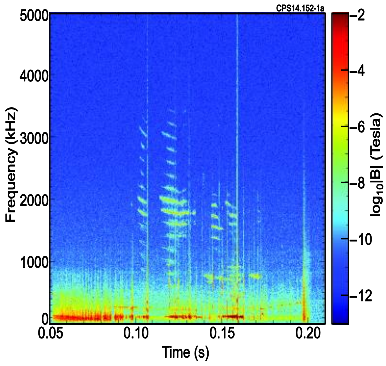

***Figure 3**. Beam-driven ACI observed in pure D plasma (MAST #30457).*

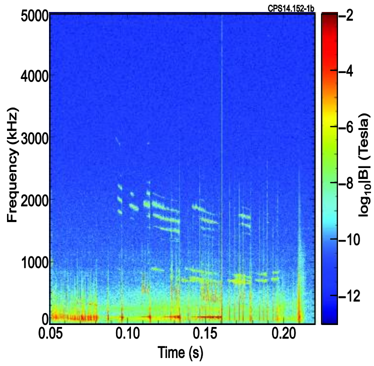

***Figure 4.** Beam-driven ACI observed in discharge with 60 ms H puff giving $n_H/n_D \approx 33\%$ (MAST discharge #30464).*

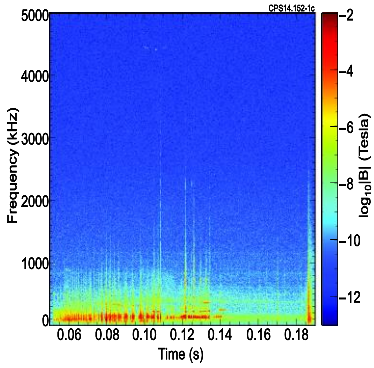

***Figure 5.** Beam-driven ACI observed in discharge with longest H puff giving $n_H/n_D \approx$ 60-80 % (MAST #30471).*

In MAST discharge with highest H concentration, modes were detected (Figs.6, 7) at a frequency of ~4.5 *MHz*, which is close to hydrogen cyclotron frequency, $\omega \approx \omega_{BH}$.

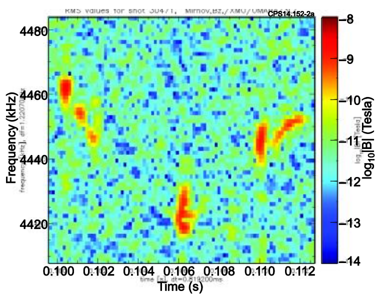

***Figure 6**. Amplitude magnetic spectrogram showing modes excited by D beam in the frequency range $\omega \approx \omega_{BH}$ (MAST #30471)*

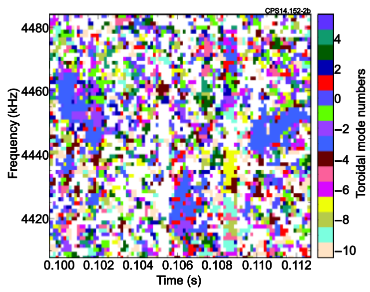

***Figure 7.** Phase magnetic spectrogram showing toroidal mode numbers (dominant n=-3) of the modes shown in Fig.6.*

For assessing the properties of the eigenmodes, a simplified 1D "hollow cylinder" model [10] was used. Within this model, existence and positions of the wave reflection points and resonance layers were investigated by considering the perpendicular refraction index

$$N_\perp^2\left(R,\omega,k_\parallel,\kappa_D\right)=\left(\frac{ck_R}{\omega}\right)^2=\varepsilon_1-N_\parallel^2-\frac{\varepsilon_2^2}{\varepsilon_1-N_\parallel^2}.$$

for different concentrations $\kappa_D = n_D/n_e = 1-\kappa_H$ (Figure 8 shows an example). The quantisation condition $\int_{R_1}^{R_2} k_R dR = \pi(l+1/2)$ was solved then together with condition of a weak mode conversion damping determined by the distance from the turning points to the resonance layers [11]. The modes with lowest damping were then assessed for a compatibility with the resonance condition [12]

$$\omega = \left(k_{\parallel} + \frac{s}{qR} \right) V_{\parallel b} + p\omega_{Bb}$$

and it was found (Figure 9) that for low negative *n* and high hydrogen concentration, a resonance with relatively low *s*=4 exists at high frequencies. This could explain the appearance of the record high frequency modes shown in Figures 6, 7 in MAST plasmas with highest H/D ratio.

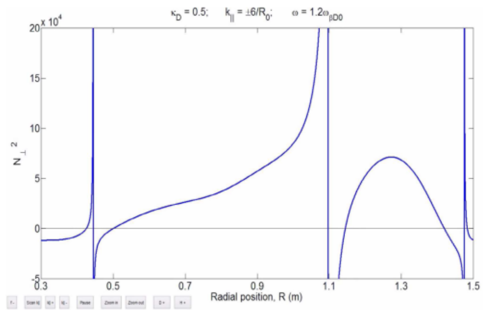

***Figure 8**. Example of the computed perpendicular refraction index in H-D plasma for a given frequency.*

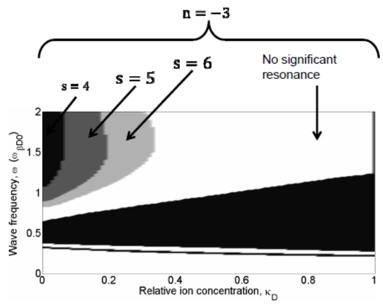

***Figure 9.** Wave-particle resonances within the transparency regions. The regions of lowest mode conversion are shown in darker colour.*

4. Conclusions

- MAST experiment on beam-driven Alfvén cyclotron instabilities in H-D plasmas was performed with H/D mix varied from 0 to >60%;
- It was observed that at increasing H/D concentration CAEs are suppressed, with the strongest effect (CAEs disappear) in the ion-ion hybrid frequency range $\omega_{BD} \leq \omega \leq \omega_{BH}$. Similar effect of CAE suppression in the frequency range $\omega_{BT} \leq \omega \leq \omega_{BD}$ is expected for D-T plasma;
- Beam-driven modes observed on MAST at a record-high frequency of ~ 5 MHz (i.e. at $\omega \approx \omega_{BH}$) could be explained by the H/D mix effect on the wave transparency region combined with the resonance condition;
- An accurate eigenmode analysis may provide a diagnostic technique for measuring H/D or D/T mix in the plasma core.

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