Spatial structure of NBI-driven shear Alfvén waves in the TJ-II stellarator: experiments and modeling

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Introduction

Alfvén waves in magnetic confinement devices are excited by the alpha particles born in fusion reactions of by the fast ions generated by heating systems such as neutral beam injection or ion cyclotron heating. Validation of models for energetic particles and Alfvén wave's is an essential ingredient to understand the interplay between fast particles, electromagnetic turbulence and Alfvén waves and how this "ecosystem" impacts the performance of fusion plasmas. In this context, during the last years, we have dedicated a significant effort in TJ-II to measure the properties of the Alfvén waves driven by co- or counter-beam injection and to progress in the theoretical understanding of these modes. This paper present the first attempts to compare the full spatial structure of the Alfvén waves, measured by means of magnetic diagnostics and heavy ion beam probes [1], to the theoretical predictions of linear MHD simulations. Motional stark effect was also used in [1] to measure the variations in rotational transform profile induced by plasma current. This is probably the most critical input when it comes to compare with theory. As we showed in [1], MSE cannot actually resolve such small changes in iota and therefore it becomes necessary to calculate the evolution of the toroidal current in order to have an estimate of iota. Numerical tools to carry out the validation studies are ASCOT5 [5], which we use to calculate the fast ion pressure and the average energy of the slowing-down distribution function, Stellgap [4] to calculate the shear Alfvén spectrum and FAR3d [6] to produce estimates of linear growth rates of the modes.

Experiments

A summary of experiments and results is shown in figure 1. We have used on-axis electron cyclotron current drive because of its ability to induce current having almost no impact on the plasma profiles and thus explore a set of different shots, with very similar plasma density and plasma heating conditions, but with different rotational transform profiles. We have explored five ECRH beam-launching directions. The results shown here are the ones obtained for the so-called standard magnetic configuration and counter-NBI injection. The rest have been presented in [1].

Having a constant density and temperature both in ECRH and ECRH+NBI phases is important to ensure that external current sources are also constant and therefore we can assume that changes in toroidal current are only due to the electrodynamic evolution of the shielding current.

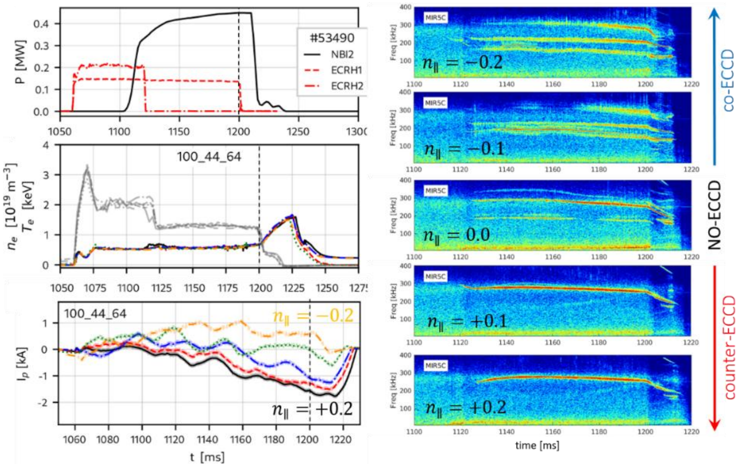

Figure 1: Heating scenario and time evolution of main plasma parameters are shown on the right panel. Line densities and plasma temperature are very reproducible and only the toroidal current is modified by driving different amounts of EC current. Changes in current produce the variations in the magnetic fluctuations spectrum shown on the right.

Mode number and electrostatic potential profiles.

The details on mode number measurements technique are given in [2]. A couple of helical arrays of tri-axial coils and a poloidal array are used measure the footprint of the modes outside the plasma. Mode number analysis using the 3D Lomb Periodogram is carried out at several time intervals along the shot and the mode number pair with the highest occurrence rate is taken (see Figure 2).

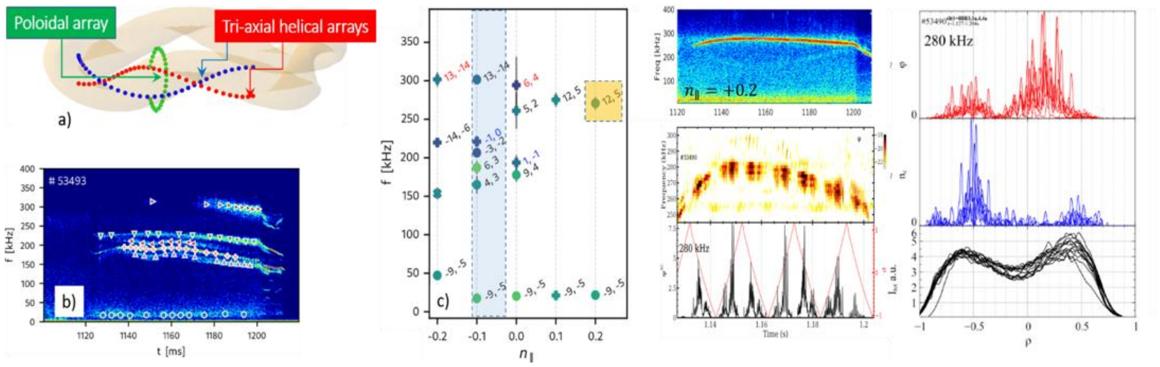

Figure 2: a) Distribution of the helical and poloidal arrays of Mirnov coils around the plasma. b) Spectrogram of one of the coils and time intervals selected to obtain the results shown in c). The shaded blue region correspond to the mode numbers n/m of all the relevant modes found in #53493 ($n_\parallel = -0.1$). The shaded orange region highlights the mode number measured for $n_\parallel = +0.2$, and corresponds to the single frequency mode represented in figure 1. HIBP measurements, that is, perturbed electrostatic potential and density profiles are shown on the right panel for the $n_\parallel = +0.2$ case.

A heavy ion beam probe [3] was performing a full scan of the plasma column up to six times during the NBI phase. Combining the beam position in time with the spectrogram of electrostatic potential and beam intensity fluctuations we can get a reconstruction of the radial profiles at the different mode frequencies. For stable densities, we can increase measurement reliability by overlapping the result of several scans. The result of this analysis for mode potential in the counter-ECCD case, with $n_{\parallel} = 0.2$, is shown in figure 2. Radial profiles are clearly asymmetrical, pointing towards a structure of coupled modes with different m's and n's as the ones we may find in gaps in the shear Alfven spectrum. Electrostatic potential and density fluctuations shows opposite asymmetric behavior. This feature is very interesting from the point of view of theory validation since it provides a prediction not only on the potential perturbation but also on the MHD fluid perturbation.

Rotational transform estimates.

Solving the shielding current (I_E) diffusion equation in cylindrical plasma,

$$\mu_0 \frac{\partial I_E}{\partial t} = \mathrm{r}\left[\frac{\partial}{\partial r}\left(\frac{\eta}{r}\frac{\partial I_E}{\partial r}\right)\right]; \qquad I_E(\rho = 1, \tau) = I(\rho = 1, \tau) - I_{NBCD+ECCD}(\rho = 1)$$

using TRAVIS simulations for the ECCD and ASCOT5 simulations for the NBCD current sources [1] we obtain an estimate of the rotational transform profile for the $n_{\parallel} = 0.2$ case.

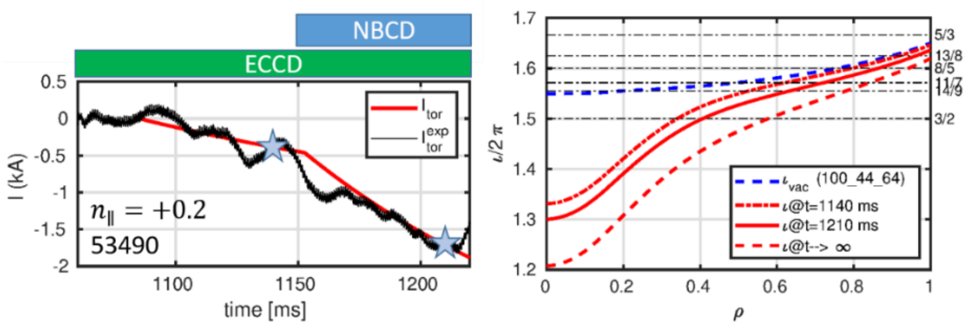

Figure 3: On the left we show the plasma toroidal current (black solid line) in the ECRH (with ECCD) and ECRH+NBI (with ECCD+NBCD) phases. On the right, the time evolution of the rotational transform profile due to this current. The rotational transform profile taken for the Stellgap simulations is the one at $t = 1210$ ms.

The toroidal plasma current measured by Rogowski coil ($I(\rho = 1, \tau)$) is taken as boundary condition to solve the I_E evolution equation. The bootstrap current contribution, lower than ECCD or NBCD is the studied case is neglected. The result is shown in figure 3.

Stability analysis for the maximum counter-current case

Using the rotational transform profile presented in figure 3 ($\mathrm{t} = 1210$ ms) we can calculate the shear Alfvén continuum of the $n_{\parallel} = 0.2$ case. We use the Stellgap code for this purpose. The result appears in figure 4. Coupling to sound waves is included in the calculation.

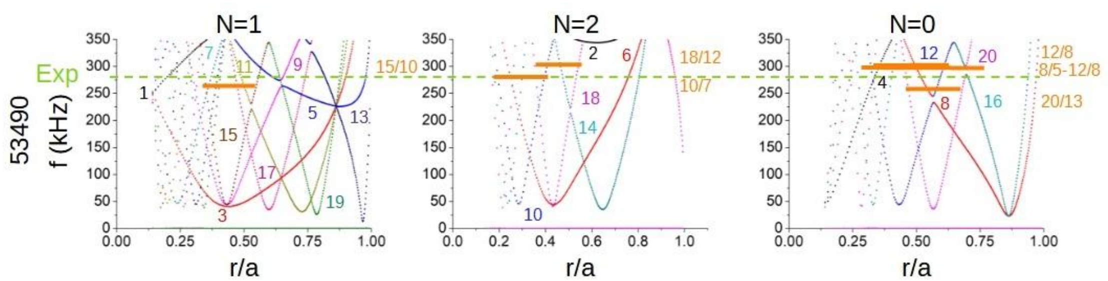

Figure 4: Continuum of Alfvén waves for the plasma equilibria with maximum counter current. TJ-II stellarator is a

4-period device and therefore modes distribute into three distinct families. We indicate the dominant modes found close to the experimental observed frequency (280 kHz).

We use ASCOT5 to calculate the fast ion density profile and the average energy of the distribution function and then plug the result into FAR3d to estimate the linear growth rates of the dominant modes. Growth rates, mode numbers and frequencies of the destabilized modes are show in figure 5. The radial profiles of the measured and calculated modes are also represented.

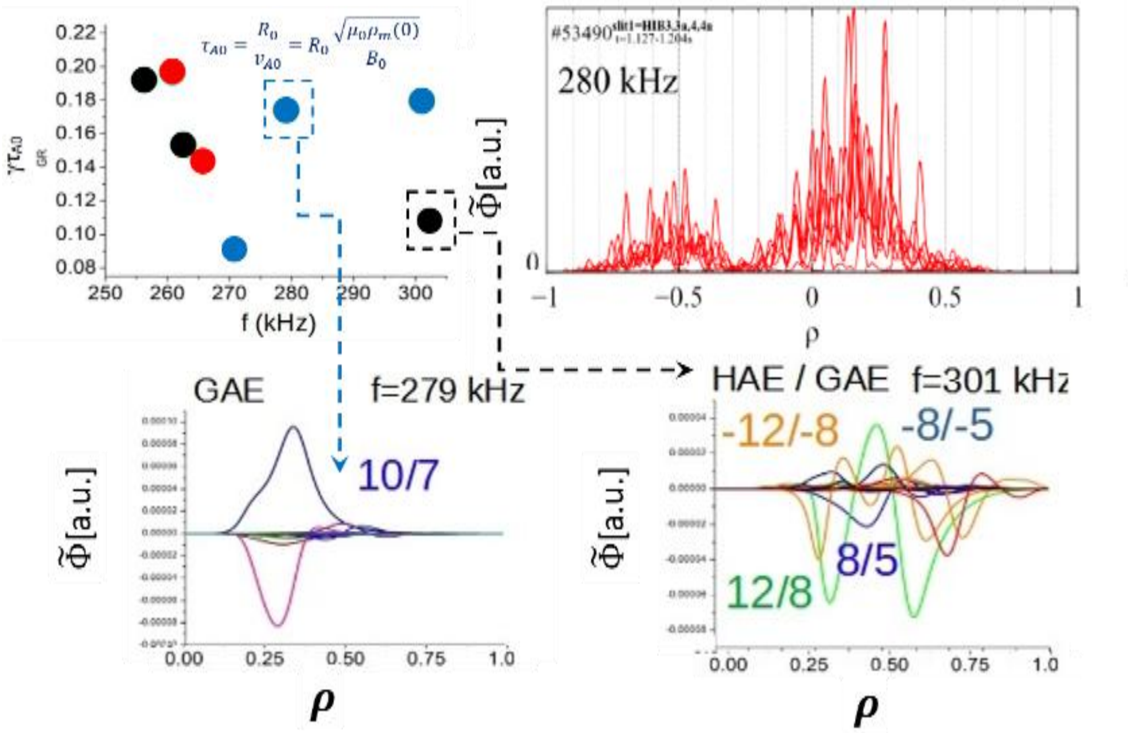

Figure 5: Linear growth rates calculated with FAR3d. The modes consistent in frequency and mode number within each family (blue for N=2, red for N=1 and black for N=0) are indicated together with their mode numbers n/m. The radial profile of the electrostatic potential, with measured mode numbers $n/m = 12/5$ is shown for comparison.

The $n/m = 10/7$ exhibits a radial structure and frequency in agreement with the observations but it is a GAE and cannot actually explain the asymmetry measured in potential. On the contrary, the pair of modes $n/m = 12/8$ and $n/m = 8/5$ is consistent with an HAE_{21} mode and matches almost perfectly the observations. Note that this mode appears as an $n/m = 12/5$ in the periodogram analysis. Due to the decay power law dependence on mode number m $(1/r^{m+1})$, confirmed with synthetic simulations, the footprint of the $m = 5$ component would be higher at the Mirnov arrays position than the $m = 8$ thus explaining the m measurement. Further work on MHD simulations, mode number identification using synthetic simulations and better estimates of iota profile are needed to address uncertainties. The database is large and a consistent picture is expected to emerge as we add more cases to our analysis.

References

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