FUSION ALPHA-PARTICLE-DRIVEN ALFVÉN EIGENMODES IN JET D-T PLASMAS: EXPERIMENTS AND THEORY

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INTRODUCTION

Excitation of Alfvén eigenmodes (AEs) by fusion-born α-particles is one of the most important problems for burning DT plasmas such as ITER [1]. Investigation of this problem has been performed during DTE2 and DTE3 campaigns on JET [2] with following dedicated scenarios for achieving α-particle excitation of AEs:

- "Beam afterglow" scenario [3], where the NBI power is switched off at peak fusion performance. The ratio between AE drive due to α-particles and the AE damping is maximized then in the time window τ_{SD}(beam)< t < τ_{SD}(α) as Fig.1 explains;
- A novel scenario aiming at AE excitation by α-particles with bump-on-tail (BOT) distribution;
- AE excitation at the edge of plasma.

During these DTE2 and DTE3 experiments, plasma auxiliary heating by NBI only was used so that fusion-born α-particles were the only ions present in the MeV energy range in JET plasmas.

BEAM AFTERGLOW SCENARIO FOR TAE EXCITATION BY α-PARTICLES

- Experiments were first conducted before DTE2 in JET deuterium plasmas with beam afterglow [4]. ICRH was used to probe TAE stability, and modelling of TAE excitation threshold was performed [5].
- During DTE2 campaign, high DT fusion performance was obtained in the beam afterglow discharges reaching neutron rate of R_{DT} = 4.2x10^{18} s^{-1} at P_{NBI}= 26 MW, which correspond to P_{FUS}= 11.8 MW of fusion power and Q= P_{FUS}/ P_{NBI} =0.45 (discharge #99802 of hybrid scenario with safety factor q(0)~1).
- The excitation of a TAE was detected [6] in JET discharge #99946 in an internal transport barrier scenario with elevated q-profile, $q(0)$ = 1.6. In this pulse, toroidal field B_0 = 3.45 T, plasma current I_P = 2.9 MA, and D:T = 50:50 plasma were used resulting in R_{DT} = 1.6x10^{18} s^{-1}.
- The excited TAE had frequency of ~115 kHz (see Figure 2) and n=3, with the excitation threshold in the α-particle pressure gradient close to the marginal stability predicted from D discharges with ICRH.

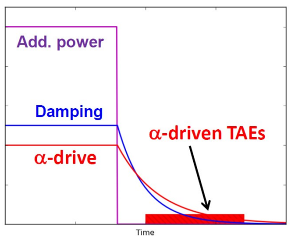

Figure 1. Cartoon showing the damping and α-drive evolution in the NBI afterglow scenario [3].

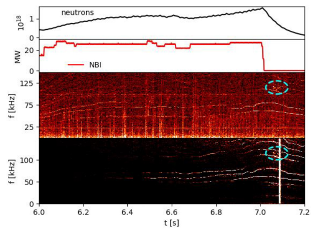

Figure 2. Mode observations during the afterglow in JET DT shot #99946 [6]. Top to bottom: Fusion neutron rate, input NBI power, Fourier spectra from interferometry and SXR. TAE appears in spectra at 7.05s at 115kHz (circled).

- Figure 3 shows the radial structure of the n=3 TAE while Figure 4 summarises all the damping effects of TAEs against α-particle drive. Radiative damping of TAEs is found to play a major role in this balance.

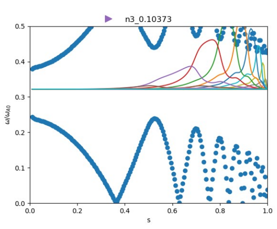

Figure 3. The computed modes with HELENA+MISHKA codes: TAE with n=3 is best matching the experiment.

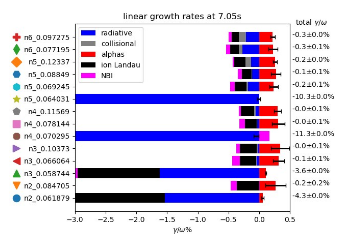

Figure 4. Left: α-particle drive and various damping effects of the relevant TAEs with frequencies close to the experimentally observed ones [6].

REVISITING TAE RADIATIVE DAMPING THEORY

- Radiative damping of TAE [7] due to emission of kinetic Alfvén waves was found to be substantial on JET and can be important in high-temperature ITER baseline scenario,
- Due to the difficulty in benchmarking numerical codes in computing the radiative damping, theory of this damping was revisited and real-space analytic calculation of the radiative damping performed [7]. This provided more transparent formalism than the pre-existing Fourier-space approach, with a more accurate numerical factor (~33% lower) in the damping → Good for benchmarking numerical codes.
- This result, which makes TAE instability more likely, is important for assessing the excitation of TAE.

EXPERIMENT ON EXCITATION OF MODES BY α-PARTICLES WITH BUMP-ON-TAIL DISTRIBUTION

- For creating α-particle BOT, a scenario was developed [8] with NBI power modulating the source of α-particles on a time scale shorter than τ_{SD}(α) as Figure 5 shows.
- Five DT pulses (##99500-99503, #99627) were performed in this scenario with B/ I = 3.7 T/ 2.5 MA and modulated NBI power up to ~ 10-15 MW delivering up to R^{DT} = 6.5x10^{17} s^{-1}. Both D and T beams were used and T concentration was varied from D:T = 33:67 (T-rich plasmas) to D:T = 55:45.
- Analysis with the FIDIT [9] and TRANSP [10] codes confirm that BOT α-particle distributions were achieved during some time intervals in this beam modulation scenario as Figures 5,6 show.
- A wide frequency range modes were detected with interferometry, SXR, and reflectometry as Fig.6 shows, but not in the Mirnov coils →mode numbers n were not identified.

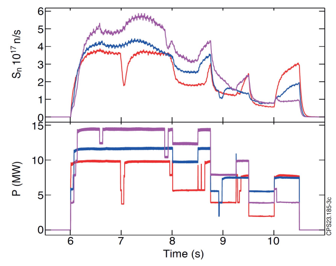

Figure 5. Top: DT neutron rates in discharges #99501 (pink), #99503 (red), and #99627 (blue). Bottom: the corresponding modulated NBI power.

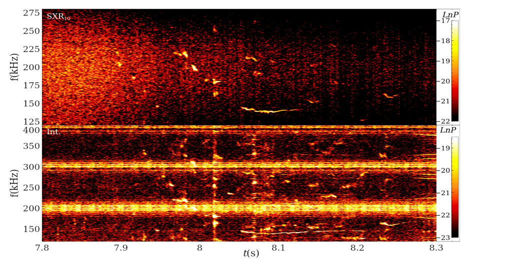

Figure 6. Top: the multiple modes going down in frequency in #99502 seen in SXR through the magnetic axis. Bottom: same modes seen with interferometry vertical line-of-sight near the magnetic axis.

- Interpretation of these modes was given in terms of kinetic Alfvén eigenmodes with their reflection points surrounding the magnetic axis as described by Rosenbluth and Rutherford [11]. In 1st order FLR approach these were computed with complex resistivity MISHKA [12] as Figs. 7, 8 show.

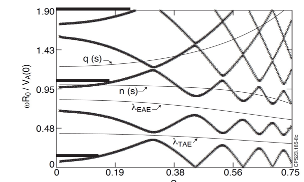

Figure7. Alfvén continuum structure for q(0)=1.22 in #99502. RR-modes marked with three horizontal thick lines exist in the potential "wells" on-axis. Here, λ_{TAE} =ω_{TAE} R_0/ $V_A(0)$, λ_{EAE}=$\omega_{EAE}R_0/V_A(0)$ are normalised frequencies.

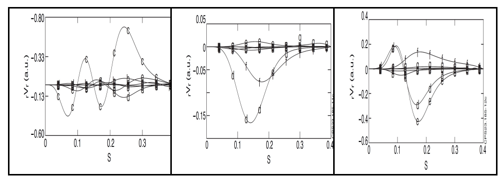

Figure 8. The wave potential variable s*V^r≈rV^r as a function of s=(ψ_P/ $\psi_P(a)$)$^{1/2}$≈r/a for the n = 5 modes [13] for q(0)=1.22. The normalised frequency is λ=ωR$_0$/V$_A$(0), and harmonics labelled c, d, e, f correspond to m= 9, 8, 7, 6.

AXISYMMETRIC n=0 MODES EXCITED BY ENERGY GRADIENTS OF ALPHA-PARTICLES

- Hybrid plasmas developed to explore W screening at edge in discharges with B_0 / I_P = 3.85 T/ 2.1 MA. D beam was Injected into ~20/80 D/T plasma, ICRH only starts after time of interest
- Figure 9 shows the spectrogram with the n=0 modes [13]. Frequency and amplitude of the modes are strongly modulated by Type III ELMs indicating the modes are associated with the density pedestal.
- Two possible n=0 types of the modes were investigated: Global Alfvén Eigenmode (GAE) and/or Vertical Displacement Oscillatory Mode (VDOM) [14].
- The α-particle BOT in these discharges was associated with the edge localisation of the modes, so that only α-particles with very high energies could reach the edge region.

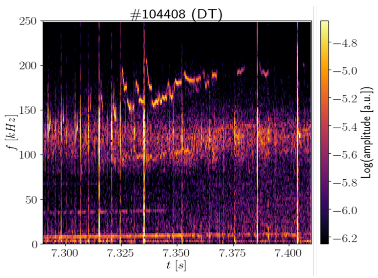

Figure 9. The n=0 modes seen in the range of 150-200 kHz with Mirnov coils.

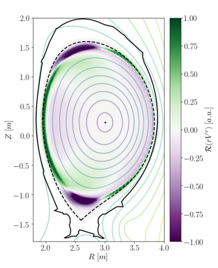

Figure 10. The computed n=0 GAE with HELENA+MISHKA codes.

CONCLUSIONS

- TAE excitation was observed in the afterglow scenario of JET DTE2 discharges and a satisfactory agreement between the predictive modelling and the DT experiment was found.
- TAE radiative damping theory was revisited [7] aiming at better benchmark for numerical codes.
- A significant activity of short-lived near-axis modes was observed in DTE2 scenario aiming at BOT α-particle distribution. These modes were identified as the ones predicted in [11].
- Axisymmetric n=0 modes were observed during early NBI-only phases of hybrid scenarios [13]. These were identified as likely GAM or VDOM [14] edge-localised modes excited by energy gradient of α-particle distribution at the plasma edge.

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