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

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Abstract

α-particles born in deuterium-tritium (D-T) fusion reactions are pivotal for plasma self-heating in future magnetic-confinement burning plasma devices such as ITER, DEMO and STEP [1]. Due to these particles being born at energies ~100 times higher than the fuel ion temperature, they are super-Alfvénic and constitute an energetic ion population that requires special consideration with regard to a wide range of issues, including plasma heating, confinement (both of the α-particles themselves and of thermal plasma), instabilities and losses. The delicate balance between plasma heating by α-particles and possible detrimental instabilities excited by them is a subject of major interest for D-T plasma studies. Results confirming classical plasma heating by α-particles have been published in [2]. This presentation will focus on α-particle-driven instabilities studied during the DTE2 and DTE3 experimental campaigns on the Joint European Torus (JET) [3].

INTRODUCTION

All of the scenarios used in D-T experiments on α-particle-driven instabilities had NBI as the only auxiliary heating source during the times of observation, and consequently fusion α-particles were the only ions with energies in the MeV range during these periods. During the time since DTE1 (1997) the diagnostics capabilities were strongly enhanced on JET. Internal measurements of AE perturbations in the plasma core became possible with interferometry, sweep-frequency reflectometry, and multi-channel soft X-ray camera. Together with Mirnov coils, this set of diagnostics provided a robust and reliable tool for detecting even small amplitude perturbations in the relevant frequency range up to 500 kHz on JET. DTE2 and DTE3 provided a vital opportunity to validate energetic ion stability codes in experiments with fusion α-particles as the driving energetic ion species. An overview has been presented [4] on several and complementary experimental approaches used to cover different physics aspects of burning plasmas during DTE2; here we report on further analysis and modelling of the experimental data. Investigation of this problem has been performed during DTE2 and DTE3 campaigns on JET [2] with following scenarios for achieving α-particle excitation of AEs:

“Beam afterglow” scenario [5], 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 of NBI power modulation aiming at AE excitation by α-particles with bump-on-tail energy distribution;

The axisymmetric n=0 high frequency mode excitation by α-particles at the edge of plasma.

BEAM AFTERGLOW SCENARIO FOR TAE EXCITATION BY α-PARTICLES

To excite toroidal Alfvén eigenmodes (TAEs) via resonant interaction with α -particles, which possess a free energy source associated with their radial gradient, a “beam afterglow” scenario was developed based on successful TFTR D-T results [5]. In this scenario NBI power is switched-off during peak fusion performance. The beam density and plasma temperature then decline on the beam ion slowing down timescale, while α -particles have a longer slowing down time with the result that their drive may overcome the sum of beam and thermal plasma damping rates, and excite TAEs in some time window after the NBI switch off.

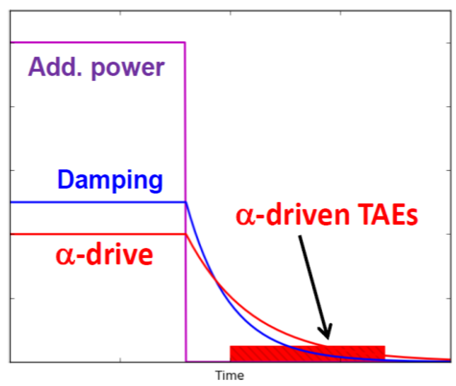


FIG.1 Cartoon showing the beam damping and α-drive temporal evolution in the NBI afterglow scenario [5].

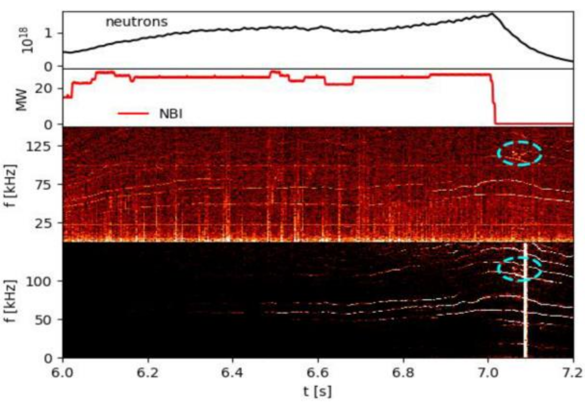


FIG.2 Mode observations during the afterglow in JET DT shot #99946 [8]. Top to bottom: Fusion neutron rate, input NBI power, Fourier spectra from interferometry and SXR. TAE appears in spectra at 7.05s at 115kHz (circled).

Dedicated experiments were first conducted before DTE2 in JET D plasmas with beam afterglow [6] to prepare the scenario designed to excite TAEs with α-particles in JET D-T plasmas. Discharges were executed at low density and high core temperatures associated with the presence of internal transport barriers (ITBs), and characterized by good energetic ion confinement. ICRH was used in the hydrogen minority heating regime to probe TAE stability in these D discharges, and modelling was performed to assess the TAE excitation threshold. It was found that radiative damping of TAEs [7] plays a major role in hot JET plasmas due to large non-ideal effects of finite ion Larmor radius and finite parallel perturbed electric field. TAEs in the core of ITB plasma were predicted to be suppressed by radiative damping, but modes in the edge were predicted to be marginally stable due to the plasma being colder there. During the actual DTE2 campaign, high DT fusion performance was obtained in the beam afterglow discharges, the neutron rate reaching R_{DT} = 4.2×10^{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). The excitation of a TAE shown in Figure 2, albeit a weak one, as anticipated before the DTE2 campaign, was detected in JET discharge #99946 in an ITB discharge with monotonic safety factor and an elevated core value $q(0)$ = 1.6. In this pulse, toroidal field B_0 = 3.45T, plasma current I_P = 2.9 MA, and D:T = 50:50 plasma mix were used, resulting in R_{DT} = 1.6×10^{18} s^{-1} [8]. The excited TAE had frequency ~115 kHz, n = 3, and appeared ≈50 ms after the NBI was switched off, with the excitation threshold in the α-particle pressure radial gradient close to the marginal stability value predicted from D discharges with ICRH-accelerated ions.

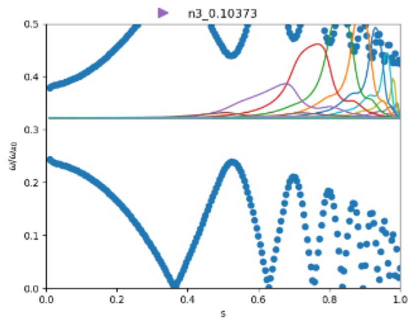


FIG.3 The computed mode with HELENA+MISHKA codes: TAE with n=3 is best matching the experiment.

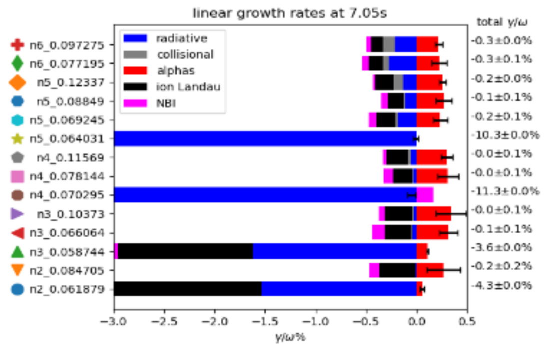


FIG.4 α-particle drive and various damping effects of the relevant TAEs with frequencies close to the experimentally observed ones [8].

The excited TAE had frequency ~115 kHz, n = 3, and appeared ≈50 ms after the NBI was switched off, with the excitation threshold in the α-particle pressure radial gradient close to the marginal stability value predicted from D discharges with ICRH-accelerated ions. Figure 3 shows the radial structure of the TAE mode best matching the experimental observations in the beam afterglow phase, while Figure 4 summarizes α-particle drive and various damping effects for the set of TAEs from n=2 to n=6 in the plasmas of interest. It is seen that the radiative damping plays a major role in the stability of many TAEs apart from the n=3 mode localized outside the mid-radius.

The TAE detected in the beam afterglow DTE2 discharge was not observed in the reference D plasmas with NBI only, leading to the conclusion that the mode was indeed excited by α-particles. This is the first clear identification of a TAE being driven by D-T fusion α-particles in JET.

REVISITING TAE RADIATIVE DAMPING THEORY

The threshold α-particle pressure gradient required for exciting TAEs is determined by its damping rate. The damping mechanisms include kinetic damping due to interactions with thermal particles, continuum damping due to the TAE frequency crossing the Alfvén continuum, and radiative damping [7] due to emission of kinetic Alfvén waves. Since it was found in our JET experiments that the radiative damping of TAE is substantial and can even dominate in high-temperature burning plasmas [8], and a similar conclusion was earlier drawn for the ITER baseline scenario [9], an in-depth study revisiting TAE radiative damping theory has been conducted [10]. In contrast to earlier work, the calculations were performed in real space rather than Fourier space. This approach is straightforward technically and more enlightening from a physics standpoint for benchmarking numerical calculations of the damping rate. Although the parametric dependence of the damping was found to agree with a result obtained previously using different methods, the overall radiative damping rate was found to be 33% smaller. This result, which makes TAE instability more likely, is important for assessing the excitation of TAE in burning plasmas since TAEs are often found to be close to marginal stability.

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

During DTE2, a novel scenario was developed aiming at α-particles with bump-on-tail (BOT) distribution. In this case, the free energy source for excitation of high-frequency modes could be associated with the α-particle distribution in velocity space rather than with the radial gradient in real space. Different types of modes can be excited by such distributions, including some that, e.g., are localised close to the magnetic axis, while some others have n = 0. JET baseline discharges with q(0) ~ 1 and pure NBI external heating were used. To create the α-particle bump-on-tail distribution, the source of these particles was varied in time by modulating the NBI power as Figure 5 shows, on a time scale shorter than α-particle slowing-down time. A Fokker-Plank code FIDIT [11] was employed before the experiment to optimise the NBI modulation required to sustain a BOT in the α-particle distribution.

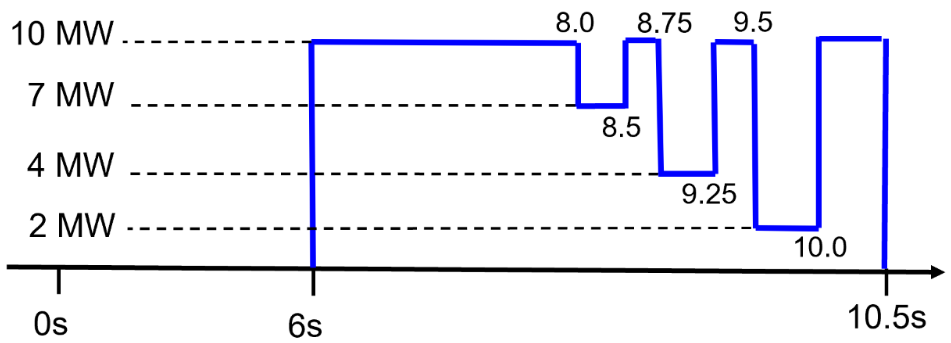


FIG.5 NBI power modulation wave-form aiming at creating BOT distribution of α-particles.

Five D-T pulses (#99500-99503 plus contingency pulse #99627) were executed in this scenario with B_T = 3.7 T, I_P = 2.5 MA and modulated NBI power up to P_{NBI}= 10-15 MW (see Fig.6), delivering up to R_{DT} = 0.65×10^{18} s^{-1} [12]. Both D and T beams were used and the T concentration was varied from D:T = 33:67 (T-rich) to D:T = 55:45 (D-rich). Strong high-frequency mode activity was detected in these discharges as Figure 7 shows over a wide frequency range from ≅100 kHz to ≅400 kHz, with no correlation to the characteristic frequencies of TAEs or elliptical Alfvén eigenmodes (EAEs). Multiple modes were observed, most of them short-lived. Interferometry, soft X-ray and reflectometry measurements established that the modes were localised close to the magnetic axis. These modes were not however seen in the Mirnov coils making it impossible to determine toroidal mode numbers.

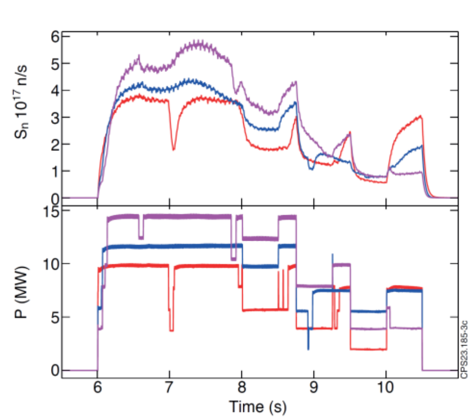


FIG.6 Top: DT neutron rates in discharges #99501 (pink), #99503 (red), and #99627 (blue). Bottom: the corresponding modulated NBI power.

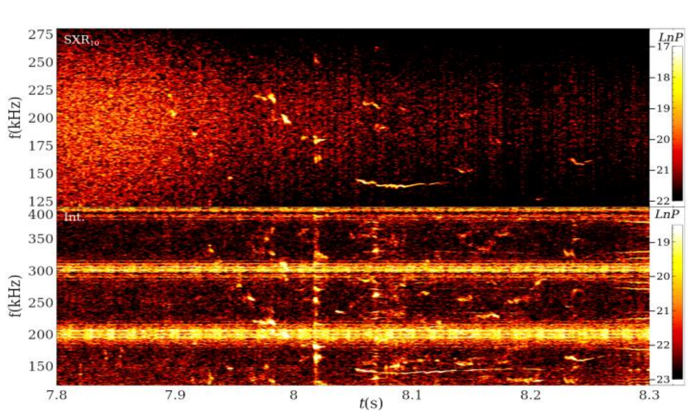
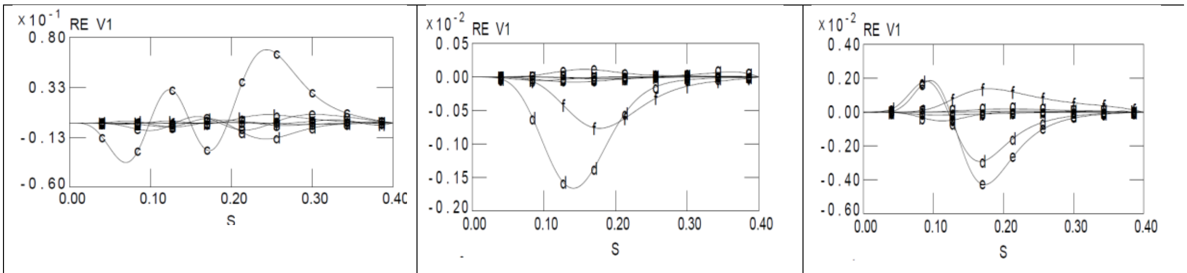


FIG.7 Top: the multiple modes going down in frequency in #99502 seen in SXR through the magnetic axis. Bottom: same modes seen with interferometry vertical line-of-sight near the magnetic axis.

No similar modes were detected in pure D reference discharge #100797 with similar plasma parameters and diagnostic settings. This implies the mode excitation by fusion-born α-particles.

These modes have been identified as on-axis kinetic Alfvén eigenmodes, first described by Rosenbluth and Rutherford in [13] (we may call them "RR-modes"). These are kinetic Alfvén eigenmodes with reflection points on both sides of the magnetic axis. To leading order in normalised Larmor radius they can be modelled using complex resistivity [14] in the MISHKA code [15] as Figure 8 shows.



λ = 1.906 | **λ = 1.057** | **λ = 0.150**

FIG.8 The "Complex Resistivity" [14] MISHKA modelling: The radial mode structure is given by variable $s*V^1$ as a function of $s=(\psi_P/\psi_P(a))^{1/2}$ for $n = 5$ modes computed for $q(0)=1.22$. The normalised frequency is $\lambda=\omega R_0/V_A(0)$. All modes are within the radius of $s\approx r/a=0.4$.

The MISHKA modelling shows a rather restrictive range of $q(0)$ values allowing RR modes:

$$\text{(a)}\quad \frac{m}{n} < q(0) < \frac{m+1/2}{n}$$

In the particular case of n=5 RR-mode this implies the following windows for the mode existence:

$$\text{(b)}\quad 1.4 < q(0) < 1.5\,;\ 1.2 < q(0) < 1.3\,;\ 1 < q(0) < 1.1$$

As $q(0)$ decreases in time with the inductive current penetrating to the plasma centre, the conditions for RR-mode existence above can occur one-by-one during some time windows. The modes can be excited then by α-particles, via their combined gradients in radius and in energy, and providing the mode damping is not high. The α-particle population was shown to exhibit BOT distribution at different times [12] with the TRANSP code [16]. The observed temporal evolution of the on-axis RR-modes is caused by a combination of the changes in the $q(0)$ and the transient BOT of the fusion α-particles, making it potentially possible for these modes to be used for MHD spectroscopy of $q(0)$ and α-particles.

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

Another type of energetic particle-driven mode that could be excited by free energy associated with BOT distribution functions has $n = 0$. First observed at rather low frequencies (≈30 kHz) in JET discharges with high-field-side ICRH [17], axisymmetric modes were quite often detected in later discharges in a broader frequency range, including that of EAEs, ≈325 kHz [18] and higher. These high-frequency $n = 0$ modes have been explained in terms of two different types of MHD oscillation, the vertical displacement oscillatory mode (VDOM) and the global Alfvén eigenmode (GAE) [19]. These differ somewhat in frequency and have different polarisations of perturbed fields. They are also typically located in different parts of the plasma (VDOMs in the core, GAEs at the edge).

Axisymmetric n=0 modes have been observed in JET D-T discharges as Figure 9 shows. No similar modes were detected in the pure D reference discharge thus suggesting the α-particle drive of the modes.

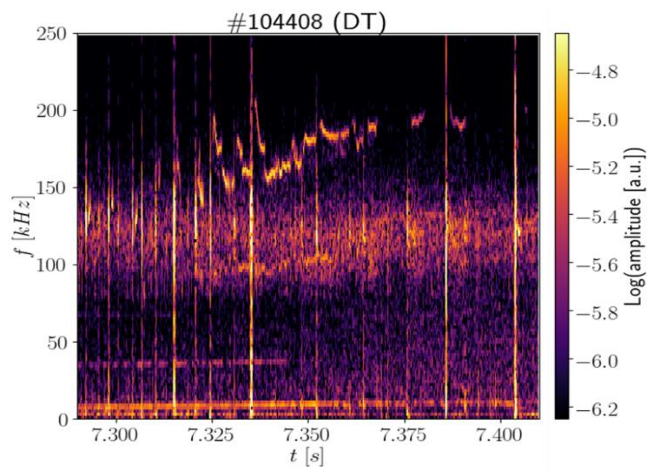


FIG.9 The n=0 modes seen in the range of 150-200 kHz with Mirnov coils.

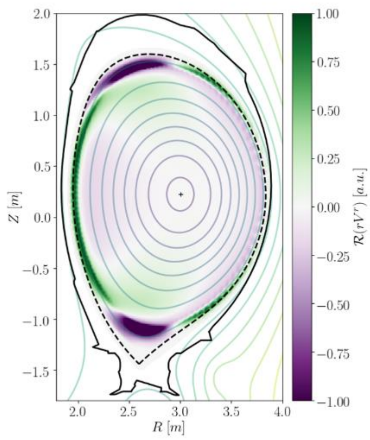


FIG.10 The computed n=0 GAE with HELENA+ MISHKA codes [20].

These modes were detected in hybrid plasmas developed to explore W screening at edge in discharges with with B_T = 3.85 T, I_P = 2.1 MA. High power D beam was injected into ~20/80 D/T plasma delivering high fusion rate. ICRH only starts after time of interest. Frequency and amplitude of the modes are strongly modulated by Type III ELMs (these are seen as vertical lines in Fig.9) indicating the modes are associated with the density pedestal.

Both possible n=0 types of the modes were investigated for explaining the experimental observation: Global Alfvén Eigenmode (GAE) [20] and/or Vertical Displacement Oscillatory Mode (VDOM) [21]. Figure 10 shows the possible GAE with n=0 localized at the plasma edge, where the Type III ELMs do affect the pedestal thus affecting the GAE as well.

For assessing the distribution function of fusion α-particles, the DT neutron rate was calculated first by TRANSP, that matches the experimentally measured rate during the time window of interest. TRANSP also produced a large sample of beam markers at the time of their ionisation in the plasma core. These markers were loaded in the LOCUST-GPU code [22], which follows the full orbits of the markers until thermalisation, thereby computing the distribution function including all features of slowing down physics, full orbit effects, full/third/half energy injection, and the trapped-passing boundary.

The drive of the fusion α-particles was assessed then with the n=0 eigenmode computed by the MISHKA code combined with the LOCUST-GPU-generated distribution using the HALO code [23]. Figure 11 shows the results of this computation. The BOT in α-particle distribution that drives the GAE at the edge of the plasma is shown in red. It reflects the fact that only highly energetic particles with large orbits can reach the plasma edge.

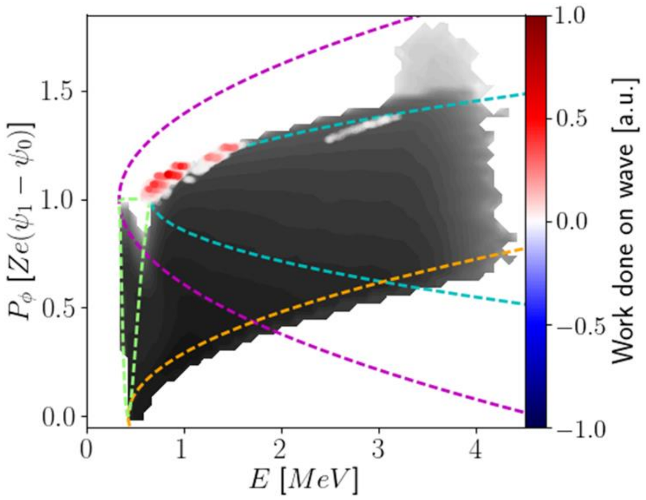


FIG.11 The counter-current alpha-particle distribution for 100≤μ[keV/T] ≤125 in black and white. Highly resonant alpha particles are overlaid, with red denoting drive. Dashed lines show approximate orbit topological boundaries: trapped-passing boundary (green), magnetic axis (orange), low-field-side separatrix(magenta), and high-field-side separatrix(cyan).

CONCLUSIONS

- TAE excitation was observed in the afterglow scenario of JET DTE2 discharges [8] and a satisfactory agreement between the predictive modelling and the DT experiment was found.

- TAE radiative damping theory was revisited [10] aiming at better benchmark for numerical codes.

- A significant activity of short-lived near-axis modes was observed in DTED2 scenario aiming at BOT α-particle distribution. These modes were not seen in the magnetic Mirnov coils. These were identified as the on-axis kinetic Alfvén eigenmodes predicted by Rosenbluth and Rutherford [13].

- Axisymmetric n=0 modes were observed during early NBI-only phases of hybrid scenarios [20]. These were identified as likely GAM [20] or VDOM [21] edge-localized modes excited by energy gradient of α-particle distribution at the plasma edge.

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