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

[1]S.E. SHARAPOV, [1]M. FITZGERALD, [1]H.J.C. OLIVER, [2]T. BARBERIS, [3]B.N. BREIZMAN, [4]M. DREVAL, [5]R. DUMONT, [5]J. GARCIA, [6]V. GOLOBOROD'KO, [7]Ye.O. KAZAKOV, [1]D. KEELING, [1]V.G. KIPTILY, [1]J. MAILLOUX, [8]F. PORCELLI, [1]Z. STANCAR, [8]D. BANERJEE, THE JET CONTRIBUTORS[a], and THE EUROFUSION TOKAMAK EXPLOITATION TEAM[b]

[1]UKAEA, Culham Campus, Abingdon, Oxfordshire OX14 3DB, UK
[2]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[3]Institute for Fusion Studies, University of Texas at Austin, Austin, USA
[4]Institute of Plasma Physics, National Science Center, KIPT, Kharkiv, Ukraine
[5]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France
[6]Institute for Nuclear Research, Kiev, Ukraine
[7]Laboratory for Plasma Physics, LPP-ERM/ KMS, TEC Partner, Brussels, Belgium
[8]Department of Applied Science and Technology, Polytechnic University of Turin, Torino, Italy
[a]See the author list of C F Maggi et al., Nucl. Fusion **64** (2024) 112012
[b]See the author list of E Joffrin et al., Nucl. Fusion **64** (2024) 112019

Email: Sergei.Sharapov@ukaea.uk

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]. 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. 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.

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.

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 characterised 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 $R_{DT} = 4.2\times10^{18}\ s^{-1}$ 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, 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 $R_{DT} = 1.6\times10^{18}\ s^{-1}$ [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. Such TAEs were 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.

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 due to emission of kinetic Alfvén waves (KAWs). Since it was found in 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 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.

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 also 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 are localised close to the magnetic axis while 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 on 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. 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, delivering up to $R_{DT} = 0.65\times10^{18}\ s^{-1}$ [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 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. They have been identified as on-axis kinetic Alfvén eigenmodes, first described by Rosenbluth and Rutherford in [13] ("RR-modes"). These are kinetic Alfvén eigenmodes with reflection points on both sides of the magnetic axis. To leading order in normalised Larmor radius thay can be modelled using complex resistivity [14] in the MISHKA code [15]. The TRANSP code [16] was used to model the α-particle population. Temporal evolution of RR-mode frequencies is caused by changes in the q-profile, making it possible for these modes to be used for MHD spectroscopy of q(0).

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). Analysis to unveil the physics behind the drive and damping of both modes is ongoing, and is likely to provide the first positive identification of an axisymmetric α-particle-driven n = 0 mode in a D-T plasma [20].

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