Abstract

A deuterium-tritium (D-T) experimental campaign DTE2 on JET scheduled for 2020, will take place in the Be/W vessel and will address essential operational, technical, diagnostic and scientific issues in support of ITER. In preparation for the campaign, experiments have been performed on JET aiming at studies of alpha-particles. For studying AEs driven entirely by alpha-particles, a scenario similar to the TFTR beam “afterglow” has been developed for JET. In DT plasmas, after NBI is switched off, alpha-particles will be the only energetic ions during time interval \( \tau \) between slowing-down times for NBI-produced ions and alpha-particles, \( t_{SD}(NBI) < \tau < t_{SD}(\alpha) \). Detection of alpha-driven AEs in this time window may help in diagnosing the temporal evolution of the alpha-particle pressure profile and slowing-down time. JET advanced tokamak scenarios with \( q \approx 1.5-2.5 \) were chosen and discharges have been successfully developed. The transport modelling extrapolated to DT predicts that alpha-particle beta of \( \approx 0.1\% \) could be achieved, comparable to that in successful TFTR experiments. In “hybrid” scenario plasmas with \( q_0 \sim 1 \), fast ion losses in the MeV energy range were observed during \( n=1 \) fishbones driven by a resonant interaction with D beam ions in the energy range \( \leq 120 \) keV. The losses are identified as an expulsion of D-D fusion products, 1 MeV tritons and 3 MeV protons. A mode analysis with the MISHKA code combined with the study of nonlinear wave-particle interaction with the codes HAGIS and HALO show that the loss of toroidal symmetry strongly affects the confinement of high energy tritons and protons by perturbing their orbits and expelling them in good agreement with experiment. The extrapolation to the case of alpha-particles in DTE2 hybrid scenarios with similar fishbones has shown an additional alpha-particle loss of \( \sim 1\% \). Further development of alpha-particle and Alfvén wave diagnostics suitable for JET DT operation is also reported.
1. INTRODUCTION

A deuterium-tritium (D-T) experimental campaign DTE2 is scheduled to take place on the Joint European Torus (JET) during 2020. In contrast to the first high power D-T experiment in JET in 1997 (DTE1), when JET was equipped with carbon PFC’s, the campaign DTE2 will be carried out in a Be/W vessel and will address essential operational, technical, diagnostic and scientific issues in support of ITER [1]. Alpha particle-driven instabilities, confinement and losses, as well as the efficiency of alpha-particle heating are the issues of paramount importance for confident predictions of burning plasmas and successful ITER operation. In preparation for the DTE2 campaign, significant developments have taken place on JET in specific plasma scenarios and fast ion diagnostics aiming at future dedicated studies of alpha-particles. Three main avenues were explored: i) Development of plasma scenarios with elevated q-profile, in which the extrapolated alpha-particle pressure in DT is comparable to that in TFTR pulses with alpha-driven TAEs [2], ii) Experimental investigation of non-resonant fusion product losses due to fishbones in the hybrid scenario [3, 4], and iii) Further development of fast particle and Alfvén wave diagnostics suitable for the study of alpha-particles in JET DT [5]. In all cases, particular attention was paid to experimental and operational conditions expected during DTE2, which are also relevant to burning plasmas in general [6].

2. THE POSSIBILITY OF ALPHA PARTICLE-DRIVEN TOROIDAL ALFVÉN EIGENMODES IN JET

Studies of fast ion-driven Alfvénic instabilities and related transport are of high importance for a burning plasma experiment since these are the key to understanding, and possibly controlling, the behaviour of alpha-particles in burning plasmas. A study of AEs driven entirely by fusion-born alpha-particles in JET DT plasmas has shown that such modes are difficult to excite during the main heating phase [7]. A scenario similar to the TFTR beam “afterglow” [8, 9] was developed for JET in view of DTE2 approaching [2]. In JET DT plasmas without ICRH, after NBI is switched off at the time of highest fusion performance, the fusion alpha-particles will be the only energetic ions in the plasma during time interval, \( t_{SD}(NBI) < \tau < t_{SD}(\alpha) \) (the beam “afterglow” phase). Possible excitation and detection of alpha-particle driven AEs in the beam afterglow phase will be one of the important issues which could help diagnosing the temporal evolution of the alpha-particle pressure profile and slowing-down time of alpha-particles in DTE2. In
order to develop a scenario of AE excitation in the beam afterglow DT plasmas, experiments were performed in JET reference deuterium plasmas first. Instead of alpha-particles, ICRH-accelerated hydrogen minority ions were used to probe the AE stability. JET advanced tokamak scenarios with safety factor $q \approx 1.5$-2.5 were chosen since the growth rate of AEs scales favourably with $q$ as $\gamma_\alpha/\omega \propto q^2 d\beta_\alpha/d\rho$. A variety of magnetic fields and plasma currents was tested during the scenario development (see [10, 11] for details). Eventually, plasmas with internal transport barriers (ITBs) were obtained for the first time since the installation of the ITER-like wall (ILW) in JET, at $B_T=3.4$ T and $I_P \approx 2.5$ MA. The presence of an ITB gave a significant increase in thermonuclear contribution to the neutron rate. Central ion temperatures, $T_i(0) \sim 13$ keV with 25 MW of NBI power were obtained, resulting in a neutron yield of $\sim 1.2 \times 10^{16}$ neutrons/s, with about 40% of this being thermonuclear. Figures 1, 2 display the temporal evolution of main plasma parameters and the plasma profiles at the time close to the maximum fusion rate in the best discharge #92054. During the scenario development, ICRH was used in many discharges in the hydrogen minority regime to probe the TAE stability. The presence of ICRH-accelerated ions resulted in the observation of unstable TAEs in many instances, and the toroidal mode numbers $n=4, 5, 6$ were identified for the most unstable TAEs.

![FIG 1. Best JET with elevated q and NBI only in high performance phase. From top to bottom: NBI and ICRH power waveforms, maximum values of $T_{e0}$ and $T_{i0}$, and toroidal rotation frequency $\omega_{tor}$.](image1)

![FIG 2. Top: Radial profiles of $T_e$ (from high resolution Thomson scattering, HRTS) and $T_i$ (from charge-exchange); Bottom: profile of $n_e$ (HRTS) at $t=6.4$ s.](image2)

The search for TAEs in the beam afterglow phase (starts at 6.5 s) with the suite of MHD spectral codes (HELENA, CSCAS, and MISHKA) has shown that a pressure-constrained
EFIT with a low order polynomial approximation (see Figure 3) is required for the equilibrium reconstruction to be free of unphysical surface current. The core-localised TAEs with the relevant toroidal mode numbers can then be computed as shown in Fig.4.

For the JET discharge considered, TRANSP scenario modelling and extrapolation to D:T=50:50 indicates that alpha-particles could achieve the range of $\beta_\alpha \sim 0.08\%-0.12\%$, which is slightly higher than that in TFTR plasmas with alpha particle-driven TAEs (0.02%-0.07%). Furthermore, HAGIS code runs for the computed TAEs with $n=4, 5, 6$ for the isotropic alpha-particle population with parameters found from TRANSP, gave the values of the TAE growth rates caused by alpha-particles $(\gamma/\omega)_{n=4} \approx 0.33\%$, $(\gamma/\omega)_{n=5} \approx 0.31\%$, and $(\gamma/\omega)_{n=6} \approx 0.29\%$ [10]. Our calculations of alpha drive are very close to that computed for JET pulse # 41723 [7], while in our case the damping effects caused by thermal ions and the beam could be lower due to lower $T_i$ and lower beam energy. This is encouraging further development of the scenarios for alpha-particle driven AEs for DTE2.

3. FAST ION LOSSES DURING BEAM-DRIVEN FISHBONES AND PROJECTION TO JET DT

In high performance “hybrid” scenario plasmas with $q_0 \geq 1$, fast ion losses in the MeV energy range were observed during $n=1$ fishbones [3]. These fishbones have frequencies 10 – 25 kHz, i.e. well below AEs, and are identified to be driven by a resonant interaction with NBI-produced D beam ions in the energy range $\leq 120$ keV. Figures 5, 6 show a typical example of the fishbones and fishbone-induced losses of ions in the MeV energy range.
The fast particle losses seen in Figure 6 are all localised in the squares 6, 10, and 14, i.e. along the trapped-passing boundary and out of the ICRH resonance phase region. The very large Larmor radii up to 13 cm indicate that the losses are associated with an expulsion of D-D fusion products, 1 MeV tritons and 3 MeV protons, in correlation with the fishbone bursts. Figure 7 shows the characteristic fast ion orbits at the trapped/passing boundary that are lost and detected by the FILD. An MHD mode analysis with the MISHKA code combined with the nonlinear wave-particle interaction code HAGIS shows that the loss of toroidal symmetry caused by the n=1 fishbones strongly affects the confinement of non-resonant high energy tritons and protons by perturbing their orbits. Such an effect was predicted in [12], and modelling of this effect shown in Figure 8 is in a good agreement with the experimental data. The extrapolation to the case of alpha-particles in DTE2 hybrid scenarios with similar beam-driven fishbones has shown an additional alpha-particle loss of ~ 1% [4]. In the case of ITER, fishbones are not expected to have a significant impact on alpha-particle losses due to a much smaller ratio of alpha-particle drift orbit width to the plasma minor radius.
FIG. 7. The inverse orbit modelling with the ORBIT code, which identifies the topology of fusion product orbits escaping to FILD.

FIG. 8. MISHKA/ HALO modelling showing the initial unperturbed orbit of a confined passing fast ion (left) and an unconfined trapped orbit (right) transformed by the fishbone perturbation (the mode structure is shown in blue-yellow).
4. UPGRADES TO ALPHA-PARTICLE DIAGNOSTICS

Diagnostics relevant to the study of alpha-particle physics and the physics of Alfvén eigenmodes in burning plasmas have recently been upgraded: neutron [10] and gamma-ray cameras and spectrometers, fast ion lost detectors, as well as active TAE antennae for probing stable TAEs [13]. Two major gamma-ray systems have been successfully upgraded in the past two years: the JET gamma-ray camera (GC) and the tangential gamma-ray spectrometer (TGRS) [14-17]. Both systems are aimed at measuring fast particles, either energetic ions accelerated by ICRH or born from fusion reactions, or runaway electrons in disruption mitigation experiments. In the case of energetic ions, the sources of gamma-ray emission are nuclear reactions, most notably the interaction between fusion born alphas and naturally occurring $^9$Be impurities that leads to the emission of gamma-rays at a characteristic energy of 4.44 MeV. As far as runaway electrons are concerned, the main process of interest is here the bremsstrahlung in the gamma-ray energy band. The GC aims at measuring the spatial profile of the fast ions and consists of two sets of detectors that view through collimated lines of sights displaced in a fan arrangement. The upgrade project has developed new dedicated detectors based on high resolution LaBr$_3$ crystals coupled to silicon photomultipliers [15, 16] which make it possible to combine high energy resolution, insensitivity to the magnetic field, MHz counting rate capabilities and compact dimensions. All of these properties are essential for measurements of fast ions in high performance plasmas, as the gamma-ray peaks produced by energetic ions must be clearly separated and distinguished from the background, which is possible only with fast high resolution detectors. Unlike with the former detectors, all the different gamma-peaks can be clearly distinguished. This opens up the possibility of simultaneously measuring the profiles of different fast ions.

The tangential gamma-ray spectrometer upgrade project has replaced a former BGO detector with a 100 times faster, higher resolution LaBr$_3$ crystal to provide enhanced diagnostic capabilities for fast ion and runaway electron experiments. When combined with an almost identical spectrometer installed on a vertical line of sight, the two instruments together are expected to separate the dynamics of passing and trapped ions thanks to their complementary views. An important component of the upgraded detector is the dedicated 14 MeV neutron attenuator based on LiH [17] and installed in front of the spectrometer. This is an essential element in view of DT operations as it makes it possible to measure 4.44 MeV gamma-rays born from alpha particles, which would otherwise be masked by the
\( \approx 30000 \) times more abundant neutron induced background on the detector. From a technological perspective, the TGRS will also test alpha-particle measurements by gamma-ray spectroscopy in high power DT plasma in the configuration envisaged for ITER.

5. SUMMARY

In summary, in preparation for the DT campaign on JET, dedicated experiments with elevated q-profiles and analyses of new relevant observations in hybrid scenario have been performed on JET aiming at future studies of alpha-particles. All diagnostics relevant to alpha-particle measurements have been upgraded. These preparations provide a confidence that alpha-particle physics will be assessed with a satisfactory set of experimental and modelling tools in future JET DT campaign.

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