Insights from fast-ion physics studies on JET in support of JT-60SA and ITER rebaseline

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In ITER and future fusion reactors, plasmas will primarily be heated by alpha particles. However, rather than directly heating the fuel ions, the majority of the energy of alpha particles will be transferred to plasma electrons. The resulting temperature of the deuterium (D) and tritium (T) fuel ions will be determined by the combined effect of the collisional power transfer from electrons to bulk ions, as well as the characteristics of the ion-temperature-gradient instability. Furthermore, the presence of MeV-range alpha particles in fusion plasmas is also expected to result in a range of fast-ion phenomena, including the sawtooth stabilization, the destabilization of Alfvén eigenmodes (AEs), and the modification of the plasma equilibrium [1]. While the fraction of MeV-range fast ions in most of present-day fusion experiments is fairly low and the fast-ion effects can be studied individually, a non-linear coupling between fast-ion phenomena is expected in future burning plasmas. This complexity introduces significant challenges in accurately extrapolating alpha particle heating behavior to the conditions of burning plasmas.

In this contribution, we present recent findings and analyses from a series of fast-ion physics experiments conducted at JET [2] during the last operational years. These experiments generated a significant population of MeV-range fast ions under various plasma conditions, including D-T scenarios [3-8]. We begin by discussing the mechanisms for sustaining plasmas with an inverted q-profile in the plasma core (inside the q = 1 surface), using fast ions as an actuator at JET. We then analyze different Alfvén eigenmodes (AEs) observed in these experiments, including axisymmetric and high-frequency reversed-shear AEs. Next, we focus on the improved plasma confinement observed in JET experiments with MeV-range fast ions and destabilized AEs. While this effect was initially reported in D-^{3}He plasmas [6], similar observations have recently been confirmed in D-T plasmas [7]. To isolate the effects of tritium, additional identity experiments were conducted in pure deuterium plasmas, as discussed in this contribution. Our results show that the addition of tritium to the fuel mix enhances the stabilization of turbulence by fast ions. Furthermore, recent studies in JET H-D plasmas heated with MeV-range ^{3}He ions, generated using the three-ion D-(^{3}He)-H ICRF scenario, have reported similar findings [8]. This ICRF scenario is particularly relevant for fast-ion studies during the ITER SRO phase, as it serves as a unique tool for generating MeV-range energetic ions with P_{ICRF} = 10 MW, available during this phase.

During JET's final operational year, we also investigated the non-linear interplay between fast ions, AEs and microturbulence with off-axis generation of fast ions, a scenario expected in future operations with N-NBI on JT-60SA. Figure 1 shows an overview of JET pulse #105816 (I_p = 1.9MA, $n_{e0} \approx 4\text{x}10^{19}$ m^{-3}, $n_H/n_e \approx 5\%$), where the magnetic field was varied (B_0 = 2.9T, 2.8T and 2.65T) to modify the radial deposition of ICRF power (f_{ICRF} = 42.5 MHz, dipole phasing) and fast-ion characteristics. This variation led to the destabilization of several types of AEs and changes in ion temperature throughout the pulse. We present the analysis of these experiments and discuss their implications for preparing future fast-ion studies on JT-60SA.

Next, we introduce a new, efficient ICRF scenario for increasing T_i in D-T ≈ 50%-50% plasmas by utilizing a small amount of impurities [3, 4, 9]. Recent experiments during the final D-T campaign at JET (DTE3 [10]) successfully demonstrated the use of intrinsic ^{9}Be and externally seeded argon impurities for bulk ion heating. This technique holds potential for ITER, where it could be used during the ramp-up phase to facilitate achieving fusion-grade ion temperatures (T_i ≈ 10-15 keV) before alpha heating becomes dominant. Additionally, raising T_i with ICRF heating of impurity ions is of particular relevance for future D-T plasma studies and operations at BEST.

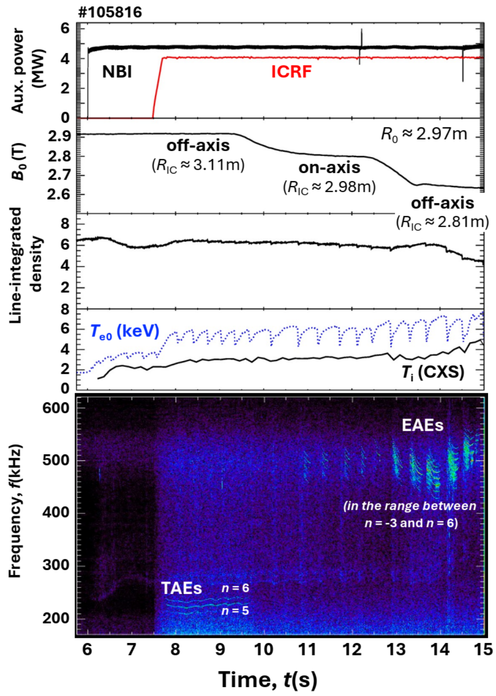

Figure 1. Overview of JET pulse #105816 (n_{e0} ≈ 4x10^{19} m^{-3}, P_{ICRF} = 4MW, P_{NBI} = 5MW). The magnetic field was varied to assess the impact of on-axis vs. off-axis fast-ion generation on the plasma performance.

In the second part of this contribution, we discuss the planned fast-ion studies at JT-60SA. As the world's largest superconducting tokamak, JT-60SA will play a pivotal role in supporting ITER and DEMO [11] and advance our understanding of high-energy ions and their impact on plasma confinement in large-scale tokamaks. Although tritium operations for studying D-T fusion-born alpha particles will not be conducted, JT-60SA offers a valuable opportunity to advance alpha particle physics through experiments with mixed D-^{3}He plasmas. This approach allows for the study of fusion-born alpha particles (E_α = 3.6 MeV), with the D-^{3}He fusion cross-section peaking at deuterium energies of 400-450 keV. Equipped with a powerful negative-ion-based neutral beam injection (N-NBI) system capable of delivering fast deuterons at energies up to 500 keV, JT-60SA is exceptionally well-suited for alpha-particle experiments in D-^{3}He plasmas, providing critical insights into fast-ion-driven phenomena relevant for future fusion reactors. We will proceed with a short summary of modeling results for a dedicated fast-ion scenario currently developed for alpha-particle experiments in JT-60SA plasmas. The modeling shows that an alpha production rate of approximately 2-3x10^{16} s^{-1} can be achieved with the high-power N-NBI system on JT-60SA at moderate ^{3}He concentrations of 10-15% [12], surpassing the alpha production rate observed in D-^{3}He plasmas with a combined ICRF and NBI heating on JET. Based on the past JET experience of alpha studies in D-^{3}He plasmas [3], this production rate is expected to be sufficient not only to develop high-quality measurements of alpha particles, but also to observe instabilities driven by alphas and study the redistribution of fusion-born alphas in the presence of fast-ion-driven instabilities destabilized by external heating sources.

In the final part of this contribution, we discuss how the analysis of past experiments at JET and future planned fast-ion experiments at JT-60SA can support the ITER rebaseline [13] in the areas of alpha particle and fast-ion physics. We conclude with a brief discussion on potential strategies to enhance the alpha-physics programme, including new fast-ion diagnostics, at JT-60SA in the future.

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