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INSIGHTS FROM FAST-ION STUDIES ON JET IN SUPPORT OF JT-60SA AND ITER REBASELINE

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Abstract

Significant progress was achieved during the final operational campaigns of JET in the area of energetic particle physics and fast-ion diagnostics. This contribution summarizes some of the main highlights. In particular, MeV-range fast ions and fast-ion-driven instabilities were studied in D-^{3}He, D-T, and H-D plasmas, revealing their role in stabilizing core turbulence. Fast-ion studies using the three-ion D-(^{3}He)-H scenario and the variation of ICRF antenna phasing demonstrated efficient generation of high-energy ions and fast-ion-driven modes. This scenario provides an opportunity for early testing of energetic-particle modeling and fast-ion diagnostics in the SRO phase of ITER. DTE3 experiments highlighted the flexibility of ICRF heating, with H-minority heating producing the highest electron temperatures and three-ion schemes with impurity resonance achieving the highest ion temperature. Additionally, D-^{3}He experiments explored alpha-particle generation in tritium-free plasmas using third-harmonic deuterium acceleration and the three-ion D-(D_{NBI})-^{3}He scheme, including radial fast-ion-source variations relevant to JT-60SA. These results advance understanding of fast-ion dynamics and provide valuable input for fast-ion studies in future large-scale tokamaks.

1. INTRODUCTION

The presence of energetic alpha particles in a fusion reactor gives rise to a wide variety of fast-ion phenomena that are crucial for achieving and maintaining high plasma performance [1]. Alpha particles, born at MeV energies from D-T fusion reactions, act as a primary source of plasma heating, predominantly through collisional energy transfer to electrons. This self-heating is essential for sustaining the plasma in a burning regime. Beyond heating, energetic alphas play a decisive role in plasma dynamics: they can influence sawtooth stabilization, modify the plasma equilibrium, and drive a variety of fast-ion instabilities [2]. In addition, increasing attention has been paid in recent years on the impact of fast ions on plasma turbulence [3].

At high plasma beta, these mechanisms are strongly coupled through nonlinear interactions, making the overall picture complex. As a result, the extrapolation of alpha heating and non-linearly coupled fast-ion effects from present experiments to next-step burning plasmas is not straightforward. A robust experimental and theoretical understanding of fast-ion phenomena is therefore critical for reliable predictions in future devices.

In this contribution, we present recent findings from a series of dedicated fast-ion physics experiments performed during the last operational years at JET. These experiments generated a significant population of MeV-range fast ions under a variety of plasma conditions, including deuterium-tritium (D-T) scenarios. We discuss how the insights gained from these studies can inform and guide fast-ion research in upcoming devices such as JT-60SA and ITER, where the role of fast ions and energetic alphas will be even more central to achieving efficient plasma performance.

2. TURBULENCE SUPPRESSION IN PLASMAS WITH MEV-RANGE FAST IONS

Future burning plasmas will be characterized by dominant electron heating provided by fusion-born alpha particles. For economical operation of a D-T fusion device, it is essential to achieve and sustain fusion-grade ion temperatures $T_i \approx$ 15-20 keV. Recent tokamak experiments showed that fast ions can improve thermal plasma confinement and contribute to breaking the ion temperature clamping in electron-heated plasmas [4, 5]. An overview of the mechanisms by which fast ions in the energy range 50-150 keV suppress turbulence is provided in Ref. [3].

The beneficial impact of MeV-range fast ions on plasma confinement was first demonstrated in JET D-^{3}He plasmas [6]. In these experiments, fast deuterons with energies $E_D \approx$ 1-2 MeV were generated using ICRF and the three-ion D-(D_{NBI})-^{3}He scenario [7]. Improved plasma confinement was observed despite the presence of a broad range of fast-ion-driven instabilities.

Building on these results, follow-up experiments in D-T plasmas were performed at JET. As reported in [8], improved plasma confinement was also observed in JET D-T plasmas with dominant core electron heating from ICRF. In these experiments, hydrogen minority heating at low concentration $n(\mathrm{H})/n_e \approx$ 1-1.5% was used and a range of fast-ion-driven instabilities, including TAEs, was observed. Analysis revealed a significant reduction in the thermal ion heat conductivity in the plasma core, consistent with local gyrokinetic simulations. Global GENE modelling further clarified that multiple mechanisms contribute to turbulence reduction at different radial locations [9]. A stronger turbulence reduction was observed in D-T plasmas compared to equivalent D-D plasmas. Nonlinear FAR3d simulations suggest this enhancement may be linked to stronger shear flows in the D-T case [10], consistent with experimental observations.

More recently, similar effects have been reported for H-D mixed plasmas at JET [11], where the three-ion D-(^{3}He)-H ICRF scheme was applied to maximize electron heating. TRANSP-TORIC modelling indicates that more than 90% of the ICRF power was transferred from resonant ^{3}He ions to electrons. These results reinforce the observation that fast ions can substantially reduce turbulence and improve confinement, even in regimes with dominant electron heating and fast-ion-driven instabilities. Ongoing analysis aims to consolidate this understanding and identify pathways to exploit the beneficial role of fast ions and alpha particles in ITER and future burning plasma devices [12].

3. FAST-ION SCENARIOS FOR EARLY TESTS OF EP MODELING AND DIAGNOSTICS IN ITER SRO

ITER has recently proposed a new baseline to ensure the robust achievement of the project goals [13]. This includes replacing beryllium with tungsten as the first wall material and modifying the heating and current drive mix. In the Start of Research Operation (SRO) phase, 40 MW of ECRF and 10 MW of ICRF power are foreseen. A large variety of efficient ICRF scenarios, tailored to specific objectives, is available at ITER, depending on the background plasma composition and the magnetic field. Among these, hydrogen minority heating in deuterium plasmas is a very robust scenario (B_0 = 2.65T, $f \approx$ 40 MHz, $n(\mathrm{H})/n_e \approx$ 2-5%), particularly suitable for testing the compatibility of ICRF in H-mode plasmas during the SRO phase. The planned scan in the hydrogen minority concentration will provide valuable insights into RF coupling and impurity production with ICRF in ITER plasmas, essential for informing potential extensions of ICRF power up to 20 MW in the later operational phases of ITER.

The availability of 10 MW of ICRF during the SRO phase also creates opportunities for early testing of energetic particle (EP) modeling and fast-ion diagnostics. In this context, the three-ion D-(^{3}He)-H scheme (B_0 = 5.3T, $f \approx$ 53 MHz, $n(\mathrm{H})/n_e \approx$ 70-85%, $n(^3\mathrm{He})/n_e <$ 0.5%) is particularly relevant for optimizing the generation of MeV-range fast ions and for studying fast-ion-driven instabilities [14, 15]. Given ITER's substantially larger plasma volume compared to JET, maximizing MeV-range fast-ion production requires maximizing the absorbed RF power per resonant ion. While conventional minority heating scenarios typically require resonant ion concentrations of a few percent, three-ion scenarios can be designed to channel ICRF power into a very small resonant population, with concentrations well below ~0.5%.

A new series of dedicated experiments with this scenario was conducted at JET (3.2T/2MA, $f \approx$ 33MHz, $n_{e0} \approx 4\times10^{19}$ m^{-3}, H-D ≈ 80%-20%) to investigate the impact of ICRF antenna phasing on fast-ion behaviour and overall plasma characteristics. Figure 1(a) shows the configuration of the ICRF resonances in the plasma, with the resonance for ^{3}He ions located in the plasma core. The experiments were performed in L-mode, with P_{NBI} = 2.2MW, and the ICRF power was scanned in three steps: 1 MW, 2 MW, and 4 MW. The ICRF antenna phasing was varied across different pulses. Figure 1(b) provides an overview of pulses #103616 and #103620, where dipole and +90 deg. antenna phasings were applied, respectively. For reference, a purely NBI-heated pulse (#103628) was also performed, with total NBI power matched to the combined $P_{ICRF} + P_{NBI}$ of the antenna phasing comparison series.

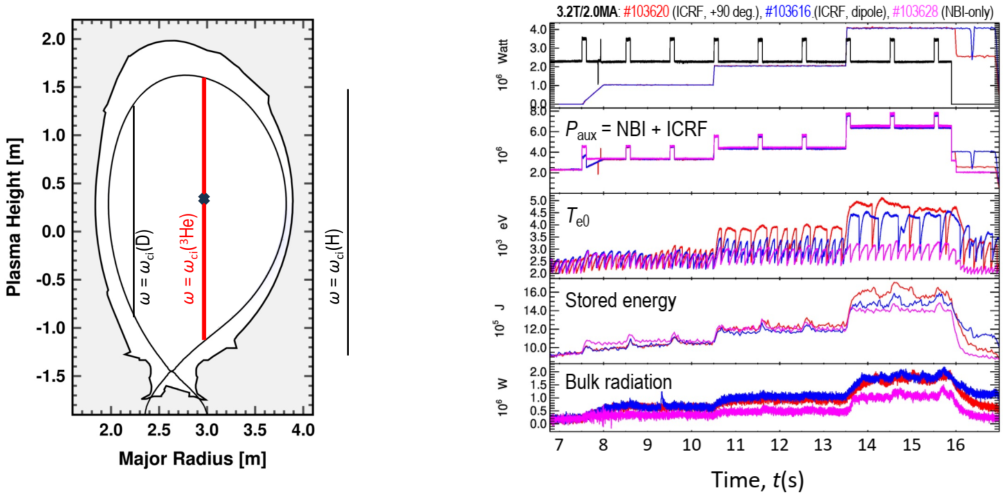

__FIGURE 1.__ The impact of ICRF antenna phasing was studied in the fast-ion experiments with the three-ion D-(^{3}He)-H ICRF scheme at JET. (a) The configuration of ICRF resonances in the plasma (3.2T/2MA, f = 33MHz). (b) Overview of JET pulses #103616 (dipole phasing) and #103620 (+90 deg. phasing). For comparison, a reference NBI-only pulse #103628 is shown.

As shown in Figure 1(b), at all three heating levels ($P_{aux.}$ = 3.2MW, 4.2MW, 6.2 MW), the NBI-only pulse #103628 exhibits lower bulk radiation compared with ICRF + NBI pulses #103616 and #103620. However, the dependence of the plasma stored energy differs. At low ICRF power (P_{ICRF} = 1 MW, P_{NBI} = 2.2 MW), the stored energy is lower than in the NBI-only pulse at P_{NBI} = 3.2MW. The situation changes at higher ICRF power (P_{ICRF} = 4MW, P_{NBI} = 2.2MW), where both the plasma stored energy and the central electron temperature clearly exceed the corresponding values in the NBI-only pulse at P_{NBI} = 6.2 MW, despite the higher bulk radiation. A detailed analysis of impurity behaviour in this series of experiments, including its dependence on ICRF antenna phasing and comparison with the NBI-only pulse, is presented in [16].

A significant dependence of the sawtooth period on ICRF antenna phasing was observed, in agreement with previous sawtooth-control experiments at JET [17]. The longest period, $\Delta t_{saw} \approx$ 0.8-0.9 s was achieved with +90 deg. phasing, indicating that this phasing strongly stabilizes the sawtooth oscillations. In comparison, dipole phasing resulted in an intermediate period of $\Delta t_{saw} \approx$ 0.45-0.5 s, while -90° phasing produced the shortest period, $\Delta t_{saw} \approx$ 0.2-0.25 s. These results clearly demonstrate that the sawtooth behaviour can be effectively manipulated by adjusting the ICRF antenna phasing, highlighting its potential for plasma stability control.

Furthermore, a strong variation in the spectrum of fast-ion-driven instabilities was observed for different antenna phasings. Figure 2(b) shows the MHD spectrogram for JET pulse #103620 with +90 deg. phasing, where multiple activities were destabilized, including TAE modes ($f \approx$ 320-330 kHz). The figure also shows the appearance of the reversed-shear AEs ($f \approx$ 80-120 kHz). These modes were not observed with other antenna phasings. This shows the potential of antenna phasing as an actuator for TAE control. These observations indicate that the distribution of fast ions and the resulting mode activity are highly sensitive to the phasing of the ICRF antennas. Together, these experimental results provide a valuable testbed for validating EP modeling tools in support of ITER and next-generation fusion devices.

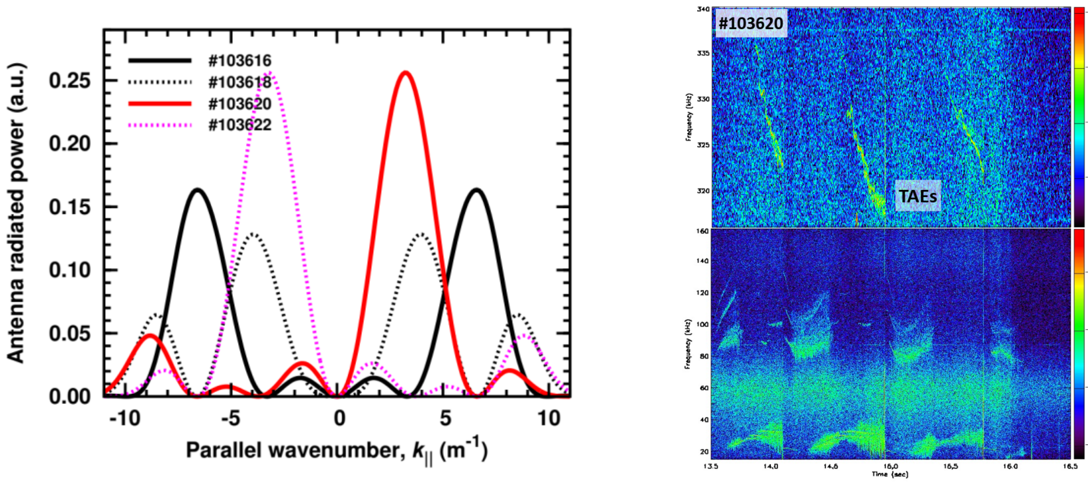

__FIGURE 2.__ (a) ICRF antenna spectra in the series of fast-ion experiments with the three-ion D-(^{3}He)-H ICRF scheme at JET. (b) MHD spectrogram in JET pulse #103620, where the co-current drive antenna phasing (+90 deg.) was applied.

4. FLEXIBILITY OF ICRF FOR BULK ION AND ELECTRON HEATING IN D-T ≈ 50%-50% PLASMAS

As discussed in [4], maximizing T_i in predominantly electron-heated plasmas benefits from a source of direct ion heating. This is particularly relevant during the ramp-up phase of larger machines, including BEST and ITER, when the plasma parameters such as plasma current and plasma density have not reached their maximum. Achieving the high-Q operational point more quickly can also reduce flux consumption during the ramp-up. One possible approach is the use of a ^{3}He minority, recently demonstrated during the second D-T campaign at JET (DTE2) [18]. An alternative strategy, using heavier impurity ions for ICRF power absorption, was proposed in [19]. The proof-of-principle demonstration of the three-ion T-(^{9}Be)-D scheme to increase T_i in both L-mode and H-mode plasmas was successfully performed in DTE2 [20].

In metallic-wall tokamaks, dominant electron heating with ICRF has been demonstrated to be beneficial for impurity control [21]. Increasing T_e with ICRF is also relevant for fast-ion physics studies, as the slowing-down of fast ions scales as $T_e^{3/2}$.

During the third D-T campaign at JET (DTE3) [22], a direct comparison of the performance of the three-ion T-(^{9}Be)-D ICRF scenario with other minority heating schemes was carried out. L-mode experiments were performed at $B_0 = 3.7$ T with a D-T mixture of approximately 50%-50%, combining 7.5 MW of NBI (deuterium) and 2.5 MW ICRF heating. At this magnetic field, the core ICRF resonance can be switched from ^{9}Be impurities to H minority ions by simply adjusting the ICRF frequency from $f = 25$ MHz to $f = 55$ MHz (see Fig. 3).

The fraction of fast-ion power transferred to bulk ions or electrons depends on the ratio of their energy to the critical energy E_{crit}

$$E_{\rm crit} = 14.8 A_{\rm fast} T_e \left(\sum_i X_i Z_i^2 / A_i\right)^{2/3} \quad (1)$$

Here, A_{fast} is the atomic mass of the energetic ions, T_e is the electron temperature, and $X_i = n_i/n_e$, Z_i, and A_i are the concentration, charge state, and atomic mass of the ion species in the plasma mix. To achieve dominant bulk ion heating, the energies of ICRF-accelerated ions should remain around E_{crit} or below, see Fig. 4(a). According to Eq. (1), fast ions with higher atomic mass have a higher critical energy. Thus, under the same conditions, heavier fast ions have a lower E_0/E_{crit} and transfer a larger fraction of their power to bulk ions via collisions.

Figure 4(b) shows the comparison of the response of T_i (measured at $\rho \approx 0.2$) and the core electron temperature, T_{e0} to ICRF power for the two ICRF scenarios. Consistent with theoretical predictions, plasmas heated with the H minority scheme exhibited the highest electron temperatures, while the pulse employing the three-ion ICRF scheme with core ^{9}Be resonance achieved the highest ion temperatures. For plasmas heated with light hydrogen minority ions, the electron temperature increases from ~3.5 keV to ~6.5 keV ($\Delta T_{e0} \approx 1.2$ keV/MW). In contrast, the pulse with dominant absorption of RF power by ^{9}Be impurities showed a significant increase of T_i by about 2.3 keV ($\Delta T_i \approx 0.9$ keV/MW). Following the decision of ITER not to use Beryllium as the first-wall material, the potential of three-ion ICRF scenarios in the absence of ^{9}Be was reassessed. A successful test of the three-ion ICRF scheme with using argon impurities for increasing T_i was performed. Under similar conditions, other impurities that are expected to significantly absorb ICRF power include ^{22}Ne, ^{11}B and ^{7}Li, offering additional flexibility for optimizing fast-ion generation and ion heating in plasmas without beryllium.

An analysis of impurity behaviour in this series of experiments is presented in [16]. No impurity accumulation was observed. Consistent with earlier findings that core electron heating helps to control impurities, slightly lower tungsten levels (~10-15%) were observed with hydrogen minority heating.

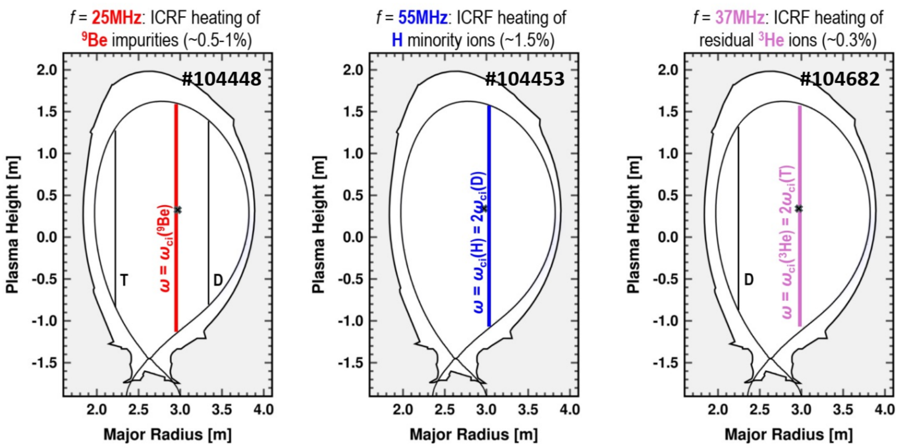

FIGURE 3. *Configuration of ICRF resonances for the series of experiments in DTE3 to demonstrate the flexibility of the ICRF system for bulk ion and electron heating. All pulses were conducted in L-mode D-T ≈ 50%-50% plasmas at 3.7T/2MA.*

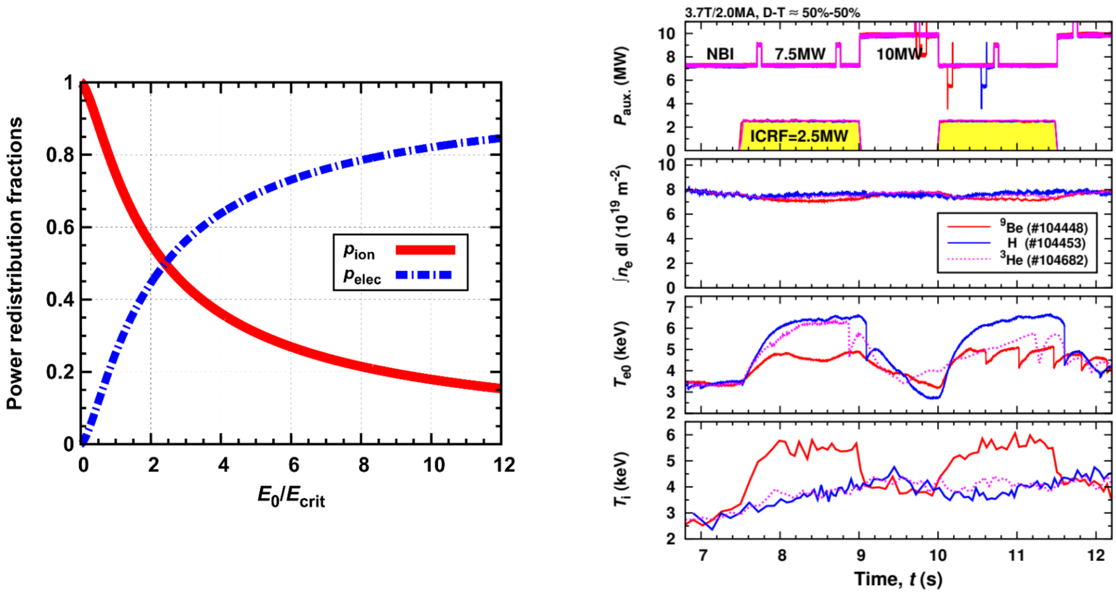

FIGURE 4. (a) Fraction of fast-ion power transferred to bulk ions and electrons via collisions as a function of the initial fast-ion energy normalized to the critical energy. (b) Overview of JET pulses #104448 (three-ion T-(^{9}Be)-D scheme, $n(^9Be)/n_e \approx 0.5$-1%), #104453 (H minority, $n_H/n_e \approx 1.5\%$, $\omega = \omega_{ci}(H)=2\omega_{ci}(D)$) and #104682 ($n_{3He}/n_e \approx 0.3\%$, $\omega = \omega_{ci}(^3He)=2\omega_{ci}(T)$), demonstrating the flexibility of the ICRF system for bulk ion and electron heating in L-mode D-T ≈ 50%-50% plasmas.

5. ALPHA-PARTICLE STUDIES IN D-3HE PLASMAS

Further progress was achieved at JET in the development and application of fast-ion diagnostics, including neutron and gamma-ray measurements, and fast-ion tomography to advance the understanding of energetic particle (EP) physics [23-25]. Methods for generating alpha particles in D-^{3}He plasmas [26], as well as the study of different types of fast-ion-driven instabilities [27] were advanced by accelerating deuterium ions from NBI to higher energies with ICRF. In the D-^{3}He fusion reaction, alpha particles are produced with birth energies of ~3.6 MeV, closely matching those of alphas generated in D-T fusion.

Figure 5 shows the dependence of the D-T, D-^{3}He and D-D fusion cross-sections as a function of the fast deuteron energy. The D-^{3}He cross-section reaches a maximum σ_{max}(D-^{3}He) ≈ 0.8b at $E_D \approx 430$ keV. This technique of producing alpha particles in plasmas without tritium is relevant for future fast-ion studies in JT-60SA, where the negative-ion NBI system will provide deuterons with energies up to 500 keV [28]. Simulations indicate that an alpha-production rate ~5×10^{16} s^{-1} can be achieved in high-performance JT-60SA plasmas with 10MW of N-NBI and 10% of ^{3}He in the deuterium plasma. This fast-ion scenario in D-^{3}He plasmas also supports the development of new alpha-particle diagnostic techniques for ITER [29].

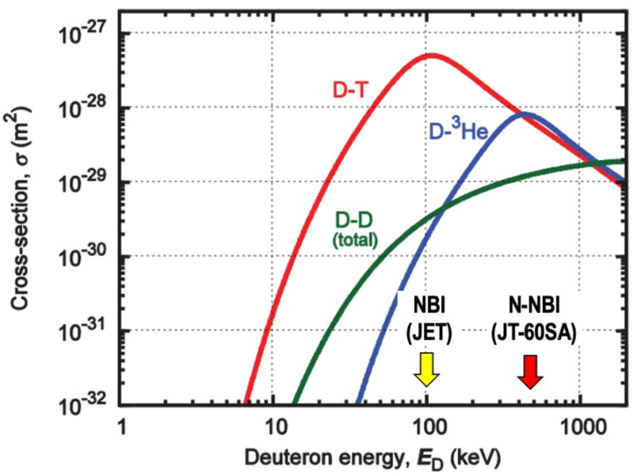

FIGURE 5. Fusion reaction cross-sections for D-T, D-^{3}He and D-D reactions as a function of fast deuteron energy. The D-^{3}He cross-section reaches a maximum at $E_D \approx 430$ keV.

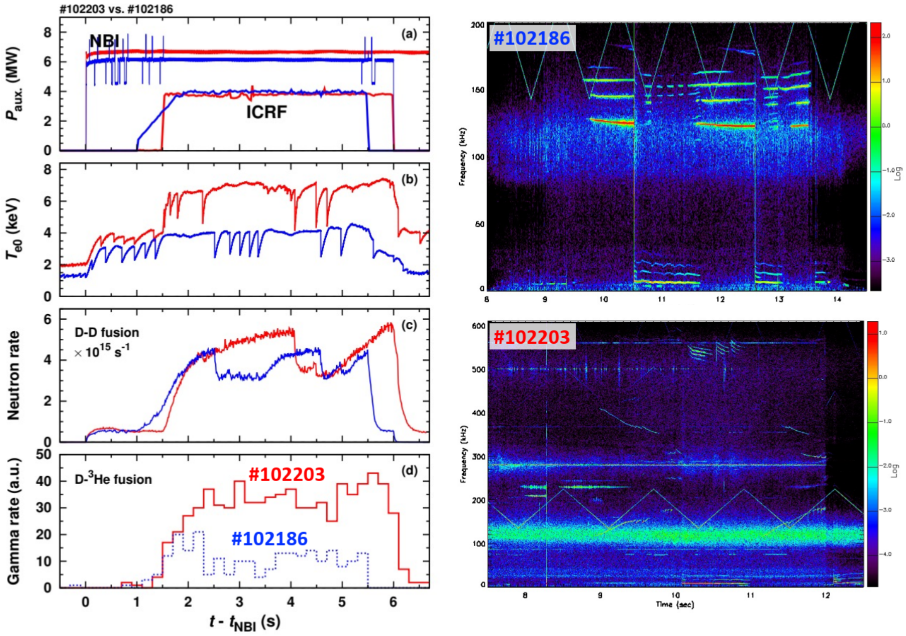

FIGURE 6. *(a) Overview of JET pulses #102186 (B_t = 2.3T, f = 51MHz, $n_{3He}/n_e \approx$ 15%) and #102203 (B_t = 3.65T, f = 33MHz, $n_{3He}/n_e \approx$ 25-30%), where D-NBI ions were accelerated to MeV-range energies in D-^{3}He plasmas with ICRF. (b, c) MHD spectrograms in pulses #102186 and #102203 illustrating a rich variety of fast-ion-driven instabilities.*

To accelerate deuterons to higher energies and produce alphas in D-^{3}He plasmas, two ICRF scenarios were applied: (i) third harmonic acceleration of D-NBI ions, $\omega = 3\omega_{ci}$(D) (B_t = 2.3T, f = 51MHz), with $n(^3\text{He})/n_e \approx$ 10-15%, and (ii) the three-ion D-(D_{NBI})-^{3}He scheme (B_t = 3.65T, f = 33MHz), with $n(^3\text{He})/n_e \approx$ 25-30%. The high efficiency of deuteron acceleration is evidenced by the sharp increase in the D-D neutron rate, immediately after ICRF power was applied. Interestingly, comparable D-D neutron rates were obtained in both scenarios despite the substantial difference in the thermal deuterium concentration. A significantly higher D-^{3}He fusion rate was observed in pulse #102203. Figures 6(b) and (c) present the MHD spectrograms for these two pulses, highlighting the rich-variety of fast-ion-driven instabilities in these plasmas.

In view of future JT-60SA experiments, a comparison study was carried out with pulse #102205, in which the magnetic field was reduced to B_t = 3.45T, shifting the heating maximum and fast-ion generation somewhat off-axis ($R_{abs} \approx$ 2.8 m). This off-axis configuration exhibited reduced efficiency of deuterium acceleration to high energies, as reflected by the lower electron temperature and the lower neutron rate compared with the on-axis heating pulse #102203. Interestingly, despite the lower T_{e0}, the D-^{3}He fusion count rate was comparable – and in fact somewhat higher – than in the on-axis pulse. This outcome is consistent with the non-monotonic energy dependence of the D-^{3}He cross-section, shown in Fig. 5.

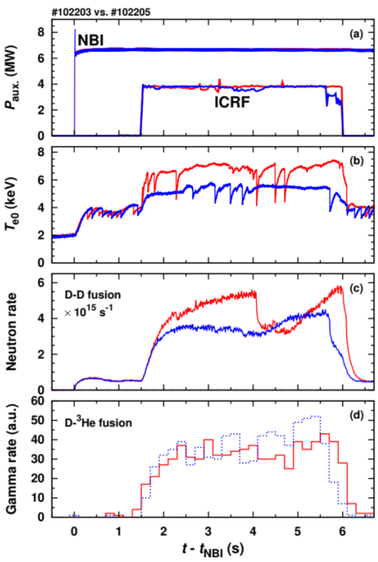

FIGURE 7. *Comparison of D-D neutron and alpha production in D-^{3}He plasmas using the three-ion D-(D_{NBI})-^{3}He scenario. Pulse #102203 corresponds to on-axis heating, while pulse #102205 corresponds to moderately off-axis heating.*

6. SUMMARY AND CONCLUSIONS

Significant progress was achieved at JET during its last operational campaigns in the area of energetic particle physics and the development of fast-ion diagnostics. The results presented here highlight advances in understanding the role of MeV-range fast ions and fast-ion-driven instabilities in stabilizing core turbulence, observed in D-^{3}He, D-T, and H-D plasmas. Further modeling and experimental studies on large-scale tokamaks are required to deepen this understanding and to explore potential pathways for exploiting the beneficial effects of fast ions and alpha particles.

Further developments were made with fast-ion studies using the three-ion D-(^{3}He)-H scenario. This scenario is very efficient in generating MeV-range fast ions and provides an opportunity for the early tests of EP modelling and fast-ion diagnostics in the SRO phase of ITER. The results of JET show that the antenna spectrum is an important actuator that allows to affect not only the sawtooth dynamics, but also serves as an actuator for TAEs in the plasma.

DTE3 experiments further demonstrated the flexibility of ICRF for bulk ion and electron heating. As predicted theoretically, H-minority heating produced the highest electron temperatures, while the three-ion ICRF scheme with core impurity resonance achieved the highest ion temperatures. Novel ICRF techniques using additionally argon impurities were developed for bulk ion heating, offering a promising approach to increase T_i and optimize the ramp-up phase in future large-scale D-T tokamaks.

Fast-ion studies in D-^{3}He plasmas were also advanced as a source of alpha-particles in tritium-free experiments. New experiments employing third-harmonic deuterium acceleration, $\omega = 3\omega_{ci}(D)$ and the three-ion D-(D_{NBI})-^{3}He scenario were performed, including investigations of the radial variation of the fast-ion source, which is relevant for future alpha-particle experiments with N-NBI on JT-60SA.

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