RECENT ADVANCES IN ICRF HEATING OF MIXTURE PLASMAS: SURVEY OF JET AND AUG EXPERIMENTS AND EXTRAPOLATION TO JET-DT AND ITER

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Abstract

This contribution summarizes recent experimental developments of the novel three-ion species ICRH heating scheme on JET and AUG. We give an overview of experiments in which a small amount of ^{3}He ions (~1% and below) were injected into H-D plasmas in order to absorb RF power and heat the plasma. In JET, effective plasma heating was observed both at extremely low ^{3}He concentrations of ~0.1-0.2% and at higher concentrations of ~1-1.5%. Heating AUG plasmas with this ICRH scenario requires ^{3}He ions to be less energetic than in JET, as otherwise they are not confined in the plasma. The combination of moderate ^{3}He concentrations of ~1% and off-axis ^{3}He resonance was successfully applied to reduce fast-ion energies and thus improve confinement of RF-heated ions in AUG. We also successfully demonstrated effective heating of H-D mixtures in JET by further ICRH acceleration of the injected D-NBI ions as resonant 'third' species in the D-(D_{NBI})-H three-ion scenario. The heating scenario was tuned such that D-NBI ions with injection energy of 100 keV absorbed most of launched RF power and were accelerated with ICRH up to ~2 MeV. The established technique of accelerating NBI ions to higher energies with ICRH in mixture plasmas holds promises for generating alpha particles in D-^{3}He plasmas and for maximizing the Q-value and D-T fusion reactivity.

1. INTRODUCTION

Auxiliary plasma heating is essential for future fusion reactors in order to reach high ion temperatures necessary for the D-T fusion. Ion cyclotron resonance heating (ICRH) is a flexible heating technique and many efficient ICRH scenarios have been developed [1]. The so-called minority heating scenarios are widely used in toroidal magnetic fusion research, as they feature strong damping of the excited RF waves in the plasma. These scenarios rely on fundamental ion cyclotron absorption ($\omega = \omega_{ci} + k_\parallel v_\parallel$) of electromagnetic waves by a small amount of resonant ions with a different cyclotron frequency than that of the main plasma ions. In turn, these RF-heated minority ions transfer their energy via Coulomb collisions during their slowing-down to the other plasma particles, bulk ions and electrons.

Recent theoretical and experimental developments have demonstrated the existence of a class of new efficient ICRH schemes, referred to as 'three-ion species' scenarios [2–5]. They open new promising routes for plasma heating in present-day and future fusion devices. The novel scenarios are relevant for heating various plasma mixtures composed of H and He isotopes, e.g. D-T, H-D, H-^{4}He, D-^{3}He or H-T plasmas, and in addition can make use of intrinsic and extrinsic impurities, e.g. ^{9}Be, Ne, Ar, etc. to optimize ICRH power deposition in fusion plasmas. In its simplest form, this novel ICRH scenario requires a plasma including at least three ion species

with a different ratio of the charge number to the atomic mass, $(Z/A)_i$. In what follows, we use indices '1' and '2' for the main plasma ions, having the largest and lowest $(Z/A)_i$, and index '3' for the absorbing minority. The (Z/A) value for the resonant 'third' species should be in between that of the two main ions, i.e. $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$. As shown in [2], even an extremely low number of minority ions with a concentration of a few ‰ is sufficient to absorb nearly all launched RF power, provided the concentrations of the main ions, $X_i = n_i/n_e$ are given by

$$X_1^* \approx \frac{1}{Z_1} \frac{(Z/A)_1 - (Z/A)_3}{(Z/A)_1 - (Z/A)_2}, \quad X_2^* \approx \frac{1}{Z_2} \frac{(Z/A)_3 - (Z/A)_2}{(Z/A)_1 - (Z/A)_2}. \tag{1}$$

Equation (1) describes the specific plasma composition for which the ICRH power absorption by an extremely low number of resonant ions (of a few ‰) is maximized. Note, however, that three-ion ICRH scenarios can also be used for plasma heating at higher minority concentrations and at majority ion concentrations different from Eq. (1) [3]. A nearly total RF power absorption by the resonant ions at extremely low concentrations cannot be achieved with traditionally used minority heating scenarios, which typically feature low single-pass absorption at such low X_{mino} and require minority ion concentrations of usually a few % for efficient wave absorption in the central regions of the plasma. Hence, the main plasma ion concentrations given by Eq. (1) are particularly relevant for generating a population of highly energetic ions in the plasma, e.g. to be used for fast-ion confinement studies. For plasma heating with three-ion ICRH scenarios at higher minority ion concentrations of about 1%, lower concentrations of main ion species '2' are more optimal, $X_2 < X_2^*$ (equivalently, $X_1 > X_1^*$). In section 2 of the paper, we discuss the results of recent JET and AUG experiments, in which a small amount of ^{3}He ions ($Z/A = 2/3$) was used as a resonant minority for heating H-D mixed plasmas.

We also discuss an extension of the three-ion technique that consists in using fast NBI ions as resonant 'third' species for ICRH heating of mixed plasmas. In this case, those fast ions in the NBI slowing-down distribution that have a Doppler-shifted resonance close to the ion-ion hybrid (IIH) layer in mixed plasmas resonate with the fast wave and efficiently absorb RF power [5]. In section 3 of the paper, we illustrate how mixed H-D plasmas on JET were effectively heated with a synergetic ICRH+NBI scenario using D-NBI ions with injection energy of 100 keV as resonant species. Finally, we conclude the paper with a short summary of various applications of three-ion ICRH scenarios that hold promise for future D-T experiments on JET and for ITER operations.

2. ICRH HEATING OF H-D MIXED PLASMAS WITH ^{3}He MINORITY IONS

2.1. Summary of D-(^{3}He)-H ICRH experiments on JET

Proof-of-principle experiments on JET and Alcator C-Mod tokamaks confirmed the validity of our theoretical predictions and demonstrated the high efficiency of three-ion ICRH scenarios for plasma heating and fast-ion generation [4]. As follows from Eq. (1), absorption of ICRH power by an extremely low amount of ^{3}He ions should be maximized in H-D mixed plasmas with $X[H] \approx 70\%$ and $X[D] \approx 30\%$. Heating H-D plasmas with $X[H] > 70\%$ can be achieved by selecting somewhat higher ^{3}He concentrations. The first series of JET experiments was conducted in L-mode plasmas at a magnetic field of 3.2T, plasma current of 2MA and central plasma densities $n_{e0} \approx 4 \times 10^{19}$ m^{-3}. RF frequencies $f = \omega/2\pi = 32.2$-33.0MHz were chosen to match the cyclotron resonance of ^{3}He ions in the plasma core. Figure 1 shows an overview of two JET pulses heated with the D-(^{3}He)-H three-ion ICRH scenario, both having extremely low ^{3}He concentrations $X[^3$He$] \approx 0.2$-0.3%. Prior to launching the ICRH power, 3.2MW of D-NBI power was applied for plasma pre-heating and charge exchange measurements.

In discharge #90752, see Fig. 1(a), the H/(H+D) ratio measured at the plasma edge varied between 0.74 and 0.83, and all ICRH power was coupled with a symmetric dipole phasing. The sawtooth period extended from ~200 ms during the NBI-only phase to ~500-600 ms during the combined ICRH+NBI phase. Note that the core hydrogen concentration was estimated using the measured edge H/(H+D) ratio, corrected for the presence of impurities and additional core fueling of D ions from the D-NBI system, resulting in $X[H] \approx 0.9 \times$H/(H+D). In discharge #90758, see Fig. 1(b), the edge H/(H+D) ratio was somewhat larger 0.88-0.92 resulting in $X[H] \approx 80\%$, and all ICRH power was coupled with asymmetric $+\pi/2$ phasing, launching waves predominantly in the direction of the plasma current. In comparison with discharge #90752, a population of more energetic ^{3}He ions was generated in the plasma, resulting in even longer sawtooth periods of ~1s, excitation of core localized toroidal Alfvén eigenmodes (TAEs) and an increased intensity of the γ-ray emission, originating from nuclear reactions between ICRH-accelerated ^{3}He ions and intrinsic ^{9}Be impurities. Furthermore, since JET is a large-scale tokamak with high plasma current, high enough to confine MeV-range energetic ^{3}He ions, effective heating of the background H-D plasmas was achieved as a result of the slowing-down of the well-confined multi-MeV ^{3}He ions. Figure 1(b) illustrates very efficient plasma heating with the three-ion ICRH scenario for pulse #90758: the heating performance reached $\Delta W_p/\Delta P_{ICRH} \approx 0.16$-0.18 MJ/MW with normalized energy confinement time $\tau_E/\tau_{E\,(ITERL96-P)} \approx 1.43$-1.48 and $\tau_E/\tau_{E\,(IPB98(y,2))} \approx 0.85$-0.88. For similar plasma conditions, the observed heating performance of the D-(^{3}He)-H three-ion scenario is somewhat smaller than for the routinely used H minority
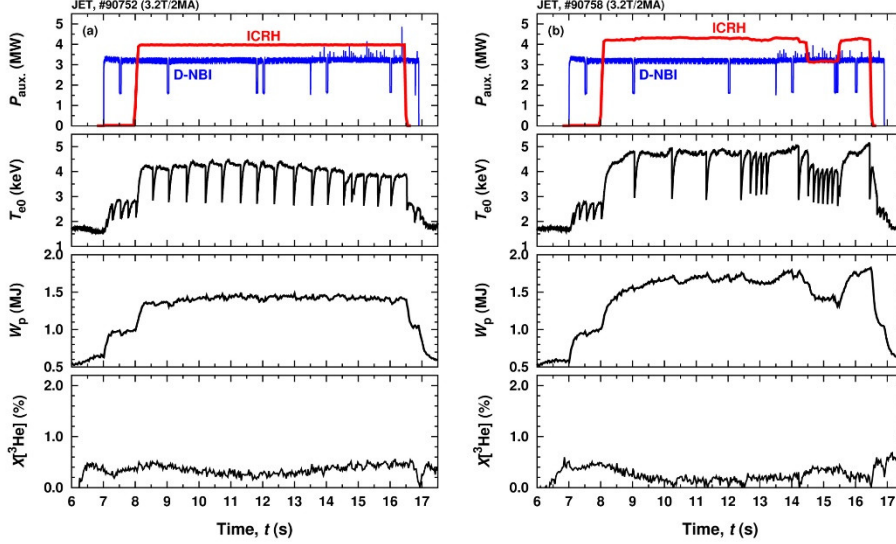
FIG. 1. Overview of JET pulses #90752 (dipole phasing) and #90758 (+π/2 phasing) heated with the three-ion D-(^{3}He)-H ICRH scenario.

scenario in D plasmas (characterized by $\Delta W_p/\Delta P_{ICRH} \approx 0.20$ MJ/MW, see [6]), but it is ~60-80% larger than the heating performance of the ^{3}He minority scenario in H plasmas ($\Delta W_p/\Delta P_{ICRH} \approx 0.10$ MJ/MW, see [7]). The dependence of the heating performance of the D-(^{3}He)-H three-ion scenario on the chosen plasma composition, X[H] and X[^{3}He], is shown in Fig. 2. This figure illustrates that using the three-ion scenario on JET, central ICRH power deposition was achieved with values for $\Delta T_{e0}/\Delta P_{ICRH} > 0.5$ keV/MW and $\Delta W_p/\Delta P_{ICRH} > 0.15$ MJ/MW for a rather wide range of X[H] and X[^{3}He]. These values are significantly larger than for the inverted (^{3}He)-H ICRH scenario in 3.2T/1.8MA plasmas [7], for which $\Delta T_{e0}/\Delta P_{ICRH} \approx 0.3$ keV/MW and $\Delta W_p/\Delta P_{ICRH} \approx 0.10$ MJ/MW were reported. We note that the increase of the plasma stored energy and temperature achieved per MW of applied ICRH power is not only related to the instantaneous efficiency of ICRH power absorption, but also includes transport and confinement effects, as well as sensitivity to the details of the slowing-down distribution of fast ions. A weak positive isotope dependence of the energy confinement time has been reported for JET-ILW L-mode plasmas, $\tau_E \sim A^{0.15}$ (here, A is the main ion isotope mass) [8, 9]. This implies that a ~10-20% better heating performance of the (H)-D ICRH scenario compared to the performance of the three-ion D-(^{3}He)-H scenario is consistent with better confinement in D plasmas than in H-D mixtures. Yet, the isotope effect is too small to explain the observed ~60-80% higher performance of the ^{3}He minority heating in H-D ≈ 80%-20% plasmas if compared to the minority heating of ^{3}He in H plasmas. The discussion of the exact mechanism(s) responsible for the observed difference in the heating performance of the two scenarios is outside the scope of this paper. However, we want to highlight that recent JET and AUG experiments show that the presence of high-energy ^{3}He ions can lead to the stabilization of the ion temperature gradient (ITG) turbulence via the enhancement of fast ^{3}He ion pressure in the plasma core [10, 11].
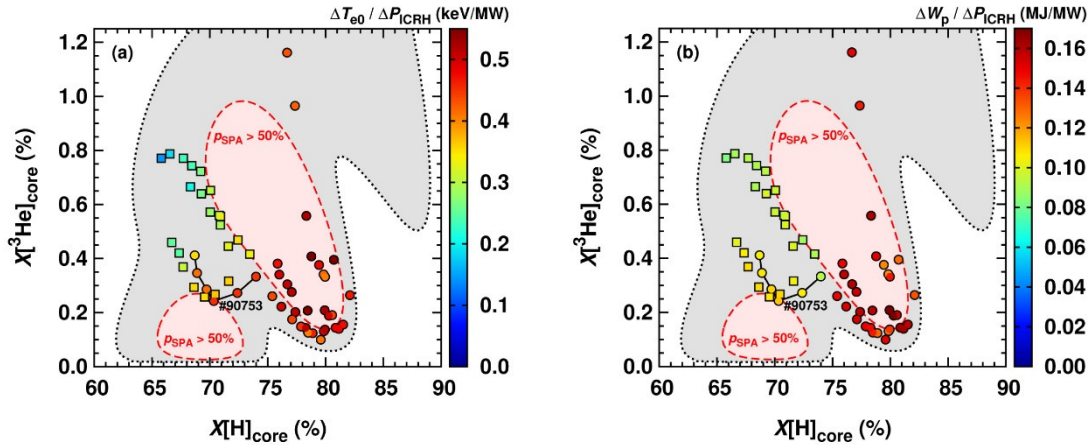

FIG. 2: D-(^{3}He)-H three-ion ICRH scenario (minority heating of ^{3}He ions in H-D plasmas) has been shown to be an efficient technique for heating H-D mixed plasmas on JET. For comparison, at similar B_0, I_p, n_e, etc., minority heating of ^{3}He ions in H plasma, viz. (^{3}He)-H scenario, is characterized by $\Delta T_{e0}/\Delta P_{ICRH} \approx 0.3$ keV/MW and $\Delta W_p/\Delta P_{ICRH} \approx 0.10$ MJ/MW [7]. Note that circles represent pulses in which more than 2MW of ICRH power was coupled with +π/2 phasing, while squares correspond to pulses in which all RF power was coupled with the dipole phasing. The grey area corresponds to the region, where more than 80% of incoming RF power was computed to be absorbed by ^{3}He minority ions.

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A similar heating scenario that channels ICRH power to a very low amount of ^{3}He ions in H-^{4}He non-active plasmas (H plasmas with ~10-15% of ^{4}He) is also of relevance for ITER [12]. Compared to the often considered (^{3}He)-H scenario, the ^{4}He-(^{3}He)-H three-ion scenario has potentially an additional advantage since injecting low quantities of ^{4}He (~10%) into H plasmas led to a reduction of the H-mode threshold on JET [13].

The efficiency of the three-ion scenario when increasing the ^{3}He minority concentration to ~1-2% was studied in pulse #90756, cf. Fig. 3(a). At the start of the discharge, the ^{3}He concentration was kept by real-time control (RTC) system at extremely low level ~0.2%. The corresponding T_e and T_i profiles measured by the ECE and CXRS systems are shown in Fig. 3(b). They show that not only electrons, but also bulk ions were heated with this ICRH scenario. As the concentration of ^{3}He was gradually increased to ~1-1.5%, efficient plasma heating continued to be observed, but the sawtooth period was reduced. Although JET has limited experience with the application of this scenario at minority concentrations of ~1%, these first results are encouraging.
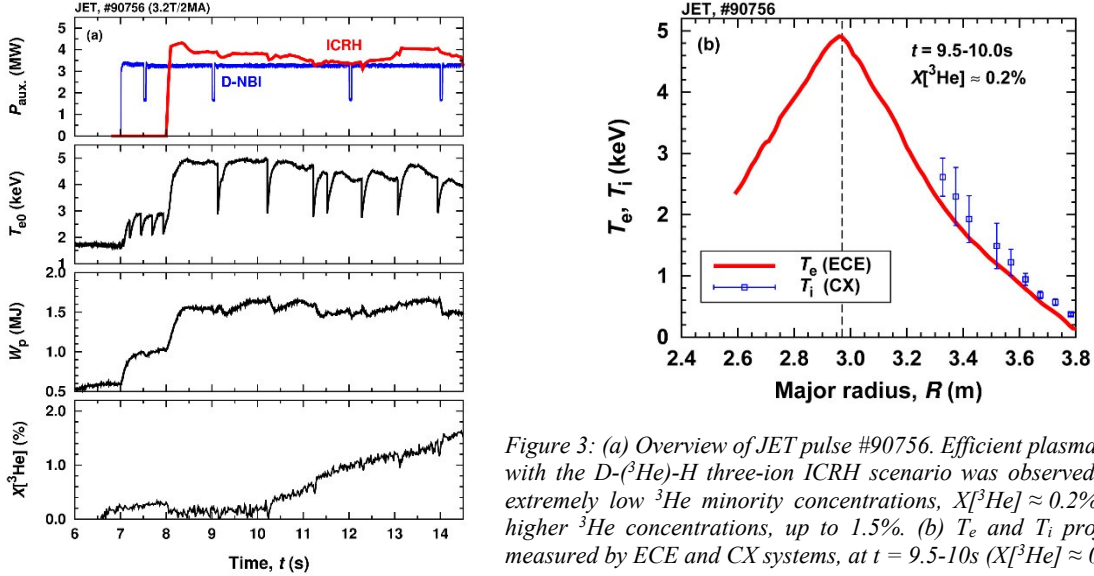

Figure 3: (a) Overview of JET pulse #90756. Efficient plasma heating with the D-(^{3}He)-H three-ion ICRH scenario was observed both at extremely low ^{3}He minority concentrations, $X[^3He] \approx 0.2\%$ and at higher ^{3}He concentrations, up to 1.5%. (b) T_e and T_i profiles, as measured by ECE and CX systems, at $t = 9.5$-$10s$ ($X[^3He] \approx 0.2\%$).

The high efficiency of three-ion ICRH scenarios for generating energetic ^{3}He ions results from the reduced number of resonant ions absorbing RF power, thus maximizing the absorbed RF power per resonant ion. The large set of fast-ion diagnostics present at JET [14] allows further detailed studies of the fast ^{3}He population in the plasma. The presence of a confined fast ^{3}He population with energies of at least 2-3 MeV in JET was confirmed by the γ-ray emission spectroscopy diagnostic [15], consisting of ten horizontal and nine vertical collimated lines of sight. A tomographic reconstruction of the emission using the γ-cameras allows to visualize spatial profiles of the γ-ray emission and the corresponding fast-ion population. In JET, we further enhanced the efficiency for fast-ion generation with the three-ion scenario by changing the configuration of ICRH antennas from dipole to $+\pi/2$ phasing, as seen from the reconstructed γ-ray emission profiles shown in Figs. 3(b) and (c) in [4]. Additional confirmation for the efficient acceleration of ^{3}He ions to multi-MeV energies was given by the fast-ion loss detector (FILD) measurements. On JET, FILD is located ~28cm below the mid-plane of the torus and provides information on the pitch-angle of a lost ion in the range 35°–85° and gyro-radius between 3cm and 14cm [16]. The energy of a lost fast ion can be inferred from the measured gyro-radius as follows

$$E_i(\text{MeV}) = \left(\frac{\rho_{\text{L}}(\text{cm}) B_{\text{FILD}}(\text{T})}{14.45} \right)^2 \frac{Z_i^2}{A_i}, \qquad (2)$$

where B_{FILD} is the magnetic field strength at the FILD location.

In the second round of ^{3}He three-ion experiments in H-D plasmas on JET, NBI heating and CXRS measurements were not available and plasmas were heated with ICRH only. Figure 4(a) shows an overview of pulse #91304 (3.1T/1.8MA, $+\pi/2$ phasing). In the first phase of the discharge ($t = 8$-10.4s), the ^{3}He concentration was increased to ~1% and very efficient plasma heating with a heating performance $\Delta W_p / \Delta P_{\text{ICRH}} \approx 0.18$ MJ/MW was achieved. Similarly to MHD observations in the first set of ^{3}He three-ion ICRH experiments on JET, core localized TAEs with a frequency $f_{\text{TAE}} \approx 280$ kHz were observed. This frequency is somewhat lower than the TAE frequencies measured in ICRH+NBI heated plasmas, in which the plasma rotation due to NBI upshifts the observed frequency. Following the phase with TAE excitation, elliptical AE modes (EAEs) at higher frequencies $f_{\text{EAE}} \approx 550$-580 kHz, with toroidal mode numbers $n = \pm 1, \pm 3, \pm 5$ were seen (see Fig. 4(b)), accompanied by the reduction of heating performance to ~0.09MJ/MW. A numerical analysis of the resonant condition for energetic ions interacting with the observed EAEs infers ^{3}He ions with energies > 4-5 MeV. FILD measurements at $t = 10.3$-
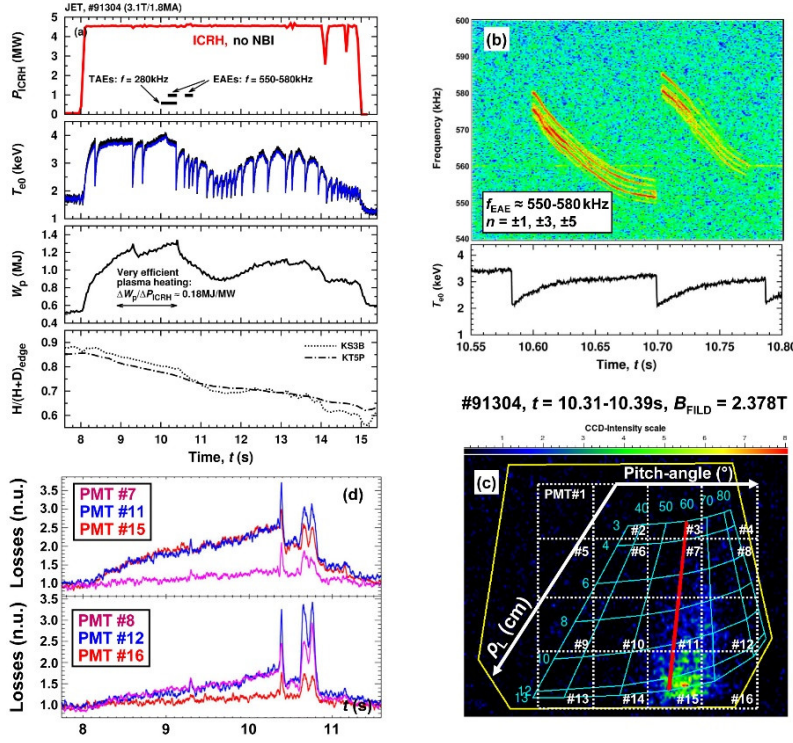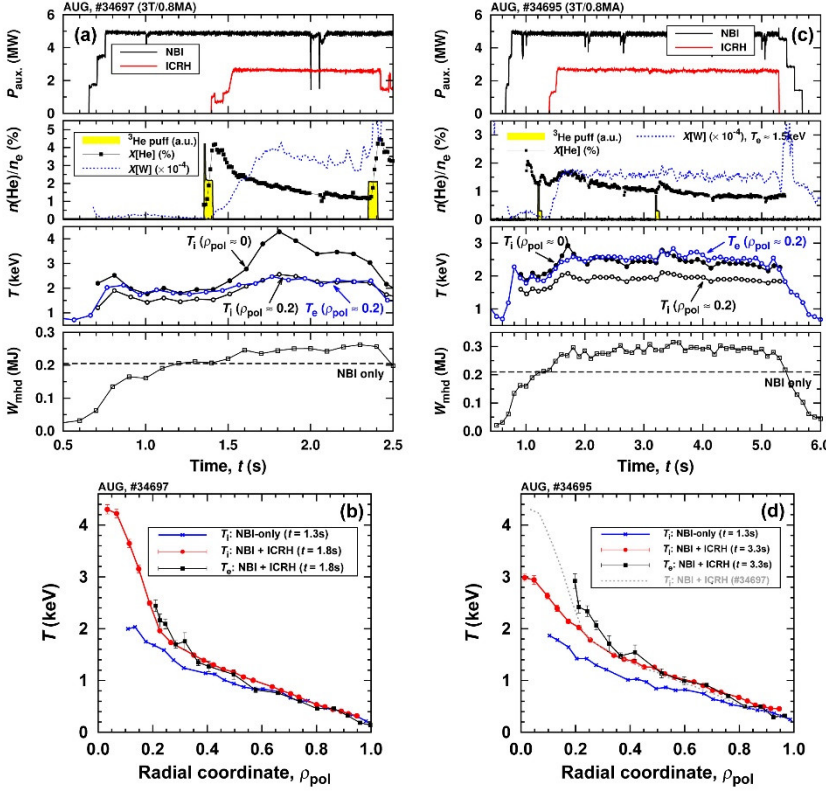
FIG. 4. An example of three-ion ICRH discharge on JET with ICRH as the only heating system, #91304 (3.1T/1.8MA). (a) Very efficient plasma heating was observed in the initial phase of the discharge, $\Delta W_p/\Delta P_{ICRH} \approx 0.18$ MJ/MW. (b) MHD spectrogram showing EAE modes at frequencies 550-580 kHz. (c) FILD measurements (t = 10.3-10.4s) infer the presence of highly energetic ^{3}He ions with energies > 4-5 MeV prior to the monster sawtooth crash and EAE modes shown in Fig. 4(b). (d) Strong losses of energetic ^{3}He ions were observed during the discharge phase, when EAE modes were detected.

10.4s (Fig. 4(c), B_{FILD}=2.38T) indicate that a population of highly energetic ^{3}He ions with energies of at least ∼ 4-6MeV ($\rho_L \approx$ 10-13cm, cf. Eq. (2)) was indeed present in the plasma prior to the monster sawtooth crash at t = 10.4s and the phase with EAE modes. The loss signals recorded by photomultiplier tubes (PMT) #7,8,11,12,15,16 (the PMT numbering and the fields of view are depicted with white dotted lines in Fig. 4(c)) show enhanced fast-ion losses during t = 10.6-10.8s, when EAE modes were observed (Fig. 4(d)). In a later phase of #91304 the heating performance recovered and reached 0.13 MJ/MW. Finally, we note that no degradation of the heating performance of the D-(^{3}He)-H three-ion ICRH scenario was observed in the presence of TAE modes on JET.

2.2. Summary of D-(^{3}He)-H ICRH experiments on AUG

In addition to the experiments on Alcator C-Mod and JET [4], the three-ion ICRH scenario has also been successfully demonstrated in the medium-size divertor tokamak ASDEX Upgrade (AUG). The experiments were conducted using ^{3}He as resonant species for ICRH heating of H-D mixed plasmas with H/(H+D) ≈ 0.7-0.8. ICRH power was delivered by a pair of 2-strap antennas with B-coated limiters and a pair of the new 3-strap antennas with W-coated limiters [17, 18]. Up to 2.6MW of ICRH power was coupled into the plasma at f = 30MHz using dipole phasing. The cyclotron resonance of the ^{3}He minority ions is located in the plasma core for discharges at 3T and at $\rho_{pol} \approx 0.3$, i.e. at the high-magnetic field side (HFS) for discharges at 2.8T. A plasma current of 800kA was adopted in the reported experiments. Plasma pre-heating and CXRS measurements were performed with hydrogen neutral beams with heating power up to 8MW. In the absence of a real-time control scheme for the ^{3}He concentration, a series of short ^{3}He puffs (with a duration of 50ms) from a gas valve at the mid-plane was applied. In order to optimize the scenario performance and assess the sensitivity of the heating scenario on the ^{3}He concentration, the ^{3}He puff rate was varied between 2×10^{20} el/s and 18×10^{20} el/s; we also varied the time interval between the ^{3}He puffs from discharge to discharge.

According to numerical computations with the TOMCAT code [19], efficient double-pass wave absorption for this scenario can be achieved on AUG at ^{3}He concentrations in the range $X[^3He] \approx$ 0.2-1.5%. At higher ^{3}He concentrations, mode conversion regime sets in, characterized by a fairly low double-pass absorption efficiency (~10-30%). In line with these modelling predictions, operation at relatively high ^{3}He concentrations of ~3-5% resulted in low heating performance and increased W content. Application of the three-ion scenario at extremely low ^{3}He concentrations did not show such clear signs of plasma heating as on JET. The reason for this difference is the reduced fast-ion confinement in the medium-size AUG plasmas compared to the large-scale plasmas of JET, also using larger plasma currents. While JET is capable to confine most of the fast ^{3}He ions with energies of a few MeV, ^{3}He fast-ion energies in AUG plasmas should be limited to ~1-1.5 MeV in order to stay confined in the plasma and heat the background plasma during their slowing down. Hence, higher ^{3}He concentrations of ~1% are more optimal for heating medium-size AUG plasmas, and controlling the ^{3}He concentration is a key factor in determining the performance of this ICRH scenario on AUG. Another option for reducing ^{3}He fast-ion energies is to apply off-axis deposition of ICRH power, and was also successfully demonstrated on AUG (see the discussion of pulse #34704 below). We also note that good confinement of energetic ^{3}He ions in three-ion ICRH experiments on Alcator C-Mod was due to the very high toroidal magnetic field of 7.8T [4].

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Figure 5(a) shows the time evolution of several plasma parameters in the ICRH+NBI heated AUG pulse #34697 with the on-axis ^{3}He resonance. High ^{3}He puff rates of 18×10^{20} el/s and 17×10^{20} el/s were applied at $t = 1.35\text{-}1.4\text{s}$ and $t = 2.35\text{-}2.4\text{s}$, respectively. The evolution of the total helium concentration (^{3}He and ^{4}He) in the plasma was measured by the CXRS system, and is shown in the second panel of Fig. 5(a). Most of the measured helium content is ^{3}He; we note that its concentration increases rapidly after each ^{3}He puff and then again decays. After the first ^{3}He puff, the He concentration decreased from ~4% to ~1.3-2%. During this phase strongly radially peaked ion temperature profiles with $T_i(0)$ up to 4.3 keV were observed, as illustrated in Fig. 5(b). For comparison, the core ion temperature during the NBI-only phase reached a mere $T_i(0) \approx 2\text{keV}$. Unfortunately, $T_e(0)$ data are not available for AUG discharges at 2.8-3T, making the analysis of the peakedness of the T_e profile and the

comparison between the T_e and T_i profiles rather difficult. We note that in pulse #34697 with a relatively high ^{3}He concentration, the electron temperature at $\rho_{pol} \approx 0.2$ closely matches the corresponding T_i value, cf. Fig. 5(b). The plasma toroidal rotation velocity profile was also peaked, and v_{rot} in the central regions of the plasma increased from 100 km/s during the NBI-only phase to $v_{rot} = 230$ km/s during the ICRH+NBI phase. These observations are quite similar to the ones reported for the (^{3}He)-D minority heating scenario on AUG [20]. Whether this effect is due to ICRF fast-ion and heating physics, or is caused by changes in the transport properties of the plasma (e.g. due to increased central radiation) needs further analysis.

Figure 5. Overview of two AUG pulses heated with the D-(^{3}He)-H three-ion ICRH scenario with on-axis ^{3}He resonance: #34697, panels (a) and (b); #34695, panels (c) and (d).

Figure 5(c) shows an overview of AUG pulse #34695, again with the on-axis ^{3}He resonance, but where we applied much smaller ^{3}He puff rates (~2×10^{20} el/s) and the He concentration was ~1%. The corresponding T_i and T_e profiles are shown in Fig. 5(d), illustrating that $T_i(0) \approx 3$ keV was reached during the ICRH+NBI phase of the pulse. That also the T_e-profile must be rather peaked in the plasma core follows from the observation that electron temperatures of 3 keV are already reached at $\rho_{pol} \approx 0.2$. This result is not surprising since at such low ^{3}He concentrations energetic ions transfer most of their energy to the electrons during the slowing-down. In Fig. 5(d), we also show the T_i-profile from #34697 (grey dotted line) in order to illustrate that the core electron temperature $T_e(0)$ in #34595 might be well in excess of the value 3 keV, measured at $\rho_{pol} \approx 0.2$. We also note that energetic ^{3}He ions were sufficiently well confined in #34695, and the plasma stored energy increased from 200 kJ in the NBI-only phase of the pulse to ~300-310 kJ in the ICRH+NBI phase.

Efficient generation of energetic ^{3}He ions was also observed in AUG plasmas, confirmed by the excitation of Alfvén modes ($f_{AE} \approx 160\text{-}190$ kHz), the appearance of fishbones and from FILD measurements. The FILD analysis was of a particular use since it allowed to validate the type of escaping ion species (^{3}He) and quantify the ^{3}He energies reached. Figure 6(a) shows the velocity-space of the escaping ions measured in pulse #34695 by FILD2 ($\rho_L \approx 6\text{-}9$ cm, pitch angle $\approx 65°$). The backward-orbit tracing of escaping ions measured by FILD was undertaken for all three species in the plasma, viz. H, D and ^{3}He, see respectively Figs. 6(b), (c) and (d). The escaping ions cannot be protons and deuterons: FILD analysis infers measured lost ions to originate from the plasma core, while the ICRH resonance for H and D ions is outside the plasma or at the HFS edge, respectively. Backward-traced orbits for energetic ^{3}He ions are consistent with the ^{3}He ICRH resonance located in the plasma core. Using Eq. (2) and $B_{FILD} \approx 2.3\text{T}$, one can estimate the energy of the ^{3}He lost ions measured by FILD: for example, $\rho_L = 7$ cm corresponds to $E[^3\text{He}] \approx 1.7$ MeV.
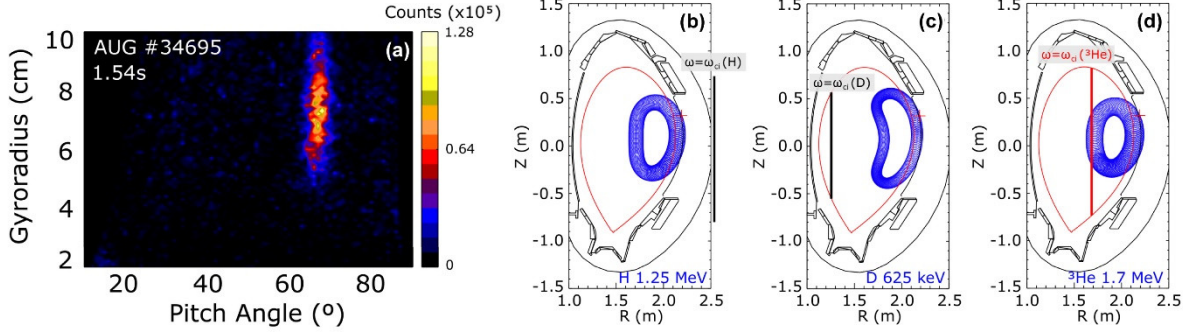
Figure 6: FILD analysis for AUG pulse #34695 with on-axis ^{3}He resonance.

In order to reduce the energies of fast ^{3}He ions, and thus improve the confinement of the ICRF-heated ^{3}He ions on AUG and heating of the background plasma, we applied off-axis deposition of RF power. In pulse #34704 (see Fig. 7), the toroidal magnetic field was reduced to 2.8T and the ^{3}He cyclotron resonance was shifted to $\rho_{pol} \approx 0.3$ at the HFS. As a consequence, for the same input ICRH power lower energies of fast ^{3}He ions were achieved. ^{3}He puffs with a puff rate of 2.3×10^{20} el/s were applied every 0.5s, resulting in a ^{3}He concentration of
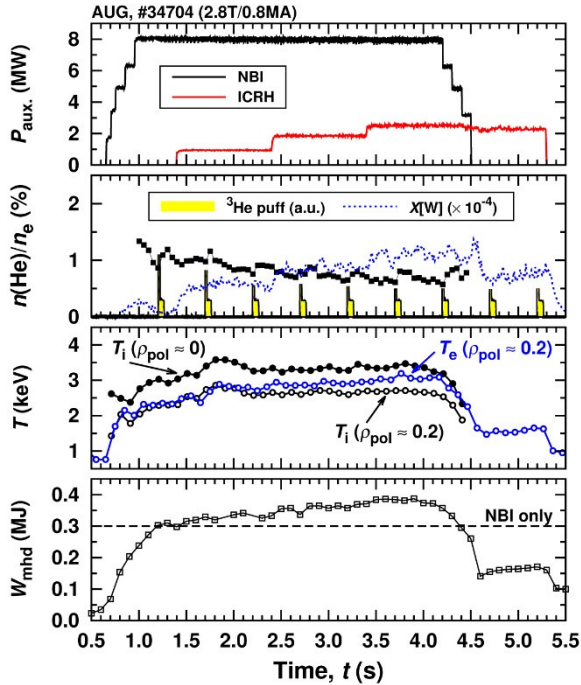

~0.5-1%. ICRH power was increased in three steps: 0.9MW, 1.9MW and 2.5MW. Consequently, the plasma stored energy increased from ~300kJ during the NBI-only phase with $P_{NBI} = 8$MW to ~400kJ during the ICRH+NBI phase. A gradual increase of T_e measured at $\rho_{pol} \approx 0.2$ is seen in Fig. 7, consistent with the fact that energetic ^{3}He ions transfer most of their energy during their slowing-down to the electrons. Furthermore, in this discharge with the off-axis ^{3}He resonance, lower W levels were observed compared to the discharges with the on-axis resonance in this series of shots. CXRS measurements confirmed the presence of confined energetic ^{3}He ions in the plasma [21]. The measured spectra were shown to agree well with the modelled spectra using the ^{3}He distribution functions predicted by the TORIC-SSFPQL modelling. For the conditions of pulse #34704, ^{3}He effective temperatures $T_\perp \approx 500$ keV and $T_\parallel \approx 15$ keV were computed at $\rho_{pol} \approx 0.3$, assuming $X[^3$He$] = 0.6\%$. The developed HFS off-axis ^{3}He heating with the three-ion species scenario on AUG is of relevance for H-mode studies in non-active ITER plasmas, for which ^{3}He minority heating in H-^{4}He mixed plasmas has been recently proposed [11].

FIG. 7: Overview of AUG pulse #34704 with HFS off-axis ^{3}He resonance.

3. ICRH HEATING OF H-D MIXED PLASMAS WITH D-NBI IONS AS RESONANT SPECIES

Energetic species, such as injected NBI ions and fusion products, can also play the role of the 'third' species and resonate in the vicinity of the IIH layer located between the two cyclotron layers of the main ions, because of the Doppler shift in their resonance position. Effective ICRH heating of H-D mixed plasmas using D-NBI ions as resonant minority was recently demonstrated on JET [5]. Figure 8(a) shows an overview of JET pulse #91256 (2.9T/2MA, H-D $\approx$ 85%-15%), where the neutron rate increased by a factor of 10-15 when 2.5MW of ICRH power (f = 25MHz, dipole phasing) was applied simultaneously with 3.5MW of D-NBI. The experimental conditions were chosen to locate the cyclotron resonance of thermal D ions HFS off-axis ($R_{IC}(D) - R_0 \approx -40$ cm), while keeping the ion-ion hybrid layer in the plasma core. The scenario was tuned such that D-NBI ions with an injection energy of 100 keV absorbed most of the launched ICRH power in the vicinity of the IIH layer and were in this way accelerated to much higher energies using ICRH. The presence of a population of energetic D ions with energies ~1-2 MeV during the combined ICRH+NBI phase was confirmed by neutron spectroscopy (TOFOR) and γ-ray measurements (see the bottom panel in Fig. 8(a)). A consistent simulation of the TOFOR measurements for this advanced heating scenario was done with the TRANSP code; validation of TOFOR measurements with SCENIC modelling is also ongoing.
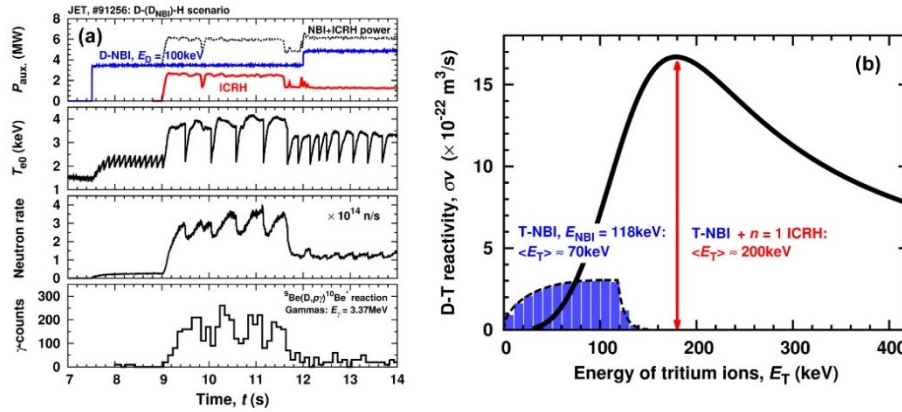
FIG. 8: (a) An example of the performance of the three-ion $D-(D_{NBI})-H$ scenario on JET-ILW with fast D-NBI ions as resonant 'third' species, #91256 (2.9T/2MA; H-D ≈ 85%-15%).
(b) In a similar way, fast D-NBI and T-NBI ions can be accelerated with ICRH in D-T plasmas in order to reach fast-ion energies optimal for maximizing D-T fusion reactivity.

The developed experimental technique for fundamental ICRH heating of injected fast NBI ions in mixed plasmas holds promises for DTE2 studies on JET since this technique allows to tailor fast-ion energies to a predetermined value. For example, as shown in Fig. 8(b), the D-T reactivity for a population of monoenergetic T ions is maximized at $E_T \approx 180$ keV. The idea behind the three-ion T-(T_{NBI})-D scenario is to apply off-axis ICRH heating of T-NBI ions, aiming at a moderate increase of an average energy of the fast T ions from $<E_T> \approx 70$ keV (as in the NBI-only slowing-down distribution) to $<E_T> \approx 180-200$ keV. The synergetic effect for the three-ion ICRH+NBI scenario was shown to depend on the choice of beam injectors since different PINIs provide not only fast ions with different initial pitch-angle distribution, but also each PINI follows a different path through the plasma. If one aims to optimize the Q-value in D-T plasmas, only those NBI PINIs which feature the largest possible synergy with ICRH should be selected. In the same way, D-NBI ions can absorb part of launched ICRH power in D-T plasmas, in particular, in T-rich plasmas, and undergo an acceleration to moderately high energies, favourable for maximizing the D-T reactivity. A similar technique of accelerating D-NBI ions with ICRH in D-^{3}He plasmas will be experimentally developed in the next D campaign on JET. The three-ion D-(D_{NBI})-^{3}He scenario will be applied to accelerate D-NBI ions to average energies of ~450keV in order to optimize the source of alpha particles from the D+^{3}He fusion reaction.

4. SUMMARY AND CONCLUSIONS

Recent JET, Alcator C-Mod and AUG experiments have demonstrated very efficient plasma heating and fast-ion generation with the newly developed three-ion ICRH scheme. Various three-ion ICRH scenarios hold promises for ITER operations, both for the non-active and D-T plasmas [12, 22]. In the non-active phase, minority heating of ^{3}He ions in H-^{4}He plasmas and minority heating of ^{4}He ions in H majority plasmas, diluted with intrinsic ^{9}Be and Ar (from seeding) impurities, complement the existing set of foreseen ICRH scenarios. For active plasmas, minority heating of intrinsic ^{9}Be impurities in D-T =50%-50% is a promising ICRH scenario for JET DTE2 and ITER, for which near pure bulk ion heating has been predicted [3]. Synergetic fundamental ICRH heating of T-NBI or D-NBI fast ions in D-T plasmas with the T-(T_{NBI})-D and T-(D_{NBI})-D three-ion scenarios has a potential for maximizing the steady-state Q-value and fusion power in future DTE2 experiments [5].

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