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Impact of ICRH heating of fast D and T ions on fusion performance in JET DTE2 campaign

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Abstract. This work studies the impact of the ICRH heating of the NBI D and T fast ion on the fusion performance in recent JET DTE2 campaign. Minorities were deliberately not injected in order to study the clear impact of RF heating of the main reactants. The study focuses on experiments in which ICRH was tuned to provide either n=2 D or n=2 T central resonances for which fast NBI ions provide a good absorber. The effect of the ICRH power on D and T beam fast ion dynamics has been analyzed with regard to fusion rates by means of TRANSP simulations. Moderate increase, 5-10% in reaction rates has been predicted and attributed to ICRH n=2 heating of D NBI fast ions. Synergistic interaction between fast T NBI ions and RF waves was found to have little or no impact on the fusion performance. Contribution of various heating and fast ion sources have been assessed and discussed.

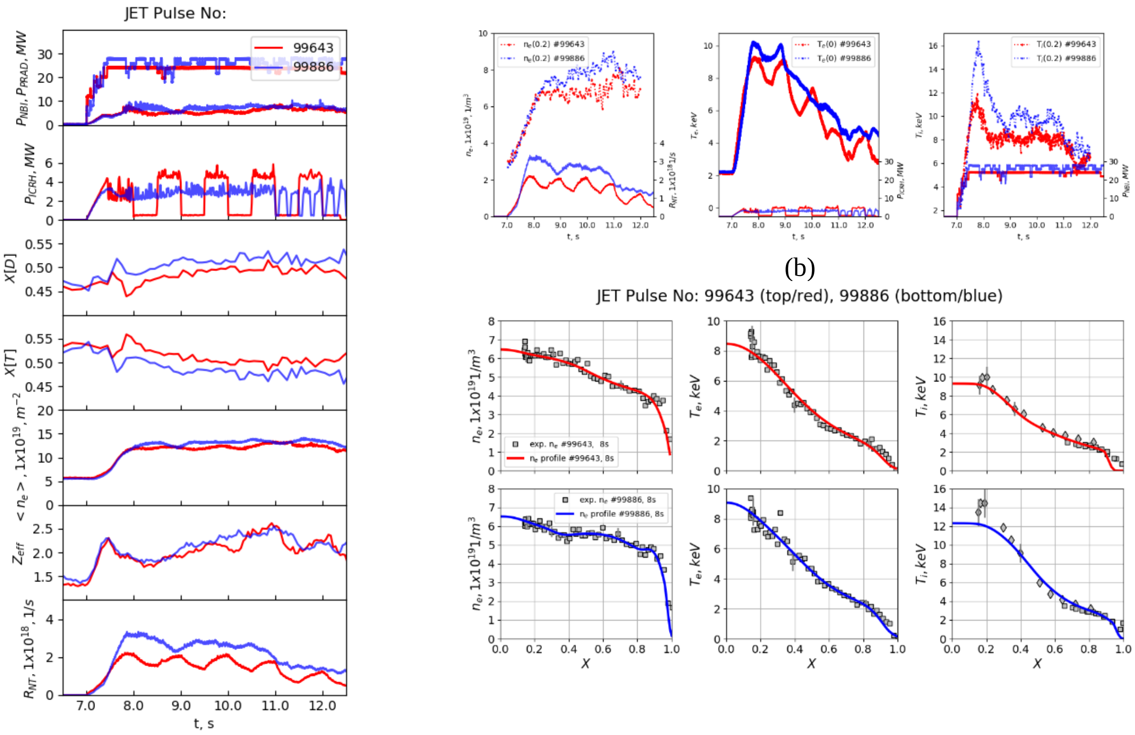
INTRODUCTION

Several Ion Cyclotron Resonance Heating (ICRH) schemes in DT plasma have been considered for the ITER reactor [1]. Most of these heating schemes are minority heating at fundamental frequency. In Deuterium and Tritium (DT) plasma, both reactants can also absorb RF power as majorities at fundamental n=1 [2, 3] or harmonic n=2 frequency [4]. Understanding benefits of directly heating fusion reactants via RF waves is essential in optimizing ITER fusion performance.

This study is on ICRH heating of fast NBI D and T ions and its impact on the fusion performance. Section 1 provides details of the experimental conditions for the selected JET DT pulses. Section 2 focuses on the analysis of calculated and measured neutron rates. Discussions on the impact of the RF wave – fast ions interaction physics insight of the processes involved is presented in the next section. Summary and conclusions are highlighted in the end.

EXPERIMANTAL RESULTS

Two identical JET 3.43T/2.3MA pulses based on hybrid scenario [5] during DTE2 campaign are studied. ICRH was setup as in minority heating scenario, but no minorities were injected during the pulse. This was needed in order to ensure maximum RF power to majority as minority heating scales with their density. The first pulse #99643 was designed to have n=2 D RF heating with ICRH at 51.4MHz, while the second one #99886 with n=2 T RF heating with ICRH at 32.2MHz. No minorities were injected in these two experiments in order to provide maximum available RF power to D and T ions. Plasma parameters and density and temperature profiles are shown in Fig. 1.



(a) (b) (c)

FIGURE 1. Time traces of (top to bottom) NBI, radiation, ICRH power, D, T concentrations, line integrated density, Zeff and neutron yield for JET 3.43T/2.3MA hybrid type pulses #99643 (red) and #99886 (blue) in (a). Time traces from the same two pulses showing (left to right) central density electron and ion temperature evolution (b). Profiles of electron density, electron and ion temperatures of #99643 (red) and #99886 (blue) at the time of maximum fusion performance, 8s.

Evenly balanced DT mixture, D/T~0.5/0.5, was sustained in these experiments, while comparable sources of fast D and T ions were provided by the two Neutral Beam Injector (NBI) sources at JET. NBI power between 25 and 30MW was injected by two NBI sources, one with D and one with T neutrals. The full energy of the injected neutrals was between 83 and 112kV for D neutrals and T.

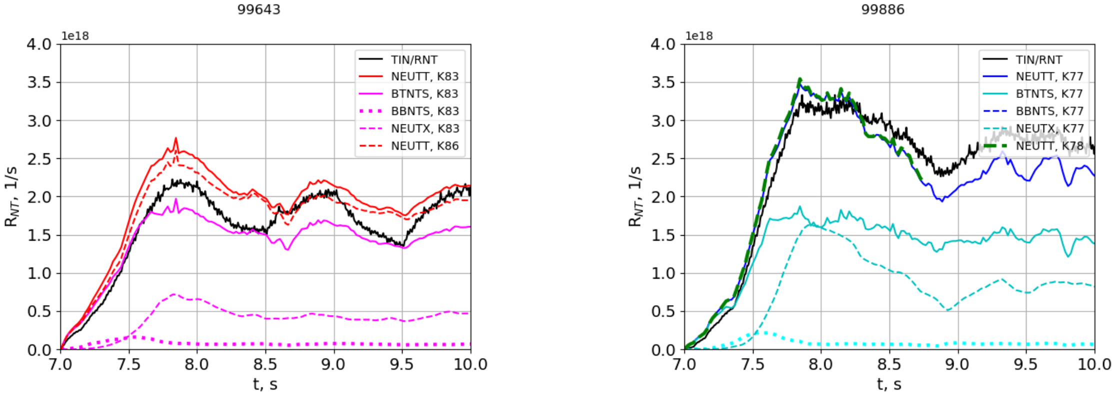
ANALYSIS OF FUSION PERFORMANCE

TRANSP [6] code was used for interpretive analysis to provide fusion performance as well as Beam-Target reaction rates. In addition, fast ions distribution functions are calculated by NUBEAM code [7] which is a computationally comprehensive Monte Carlo code for NBI injection in tokamaks. The ICRH wave solver for TRANSP is the TORIC code [8]. Monte Carlo quasi liner RF kick operator [9] is implemented in NUBEAM and used to calculate the interaction between the RF wave and energetic fast D and T ions.

The workflow of TRANSP interpretative analysis usually includes constraining the output of the code to set of available synthetic diagnostics. Achieving high level of consistency between calculated and measured neutron rates and plasma energy is an indication of good quality analysis. In addition, all set of available diagnostics can be used to constrain the analysis, e.g. data from neutron camera, neutron spectrometers, neutral particle analyzers can all be utilized to gain further confidence in the analysis.

Fusion Rates and Beam-Target Reactions

Measured and calculated neutron rates together with the beam-target reactions and thermal rates are shown in Fig. 2.



(a) (b)

FIGURE 2. Measured (black solid lines) and calculated (red solid line in (a) for #99643 and blue solid line for #99886 in (b)) neutron rates. Beam-target reactions and thermal rates are indicated by cyan (a) and magenta lines (b). Total neutron predictions without synergistic effects are provided by dashed orange (a) and dashed (b) lines.

Relatively good agreement is observed between measured and calculated neutron rates, Fig 2. While measured and calculated neutrons of #99886 are higher than the ones in #99643 a closer look at the contributions to them reveal that this is due to mainly higher thermal rates, dashed lines in Fig. 2 (a) and (b). The latter is due to higher ion temperature in #99886 as it features higher NBI power, Fig. 1 (b) and (c). Beam-target rates of the two pulses are approximately similar, solid magenta and cyan lines in Fig. 2 (a) and (b) despite higher NBI power of #99886.

Assessing the Impact of ICRH Fast NBI Ions Synergy

TRANSP runs with and without RF kick operator were used to assess the sheer synergy effect of RF interaction with fast NBI ions on DT fusion performance. By switching off the RF kick operator only the synergistic effects are discarded while all other contributions related to the background plasma parameters are preserved. Comparing calculated neutron rates with and without synergistic effects is carried out in the case with RF wave - D NBI fast ions interaction for pulse #99643 and RF wave - T NBI fast ions interaction for pulse #99886. Results of the analysis show that in the case of #99643 and RF wave D NBI fast ions interaction the enhancement of the fusion performance is of the order of 5%, Fig 2 (a). In the other case, RF wave T NBI fast ions interaction in #99886, no visible impact on the neutron rates and the fusion performance has been seen, Fig 2 (b). In the following we provide insight into physics of RF wave and fast ion interactions and discuss possible causes of the observed discrepancies.

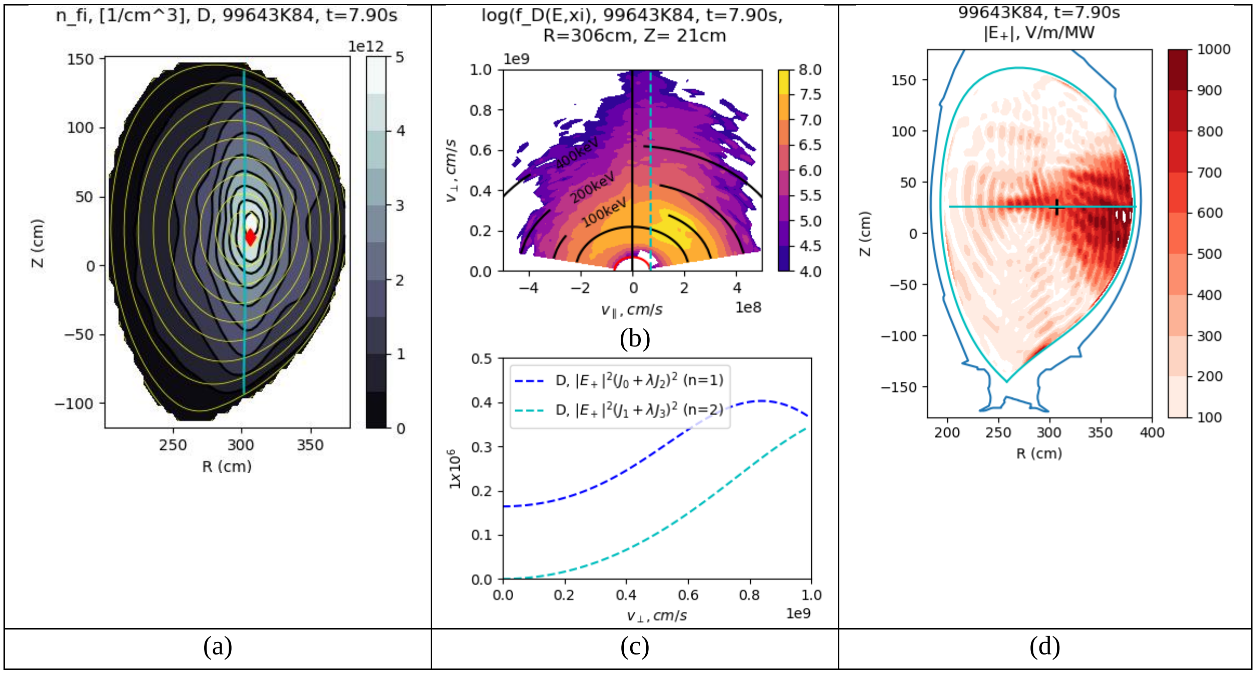
DISCUSSION

The RF wave – NBI fast ions synergistic effects are further analyzed by means of quasi-linear theory [10] in which wave-particle interaction is described via a quasilinear diffusion coefficient, which together with Doppler shifted wave particle resonance condition define the conditions for and strength of interaction between RF wave and resonant ions. There two conditions can be summarized by the following two equations:

$$\omega = n\Omega_{ci} + k_{\parallel} v_{\parallel} \;; \tag{1}$$

$$D_{QL} \propto |E_+|^2 (J_{n-1}(x) + \lambda J_{n+1}(x))^2 \;\; ; \;\; \lambda = |E_-|/|E_+| \;\; ; \;\; x = k_{\perp} v_{\perp}/\Omega_{ci} \;\; ; \; \text{n - harmonic number} \tag{2}$$

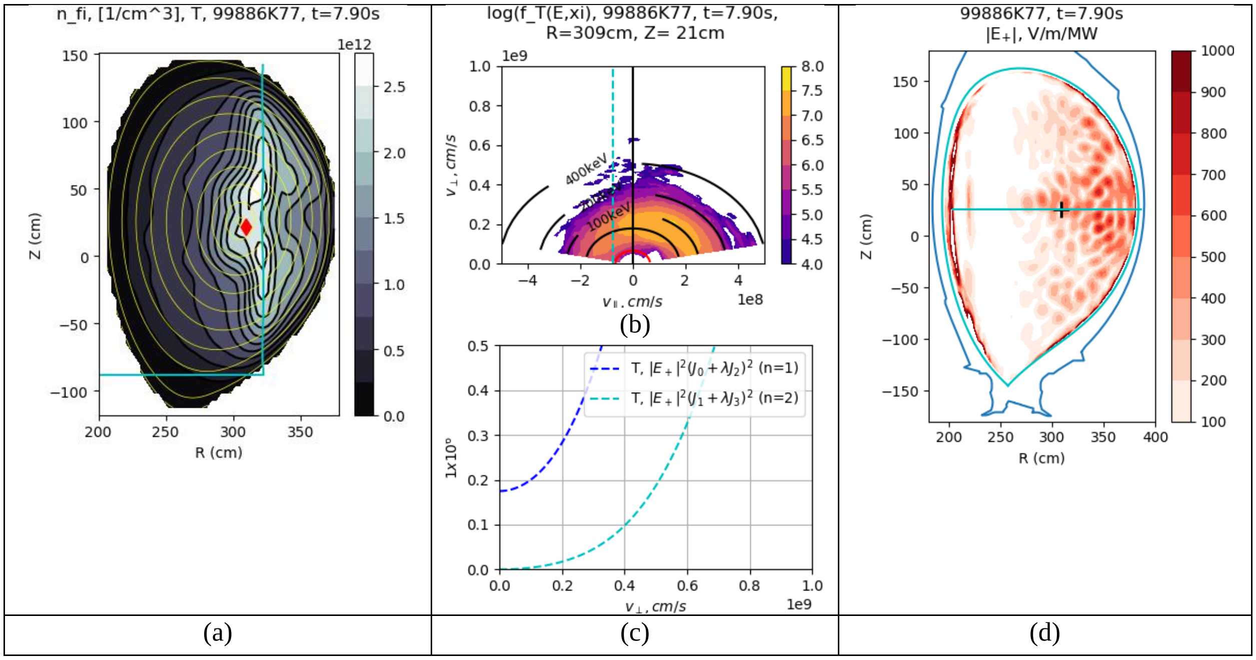
Plasma central region is naturally most interesting regarding fusion performance as there is where plasma pressure is highest. and here details from interaction of the RF wave with fast NBI ions is discussed in the very core region. For the experiments discussed here, NBI features central deposition for both, D and T, although in the latter case T fast ion density is less poloidally symmetric with higher values on the LFS. In both cases maximum of fast ion density in the central region, i.e. for normalized toroidal radius ρ<0.1. The fast ion densities, central fast ion distribution function and strength of E+ electric field from RF waves for two cases discussed here are shown in Figs. 1 and 2.



(a) (c) (d)

FIGURE 3. Fast D NBI ions density for JET 3.43T/2.3MA hybrid type pulses #99643, 7.9s (a) together with IC n=2 D resonance (cyan line). Fast ions distribution function at R=3.06m, Z=0.21m (point noted with red diamond in (a)) together with Doppler shifted IC resonance, eq. (1), (cyan dashed lien) in (b). Quasi-linear diffusion operator for n=1 (dashed blue line) and n=2 (dashed cyan line) at R=3.06m, Z=0.21m calculated from eq, (2) is shown in (c). Amplitude of E_+ filed by TORIC (d)

Fast D NBI density, Fig 3 (a), peaked in the center, while the cold plasma resonance is also in the vicinity of the core region. Central fast D densities are of the order of 5×10^{12} cm^{-3}. Fast ion DF and Doppler shifted resonance, Fig 3 (b), indicate that in the central region, R=3.06m, Z=0.21m, there are sufficiently high number of fast D ions with energy up to 100keV that can interact with the RF wave. Indeed, because of this interaction fast D ions absorb energy from the RF wave and their distribution function is modified significantly for energies above 100keV, Fig 3 (b). As the injected NBI neutrals were with energies <112kV the enhancement of fast ions distribution function for higher energies is purely due to interactions between the RF wave and the fast ions. These changes to DF have direct and indirect impact on the fusion rates. Direct enhancement is a result of increased energy of the fast D ions, maximum of fast D monoenergetic beam to T target with T_i~14keV is for beam energies of about 130keV. Accelerating ions between 11keV2 and 130keV has direct impact on fusion rates. The latter decrease for D energies >130keV so effect is somewhat limited and our TRANSP assessment gives an estimate of about 5-10% higher BT rates due to synergistic effects. The indirect effect of synergistic effects on fusion performance is due to the fact that by further energizing the fast D ions bulk ion heating is enhanced. The latter is clearly observed as from the central T_i modulations with ICRH power in Fig 1(b) assuming bulk D interaction with n=2 RF wave is negligible. The direct influence of the synergistic effects on fusion performance is assessed to give about 5-10% enhancement in fusion performance.



(a)

(b)

(c)

(d)

FIGURE 4. Fast T NBI ions density for JET 3.43T/2.3MA hybrid type pulses #99866, 7.9s (a) together with IC n=2 T resonance (cyan line). Fast ions distribution function at R=3.09m, Z=0.21m (point noted with red diamond in (a)) together with Doppler shifted IC resonance, eq. (1), (cyan dashed line) in (b). Quasi-linear diffusion operator for n=1 (dashed blue line) and n=2 (dashed cyan line) is at R=3.09m, Z=0.21m calculated from eq. (2) is shown in (c). Amplitude of E_+ filed by TORIC is shown in (d).

Fast T NBI density, Fig 4 (a), peaked near the axis and in general is more poloidally asymmetric than fast D density. Central fast T densities are twice lower that D reference case, of the order of 2.5×10^{12} cm^{-3}. The cold plasma resonance is furtherer from the core region on the LFS. Doppler shifted resonance is however withing the range of fast T ion energies as fast ion DF, Fig 4 (b), indicates, i.e. in the central region, R=3.09m, Z=0.21m, there are sufficiently high number of fast T ions with energy up to 100keV that can interact with the RF wave. The shape of the modified distribution function, however, shows that RF wave – fast T ion interaction was not as great as with fast D case. Modifications in the high energy tail of fast T DF are small, therefore the excited impact on the fusion performance is negligible. The latter is confirmed by comparing TRANSP runs with and without synergistic effects.

In order to understand the reason for observing different effects with regard to D and T ions further insight into fundamentals of RF wave interactions with fast particles is provided. Figures 3 (c) and 4 (c), show quasilinear diffusion coefficients for n=1 (blue lines) and n=2 (cyan lines) for D and T in the central regions of the plasma. Figures 4 (c) and 4 (c), show E_+ field for the two cases. It has been assessed that the strength of the E_+ field in the center for the two cases is approximately the same. For typical fast D NBI fast ions of energy of 100keV near resonance, dashed cyan line if Fig 3 (b), we have assessed that $v_\perp \approx 0.31\times10^9$ cm/s, $v_\parallel \approx 0$. For this value of $v_\perp$ quasilinear diffusion operator is assessed to be of the order of 4×10^4 (V/m)^2 For fast T NBI ions these numbers read $v_\perp \approx 0.25\times10^9$ cm/s, $v_\parallel \approx 0$ for T ion at 100keV for which the quasilinear diffusion operator is assessed to be of the order of 2.8×10^4 (V/m)^2. So despite having similar E_+ electric field, about 405V/m for D, 418V/m for T, in the two cases, D NBI fast ions are absorbing more RF power due to their higher $v_\perp$ velocity. In addition, the factor $k_\perp/\Omega_{ci}$ in the Belles functions argument, $x= v_\perp k_\perp/\Omega_{ci}$ is also slightly higher for fast D NBI ions meaning that larger values of D_{QL} can be reached for lower value of $v_\perp$.

CONCLUSIONS

TRANSP simulations were used to study the impact of the synergistic effects between fast D and T NBI and RF waves on DT fusion performance. Conditions with ~0.5% minority concentration were selected to maximize the amount of RF power available for n=2 resonance interaction with D and T ions.

It was assessed that synergistic interaction between fast D NBI ions and RF waves lead to modest improvement of the fusion performance, approximately 5-10% higher. On the other side, synergistic interaction between fast T NBI ions and RF waves was found to have little or no impact on the fusion performance as no increase in fusion rates has been observed. Possible causes of lower impact of the synergistic effect in T NBI case are discussed and the following effects were highlighted. It has been observed that D NBI fast ion densities are more central and higher than T NBI fast ions. Lower densities of fast T NBI ions leads directly to lower intensity of wave particle interactions. In addition, it has been observed that $k_\perp/\Omega_{ci}$ factor for T NBI case is lower leading to the need to access particles at higher $v_\perp$ able to interact with the RF wave as shown in Fig. 4 (c) and the expression for D_{QL}, equation (1). For the injected T NBI energies the necessary $v_\perp$ is too high, Fig. 4 (b). At the same time lower values of $k_\perp/\Omega_{ci}$ factor for fast D NBI case indicate that for $v_\perp$ for D injected energies provides reasonably high D_{QL} for particle – wave interactions to take part. Another factor that contributes to the observed dependencies is that the velocity $v_\perp$ of T NBI ions are smaller for the same injected energies than the velocity $v_\perp$ of D NBI ions for the same energy. As a result of this study, we conclude that the scenario with T NBI ions can be further optimized with respect to achieving higher fusion performance.

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