RESEARCH ARTICLE | AUGUST 18 2023

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AIP Conf. Proc. 2984, 040001 (2023)
https://doi.org/10.1063/5.0162598

Impact of ICRH Heating of Fast D and T Ions on Fusion Performance in JET DTE2 Campaign

K. Kirov[1, a)], C. Challis[1, b)], E. De la Luna[2, c)], D. Gallart[3, d)], J. Garcia[4, e)], M. Gorelenkova[5, f)], J. Hobirk[6, g)], P. Jacquet[1, h)], A. Kappatou[6, i)], Y. Kazakov[7, j)], D. Keeling[1, k)], D. King[1, l)], E. Lerche[1,7, m)], C. Maggi[1, n)], J. Mailloux[1, o)], MI. Mantica[8, p)], M. Mantsinen[3,9, q)], M. Maslov[1, r)], S. Menmuir[1, s)], Z. Stancar[1, t)], D. Van Eester[7, u)] and JET Contributors

[1] CCFE, Culham Science Centre, Abingdon OX14 3DB, United Kingdom
[2] Laboratorio Nacional de Fusión, CIEMAT, 28040 Madrid, Spain
[3] Barcelona Supercomputing Center, Barcelona, Spain
[4] CEA, IRFM, F-13108 St-Paul-Lez-Durance, France
[5] PPPL, Princeton University, P.O. Box 451, Princeton NJ 08543-0451, USA
[6] Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching, Germany
[7] Laboratory for Plasma Physics, ERM/KMS, B-1000 Brussels, Belgium
[8] Institute of Plasma Science and Technology, CNR, 20125 Milano, Italy
[9] ICREA, Barcelona, Spain

[a)] Corresponding author: Krassimir.Kirov@ukaea.uk

[b)] Clive.Challis@ukaea.uk ; [c)] Elena.De.La.Luna@jet.euro-fusion.org ; [d)] daniel.gallart@bsc.es ;
[e)] Jeronimo.GARCIA@cea.fr ; [f)] mgorelen@pppl.gov ; [g)] joerg.hobirk@ipp.mpg.de ;
[h)] Philippe.Jacquet@ukaea.uk ; [i)] Athina.Kappatou@ipp.mpg.de ; [j)] kazakov@chalmers.se ;
[k)] David.Keeling@ukaea.uk ; [l)] Damian.King@ukaea.uk ; [m)] ealerche@msn.com ; [n)] Costanza.Maggi@ukaea.uk ;
[o)] Joelle.Mailloux@ukaea.uk ; [p)] paola.mantica@istp.cnr.it ; [q)] mervi.mantsinen@bsc.es ;
[r)] Mikhail.Maslov@ukaea.uk ; [s)] Sheena.Menmuir@ukaea.uk ; [t)] Ziga.Stancar@ukaea.uk ;
[u)] d.van.eester@fz-juelich.de

Abstract. This work studies the impact of the Ion Cyclotron Resonance Heating (ICRH) of the fast Neutral Beam Injected (NBI) D and T ions on the fusion performance in recent JET DTE2 campaign. The effect of the Radio Frequency (RF) wave on fast NBI D and T ion dynamics was analyzed by means of TRANSP simulations. Moderate increase, 5-10%, in DT reaction rates was predicted by TRANSP for the case of ICRH heating of fast NBI D ions at n=2 harmonic of ion cyclotron resonance. The simulations have shown that synergistic interaction between fast NBI T ions and RF waves have little or no impact on the fusion performance in the experimental conditions discussed here. Contribution of various heating and fast ion sources have been assessed and discussed. The absence of strong interaction between fast NBI T ions and RF waves was attributed to the poorer penetration of the T beams leading to lower fast T ion densities in the core and the lower perpendicular velocity of the fast NBI T ions resulting in diminished intensity of fast particle – RF wave interaction.

INTRODUCTION

Several Ion Cyclotron Resonance Heating (ICRH) schemes in Deuterium-Tritium (DT) plasma are proposed for the ITER reactor [1]. Well established H minority heating scenario at fundamental frequency in D plasmas is not

24th Topical Conference on Radio-frequency Power in Plasmas
AIP Conf. Proc. 2984, 040001-1–040001-6; https://doi.org/10.1063/5.0162598
Published by AIP Publishing. 978-0-7354-4604-5/$30.00

considered for reactor scale devices due to the anticipated parasitic interaction of Radio Frequency (RF) waves with energetic alphas. The other scheme which involves minorities in DT plasma is by means of ICRH heating of He3 at fundamental frequency and it has been considered as one the main scenarios for the active phase of ITER operation. In conditions of DT plasmas both reactants, D and T ions, can also absorb RF power as majorities at fundamental n=1 [2, 3] or harmonic n=2 frequency [4]. Understanding the benefits of directly heating fusion reactants via RF waves is essential in optimizing ITER fusion performance [1]. This paper discusses the synergy between RF waves at frequency close to n=2 D and T resonances and energetic D and T ions.

Data from the recent JET DT experimental campaign (DTE2) were analyzed. The source of fast D and T populations in these studies was via Neutral Beam Injection (NBI) which together with ICRH were the main heating sources in the experiment discussed here. In NBI heated plasma there are in general two contributions to the fusion rates: thermal and Beam-Target (BT) reactions, which in typical JET conditions, i.e. ion temperature T_i≈10-15keV and NBI power P_{NBI}≈25-30MW, are of similar magnitude. There are also Beam-Beam (BB) reactions, but they are at least two orders of magnitude lower than BT rates and therefore their contribution is usually ignored. The thermal DT reactivity peaks up for ion temperatures of DT mixture at about T_i≈65keV, while BT reactions have different maxima for fast D/T collisions on thermal T/D ions. In conditions of JET DT plasma, the latter are for energies of E_D≈130keV and E_T≈190keV. For comparison, the JET NBI system can inject D and T ions with maximum energy of the order of 100keV. At these energy levels BT reactions are not fully optimized for fusion performance and further energizing of fast NBI D and T ions would have a beneficial impact on BT rates.

The study presented here focuses mainly on n=2 ICRH heating of fast NBI D and T ions and its impact on the fusion performance. Section 1 provides details of the experimental conditions and provides details about plasma parameters in 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.

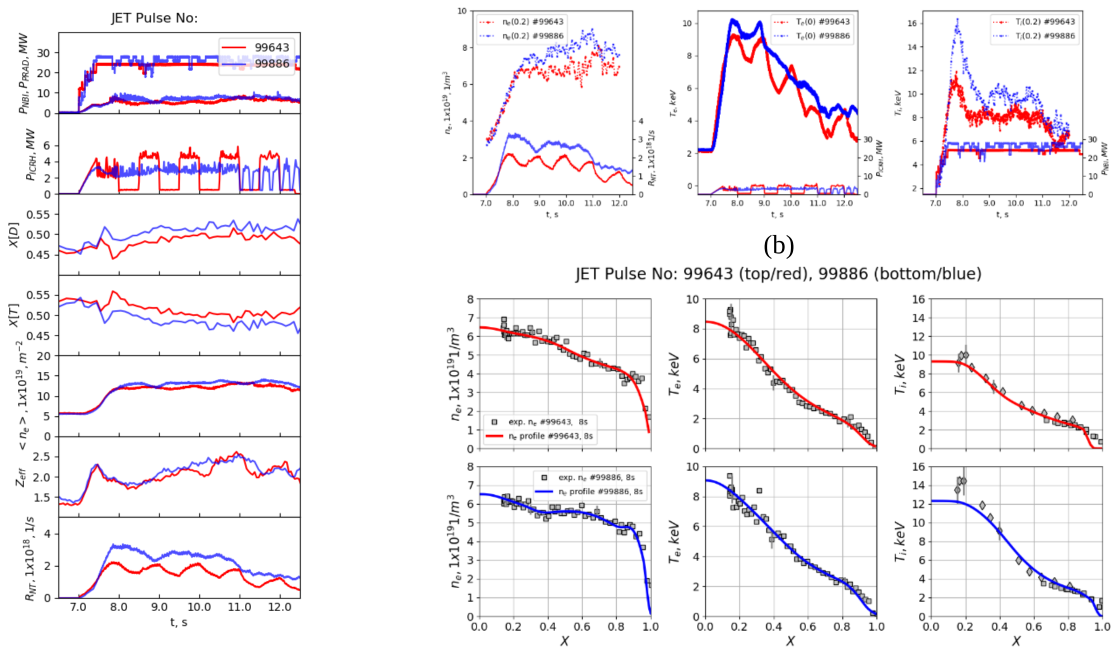
EXPERIMANTAL RESULTS

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

The two pulses shown in Fig. 1 were at similar electron density, line averaged values of about 5×10^{13} cm^{-3}, central electron temperature of about 10keV and ion temperature of about 10-15keV, Fig. 1 (a) and (b). Both pulses were analyzed during high performance phase of heating window during initial 1s, between 7s and 8s. Slightly higher ion temperature in #99886 is attributed to higher NBI ion heating during initial phase of this pulse. 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 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 injected NBI neutrals are at three energy levels, full/half/third energy component with typical values of the power fractions in them ~0.5/0.3/0.2 for 100kV of D beam and ~0.6/0.2/0.2 for 100kV of T beam. The full energy of the injected D and T neutrals in reported experiments was between 83 and 112kV.

ANALYSIS OF FUSION PERFORMANCE

TRANSP [6] code was used for interpretive analysis of the pulses discussed above and to provide fusion performance as well as Beam-Target reaction rates. In addition, fast ions distribution functions (DF) were 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.



(a) (c)

FIGURE 1. Time traces of (top to bottom) NBI and radiation power, ICRH power, D concentrations, T concentrations, line integrated density, Z_{eff} 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 8s.

Fusion Rates and Beam-Target Reactions

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 of the analysis. In this study the full set of available diagnostics was used to constrain the analysis and this includes data from neutron camera, neutron spectrometers, neutral particle analyzers.

Measured and calculated neutron rates together with the beam-target reactions and thermal rates are shown in Fig. 2. Relatively good agreement was observed between measured and calculated neutron rates with TRANSP overpredicting total neutrons by about 17% in #99643 and less that 5% in #99886. TRANSP results for plasma energy were found fully consistent, within 1%, with the diamagnetic measurements.

While measured and calculated neutrons of #99886 were 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. Calculated neutron rates with and without synergistic effects were compared for the case with RF wave - fast NBI D ions interaction, pulse #99643, and RF wave - fast NBI T ions interaction, pulse #99886. The analysis showed that in the case of #99643 and RF wave - fast NBI D ions interaction the enhancement of the fusion performance was of the order of 5% to 10%, Fig 2 (a). In the other case, RF wave - fast NBI T ions interaction in #99886, no visible impact on the neutron rates and the fusion performance was 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 effects.

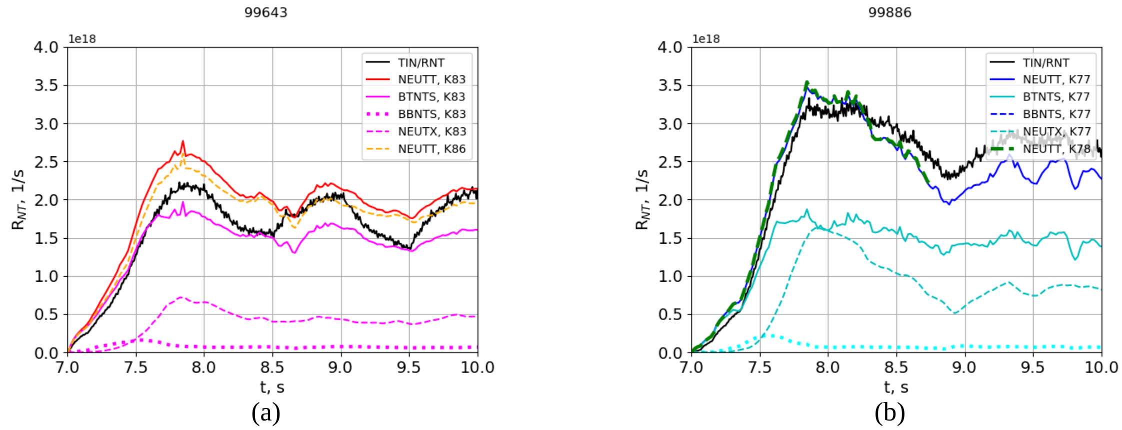


FIGURE 2. Measured (black solid lines) and calculated (red solid line in (a) for #99643 and blue solid line for #99886 in (b)) neutron rates. Beam-target reactions and thermal rates are indicated by cyan (a) and magenta lines (b). Total neutron predictions without synergistic effects are provided by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

DISCUSSION

The observation reported here are based on TRANSP/TORIC simulations in which fast particles – RF wave interactions are accounted for. The RF wave – fast NBI ions synergistic effects were 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 and the strength of interaction between RF wave and resonant ions. These two conditions can be summarized by the following two equations:

$$\omega = n\Omega_{ci} + k_{\parallel} v_{\parallel} \quad (1)$$

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

Plasma central region, where plasma pressure is highest, is naturally most interesting regarding fusion performance therefore the analysis presented here is focused on the very core region. In the experiments discussed here, NBI featured central deposition for both, D and T. In both cases the maxima of fast ion densities were in the central region, i.e. for normalized toroidal radius ρ<0.1. While the fast D ion density was poloidally symmetric, peaked in the plasma core, the fast T ion density on the other side was poloidally asymmetric with higher values on the outboard indicating poorer penetration of T beams. The fast ion densities, central fast ion DF and strength of E_+ electric field from RF waves for two cases discussed here are shown in Figs. 3 and 4.

Fast NBI D density, Fig 3 (a), was peaked in the center, while the cold plasma resonance is also in the vicinity of the core region. Central fast D densities were 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=306cm, Z=21cm) there are sufficiently great number of fast D ions with energy of the order of 100keV that can interact with the RF wave. Indeed, because of this interaction fast D ions absorb energy from the RF wave and their DF is modified significantly for energies above 100keV, Fig 3 (b). As the injected NBI neutrals were with energies lower than 112kV the enhancement of fast ions DF for higher energies was 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 was a result of increased energy of the fast D ions as accelerating D ions further for energies between 112keV and 130keV has direct impact on fusion rates. The latter decrease for D energies greater than 130keV so effect is somewhat limited and our TRANSP assessment gives an estimate of about 5-10% higher fusion rates due to synergistic effects. The indirect effect of synergistic effects on fusion performance is due to the fact that further energizing the fast D ions leads to enhanced bulk ion heating. The latter is clearly observed from the central T_i modulations with ICRH power in Fig 1(b) assuming bulk D interaction with n=2 RF wave is negligible.

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}. It was assessed that NBI T penetration is poor. The cold plasma resonance is furtherer from the core region on the LFS. Doppler shifted resonance is however within the range of fast T ion energies as fast ion DF, Fig 4 (b), indicates, i.e. in the central region (R=309cm, Z=21cm) there are sufficiently high number of fast T ions with energy of about 100keV that can interact with the RF wave. The shape of the modified DF, 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 expected impact on the fusion performance is negligible.

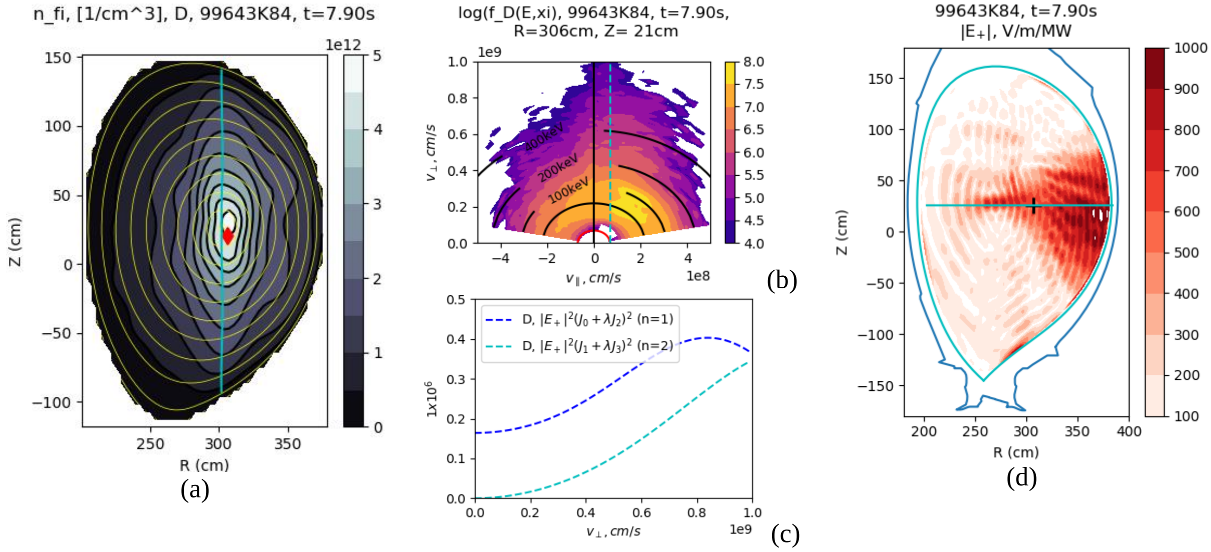


FIGURE 3. Fast NBI D ions density for JET 3.43T/2.3MA hybrid type pulse #99643, 7.9s with D/T mixture of ≈0.5/0.5 (a) together with IC n=2 D resonance (cyan line). Fast ions DF at R=306cm, Z=21cm (point noted with red diamond in (a)) together with Doppler shifted IC resonance, eq. (1), (cyan dashed lien) in (b). Quasi-linear diffusion operator for n=1 (dashed blue line) and n=2 (dashed cyan line) at R=306cm, Z=21cm calculated from eq. (2) is shown in (c). Amplitude of E_+ filed by TORIC in conditions with negligible minority H concentration is shown in (d).

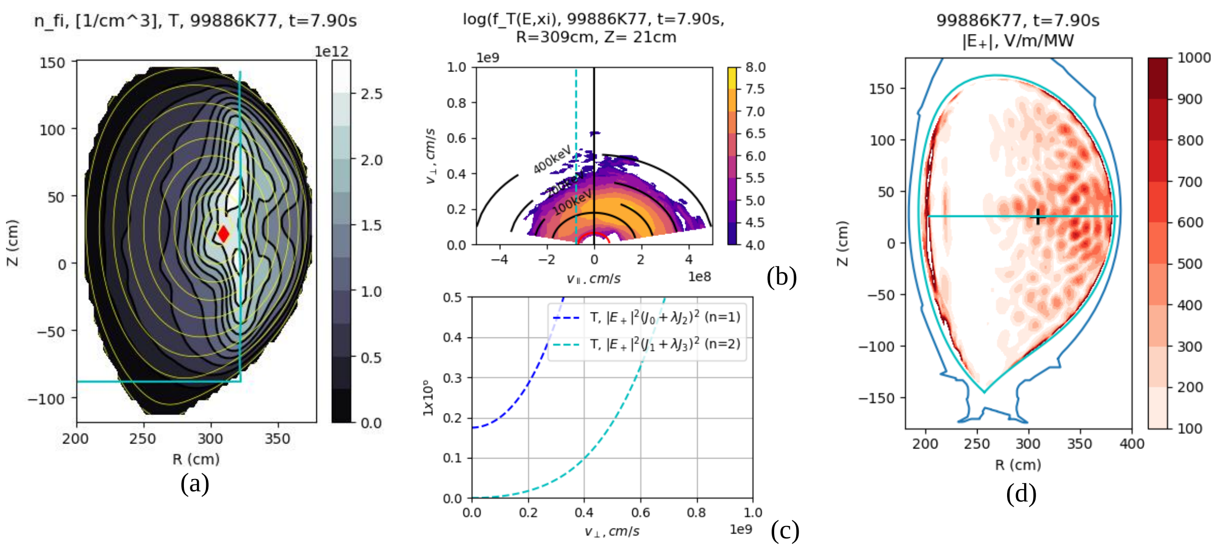


FIGURE 4. Fast NBI T ions density for JET 3.43T/2.3MA hybrid type pulses #99866, 7.9s with D/T mixture of ≈0.5/0.5 (a) together with IC n=2 T resonance (cyan line). Fast ions DF at R=309cm, Z=21cm (point noted with red diamond in (a)) together with Doppler shifted IC resonance, eq. (1), (cyan dashed line) in (b). Quasi-linear diffusion operator for n=1 (dashed blue line) and n=2 (dashed cyan line) is at R=309cm, Z=21cm calculated from eq. (2) is shown in (c). Amplitude of E_+ filed by TORIC in conditions with negligible minority He3 concentration is shown in (d).

In order to understand the reason for observed 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 was assessed that the strength of the E_+ field in the center for the two cases is approximately the same. For typical fast NBI D 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, $v_\parallel \ll v_\perp$. 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 NBI T ions these numbers read $v_\perp \approx 0.25\times10^9$ cm/s, $v_\parallel \ll v_\perp$ 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 and 418V/m for T, in the two cases, fast NBI D ions are absorbing more RF power due to their higher $v_\perp$ velocity. In addition, the factor $k_\perp/\Omega_{ci}$ in the Bessel functions argument, $x = v_\perp k_\perp/\Omega_{ci}$ is also slightly higher for fast NBI D ions meaning that larger values of D_{QL} can be reached for lower values of $v_\perp$.

CONCLUSION

TRANSP simulations were used to study the impact of the synergistic effects between fast NBI D and T ions and RF waves on DT fusion performance. Conditions with negligibly small 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 NBI D ions and RF waves lead to modest improvement of the fusion performance, approximately 5-10% higher. On the other side, synergistic interaction between fast NBI T 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 in TRANSP predictions. 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 fast NBI D ion densities are more central and higher than fast NBI T ions. Lower densities of fast T NBI ions leads directly to lower intensity of wave particle interactions. Possible impact of the non-central resonance in T NBI case has been studied by means of using slightly different RF frequencies, but this was found not having an impact on RF wave absorption and fusion performance. 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 $v_\perp$ to be 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 NBI D case indicate that $v_\perp$ in the range of injected D particles provide 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.

ACKNOWLEDGMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

See the author list of J. Mailloux et al., Nuclear Fusion 62, 042026 (2022) for the list of JET Contributors

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