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# Synergistic ICRH and NBI Heating for Fast Ion Generation and Maximising Fusion Rate in Mixed Plasmas at JET

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**Abstract:** The studies of recent JET experiments in H/D≈0.85/0.15 plasma (2.9T/2MA) in which neutron rate was enhanced by applying 2.5MW of ICRH using D-($D_{NBI}$)-H three-ion scheme are reported. An extensive analysis of this novel heating scenario has been carried out by means of integrated TRANSP/TORIC modelling, and a comprehensive validation of the computed Fast Ion Distribution Function (FI DF) with a range of fast ion diagnostics available at JET is presented. The predicted acceleration of D Neutral Beam Injection (NBI) ions beyond their injection energies and the associated changes in FI DF by RF waves are found to be in good agreement with measured neutron yield and TOFOR neutron spectrometer measurements, as well as with multi-channel neutron camera observations and neutral particle analyser diagnostic. An outlook of the possible applications of the developed technique for future DTE2 studies on JET has been highlighted. Controlled acceleration of $T_{NBI}$ ions in D-rich and $D_{NBI}$ ions in T-rich plasmas to optimal energies can be applied to maximise BT fusion rates and contribute to the success of future DT experiments at JET and ITER as illustrated in this study.

## INTRODUCTION

Achieving maximum Deuterium-Tritium (DT) fusion reaction rate is an essential milestone in today fusion research. It has been highlighted as one of the main deliverables in recent JET scenario development experiments [1] as it has direct consequences in demonstrating 15MW/5s fusion power milestone in the forthcoming DT campaign. ITER will rely on self-heating by 3.5MeV α particles from DT fusion reactions and the studies on energetic ions is a key subject in understanding their behaviour in burning plasma [2]. In Neutral Beam Injection (NBI) heated plasma there are in general two contributions to the fusion rates: thermal and Beam-Target (BT) reaction rates, which in typical JET conditions, i.e. ion temperature $T_i$≈10-15keV and NBI power $P_{NBI}$≈25-35MW, are of similar order of magnitude. There are also Beam-Beam reactions, but they are at least two orders of magnitude lower than BT rates [3] and therefore their contribution is usually ignored.

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In this study the BT reaction rates, $R_{BT}=n_{Target}\int_0^{\infty}\langle\sigma.v\rangle_{BT\_MEB}\,F_{fi}dE$, which depend strongly on the Fast Ion Distribution Function (FI DF), $F_{fi}$, and monoenergetic beam target reactivity, $\langle\sigma.v\rangle_{BT\_MEB}$, are analysed. FI DF is in general non Maxwellian and anisotropic, while the BT reactivity [4] is a function of target ion temperature, $T_i$, and beam energy, E.

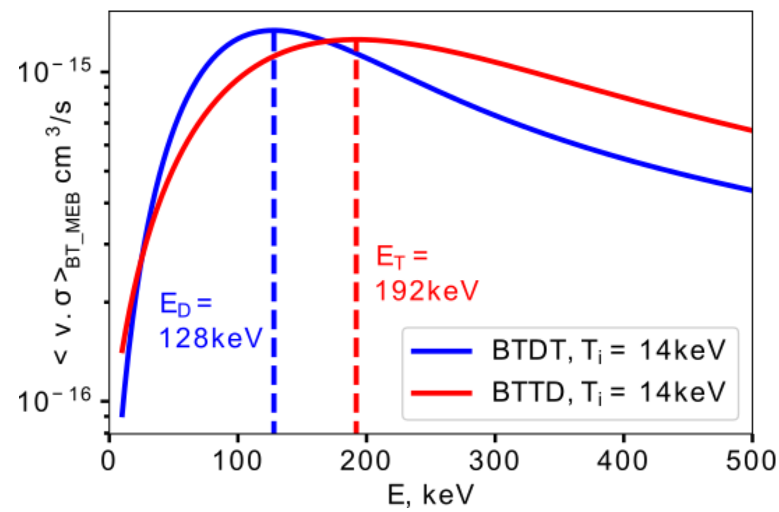



**FIGURE 1:** BT mono energetic beam reactivities $\langle\sigma.v\rangle_{BT\_MEB}$ for DT reaction of a monoenergetic beam with energy E on target ions with temperature of 14keV. D beam on T target ions (blue) is noted by BTDT, while T beam on D target ions (red) is noted BTTD. The maximum of the two reactivities is noted by vertical dashed lines.

The maximum of DT reaction cross-section, σ, in the centre of mass frame is at about 65keV, while the BT reactivity, Fig. 1, $\langle\sigma.v\rangle_{BT\_MEB}$ is different for D beams in T plasma (BT reactivity is also referred to as BTDT) and T beams in D plasma (noted as BTTD) due to difference in D and T masses. The corresponding maxima are for energies of $E_D$=128keV and $E_T$=192keV, which correspond to particle velocities of 3.5e8cm/s. For comparison, the JET NBI system can inject D and T ions with maximum energy $E_b$ of the order of $E_{bD}\approx E_{bT}\approx$120keV. At these energy levels FI DF relaxes within few slowing-down times to a slowly varying with E plateau-shaped form for $T_i\leq E<E_b$ and sharply decreasing for $E>E_b$, i.e. the so-called tail in FI DF. The slope of the FI DF tail is determined by collisions with background plasma.

The BT rates can be enhanced by modifying FI DF in the energy range $E>E_b$. For instance, in the case when T beams are injected into D plasma $\langle\sigma.v\rangle_{BT\_MEB}$ maximum is at $E_T$=192keV and $\langle\sigma.v\rangle_{BT\_MEB}$ decreases slowly with energy for 192keV<E<300keV, Fig. 1. Any enhancement in FI DF in the region $E_{bT}$(≈120keV)<E<192keV will result in an increase in BT reactivity. Various factors can affect FI DF as for instance electron density, $n_e$, and temperature, $T_e$. Radio Frequency (RF) heating of fast NBI ions can change significantly the tail of FI DF [3].

In this study the emphasis is on RF heating scenario, in which NBI fast ions are heated at the fundamental (n=1) resonance by RF waves. The three ion heating scenario [5], [6] in which NBI ions play the role of the third specie is mainly studied here. Its greatest advantage against broadly used minority heating scenario is that it relies on using n=1 resonance and benefits from having the Mode Conversion (MC) layer near the fundamental resonance of the third specie so that the later can benefit from relatively large right-hand circular polarised electric field co-rotating with ions cyclotron gyration. It is assumed that two hydrogenic species (HD or DT plasma) comprise the plasma with small amount of impurity normally present in the plasma from the surrounding wall. The Ion-Ion Hybrid (IIH) and Cut-Off (CO) layer, which in hot plasma become MC layer, is between the resonances of the hydrogenic species. The presence of impurity specie, as for instance Be or Ni in JET, introduces additional IIH/CO layers. The absorbed RF power by NBI ions is subject to wave-particle resonance condition and is proportional to the right-handed component of the RF electric field, $E_+$. The resonating ions will receive an increase in perpendicular energy proportional to the amplitude of $E_+$. The latter is maximised near MC layer and species with high enough concentration satisfying the resonance condition at that location can interact with RF wave field. Further details on this subject can be found in the fundamentals of RF heating in fusion plasma and Ion Cyclotron Resonance Heating (ICRH) physics notebooks [7].

In three ion scenario with NBI ions as third specie the synergistic effects in the interaction between RF wave and fast NBI ions are essential in FI DF evolution. The study reported here covers three important aspects: (i) numerical calculations of FI DF and experimental validation with available synthetic diagnostics; (ii) predictive modelling and extrapolation to DT and (iii) analysing neutron reaction rates and optimising regarding best thermonuclear and/or BT performance.

## EXPERIMENTAL SETUP

JET pulse #91256, Fig. 2, was carried out in HD mixture to study the three ions scheme [5] with H/D≈0.9/0.1, 2MA/2.9T, $n_{e0}$≈4×10$^{19}$ m$^{-3}$ and central electron temperature of $T_{e0}$≈3-4keV. About 3.5MW of D NBI power is applied to the plasma at 7.5s, resulting in central electron temperature $T_{e0}$ rising to 2.0–2.2keV and plasma stored

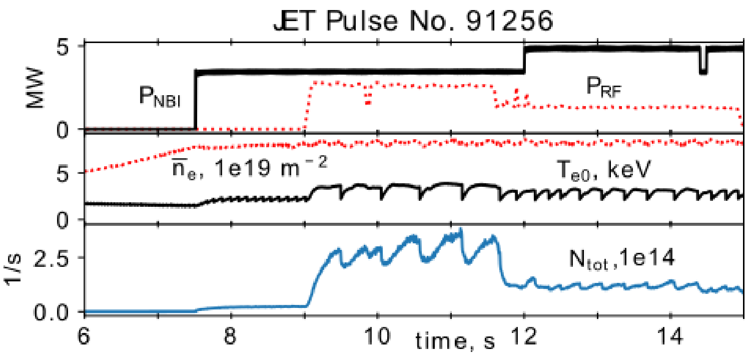



**FIGURE 2**: Time traces of JET pulses #91256 in a) and #92398 in b). From top to bottom shown in the two graphs are the time traces of plasma current and magnetic field, $I_p/B_0$, NBI and ICRH heating power, $P_{NBI}/P_{ICRH}$, line integrated central electron density, $n_e$, central electron temperature, $T_e$, plasma energy, $W_p$, and total neutron count, $N_{tot}$.

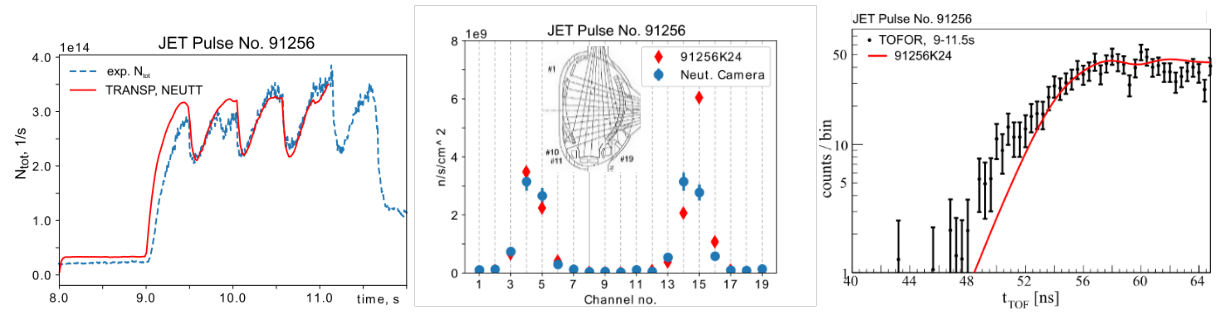
energy of 1.05 MJ. Latter in the heating phase at 9.0s, 2.5MW of ICRF power (dipole phasing at f=25MHz) is coupled to the plasma leading to further increase in $T_{e0}$≈4keV while the plasma stored energy reaches 1.45MJ, meaning that the increase in plasma stored energy per MW of injected NBI or ICRF power is similar. The stabilization of the sawtooth oscillations, Fig. 2 $T_{e0}$ time traces from 9s to about 11.5s, is a clear indication for the presence of fast particles due to synergetic NBI/RF interactions backed up by the large increase in the neutron yield (bottom graph in Fig. 2). In the second phase of the discharge, 12s to 15s, the coupled ICRH power was reduced to 1.3MW and the NBI power was increased to 4.9MW, in order to keep the total heating power approximately constant. The fact that this led to a shorter sawtooth period and to a reduced total neutron counts indicates the important role of ICRH waves in accelerating D particles to high energies. The pulse was modelled with TRANSP code [8] in the time interval 8-11s. FI DF are produced by means of NUBEAM code [9] coupled to the RF wave solver TORIC [10] via the RF kick operator [11]. TRANSP calculations predict that about 94% of the total absorbed RF power of 2.5MW is absorbed by fast NBI D ions. The resulting FI DF were checked against synthetic diagnostics: neutron spectrometer, neutron camera and NPA.

Data from JET neutron time-of-flight spectrometer (TOFOR) were exclusively used in the neutron spectra analysis. The TOFOR diagnostic is described in detail in [12], [13]. It has a vertical line of sight through the plasma core and perpendicular to the magnetic field covering the region between 2.74m<$R_{maj}$<3.02m. TOFOR consists of two sets of plastic scintillator detectors. First is placed in the collimated flux of neutrons from the plasma and the second is placed 1.2m away. A fraction of the incoming neutrons scatter in the first detector and then some of them are detected by the second one. The time of each scattering event is recorded and from the two arrays of scattering times a time-of-flight (TOF) spectrum is constructed. The energy of incoming neutrons is determined by $t_{TOF}$ related to the measured distance between the two detectors. DD neutrons, which typically have energies of about 2.5MeV, give rise to flight times around 65ns. The full response function of TOFOR has been calculated with Monte Carlo methods [14]. For the cases simulated and discussed here TOFOR time-resolution is a limiting factor; in order to obtain data with reasonable confidence one has to integrate over 0.5 s around the time of interest. Significant enhancement of BT neutron spectra by the RF power is expected for lower, $E_n$<2MeV, and higher neutron energies, $E_n$>2.8MeV. Monoenergetic beams with energies of 100keV and 500keV are expected to create double-humped shaped neutron spectra with high-energy peaks at $E_n$=2.8MeV and $E_n$=3.5MeV respectively. These estimates of $E_n$ correspond to $t_{TOF}$=61ns and $t_{TOF}$=55ns [13]. This constitutes the basis of detection of fast ions created by RF by means of the TOFOR diagnostic.

The Neutral Particle Analyser (NPA) [15] at JET is of the conventional $E_{\|}B$ type with eight energy channels having common mass selection. It is capable of time resolved measurements of H, D, T, He3 and He4 atomic flux emitted by the plasma, in the energy range 0.3MeV<E<3.5MeV. The NPA is located at the top of the torus at Oct. 4 its vertical line of sight at major radius of R=3.07m and viewing area of 5×5cm$^2$ on the torus midplane. The collecting solid angle is 1.2x10$^6$sr. The NPA beam line geometry determined that only atoms with $v_z/v$>2×10$^2$ entered the NPA, where $v_z$ is velocity towards the NPA and v is that perpendicular to it.

## VALIDATION OF THE NUMERICAL RESULTS BY SYNTHETIC DIAGNOSTICS

The main conclusions in this study are based on analysis of FI DF and BT fusion reaction rates therefore a considerable attention is paid to the validation of TRANSP/TORIC calculations versus available synthetic diagnostics. Figure 3 (a) shows the time traces of total neutron count, $N_{tot}$, for pulse #91256. Reasonably good agreement in measured and simulated neutron counts have been observed: the averaged in time interval 9.5-10.5s measured total neutron count was $2.69\times10^{14}$ $s^{-1}$ while the calculated was $2.79\times10^{14}$ $s^{-1}$ i.e. about 3% higher. TRANSP calculations indicate that pulse #91256 has a significant number of BT neutrons, about 80%, while thermal neutrons account for about 19% of all the neutrons.

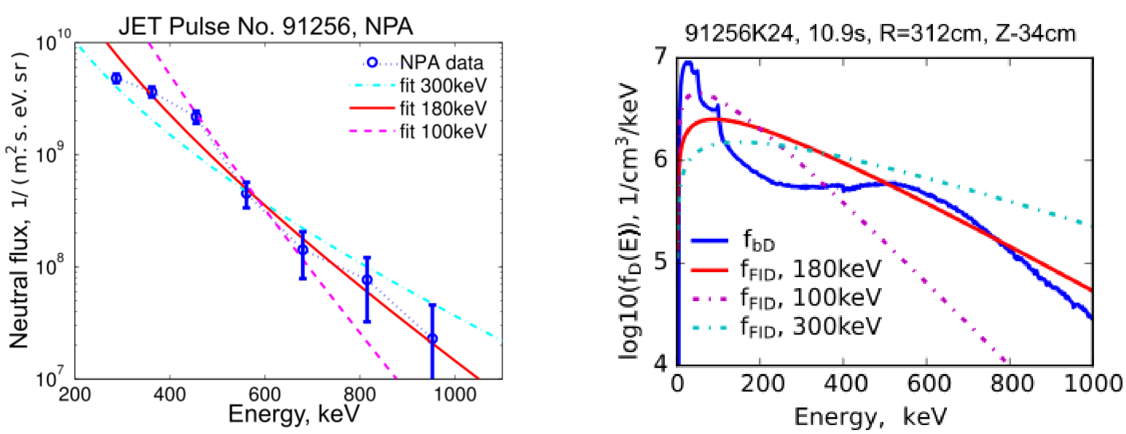



(a) (b) (c)

**FIGURE 3:** (a) Total neutron count, $N_{tot}$, for pulse #91256, dashed blue line for the experimental data and red line for TRANSP result; (b) Neutron camera data for #91256, blue points, and simulated neutron fluxes through channels 1 to 19 red diamonds. The lines of sight of the different channels is provided in the embedded graph. (c) TOFOR analysis for #91256. Experimental TOFOR data are in black, while TRANSP simulated spectra are given by a red line.

The neutron camera with measurements along all 19 lines-of-sight (LOS) is shown in Fig. 3 (b). Good agreement is observed for lines 3 to 6 and 13. For these LOS TRANSP data are well in the error-bars of the measurements. The other three vertical lines with good signal, 14 to 16, are inconsistent with the TRANSP simulation. A possible reason for this could be due to incorrect or slightly misaligned Shafranov shift used in TARNSP. Indeed, with LOS 14 data higher than the simulation data, while channels 15 and 16 are well below calculations small misalignment could possibly be a reason for the observed discrepancies.

The TOFOR analysis of #91256, Fig. 3 (c), shows that the FI DF provided by TRANSP is consistent with the measured spectra. The calculated data are in good agreement for up to about 51ns which covers the region where energetic particles, E>120keV, should be present. The inability of the simulated data to match the spectra for $t_{TOF}$<51ns is probably due to the fact that in the experiment even more energetic particles with E>500keV are present.




(a) (b)

**FIGURE 4:** (a) NPA measurements for pulse #91256, integrated over time interval 9s-11.5s in 7 energy bins centered at 287, 361, 455, 561, 679, 815 and 952keV (blue circles). Expected NPA spectra for Maxwellian fast particles with temperatures 300keV (cyan dash-dotted line), 180keV (red line) and 100keV (magenta dashed line). (b) FI DF in plasma core by TRANSP case 91256K24, 10.9s (blue), compared to Maxwellian fast ions with temperatures 300keV (cyan dash-dotted line), 180keV (red line) and 100keV (magenta dashed line)

Neutral Particle Analyser (NPA) spectra for fast D atoms are derived for low density pulse #91256 by a simple synthetic model. Uniform plasma and Maxwellian fast particle distribution were assumed in the model, while energy dependent charge-exchange and recombination cross-sections and neutral particle flux attenuation were used. Due to low count rate the data from NPA were averaged in 9-11.5s, Fig. 4. The higher energy channels have poor statistics, while the highest one at 1100keV has not detected particles at all. Fast deuterons with energies up to 950keV were measured, Fig. 4 (a). Fast ions with energy larger than 400keV matches a Maxwellian with temperature 180keV, Fig. 4 (a). This observation is consistent with TRANSP predictions, Fig. 4 (b).

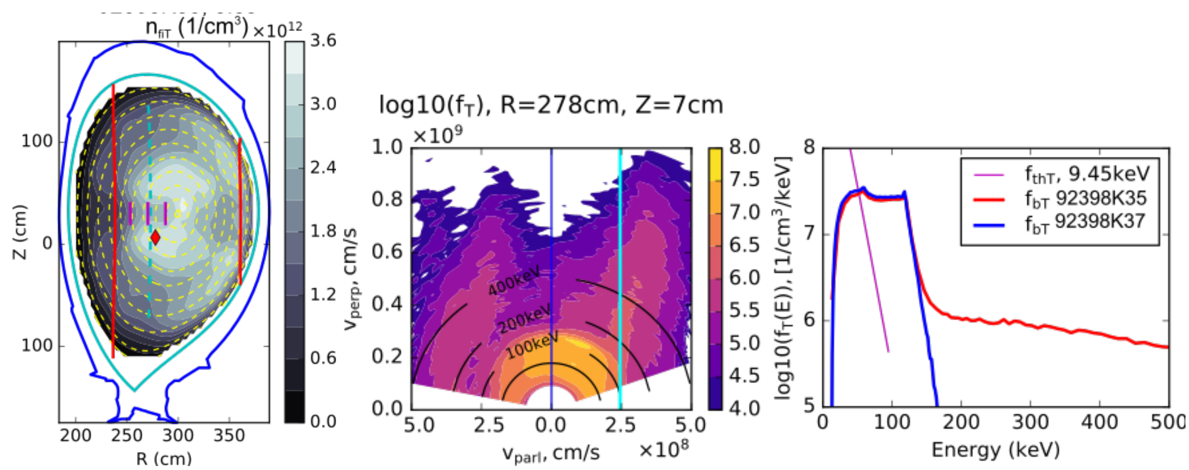
## PREDICTIONS FOR DT EXPERIMENT

JET pulse number #92398 is one of the recent best performing hybrid scenario pulses. Its main parameters are as follows: 2.2MA/2.75T, line integrated density $<n_e>\approx 1.3\times 10^{20} m^{-2}$ (line averaged of about $4.6\times 10^{19} m^{-3}$), central $T_{e0}\approx 7.6$keV and $T_i$ near the core of about 8keV were achieved by means of 27MW of NBI power and 5MW of ICRH in dipole at 42.5MHz for H minority heating. H minority concentration was kept at about 2-2.5%. Record neutron yield of up to $2.6\times 10^{16} s^{-1}$ were measured, which is one of the highest for JETs ILW pulses. This pulse was comprehensively modelled predictively with JETTO and successfully extrapolated to DT mixture [16], [17]. The latter has been performed by means of QuaLiKiz model [18]. Impurities transport was included but source was assumed unchanged when switching form D to D-T mixture. Isotope effects on the confinement has been accounted for as well. TRANSP code was used in interpretive analysis to provide FI DF and BT reaction rates as well.

In JET conditions, both schemes — D beams in T target and T beams in D target plasma — are largely limited by the machine and ICRH plant capabilities. The main restrictions in this case are for the magnetic field, $B_0<4$T, and RF wave frequency, f>23MHz.

For **T beam in D target plasma** the maximum of BTTD reactivity in typical JET conditions would be for beam energy of about 192keV, see Fig. 1. JET can inject T NBI in the range of 80keV to about 120keV, which means if optimised RF heating is applied by means of T-($T_{NBI}$)-D three ions scheme the BTTD rates can be significantly increased. This scheme features the following advantages: (i) more beneficial than D beams in T rich plasma as for T beams the reactivity maximum is for about 190keV, i.e. larger than T beam voltage; (ii) no n=1 D (also α particles) resonance present in the plasma core. It would also be beneficial regarding the T budget in DT experiments as the target would be predominantly D and the experiment would require smaller amount of T. The scheme has a disadvantage that it requires operating near JET and ICRH plant capabilities.

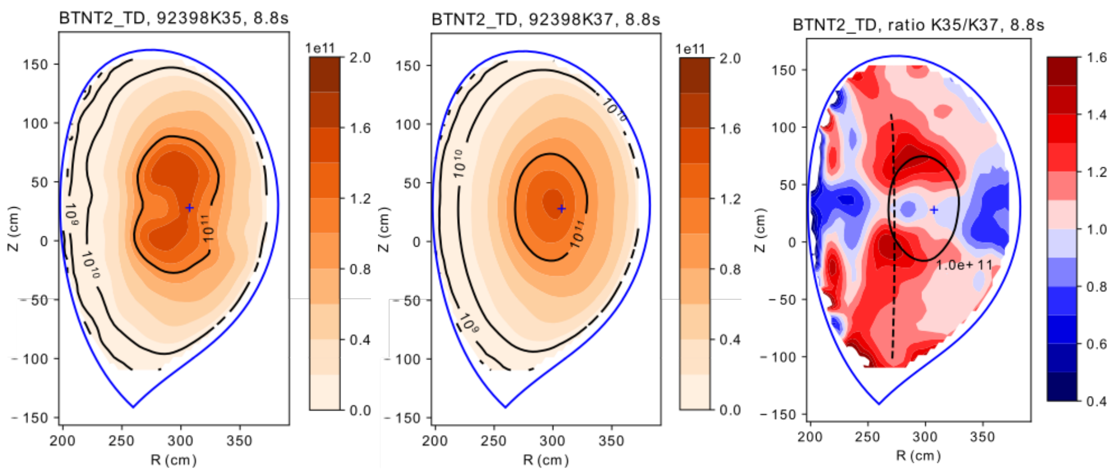
Results of DT extrapolation of pulse #92398 for 3MA/3.9T with 16 T beams at 118kV, $P_{NBI}$=31.8MW, $P_{RF}$=4.8MW, f=25MHz and mixture ratio D/T≈0.69/0.31 are shown in Fig. 5.



(a) (b) (c)

**FIGURE 5:** (a) FI density of T NBI from TRANSP run of pulse #92398 with D/T~0.7/0.3 and n=1 T and D resonances (red lines) and IIH layer (dashed cyan line). The three short vertical lines (magenta) indicate the Doppler-shifted beam positions for $v_{\|}$=1, 2 and $3\times 10^8$cm/s. The red point indicates where the FI DF in (b) and (c). (b) FI DF at R=278cm, Z=7cm versus $v_{\|}$ and $v_{\perp}$. The $v_{\|}$ value satisfying the wave particle resonance condition is indicated by a cyan line. (c) FI DF at R=278cm, Z=7cm is shown versus FI energy for two cases with RF power (in red) and without RF kick operator (blue).

In Fig. 5 (a) FI density of T NBI is plotted on JET plasma cross-section together with n=1 T and D resonances, IIH layer and the Doppler-shifted positions for $v_{\|}$=1, 2 and $3\times 10^8$cm/s. The FI DF at point with maximum RF absorption near IIH layer (R=278cm, Z=7cm, red diamond) is shown in Fig. 5 (b) where the Doppler shift of $v_{\|}=2.44\times10^8$cm/s is indicated by a cyan line. The FI DF is shown versus FI energy for the cases with RF power and without RF kick operator in Fig. 5 (c). TORIC gives the following parameters at the point of interest: $k_\perp=0.22$cm$^{-1}$, $|E_+|=5.13$V/cm, $|E_-|/|E_+|=3.2$. Clearly, NBI/RF synergy is playing an important role in FI DF evolution, particularly in building up a tail for E>120keV. The tail in FI DF in Fig. 5 (c) accounts for about 10% enhancement in BTTD rates. Based on Fig. 5 one can conclude that the smaller Doppler shift is, e.g. $v_{\|}\approx1\times10^8$cm/s, the greater the impact on the FI DF. This trend would however require to further reduce the T concentration and move IIH layer closer to n=1 T resonance as well as to operate at higher $B_0$ (or smaller f) so that to be able to shift the resonances further to the LFS where NBI penetration is greater and FI density higher. Further to the analysis in Fig. 5 the BTTD rates are investigated and compared to the case where RF synergistic effects are not accounted for. These rates and their ratio are shown in Fig. 6.



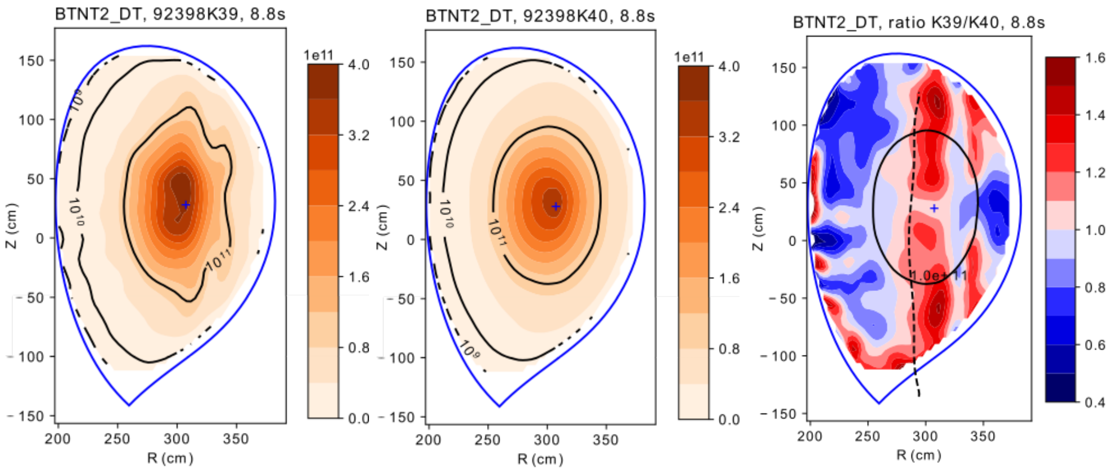

(a) (b) (c)

**FIGURE 6:** Comparison in BTTD reaction rates R (1/cm$^3$/s) for TRANSP run with 4.8MW of RF power in (a) and a case with RF kick operator turned off in (b). The ratio of the two reaction rates is shown in (c) where region with BT neutron rates of 1.0e11 1/(cm$^3$ s) from (b) is shown in black and IIH layer is plotted in black dashed line.

The role of the synergistic effects is highlighted by the fact that the BTTD neutron rates are enhanced along IIH layer, Fig. 6 (c), ≈1.2 times inside region $R_{BT}>1\times10^{11}$ (1/cm$^3$s). Regarding the total neutron counts synergistic effects account for about 9% increase in BT neutrons or about 5% increase in total neutrons. The equivalent fusion power in this case was computed to be of the order of 16.5MW of which 9.6MW (or 58%) from BTTD reactions.

The case with **D beams in T target plasma** in high performance hybrid plasma, #92398, has been simulated as well for 3MA/3.4T with 16 D beams at 118kV, $P_{NBI}=34.7$MW, $P_{RF}=4.8$MW, f=24MHz and mixture ratio in the core D/T≈0.22/0.78. BTDT reactivity $\langle\sigma.v\rangle_{BT\_MEB}$ maximum, Fig. 1, is close to JET D NBI beam voltage, which is of the order of 120keV. In case of large Doppler shift, the synergistic effects by the RF power are expected to affect mainly the tail of FI DF for energies larger than 120keV, i.e. the region where BTDT reactivity is expected to start to decrease. In these conditions it seems that synergistic effects will not benefit BTDT reaction rates significantly. By careful selection of the plasma and ICRH plant parameters however we show in this study that some improvement of BTDT rates can still be achieved. The main advantage of the T-($D_{NBI}$)-D three ion scheme is that it allows for more relaxed parametric space regarding JET operations, i.e. it can be performed at lower $B_0$ and larger f without having resonances near the wall. The disadvantages are: (i) the presence of n=1 D (and α particles) resonance in plasma core which can lead to interaction with fast α and possibly enhance their losses; and (ii) accelerating fast D ions for energies larger than beam energy (~100keV) is practically unbeneficial as for D beam into cold T target DT reactivity maximum is at about 128keV. In general, this scheme can benefit BTDT rates if accelerating D beam ions in the beam energy region, $E\leq E_{bD}$ is achieved. One should note however that this implies smaller Doppler shift in the core, i.e. n=1 resonance and IIH layer have to be close to the plasma centre meaning lower D concentration as well.

Results of the simulations show the following parameters at the location of maximum of RF absorption near IIH layer (R=280cm, Z=6cm): $k_\perp=0.29$cm$^{-1}$, $|E_+|=1.53$V/cm, $|E_-|/|E_+|=3.6$ and n=1 Doppler shift for D beam $v_{\|}=2.3$e8cm/s. In Fig. 7 shown are the BTDT rates calculated by TRANSP for the two cases with, Fig. 7 (a), and without synergistic effects, Fig. 7 (b). The ratio of the rates in the two cases is shown in Fig. 7 (c).




(a) (b) (c)

**FIGURE 7:** Comparison in BTDT reaction rates R (1/cm$^3$s) for TRANSP run with 4.8MW of RF power in (a) and a case with RF kick operator turned off in (b). The ratio of the two reaction rates in RZ geometry is shown in (c) where region with BT neutron rates of $1\times10^{11}$ (1/cm$^3$s) from (b) is shown in black and IIH layer is plotted in black dashed line.

The role of the synergistic effects is clear when comparing Fig. 7 (a) and (b). By turning on the interaction between the RF waves and beam particles, Fig. 7 (a), the region where BTDT rates exceed $1\times10^{11}$(1/cm$^3$s) is expanding and rate maximum in the plasma core is about $3.9\times10^{11}$ (1/cm$^3$s), while without RF interaction, Fig. 7 (b), rate maximum in the plasma core is about $3.6\times10^{11}$ (1/cm$^3$s), Fig. 7 (a) and (b). Significant enhancement in BT rates, 1.2-1.4 times increase, is observed along the IIH layer, Fig. 7 (c). This is a clear indication that synergistic effects are beneficial in increasing BTDT neutron rates. Total neutron count increases by about 5%, while BT neutron yield is up by about 7% due to synergistic effects. The equivalent total fusion power was 21.1MW of which 15.5MW (or 73%) from BTDT reactions.

## CONCLUSIONS

This work demonstrated that the available modelling tools and synthetic diagnostics are capable of providing important insight into NBI/RF synergistic effects and FI DF evolution. JET three ion scenario pulse in HD mixture, #91256, has been modelled with TRANSP and FI DF is shown to be consistent with available synthetic diagnostics: neutron camera, TOFOR, NPA. Best performing JET hybrid pulse #92398 has been successfully extrapolated for DT mixture. Synergistic effects provide important contribution to FI generation and maximising DT fusion rates. An increase of the order of 9% in BTTD rates, i.e. about 5% of the total rates, is predicted due to synergistic NBI/RF heating in T-($T_{NBI}$)-D three ions scheme. Fusion power increases from 15.6MW to 16.5MW. BTDT rates are up by 7% for T-($D_{NBI}$)-D scenario which is if the order of 5% increase for the total rates. Fusion power increases from 20MW to about 21.1MW due to synergistic effects in this case. The two scenarios are comparable regarding DT fusion rate enhancement in the conditions studied here.

For the synergistic effects to have an impact on BT fusion rates in three ions schemes with NBI ions a small Doppler shift is needed at IIH. This means that in DT mixture the NBI specie concentration needs to be lower. In this way, the NBI/RF synergistic effects in the three ion schemes would benefit cases where D (or T) concentration is lower, about 20%, than the other specie, i.e. T (or D). Otherwise if D/T=0.5/0.5 mixture is used the MC layer will be in the middle between D and T resonances, meaning that for either D (or T) beam to be used as a third specie in three ion scenario a high Doppler shift would be needed. Particles with such a high velocity have much larger energies as well exceeding the maximum of DT fusion cross-section therefore there will be not benefit from modifying FI DF in this energy range.

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