High fusion power in tritium rich scenario in JET

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Magnetically confined fusion devices are usually assumed to produce D/T reactions in plasmas with the two isotopes mixed in equal proportions. This indeed produces maximum power if both D and T components are in thermal equilibrium, i.e. in the case of pure thermonuclear fusion. However, due to the nature of the neutral beam injection (NBI) and ion-cyclotron resonance heating (ICRH) systems, a non-thermal component of D and/or T is often present. While the contribution of the non-thermal ions to the total plasma pressure is usually minor, the fusion power produced by collisions between non-thermal minorities and thermal plasma species can be significant if the fast minority ions have energies comparable to the maximum of the DT cross-section. In such conditions, maximum fusion power is not necessarily generated at 50/50 isotope mixture.

As JET is moving on towards the second DT campaign (DTE2), different plasma scenarios are being developed with the main goal to demonstrate at least 15MW of fusion power during 5s flattop time [1]. These are planned to be done with ~50:50 DT plasma composition and balanced D- and T-NBI heating, in total producing ~32MW of power. In addition to these main scenarios, an alternative approach to reach high values of P(DT) was proposed recently. It consists of using only D-NBI to heat a plasma with imbalanced (different from 50/50) isotope composition, namely biased towards less deuterium and more tritium. Deviation from the equally mixed isotope mixture will cause the reduction of the thermonuclear fusion power but will improve the non-thermal reactivity as the number of targets for reactions between fast D and thermal T will increase. TRANSP [2] modelling was done for a typical hybrid

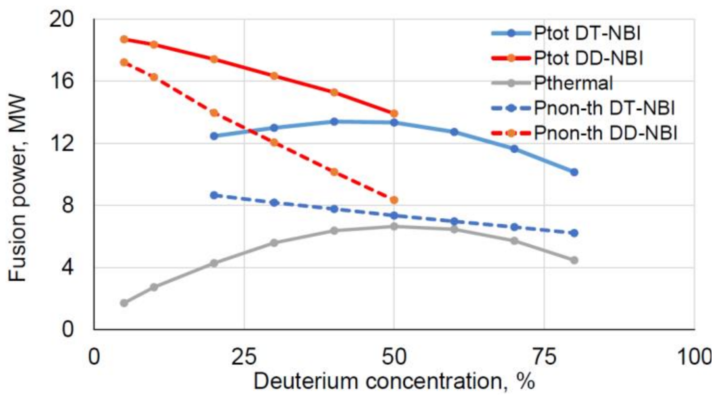

Figure 1: TRANSP calculation of DT fusion reactivity as a function of plasma D/T isotope composition for a typical JET hybrid scenario upscaled to P_{aux}=40MW and two different NBI configurations

See the author list of E. Joffrin et al. accepted for publication in Nuclear Fusion Special issue 2019, https://doi.org/10.1088/1741-4326/ab2276 scenario conditions on JET upscaled to P_{aux}=40MW of additional heating planned for DTE2 (32MW NBI + 8MW ICRH). The results show that the trade-off between thermal and non-thermal fusion reactions will produce a net increase of the total power by ~25-30% and shall confidently exceed the 15MW target (Figure 1). Such a significant improvement in the output power is also achieved by a higher fusion reaction cross-section of fast D and thermal T collisions at the NBI energies used at JET (<125keV), than in the opposite case of fast T and thermal D. That can be observed in Fig.1 from the inclination of the dashed blue line, showing non-thermal reactivity in the case of D+T NBI injection. In addition to that, the slowing down time of D-NBI ions is longer in a plasma with larger average isotope mass [3]. An important conclusion from the TRANSP simulations is that the fusion power increases with reduction of the plasma deuterium content all the way down to very small concentrations.

In addition to the NBI heating, the standard 50/50 DT scenarios in DTE2 will use ICRH power of up to 8MW [4]. Two different heating schemes are considered: fundamental harmonic N=1H minority heating (overlaps with the second harmonic N=2D), and N=1 ^{3}He minority heating (overlaps with N=2T). Both schemes are available for a range of toroidal magnetic fields and RF frequencies, and routinely used also in deuterium plasmas. Among disadvantages of using either of the schemes is the presence of extra plasma species which dilutes the DT fuel, and relatively minor boost to the non-thermal fusion reactivity, as only part of the coupled power is absorbed by the fuel ions. Second harmonic heating is also not the most efficient for enhancement of the D/T fusion power, as due to the Finite Larmor Radius effect, it tends to accelerate ions to large energies beyond the maximum of the DT reaction cross-section.

Scenarios with T-rich fuel composition allows to implement another ICRH heating method: fundamental harmonic heating of deuterium ions. In practice, on JET it is only usable for a single combination of the toroidal field and RF frequency: 3.85T and 29MHz. Maximum coupled power is also lower compared to the other scenarios and estimated to be around ~4.5MW. However, this heating method has important advantages: it does not require injection of extra plasma species (thus no additional plasma dilution), and it can potentially produce a significant boost to the non-thermal fusion reactivity, as most of the power can be absorbed directly by the deuterium. The resultant distribution function will not have a high energy tail, therefore potentially keeping more ions at the energies near the maximum of the DT reaction cross-section. N=1D heating scheme was tested in DTE1 and has demonstrated the highest Q_{fus}=0.22 among the ICRH-only heated plasmas [5], although it has not been used in combination with a strong D-NBI heating on JET before.

In Figure 2 we show results of the 2D full-wave code TORIC [6] for ICRH power coupling in the N=1D heating scenario in the presence of D-NBI ions and 0.5% of ^{9}Be impurity, which is intrinsic to the plasmas in JET with the ITER-like wall. As one can see, the power is distributed between three recipients: thermal D, fast D injected by the NBI and beryllium. The fractions depend on the position of the maximum of the left-hand polarized E_+ electric field component of the fast magneto-sonic wave [7], which in turn is determined by the actual D/T isotope composition of the plasma. At low deuterium concentrations n(D)<20%, absorption near the cold IC resonance is possible and most of the power is channelled to the thermal and fast deuterium, thus giving the maximum fusion gain. At the higher concentrations, the position of the maximum of E_+ moves to the high field side towards the IC resonance of ^{9}Be, therefore increasing the fraction of the power it receives. At n(D)>30%, the majority of the ICRH heating is split between the impurity and D-NBI ions, thus giving less fusion power boost but still providing efficient plasma heating.

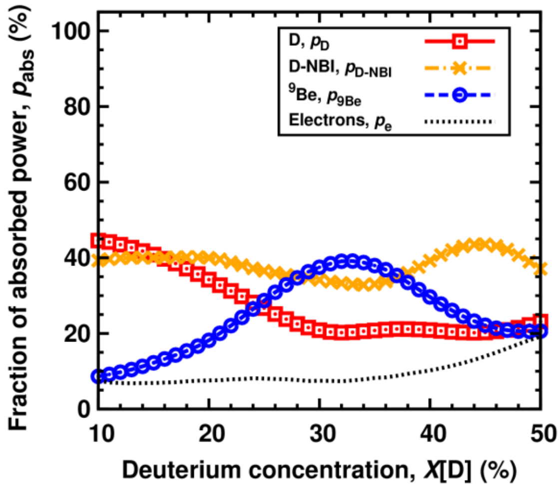

Figure 2: TORIC modelling results for ICRH power absorption between different species in B=3.85T, F=29MHz configuration, as a function of D/T composition

As we can see, both D-NBI heating of the T-rich plasma and the fundamental harmonic N=1 D ICRH heating are very efficient at generating the non-thermal fusion power in JET plasma conditions and can be used in synergy in the same scenario. The cornerstone for this scenario to work is the ability keep deuterium concentration low (ideally <20%) in the plasma core, where most of the fusion reactions take place. It must be maintained despite the strong fuelling of the core with high power D-NBI system.

In the past JET experiments with H/D mixtures, it was shown that the core isotope content is not affected by the NBI fuelling. This was interpreted by much stronger diffusion and convection particle transport coefficients of ions compared to those of the electrons in the presence of ITG turbulence [8], which was then explained theoretically and reproduced in the gyrokinetic modelling [9,10]. It was called the fast isotope mixing effect. In the JET scenario discussed here, NBI and ICRH are working in the dominant ion heating regime, thus ITG is strongly destabilized and efficient isotope transport takes place, preventing the accumulation of deuterium in the core and thus keeping D/T isotope ratio the same in the whole plasma volume.

Integrated JETTO-QuaLiKiz [11,12] modelling was performed for the T-rich scenario on JET to compare the fusion power output with a similar 50/50DT case, complementary to the TRANSP simulation shown earlier. Simulations were done at otherwise similar conditions, assuming total heating power is 40MW for both cases.

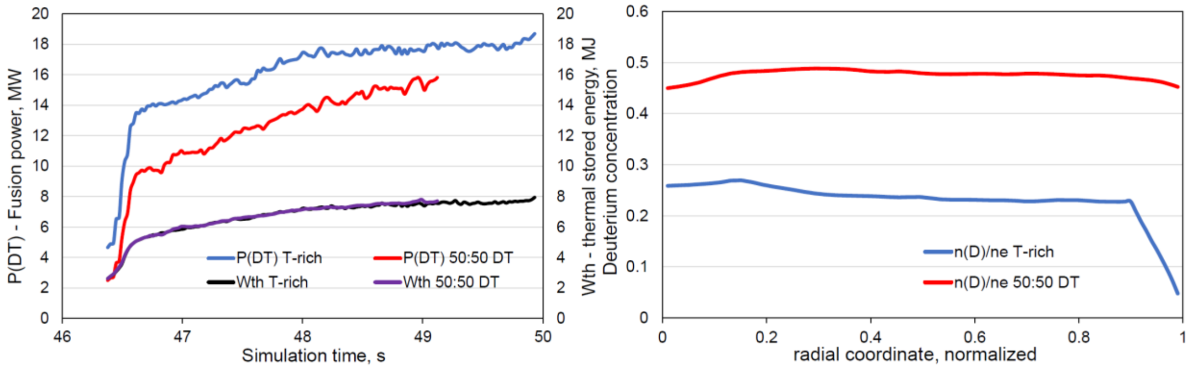

Figure 3: Left - comparison of JETTO-QuaLiKiz predictive simulation runs for JET hybrid scenario at 50:50 DT and T-rich (D-NBI fuelling only) cases. Right - comparison of deuterium concentration profiles in both runs, with DT-NBI (red) and DD-NBI (blue).

As one can see in Figure 3, both runs show similar evolution of plasma thermal stored energy, but the T-rich case demonstrates higher fusion power output at all simulation times, reaching ~18MW. In Figure 3b deuterium concentration profiles are shown for both cases. Full power DD-NBI does not affect the deuterium concentration profile significantly, thus demonstrating the isotope mixing is sufficiently strong for this scenario. Note that this modelling doesn't calculate fusion power boost from ICRH effect on fast ions, which should come on top of the shown P(DT).

Development of the T-rich scenario for high P(DT) is included into the current JET programme in preparation for the DTE2 campaign. If successful, the scenario then can be exploited to demonstrate alpha heating and other effects associated with alpha particles.

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