Extrapolations of the fusion performance in JET

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Abstract**-** *In preparation of the forthcoming high power campaign with the reactor-relevant deuterium-tritium (DT) fuel mixture in the Joint European Torus (JET), significant efforts are being devoted to DT scenario extrapolation using computer modelling. We report on simulations aimed at optimizing external heating using neutral beam injection (NBI) and radiofrequency waves in the ion cyclotron range of frequencies (ICRF) for high DT fusion yield. Our results show that by increasing external heating power to the maximum power available, the fusion neutron rate can be enhanced by a factor of 4-5 with respect to the recent record values. The comparison of two ICRF schemes using different resonant ion species, i.e. ^{3}He and H minority ions, shows that the ^{3}He minority heating scenario achieves a higher fuel ion temperature but not necessarily a better fusion performance. Finally, we study the dependence of the performance of external heating on key experimental parameters.*

I. INTRODUCTION

In preparation of the second high power campaign with the deuterium-tritium (DT) fuel mixture in the Joint European Torus (JET) [1], we report on simulations aimed at optimizing external heating using neutral beam injection (NBI) and radiofrequency waves in the ion cyclotron range of frequencies (ICRF) for high fusion yield. As a reference we use a high-performance 2.9 T/2.5 MA hybrid discharge (86614), i.e. high beta plasma with good confinement (H-mode). Here, beta is the ratio of the plasma pressure to the magnetic pressure $\beta = 2\mu_0 nk_B T/B^2$ where μ_0 is the magnetic permeability, n the plasma density, k_B the Boltzmann constant, T the plasma temperature and B the magnetic field. This discharge yielded the record fusion reaction rate (DD) so far in the JET campaigns with the ITER-like Wall (ILW) [1] and has been extensively analyzed prior to this work e.g. in Ref. [2]. In particular, we compare the performance of ^{3}He and H minority heating using the ICRF

account the synergy between ICRF waves and resonant NBI ions. The minority heating consists of introducing a small concentration of resonant ion species that is different than that of the principle ion species, i.e., D and DT in the cases studied here. For good RF accessibility and absorption we choose the cyclotron frequency of the minority species that is higher than that of main ion species. Thus, we use the hydrogen minority resonance $\omega = \omega_{cH} = 2\omega_{cD}$ and ^{3}He minority resonance with $\omega = \omega_{c^3He} = 2\omega_{cT}$, where ω is the frequency of the launched wave and the ion cyclotron frequency is defined as $\omega_c = ZeB/(Am_p)$. Here, Ze and Am_p are the ion charge and mass, respectively, and B is the confining magnetic field.

We have carried out our simulations with the coupled PION and PENCIL codes not only for fixed but also for evolving plasma parameters as calculated by the coupling of these codes to the plasma transport code JETTO [5] in order to take into account the plasma response to the applied plasma heating and fueling.

II. FUSION PERFORMANCE OF D PLASMA AT HIGH INPUT POWER

The extrapolation of the JET reference hybrid discharge to high fusion performance with D plasma considered here consists of increasing the external heating power with ICRF waves and NBI, and the toroidal magnetic field and the plasma current to 3.25 T and 2.7 MA, respectively.

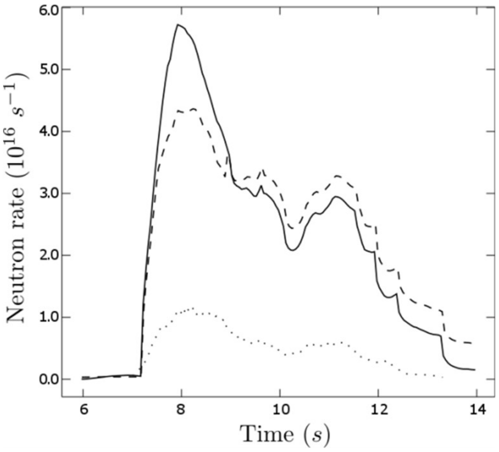

Fig.

eference pulse (dotted line) and for

He (solid line) and H (dashed line) minority ICRF heating with a minority concentration of 4% in a deuterium plasma.

Figure 1 compares the experimental total fusion reaction rate of the reference discharge which has a total of 27 MW of external heating power with two simulated cases using coupled PION, PENCIL and JETTO modelling. In the simulated cases a higher total power of 40 MW is assumed while keeping the same plasma density as in the reference discharge. The input power consisted of 34 MW of D NBI and 6 MW of ICRF power, which is the maximum power foreseen to be available for the presently planned future JET experiments. As we can see in Fig 1, our simulations suggest that the peak fusion reaction rate can be increased by a factor of about 2-3 by increasing the total injected power by a factor of 1.48 to its maximum value.

The two simulated scenarios in Fig. 1 have identical fuel mixtures except for the different minority ion species resonant with the launched waves In one of the simulations we have $\omega = \omega_{c^3\mathrm{He}}$ = 33 MHz while in the other simulation we have $\omega = \omega_{cH} = 2\omega_{cD}$ = 51.5 MHz. As we can see in Fig. 1, the $\omega = \omega_{c^3\mathrm{He}}$ scenario gives rise to a better fusion reactivity in the high performance phase up to t = 9 s as compared to the $\omega = \omega_{cH} = 2\omega_{cD}$ scenario while the situation is opposite in the lower-performance phase from t = 9 s onwards. In both scenarios, the ion temperature reaches its maximum at a minority concentration of about 4%, which are the cases considered in Fig. 1. However, the ^{3}He scenario results in a higher ion temperature during all the NBI and ICRF phase with a maximum of 16 keV at the high performance phase and 12 keV on average at the low performance phase. Although the H scenario gives rise to a lower temperature (12 keV at the high performance phase and 10 keV at the low performance phase), the synergy between the deuterium NBI and ICRF heating enhances the second deuterium harmonic damping and, thereby, the number of fast deuterons. This in its turn improves the fusion yield of the H minority scheme in the low performance phase as compared to that of the ^{3}He scenario.

III. COMBINED NBI + ICRF HEATING IN JET DT PLASMAS

We have performed our first series of simulations with coupled PENCIL and PION codes to study the dependence of the combined NBI + ICRF heating on key plasma parameters. The analysis presented here is for a 50%-50% DT plasma mixture with 5% of ^{3}He assuming equal ion and electron temperatures. A total external power of 28 MW consists of 22 MW of NBI (11 MW of T NBI and 11 MW of D NBI) and 6 MW of ICRF with a frequency of 33 MHz tuned to a central $\omega = \omega_{c^3\mathrm{He}} = 2\omega_{cT}$ resonance. While our reference discharge had a plasma electron density of 6.2×10^{19} m^{-3} and a temperature of 9 keV, in our simulations we have multiplied the density and temperature by constant factors in order to perform a scan in these two quantities. The factor of 0.5 for the density and 1.0 for the temperature correspond to the values of the reference discharge.

Figure 2 shows the power absorption from ICRF waves by resonant ions, i.e. ^{3}He minority ions and tritons. Each point in the surface presents one simulation with the coupled PION and PENCIL codes. The power not absorbed by the resonant ^{3}He minority ions and tritons is absorbed by direct electron damping by electron Landau damping and transit time magnetic pumping. As we can see in Fig. 2, absorption by resonant ions decreases weakly with plasma density and temperature. Nevertheless, it remains dominant, accounting for 65-90% of the total ICRF power, in the whole temperature and density range under consideration.

The resonant ions heat the bulk ions and electrons through collisions. The collisional bulk ion heating fraction, which is a key quantity for high fusion performance, depends on the average resonant ion energy with respect to the critical energy. They both depend on the plasma parameters. According to our simulations the resulting collisional bulk ion heating by resonant ^{3}He ions and tritons increases modestly with plasma density and temperature as shown in Fig. 2.

IV. CONCLUSION

We have extrapolated a reference record JET discharge to high NBI+ICRF power using two different ICRF scenarios, i.e. ^{3}He and H minority heating. While ^{3}He minority heating results in a z better fusion neutron rate in the high performance phase, the H minority scenario performs better in the low performance phase due to second harmonic damping of launched wave on deuterons which increases the fusion yield. We have also presented our first results on the dependence of combined ICRF+NBI heating on the plasma density and temperature for the ^{3}He minority in 50%-50% DT fuel mixtures. Our next step is to compare with the H minority scenario and analyse in detail the fusion reactivity in DT plasmas for both cases.

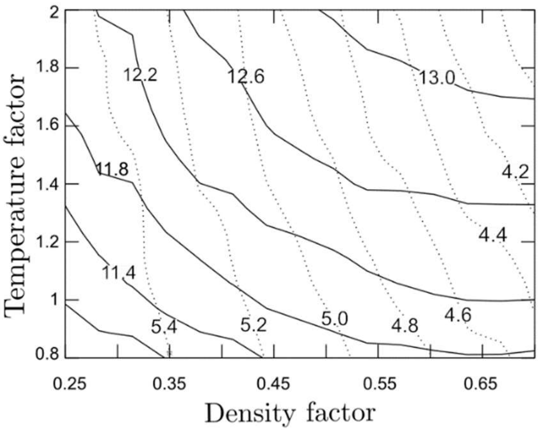

Fig. 2.Contours of constant ^{3}He and T absorption (dotted lines) and collisional bulk ion heating by resonant ^{3}He ions and tritons (solid lines) in MW as a function of plasma density and temperature factor. The total ICRF power is 6 MW and the total T NBI power is 11 MW.

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