ICRH modelling of the Baseline D-T scenario in JET

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Abstract. In the 2021 and 2023 D-T campaigns in JET various scenarios with potential for application in fusion reactors have been studied. The mandate of the "Baseline" experiments was to explore the possibility to operate at high density, magnetic field and current. Although extremely promising results were obtained in D plasmas in the running-up to the actual D-T campaign and up to 8MW of fusion power was produced when adopting this scenario in D-T [1],[2], it was - in contrast to the record T-rich scenario [3] - not possible to sustain D-T shots for the envisaged 5 seconds while also steadily producing more than 10MW of fusion power. In view of the Baseline being considered as a prime candidate for maintaining a high-density plasma in future machines, the underlying reasons are still being explored to enable offering perspectives for possible cures for next-generation experiments. The present paper contributes to that: It concentrates on the detailed modelling of auxiliary (RF & NBI) heating aspects and on the synergy between them, allowing a better understanding of the key role of the auxiliary heating in these high-performance shots. It complements papers that concentrated on key - interrelated - aspects such as transport (see e.g. [4]), MHD (see e.g. [5]), impurities [6, 7], pedestal dynamics [8] and control [9]. One aspect setting the scenarios tested in D-T apart and which has several repercussions is that the Baseline plasma current and hence the density is higher and flatter. This allows to profit optimally from the fact that the neutron rate is proportional to the densities of the fusion fuel ions. However, the higher density affects the beam penetration and modifies the collisionality as well as the beam power deposition profiles. This has nonnegligible implications, some of which will be discussed here.

1 Introduction

The 2021 and 2023 JET D-T experimental campaigns highlighted the rich potential to maintain high performance plasmas in which abundant fusion takes place in a metal (Beryllium) wall environment with a Tungsten divertor. On the other hand the accumulated experimental evidence made it clear some hurdles still need to be overtaken to ensure such discharges can be sustained. In particular the dynamics of impurities - and the radiation resulting from high-Z impurities being too abundantly present - needs to be better understood and their fate controlled, especially now that ITER has opted to directly go to a full-Tungsten vessel wall [10]. There are - at least - two aspects that play a key role there: (i) the mere presence or absence of heat sources and losses at distinct places in the discharge, and (ii) the way the various populations interact because of that. For the thermal subpopulations, the latter has been extensively covered in transport studies (see e.g. [4] and the references therein).

Energy confinement scaling laws systematically show a strong (almost linear) dependence of the confinement with the plasma current while the dependence on the magnetic field is much weaker, suggesting it makes sense to explore the high-current regime. It was the mandate of the "Baseline" team to study that regime [1]. Another - so-called "Hybrid" - regime operated at lower current [11]. Direct heating of one of the fuel ions is preferred. Lacking that, indirect heating - via Coulomb collisional energy transfer - can be used. When relying on thermal-thermal reactions increasing the bulk ion temperature is key. Whereas the Baseline aims at dominantly creating fusion neutrons by nuclear reactions between the thermalised subpopulations, the Hybrid regime relies on reactions between fast particles and the thermal background. In practice - and in contrast to what will happen in an actual reactor - also the JET Baseline harvested a fair fraction of its neutrons from reactions involving fast fuel ions: while plasmas of a reactor will primarily be heated by slowing down fusion-born alpha particles, the alpha particle power in the JET experiments ($1-2$MW) is only a

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small fraction of the total power needed $\approx 30-35$MW to sustain the discharge, making the presence of fast particle populations unavoidable: All ion heating schemes of relevance (be it NBI or ICRH) make use of high energy particles slowing down to crank up the bulk temperature and enhance the fusion yield.

To achieve a steady state regime sources and losses need to be in balance. For a given confinement time this means that to sustain a desired bulk (high) density and temperature, an easy-to determine minimal net power input needs to be guaranteed. Energy loss via impurity radiation and MHD activity have been studied for the D-T baseline shots as well as their D-only preparation phase counterparts (see the references listed in the abstract and the references therein). The present paper focusses on the energy gain: the auxiliary heating sources available at JET.

Crudely speaking, maximizing the fusion rate can be done in two ways: Since the fusion rate is highly dependent on the relative energy of the fusing populations, it makes sense to populate the region close to the energy where the reaction rate is maximal. Aside from that, neutrons can be harvested by optimizing the relative concentrations of the fuel ions since the fusion rate is proportional to the densities of the interacting populations. Whereas the second suggests operating at near-balanced fuel ion populations (relying on charge neutrality, the optimum of the density product $N_D N_T = N_D(1-N_D)$ is where $N_D = N_T = N_e/2$), the former indicates that it may be more useful to concentrate on getting higher up the fusion cross section curve, going away from balanced operation. A combination of both strategies is expected to provide the optimal response but that optimum will strongly depend on the plasma and machine conditions that simultaneously can be reached. The JET results cannot be transposed "as is" to ITER or DEMO.

2 Brief overview of a few key Baseline shots

In the preparatory phase of the actual D-T experiments the behaviour of Baseline discharges was studied in D plasmas using combined H minority fundamental cyclotron RF heating and $\approx$ 110keV D neutral beam injection. The advantage of exploiting a H minority heating scheme is that both the D bulk and beam have a second harmonic resonance in the same region where the H minority has its fundamental cyclotron layer and hence directly receive some of the RF power. The drawback is that a too small fraction of the minority tends to form high-energy tails which indirectly heat electrons rather than ions by Coulomb collisional interaction. In the actual D-T campaign half of the D bulk was replaced by T and half of the beam was fed with T rather than D. Whereas in the D preparatory phase a modest amount of fusion reactions were observed from the D-D reaction, fusion neutrons from the D-T reaction occur much more abundantly in the D-T phase. To explore the potential of operating the machine at high current and hence high density, the accent of the Baseline efforts was on operation at 3.5MA. But both in D and D-T, some experimental time was also devoted to operation at 3MA.

Figure 1 gives a brief overview of the temporal evolution of some key Baseline shots. Shot 96994 is a D plasma 3MA discharge, pulse 96482 is the corresponding 3.5MA pulse in D, JET pulse 104461 is a 3MA pulse in D-T (be it only with D beams) and discharge 99948 is the best performing 3.5MA pulse in D-T. Auxiliary heating was mainly provided by neutral beam injection: about 30MW of beam power was injected. On top of that a modest amount of $\approx$ 4MW RF power was coupled to the plasma. Whereas neutral beam injection is associated with a broad power deposition profile (and even more so when operating at high density) wave heating allows to dominantly deposit power in the actual plasma core by aligning the RF frequency with the core magnetic field. Adopting a similar edge safety factor of 3, operation at 3MA was done at $B_o = 2.8$T and $f = 42$MHz while the main focal point of attention (3.5MA) required $B_o = 3.3$T and $f = 51$MHz. Figure 2 provides an idea of the density and temperature profile. Whereas the density profile is fairly flat and characterised by a significant edge pedestal, the temperature profile is more peaked. There is a clear distinction between the D-only pulses and the pulses in D-T when looking at the density. Likewise - whereas the temperatures are crudely the same - there is a distinction between the 3MA and the 3.5MA shots. The reason for the former (isotope mix) is interpreted as resulting from a difference in transport as well as plasma edge dynamics (see e.g. [8] for details), a topic sidestepped in the present paper focussing on the impact of auxiliary heating. For what concerns the latter, the higher density is at least partly due to the higher current.

Although it seems counterproductive at first sight, all high performance shots are characterised by a significant amount of radiation. On the one hand increased radiation limits the effective power available to sustain the plasma, but on the other it helps reducing the plasma-wall interaction, as seeding experiments have demonstrated (see the work of [12]). The best performing D shot (96994) exploited seeding and managed to keep the radiation fairly steady; in contrast most Baseline shots suffered from a gradual increase of the radiated power up to a point where the net power above the L-H threshold became negative, the plasma fell out of H-mode and subsequently disrupted. Having more power available would have helped to sustain discharges longer. But the root causes of the radiation increase need to be understood and cured. The present view is that too infrequent ELMs prevent the flushing of impurities that naturally tend to climb up the edge pedestal [8]. The Baseline experiments seldomly had impurities reaching the core. Rather, the impurities formed a radiating blob at the low field side edge. While impurities could efficiently be expelled from the core relying on RF power [13], no such handle remained for the edge impurities in 3.5MA shots. Flooding the plasma with gas has the benefit of keeping the ELMs going but degrades the performance significantly, as was demonstrated at 3MA during DTE3 [14].

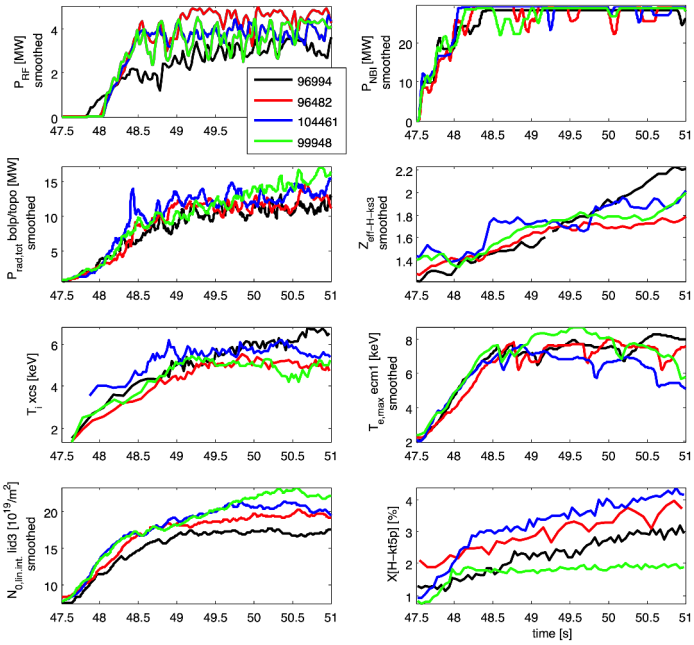

Figure 1. Key data of D and D-T Baseline shots: RF power, NBI power, radiated power, effective charge, (x-ray crystal single point) ion and (core electron cyclotron emission) electron temperature, line integrated (lidar) density and (spectroscopy) H minority concentration.

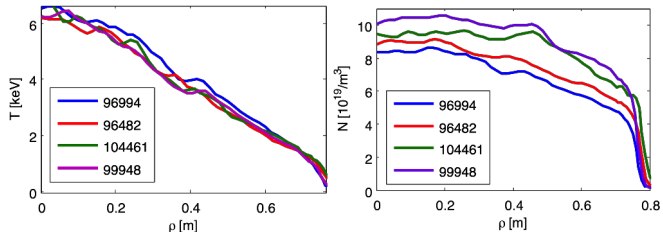

Figure 2. Electron density and temperature as provided by the HRTS diagnostic; the data shown were averaged over the interval [50 – 50.5]s.

3 Preliminary back-of-the-envelope considerations

Before embarking on the discussion of more extensive modelling, it is worthwhile to first get a rough idea of the relative importance of the various processes simultaneously taking place. Such a study will be performed here. Using simple models, we will study the power needed to maintain a given set of density and temperature profiles, and compute the fusion power production one can expect. Provided the energy confinement time τ is known (either from the experiment or from scaling laws) and a stationary state regime has been reached, the local power density P_{dens} and local energy density E_{dens} are related by $P_{dens} = E_{dens}/\tau$. The local energy is the sum of the electron and the ion contribution so assuming the plasma has reached its thermal equilibrium we have $P_{dens(thermal)} = [3/2(N_i kT_i + N_e kT_e)]/\tau = [3/2(N_i + N_e)kT]/\tau = [3NkT]/\tau$ in which it was assumed that the electron and ion temperature are

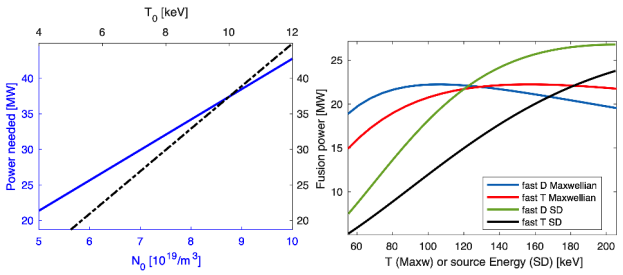

Figure 3. The left subplot shows the power needed for a given core density and temperature (left) with the blue color corresponding to the density scan and the black to the temperature scan; the adopted power reference point is 30MW of net power (so e.g. $N_{o,ref} = 7 \times 10^{19}/\mathrm{m}^3$) with typical associated JET equilibrium and kinetic profile parameters. A fusion power estimate adopting simplified distribution functions is depicted in the right subplot.

the same and that the plasma is simply composed of a balanced D & T population. Integration over the full plasma yields the required net power. Adopting a simple equilibrium model including the elongation κ and the leading order toroidal curvature effect while adopting a simple representation of the form $F = F_o[1-(\rho/a_p)^2]^{\alpha_N}$ for the density and temperature readily yields a net integrated power needed of $P_{net} = [3(2\pi)^2\kappa R_o N_o T_o k a_p^2]/[2\tau(\alpha_N+\alpha_T+1)]$ in which R_o is the major radius, N_o and T_o are the core density and temperature, and α_N and α_T are the density and temperature profile factors. Here ρ is the magnetic surface labeling parameter (in this case it is half the distance of the magnetic surface in the equatorial plane) and a_p is the minor radius. Adopting parameters for a typical JET case ($N_o = 6-7\times10^{19}/\mathrm{m}^3$, $T_o = 7$keV, $\tau = 300$ms, elongation $\kappa = 1.6$, Shafranov shift $\Delta_o = 0.1$m, triangularity $\delta = 0.3$) quickly learns that completely flat profiles ($\alpha_N = \alpha_T = 0$) would require more than 40MW to sustain such a (thermal) plasma. When deeply in H-mode the density profile ideally is flat i.e. the factor α_N is small so in order to push down the power needed (JET had maximally 35MW of power available in DTE2 and DTE3) the temperature profile needs to be peaked. Core heating schemes allow to steepen the profile but are commonly associated with increased T_o as well. So the increase of the core temperature needs to be overcompensated by a pronounced profile steepening to avoid the need for auxiliary power to increase. In practice, it is the available net power and the transport that decide on which profiles are set up. Heating schemes that deposit power in a broad region and not only in the plasma core are less effective in cranking up the temperature: the energy transport equation allowing to describe how local energy sources manage to increase the local temperature (while diffusion and convection spreads it around) involves the power *density* and not the incoming power. Heating away from the core is hard since the associated volume is large. Heating close to the core is easy and often even needs to be configured such that the heating takes place slightly away from the very core to avoid populations with too high energy - which often trigger MHD

activity when the local velocity space gradient is positive rather than negative - to be formed.

The left subplot in Fig. 3 mildly generalises the above simple formula accounting for a simplified D-shaped equilibrium with typical JET parameters and provides a scan of 2 quantities (core density and temperature) to provide an idea of the impact of a mere change of the kinetic profiles. Assuming the profiles do not change and adopting the shape of the actual profiles, an increase/decrease in the density in presence of the same amount of net power needs to be compensated by a decrease/increase of the temperature. Likewise (not shown), flatter density profiles require higher core temperature or wider temperature profiles compared to peaked density profiles.

To maximise the D-T fusion power one can optimise the concentrations of the fuel ions (suggesting balanced operation is optimal) or one can try to bring as many particles as possible in the region where the reaction rate peaks. Assuming one of the fuel ions is not directly affected by the heating and hence has energies well lower than the needed optimal energy one can adopt simplified expressions to compute the fusion rate in case the distribution is isotropic [15]. Whereas the left subplot of Fig. 3 underlined what the importance is of density and temperature profiles, the right subplot depicts an estimate of the fusion power that can be harvested if a constant density $N_e = 7 \times 10^{19}/\mathrm{m}^3$ and temperature $T_{e,i} = 8\mathrm{keV}$ are assumed in the effective core volume (25% of the total volume was used) of the plasma where abundant fusion reactions can occur. Two cases are considered: a (beam created) slowing down distribution [16] and a (wave heating created) high energy Maxwellian population. Both are assumed to be isotropic for simplicity. For a small enough minority concentration, Stix showed that a tail heated by fundamental cyclotron ICRH is crudely a Maxwellian with a tail energy given by $T_e[1 + \xi]$ in which ξ is the Stix parameter, proportional to the RF power density [17]. ξ merely gets an extra factor 3/2 in the extreme opposite case when the distribution *only* depends on $v_\perp$ rather than v). The fast population has been taken to have a concentration of 10% of the electron density. It is important to remind that the velocity related to the centre of mass is typically crudely the velocity of the faster particle if one population is much more highly energetic than the other and hence the (centre of mass) energy of relevance in the cross section is $E = m_1/(m_1 + m_2)E_2$, where "1" refers to the thermal and "2" to the fast population. For a given temperature the energy of a Maxwellian subpopulation has its peak at 108keV for D ions and 162keV for T ions whereas the cross section reaches its maximum at 65keV. A Maxwellian distribution contains particles well beyond that mean energy while the beam population vanishes at energies beyond its birth energy. For that reason the beam population reaches a higher maximum. But both RF and NBI heating can ensure ample fusion reactions when well tuned. At the energy of the JET beams ICRH allows to create a tail beyond the source energy, allowing to crank up the fusion rate. Fundamental cyclotron heating primarily affects low energy species (the associated diffusion is maximal at zero energy) while harmonic heating requires preheating and is most efficient to make already high-energy particles even more energetic. The former acts on the whole distribution but mostly in the thermal and modest energy region while the latter is efficient only for a small, hot subpopulation. Hence fundamental heating is more capable to shift ions into the region optimal for DT fusion - as was convincingly exploited in the record D-T shots [3] - while harmonic heating needs to use the detour of collisional relaxation to affect the bulk ion population. But even high energy tails can ensure a positive feedback: they slow down on electrons, which enhances the electron temperature and hence the critical energy (which is proportional to the electron temperature), allowing more of the tail energy to be of benefit for ion heating [18].

4 Modelling of the Baseline D-T shots

By definition, back-of-the-envelope computations give indications and intuition but lack many details. In this section the results of detailed modelling using ITM/IMAS/ETS tools [19] are provided and discussed. The wave equation is solved using the CYRANO code [20], the initial beam deposition profiles are computed by ASCOT [21], the set of 9 coupled Fokker-Planck equations of all ion species is solved using a 1D Fokker-Planck solver [23] and finally the fusion rate is computed using the cross-sections given in Bosch & Hale [24]. Figure 4 depicts the direct and indirect power density profile of 3.5MA Baseline D-T shot which had balanced D and T bulk and balanced D and T beam populations, the latter injected a 110keV. Note the distinct difference between the RF power density (black dashed line) and the beam deposition profile (dotted line). For the chosen frequency, RF waves are dominantly absorbed close to the plasma core, giving rise to localised and peaked power deposition. Aside from the electrons and the bulk D-T, the plasma has a 2% H minority. The beam species, finally, are described via their energy components: there is a set of D and a set of T beams. Both have a dominant fraction injected at full energy, a fraction at half and a fraction at 1/3rd energy, the relative injection fractions being computed by BBNBI/ASCOT [22] and the total beam (magnetic surface labeling factor dependent) concentration of both D and T amounting to values of 1.25% for the D beam and 1.1% for the T beam reached in the core. These modest values underline the poor penetration of the beam in high density Baseline plasmas; most of the beam particles and hence their energy are deposited in the outer half of the minor radius. The absorption of the ICRH power by the minority is dominant. It absorbs 40% of the coupled power. At the same location the D bulk and D beam absorb at their second cyclotron harmonic; for the wave equation, all distributions have been modelled as Maxwellians with the proper effective temperature to match the damping but without properly accounting for the proper Doppler shift of high-energy subpopulations. The bulk D receives 19% of the power while the highest energy beam receives 7%. The half-energy D beam absorbs 1% but the lower energy beams components do not significantly absorb power, both because of their modest concentration and the fact that the

harmonic heating requires a sufficiently high energy to be efficient. This is even more the case for the 3 T beams: although they share their 3rd harmonic layer with the other ion species, a separate investigation confirms they do not play a role for the direct heating. The electrons finally, are the second best absorbers. As Landau and TTMP damping are not restricted to the neighbourhood of a cyclotron layer, the electron deposition profile is very broad. The electrons absorb as much as 33% of the power. For 4MW of RF power and 30MW of beam power the core power density almost reaches 1.2MW/m^3, mainly because of the highly localised core RF heating. In contrast, the beam deposition profile is slightly inverted in view of the high density as the ionisation process is very efficient already in the outer layers of the plasma. The inverted peakedness of the beam profile proved more prominent in the D-T discharges than in the D discharges performed in preparation of the actual D-T campaign. The beam profiles in T plasmas were even more inverted, although it should be said that the T Baseline plasmas never reached the flat-top near-steady-state regime [1] so a straight comparison is not fully meaningful.

The electrons play an even more prominent role when looking at the Coulomb collisional interaction between the various species. The high energy Hydrogen minority slows down on the electrons and the bulk ions. Also the fast beams share their power among the background species. Note also that the Deuterons receive more power than the Tritons. In the core one could be tempted to explain this as being the result of the direct D heating by the RF but in regions where RF is not even playing a role one notices the same tendency. The reason is to be found in the character of the slowing down process: Tritons are heavier and hence their distribution is narrower in velocity space. As a result, on their slowing down path fast (be it beam or RF tail) particles first collide dominantly with the D before they reach the velocities where also T can benefit collisionally from the fast population's energy.

In total about 8MW of fusion power is generated. Somewhat surprisingly in view of the crudeness of some of the modelling tools used (for example the set of coupled Fokker-Planck equations simultaneously solved to account for the collisional interaction of all heated and non-heated species ignores effects such as trapping and anisotropy of the various distributions), the neutron rate predicted by the model is to within a few percent of the experimentally measured value (itself not without error bars). In view of the high density, the dominant fraction of the neutrons comes from reactions between thermal particles. It also makes the modelling easier than when higher energy tails are primarily responsible for the neutron creation. Aside from that D beam particles reacting with the T bulk species are responsible for about 25% of the neutrons produced, while half of that comes from the interaction of D bulk with the T beam population. Although finite, the beam-beam reactions are negligible compared to the other reactions; this is due to their modest density and the fact that the neutron rate scales with the product of the densities involved. The predicted fusion power density peaks where the power density is maximal and extends up to half the minor radius. Because of the shape of the beam power deposition profile the dominant fraction of the beam power is deposited outside that radius (a flat power density profile would approximately yield a factor 3/4 while the actual beam deposition is inverted) so energy transport is essential to carry it to the hot core but requires energy to sustain the profile width. Oppositely, RF heating is highly localised and already deposited where the neutron rate production is optimal. In spite of that, the fusion power produced is only marginally dependent on the RF power: changing the coupled RF power upwards by a factor of 3 up to 12MW only adds about 0.6MW - i.e. less than 10% - of fusion power. This is interpreted as being a consequence of the fact that the dominant absorber of RF power (the hydrogen minority) is not a fuel ion nor does it easily yield indirect fuel ion heating for concentrations for which the absorption is strong. NBI-RF synergy plays a role in that the tail H energy collides on the electrons, increasing the electron temperature and hence the critical energy (which is proportional to the electron temperature) so that a bigger fraction of the beam population can slow down on the bulk ions. Exploiting a ^3He minority in the D-T and operating at $\omega \approx \Omega_{^3He} = 2\Omega_T$ could have allowed to benefit more from the RF heating as the heavier minority would have dumped more of its power on the bulk ions where the T bulk and beam would have been heated by second harmonic heating, similar to the D bulk and beam in the actually tested shots. But being heavier, less energetic tails would have been formed. Lacking experimental time and despite promising modelling [25] while baseline operation currently is still ITER's primary RF heating scenario for the burning phase, this path was considered but never actively pursued. In ITER, the ^3He minority will be used when setting up the scenario while omitting the minority when the $N = 2\ T$ heating has become more prominent. The study of JET pulse number 96482, the 3.5MA shot in D (with D beams and a H minority, and performed in preparation of the D-T campaign) offers an interesting comparison. This shot was equally dominated by H minority heating but the density was lower and the H concentration almost double of the value in pulse 99948 (4 rather than 2%). Hence the conditions were somewhat closer to the optimal value for maximising minority dominated RF single pass absorption. The electron damping as well as the D second harmonic heating were reduced: for the simulations at the same time in the corresponding shot the electron absorption dropped to 27% and the D damping to 14%. As a consequence a higher energy tail was formed. So, close to where the RF heating takes place the RF power density of electrons is more than a factor 2 higher than the indirect heating of the D and more than a factor 3 higher than the power ending up on the Tritons. It is interesting to note that adopting the experimental density profile but assuming that it is composed of half T and half D ions, and likewise for the beams yields a neutron rate that would correspond to as much as 12MW of fusion power. Upon correcting for the different density the predicted fraction attributed to the DD reactions matches the experimentally found neutron rate of the actual shot. As the adopted model omits some effects known to be impor-

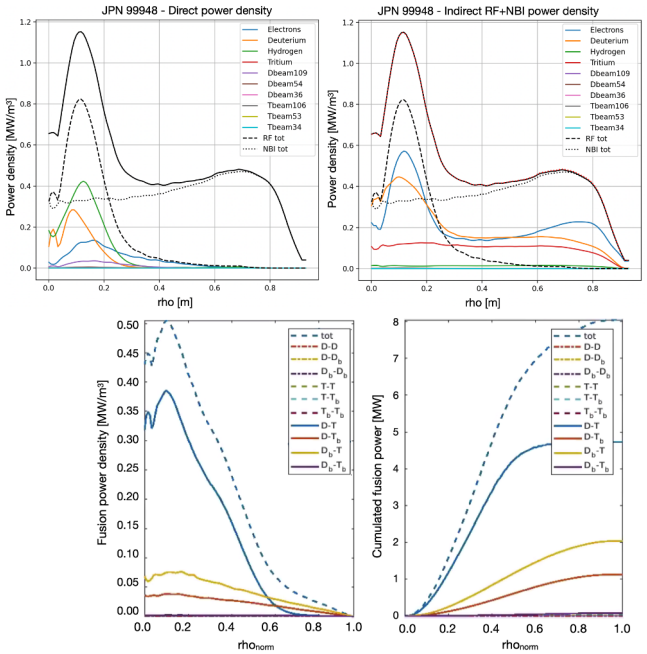

Figure 4. Direct and (Coulomb collisional) indirect power deposition due to combined beam and wave heating of shot 99948 in the flat-top phase (49.5s; top figure) and corresponding fusion power (bottom).

tant but accounts for the Coulomb interaction between all thermal and nonthermal plasma constituents, this match underlines the importance of understanding the fast particle dynamics. Although various effects contributed to the reduced fusion power seen in the actual D-T shots, the difference in density can be seen as one of the contributors.

Inspired on the preliminary back-of-the envelope estimates and the study in the previous paragraphs, the parameters of the discharge 99948 are now modified to get a sense of the sensitivity of the fusion power on some adopted parameters. As mentioned in the outset, transport considerations are purposely not included here to examine the isolated impact of the auxiliary heating. The profiles are considered given rather than self-consistently computed. In view of the modest concentration of the beam, the beam-bulk contribution to the fusion power produced can crudely be approximated without even redoing a computation: to leading order, the collision dynamics is only modestly changed when modifying the bulk concentrations mildly and hence the beam-thermal contribution essentially scales as the change of the product of the 2 involved densities and thus primarily linearly with the beam concentration. Having an increased beam concentration at the locations where neutrons are dominantly created would essentially scale up the associated fusion rate by the same factor. Moreover, the steepness of the cross section curve as a function of relative energy suggests seeking for balanced concentrations of the fuel ions is not necessarily the best way to harvest abundant neutrons: for a prescribed neutron rate, directly heating one of the fuel ions allows to operate at lower concentrations of that population.

Changes of the density give rise to a number of other modifications that affect the heating: they change the beam penetration and hence the beam deposition profile, the RF heating efficiency and the collisional interaction. Naively assuming that the confinement time is unchanged, an increase of the density by a factor α to first approximation needs to be accompanied by a decrease in temperature by α^{-1}. A simulation was performed increasing/decreasing the density by 20% while simultaneously decreasing/increasing the temperature. The expected modification occurs: a decreased density and increased temperature makes the plasma less collisional and allows tails to become more energetic, which in turn results in an increased fusion rate. Increasing the density and lowering the temperature has the opposite effect. Both effects are roughly linear: the adopted changes are 15 and 17% yielding a loss of fusion potential of 2.7MW. Although not negligible, these changes in themselves are insufficient to explain the earlier predicted fusion power of the D-T mock-up of D-shot 96482. The change of the beam deposition profile further affects the dynamics. Artificially making the beam deposition centrally peaked rather than slightly edge inverted (while keeping all other parameters untouched) allows more of the 30MW of beam power to reach the core and non-negligibly increases the role of the beam-bulk fusion reaction rate. Conserving the total number of beam particles injected for each of the 3 energy levels and each of the 2 beam types D and T (so retaining the injected beam power) but adopting a core-peaked profile $N_{nbi} = (1 - [\rho/a_p]^2)^{\alpha_N}$ with a profile factor $\alpha_N = 2$ or 3 lifts up the total power density to $1.75\text{MW}/m^3$ and over $2\text{MW}/m^3$ (see Fig.5), respectively and gives rise to a much more power flowing to the bulk fuel ions which now reach power densities of $0.75/0.9\text{MW}/m^3$ for the D and $0.4/0.5\text{MW}/m^3$ for the T ions. Whereas the thermal-thermal fusion reactions are typically responsible for 2/3 of the fusion reactions, the beam-thermal contribution now gradually grows; an extra 9% is added for $\alpha_N = 2$ and 13% when $\alpha_N = 3$. The D beam reacting with the T bulk contributes most: it is responsible for about 2/3 of the beam-bulk fusion. Unfortunately, the beam deposition is not an independent variable. It sensitively depends on the density. Although the adopted peaked beam deposition is much closer to the ones typical for the record D-T shots operated at reduced current and hence reduced density (allowing beam power to penetrate deeper than is the case for the actual Baseline scenario) the overall fusion gain is not particularly striking: the fusion power only grows from 8.2MW to 9MW ($\alpha_N = 2$) or 9.4MW ($\alpha_N = 3$). But together with the increase of the temperature when decreasing the density for a given power, the combined global effect is noticeable. The final step is to also add the effect of the changed density and temperature on the computation of the RF deposition profile. As already indicated in [25], the 2 heating mechanisms mutually influence each other in various ways. Collisional preheating of a plasma by a beam reduces the plasma collisionality and allows more efficient wave heating. Operating at high density allows to keep the energies of fast particle populations modest but prevents the thermal plasma from reaching high temper-

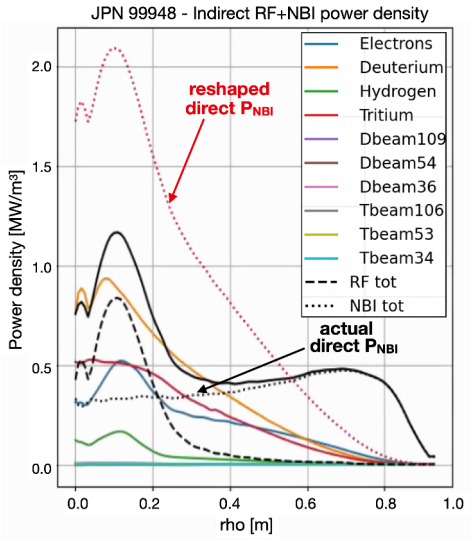

Figure 5. Collisional power redistribution for a peaked beam deposition profile with $\alpha_N = 3$; the black lines correspond to the actual beam deposition profiles.

atures. For these reasons the Baseline adopts high density and a balanced D and T population, being unable to benefit from strong temperature increase of the bulk ions. But doing so - together with observed improved confinement in D-T w.r.t. D - limits the options of the Baseline to reach high temperatures or to keep a large fraction of the beam population close to the maximum of the fusion cross section. Recall the kinetic profiles are provided as input here; in practice the lowered density gives rise to a series of modifications (e.g. better beam penetration and higher tail energies).

The determination and optimisation of a scenario suitable for a reactor is a many-step optimisation process, a key difficulty being that many processes are interlinked. But from a pure auxiliary heating point of view it is clear that putting the power where it is most useful and adopting heating that - ideally directly - deposits energy in physical and velocity space where it is most optimal for maximising the fusion rate is a key contributor to success. Since the fusion power produced in JET's D-T experiments was merely a small fraction of the total available heating, auxiliary heating played a more important role in JET than it will in future fusion machines. Unavoidably the key role of fast particle dynamics - be it induced by NBI, by ICRH or by the synergy between the two - will need to be reassessed.

5 Brief summary

Starting from back-of-the envelope computations and modelled experimental evidence, the present paper (i) underlined the primal importance of having enough power available to sustain a discharge at a desired density and temperature and (ii) illustrated the sensitivity of the neutron rate in high density H-mode Baseline shots to the density via the modified dynamics it unavoidably brings: a modified density affects the RF as well as the beam deposition profile and the collisional interaction between the species. Aside from the bare magnitude of the applied auxiliary heating, depositing it in the high density, high temperature region while aiming at populating velocity space in the region where the D-T fusion cross section peaks as efficiently as possible is optimal.

The present paper sidestepped the crucial importance of effects such as transport - extensively discussed elsewhere - and merely explored the direct role of the auxiliary heating, taking experimental kinetic profiles at face value.

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