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RF Power as Key Contributor to High Performance "Baseline" Scenario Experiments in JET DD and DT Plasmas in Preparation for ITER

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Abstract. Experimental studies of Deuterium and Tritium plasmas have been carried out at JET in the last years, yielding precious information for the next generation of fusion devices. Among the various approaches taken, JET's "Baseline" scenario experiments are pushing the machine towards its engineering limits by operating in a high-confinement H-mode at high toroidal field, plasma current and fuel density, as planned for ITER. The present paper provides a brief sketch of the Baseline scenario philosophy and discusses a number of RF-related results obtained in the preparation of the DT campaign as well as its preparations. Fusion powers of almost $9MW$ and energies of $12MJ$ have been reached in DT "Baseline" scenario plasmas. The differing role of radio frequency and beam heating is highlighted, the former allowing peaked core temperature profiles instrumental e.g. for core high-Z impurity chasing and the "landing" of high performance discharges while the latter is the main overall heating source in JET. Synergistic effects from the simultaneous use of wave and beam heating are responsible for a modest but noticeable increase in fusion power. One of the differences between D and DT plasmas is the plasma density, which impacts on the beam deposition as well as fast ion generation.

INTRODUCTION

Unless new findings will challenge presently reigning views, future fusion reactors will most likely rely on "boring" steady-state plasmas requiring minimal operator attention. Neutrons will primarily be produced by thermal-thermal fusion reactions between bulk fuels ions which are heated by Coulomb collisions with fusion-born α particles from $D-T$ reactions. As it is hard to control, MHD activity will be kept to a strict minimum. A second ("DTE2") JET $D-T$ campaign was successfully run at the end of 2021. The first JET $D-T$ campaign ("DTE1") was executed in the 90's and showed that significant fusion power can be harvested in tokamaks. However, it also demonstrated that Carbon

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walls are not suitable for a reactor, excessive erosion and T retention being just 2 important reasons. Hence JET was equipped in 2011 with the "ITER-Like Wall" (ILW), consisting of Beryllium for the plasma facing components, and equipped with a Tungsten divertor. It took several years to learn to control fusion-relevant discharges in this metal-wall machine. In 2015 the preparations for a second $D-T$ campaign started. JET's $D-T$ plasmas differ from those in ITER or DEMO in that they are not heated by slowing down α's but are kept at fusion-relevant temperatures by auxiliary heating: RF heating and neutral beam injection. Fast particle populations thus are intrinsic in JET. For that reason, JET's high performance $D-T$ plasmas - crudely speaking - come in 2 varieties: Either one opts for high current and hence high density (as intended for ITER's $D-T$ operation) to maximise fusion reactions coming from interaction between thermal populations, or alternatively one maximally exploits the presence of a fast particle population. The former is the mandate of the ITER-baseline scenario experiments. Baseline plasmas were typically ran at $q_{edge}=3$ with core safety factors slightly below 1 and hence exhibiting sawtooth activity ensuring flushing of the core. A high edge pedestal is formed; ELMs are counted on to flush high Z material out of the confined plasma. To stimulate ELM triggering pacing pellets are used. In view of the higher current and hence density Baseline plasmas only reach modest normalised β values unless sufficient auxiliary power is available. Solely counting the energy in the thermal populations and for a given confinement time one can easily show that the power required to reach a specific normalised β is $P_{needed}[MW]=B_o[T]I_p[MA]\beta_N/[1.67\tau[s]a_p[m]]$ where B_o is the static magnetic field strength, I_p is the plasma current, β_N is the normalised beta, τ is the confinement time and a_p is the minor radius. Various scaling laws indicate confinement scales almost linearly with the current (the ITER $H_{98y,2}$ scaling e.g. exhibits a factor $I_P^{0.93}$). This states that the required power essentially scales with the adopted field and hence - for a prescribed safety factor q - the current so that higher current operation becomes increasingly more dependent on the availability of auxiliary power unless fast particle physics can provide a significant extra boost. At modest density, significant high energy particle populations can easily be formed. At the higher densities where the Baseline scenario operates this is more challenging. The total fusion power is the sum of a sturdy contribution associated with thermal-thermal reactions and characterised by changes on the time scale of the slowing down time, and of a much more touchy contribution arising from neutrons born out of fast-thermal fusion reactions. The latter is sensitive to instantanenous changes in e.g. applied power and MHD activity (sawtooth crashes, ...).

BRIEF DESCRIPTION OF A BASELINE SCENARIO SHOT

Already in previous experimental campaigns it became clear that the achieved high density Baseline plasma neutron rate was only consistent with the rate predicted by TRANSP when duly accounting for the fact that the ion and electron temperatures are decoupled [1]; both in D and DT plasmas the ion temperature in the central part of the plasma clearly exceeds the electron temperature. It was also established that the neutron rate is a very sensitive function of the amount of auxiliary heating; see Fig.1: the higher the applied power, the greater the rate of increase of the neutron rate so that every *extra* MW at one's disposal is allowing to profit more optimally from the presence of fast particle populations when optimising the discharge.

The most noticeable difference between DD and DT discharges is that the latter climb to higher densities for otherwise similar engineering parameters. Whereas reaching higher densities is aligned with the Baseline scenario's philosophy, this increase is accompanied by an increased radiation caused by Tungsten (W) sputtered from the divertor and finding its way to a low field side radiating "blob" formed because of the high mass of the W and the fact that the W ions - dragged along by the main plasma - spin around rapidly so that centrifugal acceleration pushes them to the low field side of the discharge where they climb up the H-mode pedestal by neoclassical transport. DT plasmas exhibit a lower ELM frequency and amplitude than their DD counterparts. Further examination of the detailed dynamics is being investigated but increased resistivity when going to higher ion mass is believed to be a key player in the ELM dynamics, DT plasmas exhibiting increased turbulence potentially preventing the formation of a steep pedestal. Field showed that ELMs efficiently remove impurities from the plasma but that neoclassical effects are pushing material back up the steep pedestal gradient [2]. The relative efficiency of these 2 processes decides on the ultimate fate of the particles, and of the high-Z particles in particular.

RF HEATING SCHEMES IN JET *DT* PLASMAS

JET is equipped with RF heating and neutral beam injection. In DTE2 both D and T beams were available. The wide range of frequencies covered by the A2 antenna and the ILA (ITER-like Antenna) allows choosing from various

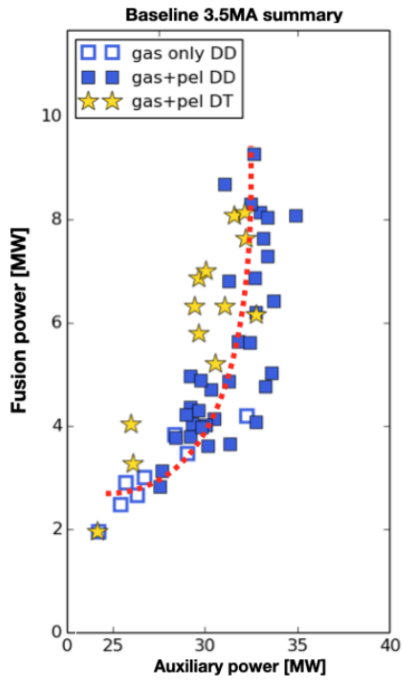

FIGURE 1. Fusion power as a function of the auxiliary power for DD and DT Baseline scenario shots. The DD data points are multiplied by the ratio of the DT to DD fusion rate coefficients to enable plotting the data on the same graph.

"classical" RF heating schemes and picking the most appropriate one for the job at hand: Aside from contributing to heating in the flat top phase of the discharge, RF power is exploited to help avoiding disruptions when terminating the plasma and is used to expel high-Z impurities from the core. Either H or ^3He minorities can be chosen. Core fundamental ($N = 1$) H minority cyclotron heating simultaneously allows for second harmonic D bulk and beam heating as well as third harmonic T bulk and beam heating. When ^3He is adopted as a minority, second harmonic T bulk and beam heating is associated with it. Second harmonic T heating is foreseen to be used in ITER's activated phase during the flat top, while ^3He can be added to the discharge in the ramp-up and landing. Also $N = 1$ D minority heating can be exploited both in JET and in ITER. Finally, so-called 3-ion schemes can be used. All of these schemes were tested during DTE2 (see [3, 4, 5]). The Baseline scenario team ultimately opted for exploiting JET's usual "work horse": $N = 1$ H and $N = 2$ D.

Fundamental cyclotron hydrogen minority heating is known to be a highly efficient RF heating scheme, in JET typically with very high single pass absorption exceeding 90%. At the high densities at which the Baseline scenario operates also second harmonic D heating is very efficient: combined D bulk and D beams account for well over 50% of the absorbed power at modest H concentrations of a few %. Even 3rd harmonic T heating plays a small role, absorbing a few % of the power. Direct electron Landau and TTMP (Transit Time Magnetic Pumping) damping can never be fully avoided in a sufficiently hot and dense plasma. Absorption of RF power by alpha particles - the concentration of which is typically only about 0.01% in JET - is negligible in the power balance but - on account of the massive Doppler shift - potentially plays a role in fast ion losses.

Various ion species are directly heated by the RF waves in $(H) - D - T - (D_{NBI}) - (T_{NBI})$ plasmas. High energy tails of non-Maxwellian minority, majority and beam populations are formed and their Coulomb collisional interaction needs to be accounted for; an example of typical fast ion 'tail' formation observed in various species is depicted in Fig. 2. In preparation of the actual DT campaign, Huynh [6] made an in-depth study to decide whether the Baseline scenario should opt for exploiting a H or a ^3He minority by replacing half of the D bulk and half of the D beam species of a well performing Baseline D shot (JPN 92436) by T and T beam particles. Assuming the D plasma experimental temperatures and densities are sufficiently representative for a DT plasma, he predicted the energy and neutron rate for a set of H as well as ^3He concentrations. He found that the total fusion power produced is largest ($\approx 11MW$) when very low minority concentrations are used. Whereas exploiting ^3He and T heating yields a mild maximum at a minority concentration of $\approx 2\%$, JET's workhorse $H + D$ scheme turned out to be most efficient at negligible minority concentration when operating at high density and high auxiliary power (as was the case in the recent experiments); recall that second harmonic heating - a key player in the high performance shots - scales both with density and temperature. Consistent with the philosophy of the Baseline scenario, most of the neutrons ($\approx 60\%$) are born out of $bulk-bulk$ fusion reactions but $beam-target$ neutrons unavoidably play a significant role as well. Too large minority concentrations should be avoided since the fuel ions then are too much diluted. Omitting the RF power but solving the set of coupled Fokker-Planck equations adopting the experimentally obtained (D plasma) densities and temperatures Huynh also assessed that the synergistic effects of combining RF and beam heating represents about 15% of the total neutron yield.

The choice between H and ^3He minority was also studied experimentally, be it in D and not in DT plasmas. Aside from being backed by fully compatible independent PION modelling [7], the findings of Huynh were confirmed experimentally, both for what concerns the choice of the minority concentration and the type of minority species as well as the critical role beam power plays. Moreover, it was found - for both minority types - that 2 separate regimes exist where RF heating can be optimally exploited: a very low concentration window - where it is believed that the various tails formed are contributing to the overall energy response - and a window at $6-8\%$ - where modelling predicts the impact of the second harmonic tails has largely been eliminated and where minority tails formed by fundamental cyclotron heating take the upper hand. The former is used in the main phase of the discharge while the latter is exploited in the current ramp-down "landing" phase (see further). Some years ago, Goniche [8] demonstrated that high-Z flushing from the core is most efficiently achieved using a H minority tail in JET plasmas, likely because higher energy tails are more easily formed with the light H minority than with the heavier ^3He plasmas and both the neoclassical outward pinching due to the steep core temperature profile as well as the sawtooth triggered are more efficient at flushing particles from the core. Huynh's studies, the experimental evidence from the minority study and the evidence provided by Goniche led to $N = 1\ H + N = 2\ D$ being preferred for the actual DT tests.

Since JET's NBI system injects approximately an order of magnitude more power than do the RF waves, it is fair to say that neutral beam injection largely determines the setting up of the temperature profile in that machine in high density H-mode plasmas. The two heating systems play a very different role, however. Simply looking at the power density of the beam it is seen that about 75% of the beam power is deposited in the outer half of the discharge. To contribute to the neutron production, beam heating relies on *diffusion* (which is a 2-way process) to transfer the power to the core (while equally diffusing power towards the edge). Whereas in D plasmas the beam power density profile is fairly flat, it is hollow for DT and even more hollow for T plasmas. RF heating on the other hand allows to deposit power directly in the core of the machine. Figure 3 provides an example of the power deposition profiles as predicted by the RF+NBI modules in the ETS (European Transport Solver) for DT shot 99520, the middle subplot corresponding to the actual experimentally available power. Even at modest RF powers of a few MW the RF power density in the core (dashed line with star indicating the maximum value) is larger than that of the beam (dotted line). When $P_{RF} = 5MW$ the wave power density is more than a factor of 3 larger than that of the beam. The beam primarily heats the bulk ions (orange and green lines). Since tail formation depends on power density and not on power, RF tails near the core tend to be highly energetic and mainly slow down on electrons (blue lines), particularly when the RF power is significant. They indirectly trigger increased *ion* heating as well, though: the RF power flowing to the electrons increases the local electron temperature and hence pushes the critical energy to higher values. As a consequence *more* of the beam power is transferred to the ions than would be the case when RF is absent. The result is that both the ion and electron temperature are pushed upwards in the core region. For lower density plasmas allowing significant core beam deposition this tandem mechanism allows to create very highly peaked core temperature profiles (see e.g. [4]).

Modelling provides confirmation of the achieved fusion power in the DT Baseline scenario shots. The neutron source density profile is highly peaked in the plasma core but extends up to mid-radius. More than 50% of the fusion power results from bulk-bulk reactions. Beam-target contributions are significant and constitute most of the remaining fusion reactions since the beam concentrations are too low for beam-beam interactions to contribute significantly. A back-of-the-envelope computation and a glance at the DT cross section (see [9]) suffices to demonstrate that a D beam population slowing down on a T bulk yields a higher fusion yield than a T beam slowing down on a D bulk. More detailed computations confirm this finding: the $D_{NBI} - T_{bulk}$ reactions are 70% more efficient in producing neutrons than the $T_{NBI} - D_{bulk}$ reactions. In its extreme form, this difference was exploited maximally in T-rich plasma experiments in which an $\approx 15\%$ D minority was heated at the fundamental cyclotron heating, yielding the current fusion power record (see [4]). It is interesting to note that the higher the bulk ion temperature is, the less advantageous a T-rich population becomes in high density plasmas, thermal-thermal reactions - as intended for the "Baseline" scenario in an actual reactor - taking front stage. Because of the volume effect, most neutrons are harvested at normalised radius of ≈ 0.25. The total fusion power reaches about $9MW$. Recall that the computations by Huynh - made in advance of the actual DT experiments - predicted a fusion power of around $11MW$ could be achieved. A

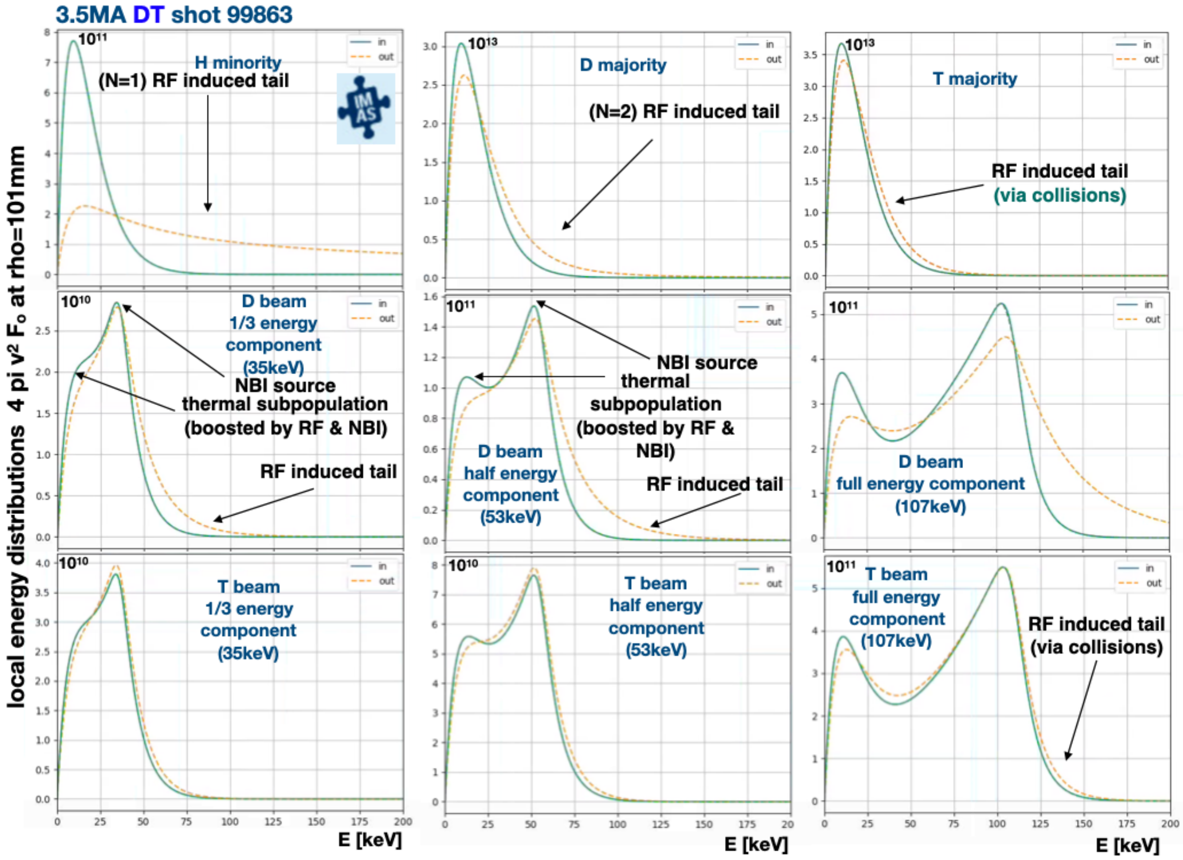

FIGURE 2. Energy densities of the various ion distributions for DT shot 99863 at the location where the optimal RF heating is achieved. The green lines represent the Maxwellian or beam energy distributions in absence of RF power while the orange curves depicts the corresponding distributions when the RF power experimentally coupled to the plasma has been accounted for.

sensitivity study was made to determine the origin of this difference. It was found that adding extra RF power did not significantly change the fusion power: even when doubling the available power the neutron yield still only changes by a few %. Adding extra beam power is more efficient. The neutron yield was found, however, to be most sensitive to the density. It was mentioned earlier that the density in DT plasmas is higher than in D. This has various repercussions on auxiliary heating power deposition profiles: As mentioned above, less beam power directly makes it to the plasma core so that heating sources in the outer half of the plasma are significant. The higher density also means that less energetic tails can be formed. Both effects degrade performance and underline that operation at high density requires sufficient power to be available to ensure high temperature can still be reached.

RF HEATING TO "LAND" HIGH PERFORMANCE PLASMAS

A particularly interesting application of RF heating in high performance JET plasmas is its role in "landing" (i.e. assisting in keeping the plasma stable during the current ramp-down phase at the end of the pulse) high performance discharges. To achieve high densities, Baseline discharges are run at high current. At such currents the disruption forces are significant (multiple hundreds of tons) and hence methods are required to avoid thermal quenches inducing disruptions. At the end of the current flat top of JET high performance plasmas, the current is gradually ramped down while the beam power and gas injection are also decreased; see Fig. 4. This is done by means of real time control. The net power (the sum of the auxiliary input power and Ohmic power minus the radiated power) is kept a few MW above the $L-H$ threshold to ensure the plasma stays in H-mode until the plasma current has been reduced significantly to allow a transition to L-mode without risking a severe disruption. Since the plasma is kept in H-mode, the density

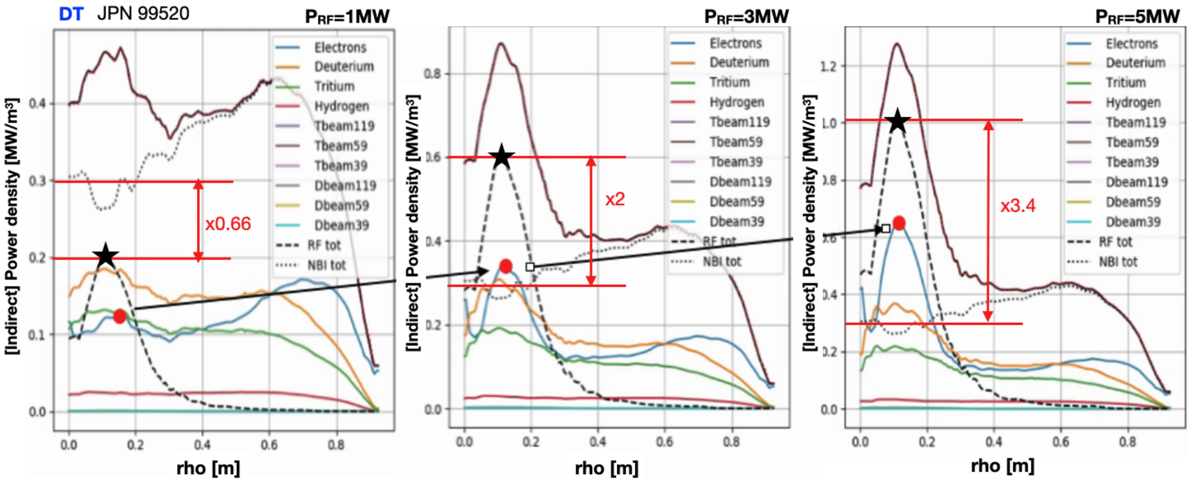

FIGURE 3. Power density of JET DT shot 99520 of the various species after Coulomb collisional redistribution for 3 RF power levels: 1, 3 and $5MW$.

remains relatively high while the temperature - requiring auxiliary power to be maintained - is decreasing. This tends to encourage increased radiation decreasing the temperature further and potentially giving rise to temperature profile hollowing. To avoid this happening H minority heating fundamental cyclotron heating is used. Contrary to what is done in the main heating phase (where the minority concentration is kept very low for the reasons explained earlier) the minority concentration in now increased to $7-8\%$. The reason for doing this is that the decreasing temperature and reduced beam power remove two of the main plasma heating schemes: second harmonic D bulk and beam heating. Increasing the concentration allows minority heating to become more efficient. Recall that - opposite to second harmonic heating which scales with the temperature - fundamental cyclotron heating *remains* potent even when the temperature is extremely low. Maintaining the RF power while the NBI power is being stepped down allows to keep the temperature at an acceptable level of $4-5keV$.

FAST PARTICLE POPULATIONS

The DTE2 experiments have been an excellent opportunity to test diagnostics and to accumulate data allowing checks of theoretical findings. In the context of auxiliary heating, the neutral particle analyser provided experimental measurements of all fast particle populations: Figure 5 illustrates the Deuterium bulk and beam, the minority Hydrogen and the fusion born α's in sets of Baseline scenario discharges. Depicted are the log_{10} plots of the fluxes (binned counts) normalised by the square root of the energy. The left subplot depicts the Deuterium up to $40keV$. The thermal subpopulation as well as part of the slowing down beam distribution can be recognised. Zooming in solely on the thermal subpopulation demonstrates the sensitivity - backed up by modelling - of the Deuterium response to the Hydrogen minority concentration: the lower the Hydrogen concentration, the steeper the distribution function i.e. the higher the D temperature in the thermal region. Gradually increasing the minority concentration from 3 to 10% in subsequent shots results in an effective temperature that decreases by a factor of almost 2. On the other hand, in the slowing down part of the beam (energies between 10 and $40keV$) it is the available power that is the dominant effect - the red dots of the shot at $P_{RF} = 4.5MW$ lying higher than those of more modestly RF heated shots - although dilution of the D population by a larger H concentration is also observed (green dots). The importance of the power as well as the concentration is also clearly visible in the middle subplot, depicting the corresponding picture for the Hydrogen population. Being heated at its fundamental cyclotron layer, the heating efficiency in the thermal region is directly proportional to the applied RF power (density) and inversely proportional to the concentration (see e.g. [10]). Of particular interest is the right subplot of Fig.5: It shows the slowing down fusion born alpha particle distribution.

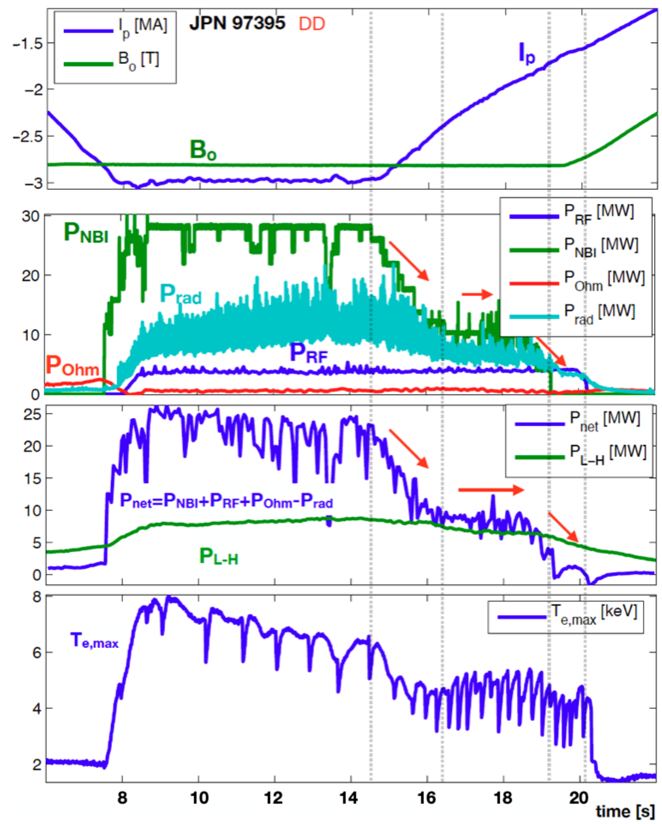

FIGURE 4. "Landing" a high performance discharge. From top to bottom are depicted: (i) the plasma current and magnetic field (note that both current and field run in the counter direction i.e. have negative values), (ii) the beam, RF, radiated and Ohmic powers, (iii) the net power and the L-H power threshold, and (iv) the core electron temperature.

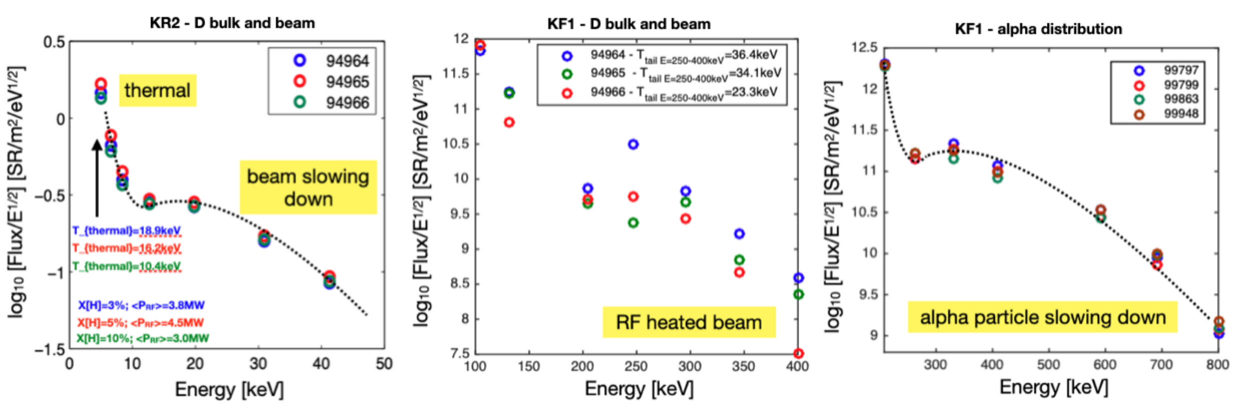

FIGURE 5. Fast particle populations observed by the low energy neutral particle analyser: (i) Deuterium beam and bulk, (ii) Hydrogen minority and (iii) fusion born α's slowing down.

RF HEATING, MHD ACTIVITY AND IMPURITIES

High performance JET plasmas are unavoidably associated with MHD activity. Aside from sawteeth in the core and ELMs at the edge, fishbones and neoclassical tearing modes (NTMs) are standardly observed in high performance Baseline scenario plasmas. Whereas the former do not usually give rise to a major loss of confinement, the impact of the latter is often significant. Disruptions are an issue for the Baseline scenario. Pucella [11] noticed that excessive radiation (observed more markedly in DT compared to D plasmas) tends to give rise to edge cooling while high Z material making it to the core causes core temperature hollowing, be it that hollowing occurs significantly less frequently than edge cooling. Although very different in location and signature, both these effects give rise to 2/1 NTMs that often grow uncontrollably and terminate the discharge. Pucella relates the emergence of the mode to the increase of the current density gradient near the surface (around normalised minor radius 0.6) on which the $q = 2$ resonant mode appears. The changes in the current density profile follow from changes in the electron temperature profile consistent with time delays associated with the effective resistive time; linear stability analysis as well as modelling support this interpretation. Too high density, accumulation of high Z impurities or too massive injection of gas or pellets ("cold shower" effect) can trigger increased radiation and cause the onset of a negative feedback loop. It is known that sawtooth activity can trigger NTMs [12], a phenomenon often observed in Baseline scenario plasmas. Chapman proposed a scaling law to determine which is the critical normalised β beyond which sawteeth crashes trigger NTMs. Aside from a dependence on the density, the resistivity and the power above the $L-H$ threshold, his scaling states that longer sawtooth periods decrease the critical β_N down and hence enhance the risk of triggering NTMs for a given amount of auxiliary power.

Sawtooth pacing is a technique that may be of help to avoid NTM onset. The condition for a sawtooth crash to occur can be expressed in terms of the $E \times B$ shear at the $q = 1$ surface and 2 shear thresholds, one of which is sensitive to the fast particle distribution function. Pacing influences the fast ion stabilisation properties and - apart from avoiding the initiation of deleterious MHD activity - can be particularly helpful for stimulating high-Z flushing from the plasma centre. Lerche demonstrated that RF heating allows triggering sawtooth crashes [13], thereby artificially shortening the sawtooth period. The fact that RF heating ensures very localised power absorption makes that it is particularly suited for heating the very core where it efficiently creates high energy tails and peaked electron temperature profiles and achieves high fast particle pressure. Studies of the applicability of the pacing method were undertaken in Baseline plasmas; Fig. 6 provides an example. The triggering of crashes itself proved to be possible but pacing comes at a price: The neutron rate is the sum of a contribution from fusion reactions between thermal particles and a contribution involving thermal and fast populations, the neutron rate being sensitive to the latter. It was observed that sawtooth crashes cause up to 20% loss of the neutron rate. In spite of the fact that the sawtooth period is mass-dependent so that DT plasmas should have longer natural sawtooth frequencies - and hence can potentially cause more violent sawtooth crashes when unmitigated when operating in DT - pacing was deemed to be counterproductive for Baseline scenario discharges and was not retained as in ingredient in the actual DTE2 campaign.

Spectroscopic analysis reveals that DT plasmas typically had a somewhat higher W and Ni concentration than D plasmas [14]. The different ELM behaviour in the discharges is a possible candidate to explain the results, and is not inconsistent with the higher density and the somewhat steeper mean increase of the radiation in DT discharges: the less efficient flushing seen in DT plasmas allows to reach higher densities but equally confines a larger amount of unwanted high-Z particles. A first hint that it is not the near-antenna RF field that is the dominant factor comes from antenna computations executed with the ERMES code [15]: adopting the density profile of JET shot 99948, Otin showed that there is little difference in the edge between the electromagnetic fields consistent with either a pure D plasma or a balanced DT plasma. He reached a similar conclusion when comparing D and DT plasmas with either a H or a ^3He minority, apart from the expected change in fast wave wavelength resulting from the different frequency required to place the respective fundamental cyclotron layers in the centre. Interestingly, *all* computations show the presence of slow wave structure and the Lower Hybrid resonance in front of the antenna, a fact that was independently checked by a 1D computation (the ERMES computation was done in 2D). Independently - and not particularly aiming at modelling DT Baseline plasmas - Maquet showed slow wave excitation and a nearby Lower Hybrid resonance - where the slow wave is damped - in the edge can prevent some of the wave power to reach the main plasma [16]. Studying earlier work by Bobkov [17], he equally confirmed the link between the presence of edge impurities and the excitation of low $k_{//}$ modes associated with the presence of "coaxial modes" and slow wave structure. Since there is no convincing difference between the electromagnetic fields close to the antenna for either of the plasma compositions, it is reasonable to assume that the observed differences in impurity levels are not due to the presence of the RF fields *per se*. They may - however - indirectly be due to the impact the fields have on sputtering, the efficiency of which is mass-dependent.

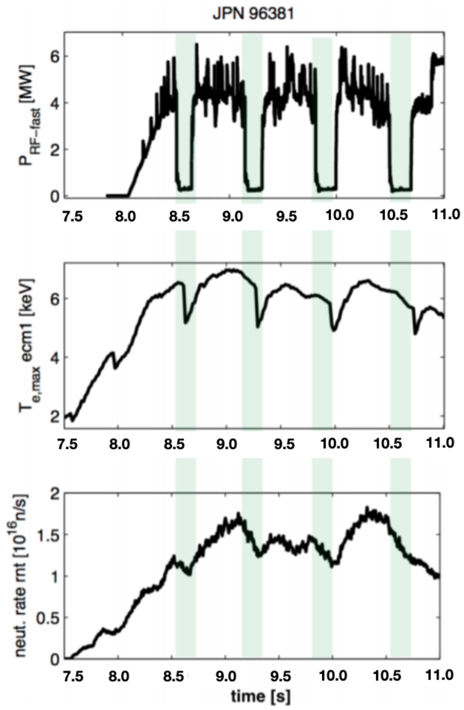

FIGURE 6. Sawtooth pacing testing in JET D shot 96381: the top plot depicts the RF power, the middle one the core electron temperature and the bottom one the neutron rate.

CONCLUSIONS

A second DT campaign - aimed at obtaining input relevant for ITER - has been successfully finished in JET. "Baseline" scenario discharges have been optimised and tested. Aligned with the present plans for ITER's activated phase, the Baseline scenario operates at high field and current and hence at high density. The auxiliary power required for these discharges is near the limit of what JET's systems can provide. Fusion powers of almost $9MW$ and energies of $12MJ$ have been reached in DT plasmas. Preliminary studies and experiments showed that the extension of the usual JET RF heating "work horse" to DT (combined fundamental cyclotron heating of a Hydrogen minority and second harmonic heating of the Deuterium bulk and beam in a $(H)-D-T-(D_{NBI})-(T_{NBI})$ plasma) is a suitable candidate for addressing the challenges posed by approaching the JET ILW machine limits. Both the use of H and ^3He as minorities is an option, the former having the advantage of creating higher energy tails allowing achievement of a peaked electron temperature profile and ensuring expulsion of high-Z impurities from the core and the latter marginally allowing better RF induced ion heating. In view of its wider potential, the former was exploited in the actual DT shots. Two interesting regimes are found for either minority: a low concentration window where minority and bulk tails are simultaneously formed, and a second at somewhat higher minority concentrations where second-harmonic tails have largely disappeared but minority tails are present. The first of these regimes is used in the main phase of the discharge while the latter - in view of the fact that it stays potent even at low temperature - was exploited in the "landing" of high performance discharges. Since operation at high current comes with increased risk for dangerous disruptions, a real time control system was developed to "land" discharges. The role played by the RF waves and by the beams is different. Although an order of magnitude more beam power compared to RF power is available at JET, the RF core power density is significantly higher than that of the beams. Formation of high energy RF tails slowing down on electrons has an indirect beneficial effect on the beam deposition: cranking up the electron temperature by high energy RF tails slowing down, shifts the critical velocity to higher values and allows to channel more beam power to ions in the core. The combined effect allows peaked core electron as well as ion deposition profiles. A wealth of data - including information on high energy minority, beam, bulk and alpha particle populations - is available and will facilitate deepening of the understanding of dynamics in DT plasmas.

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