Fundamental cyclotron ^{3}He minority ICRF heating experiments in H plasmas in JET in presence of the ILW

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Introduction

Efficient plasma heating schemes are a prerequisite for reaching fusion relevant temperatures in fusion machines. On the road to reaching ignition, non-activated scenarios - such as $(^3He)-H$ plasmas - will first be used to characterise plasma dynamics. Moreover, ^3He minority heating is intended to be adopted during the ramp-up phase of $D-T$ pulses in ITER to increase the fraction of bulk ion heating and to boost the fusion reactivity. Core fundamental ^3He minority cyclotron heating experiments were performed in hydrogen majority plasmas during the 2014 JET hydrogen campaign to help determining the road ITER should take.

Experimental results

Though the accent of the here discussed experiments was on obtaining insight in RF (radio frequency) heating dynamics, the parameters were chosen in a more general context, namely to help developing baseline heating scenarios in all-metal-wall fusion machines and allowing to ensure high confinement (H-) modes while preventing heavy impurity accumulation in the core: (i) The operating field and current were fixed at $B_o = 3.25T$ and $I_P = 2.5MA$. (ii) Up to 5MW of ICRF power were coupled using the A2 antennas in dipole phasing. To place the ^3He cyclotron layer in the core, the experiments were performed using $f = 33MHz$. (iii) Densities of the order of $n_{e,o} \approx 4 \times 10^{19}/m^3$ were used.

Compared to earlier $(^3He)-H$ experiments (see e.g. Mayoral et al. [1] and Van Eester et al. [2]), $n_{e,o}$ was higher by a factor of $1.3-1.4$. Operation at higher density reduces the temperature that can be reached. Whereas core electron temperatures up to $T_{e,o} \approx 4.5keV$ were observed when applying $5MW$ of RF power under similar conditions in the past, the maximum T_e reached now was merely $2.7keV$. No ion temperature profile is available but a 1-point guess at minor radius $\rho \approx 0.3m$ locally yields $T_i \approx 2.2-2.3keV$ while $T_e(0.3) \approx 1.8-2keV$. The left subplot of Fig.1 depicts the electron temperature. The present profiles are clipped while they were strongly peaked in the past. In absence of sawtoothing and any other anomalous transport enhancements, $T_{e,o} \approx 3.4keV$ could have been reached (see the dashed curve in Fig.1-left). For *identical* energy, the relative fraction of the peak temperatures would be consistent with the imposed density change ($4.5/3.4 \approx 1.3$) but the fact that the plasma energy was even *higher* by roughly a factor 1.5 in the recent experiments points to the differing role of energy source/loss channels. Obvious candidates that come to mind are transport phenomena of diffusive/convective type in between sawtooth crashes and shorter timescale mechanisms associated with the crashes themselves. On the other hand, one may wonder if the energy sources were less efficient or radiation more dominating.

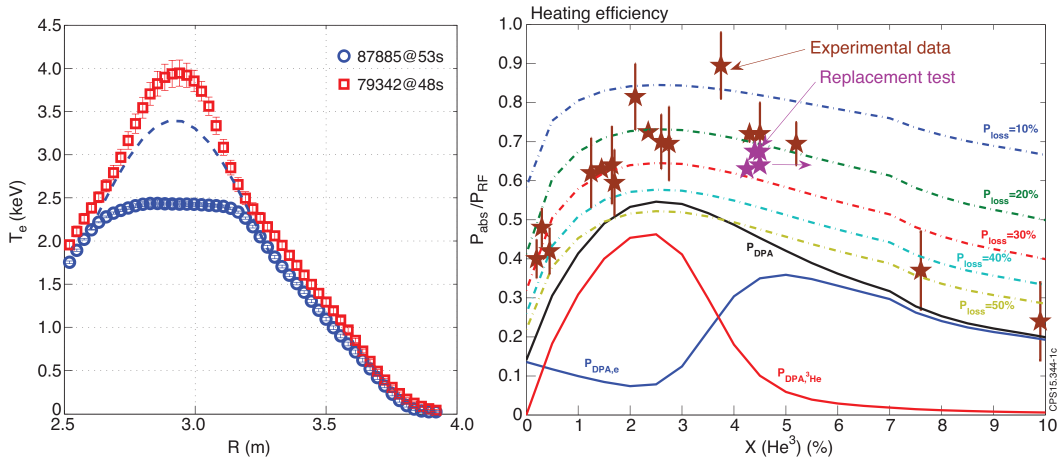

Figure 1: *Electron temperature profiles for recent ITER-like wall shot* #87885 *and comparison with Carbon wall shot* #79342 *both with* $P_{RF} = 4MW$ *(left), and experimental (stars) and theoretically predicted (lines) heating efficiency as a function of the* ^3He *minority concentration (right).*

The global RF induced energy increase was $0.25MJ/MW$, comparable to past results. It was shown through break-in-slope (BIS) analysis of the energy that up to 80% of the RF power launched was retrieved in the main plasma. In line with preparatory modelling and analysis, optimal heating was achieved at a ^3He minority concentration of around 3% (see Fig.1-right). Recall that the BIS method identifies instantaneous modification and does not capture transport effects. Bolometry shows that 20 to 30% of the launched power is radiated as bulk radiation. Compared to the earlier experiments, the peaking of the radiation was similar; no signs of impurity accumulation were seen in the main heating phase. The total bulk radiation was 60% higher but the energy in the recent experiments was already higher by as much as $0.4MJ$ before the RF heating was switched on (operating at higher I_p yields higher Ohmic power). At higher powers, the radiated power increases but the fraction stays roughly unchanged. The fraction of the radiated power is high at very low concentrations and re-increases beyond the $X[^3He]$ at which heating is optimal. Correcting the theoretically obtained prediction for the heating efficiency (labeled as DPA i.e. double pass absorption in the right subfigure of Fig.1 and obtained by the 1D wave propagation and damping code TOMCAT [3]) for the observed - radiative - losses yields efficiencies in fair agreement with the heating efficiencies found via BIS analysis. The total double pass absorption is the sum of the power absorbed by the ^3He minority and the electrons. To the exception of the region of negligibly small minority concentrations ($X[^3He] < 0.5\%$) ^3He minority fundamental cyclotron heating dominates the absorption until the mode conversion regime is reached at $X[^3He] = 3-4\%$, after which electron absorption is stronger than ion absorption. The overall double pass absorption dies away slowly beyond $X[^3He] \approx 5\%$. RF induced fast minority ion tails were observed. The tails are most prominent at modest concentrations but require a minimum of ^3He to be present, consistent with what is expected from theory. The left subfigure of Fig.2 shows the fast ion flux data obtained from the neutral particle analyser for the energy range between 200 and $400keV$.

Whereas the global heating efficiency is explained satisfactorily invoking global radiation losses, the inability to rebuild a peaked core electron temperature profile after a sawtooth crash is striking. Intended for preparing H-mode studies to be performed when topping up the RF power by neutral beam injection, the adopted value of I_P for the chosen B_o could not prevent q_o from dipping under 1 at the adopted auxiliary power level. One aspect that helps understanding why the temperature profile cannot recover is closely related to fast particle dynamics. Fig.2-right shows the redistributed power deposition profile as obtained from the 2D wave solver CYRANO [4] and the 1D Fokker-Planck solver StixRedist [5]; transport phenomena such as equipartition between bulk ions and electrons - more important at higher densities - were *not* accounted for in this simulation. Most of the power absorbed centrally by the ^3He minority is Coulomb collisionally redistributed to the bulk *ions*. Simulations made for earlier experiments (plot not included) yield another, more usual result: the fast tail transferring most of its energy to the *electrons*. This difference - mainly due to the higher collisionality - makes that a smaller fraction of the RF power is available to help T_e recover from sawtooth crashes if they occur. Note also that the deposition profile has a finite extent. In view of the error bars on various quantities, a fraction of the RF power might not even be available inside $q = 1$ to help rebuilding T_e.

The clipping limits the potential of ICRH to build up a strong electron temperature gradient. Since the sawtooth frequency f_{ST} scales as $T^{-3/2}$ [6], low T_e yields high sawtooth frequencies and hence tends to keep the core electron temperature low through frequent flushing. It requires a sufficient amount of electron heating to overcome this effect. Transport studies need to be undertaken to determine if the observed T_e dynamics can be understood.

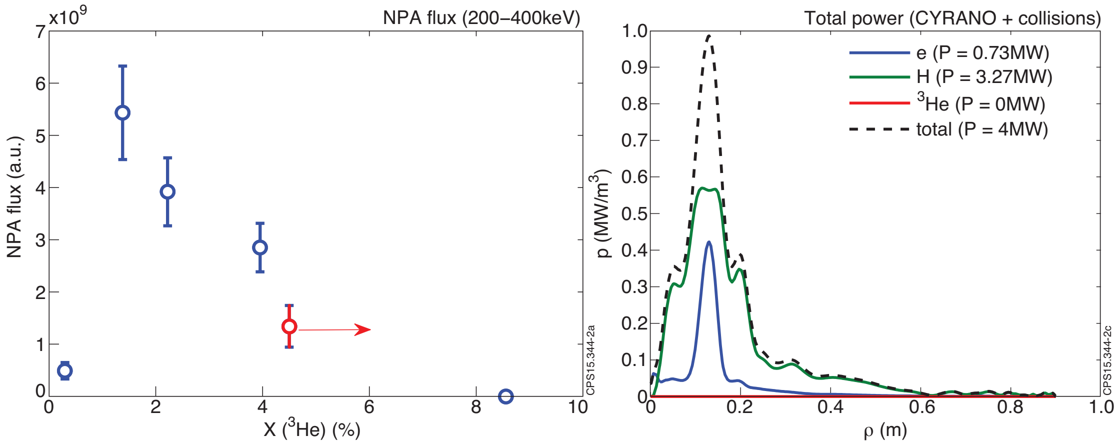

Figure 2: *Neutral particle analyser fast ion flux as a function of the ^3He minority concentration (left), and power deposition profile after Coulomb collisional redistribution of the RF induced minority tail energy to bulk ions and electrons as a function of the magnetic surface labeling parameter ρ (right).*

^3He being an extremely expensive gas [9], reducing its consumption is desirable. From the RF point of view, the key role of a minority population is to affect the polarization of the wave, hereby increasing or reducing the potential of a wave to transfer its energy to the plasma. Exploiting this dependence, Kazakov proposed replacement schemes whereby not readily available gases can partly be substituted by more common ones while not affecting the wave characteristics significantly [10]. Some first tests were performed to assess the potential of a ^3He replacement scheme relying on puffing N_2, one of the D-like impurities, into the *H* plasma. Although further testing is needed, these first results were promising. Two indications are (i) the purple stars added to the heating efficiency left subplot of Fig.2, and (ii) the red circle added to the right subfigure of Fig.2. Both data confirm the expected trend, although the *N* injection was modest.

Conclusions

^3He minority fundamental cyclotron heating experiments were performed in JET in a H majority plasma in the framework of optimising scenarii for the nonactivated phase of future fusion machines. As is characteristic for so-called inverted schemes, optimal heating occurs at ^3He minority concentrations of a few percent, and the heating efficiency dwindles when $X[^3He]$ goes beyond $6-7\%$. The heating itself was fairly efficient provided the proper $X[^3He]$ was used (the optimal efficiency reached was $\approx 80\%$ at $X[^3He] \approx 3\%$); the obtained net heating performance crudely matched earlier results: $0.15MJ/MW$. Operating at - for L-mode - high density successfully mitigated the typically high P_{rad} and W content observed in lower $n_{e,o}$ L-modes despite the low central temperatures reached, hinting at reduced edge high Z impurity sources. However, inside the $q = 1$ surface, the electron temperature is flat. The combined effect of high collisionality, radiated power and sawtoothing activity at - too - modest auxiliary heating power is thought to be responsible for the observed phenomenology but more detailed modelling is needed for better understanding. This illustrates the challenge of reaching high core (electron) temperatures in high collisionality plasmas (such as high I_p baseline H-modes) and confirms the need for high power ICRF or NBI preheating as well as the right choice of the q-profile. One directly RF-related contributing factor is that - opposite to what usually is the case and due to the chosen operation point - the minority tail Coulomb collisionally transfers the bulk of the wave energy it absorbs to the thermal majority ions and hence does not significantly contribute to the rebuilding of the core electron temperature. Optimising a heating scenario not just requires finding suitable parameters guaranteeing efficient absorption of the auxiliary energy, but also necessitates studying the losses and inefficiencies associated with these parameters.

Acknowledgements

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