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Abstract: Heating single ion species plasmas with ICRF is a challenging task: Fundamental ion cyclotron heating ($w = w_{ci}$) suffers from the adverse polarization of the RF electric fields near the majority cyclotron resonance while second harmonic heating ($w = 2w_{ci}$) typically requires pre-heating of the plasma ions to become efficient. Recently, $w = 2w_{ci}$ ICRF heating was tested in JET-ILW hydrogen plasmas in the absence of neutral beam injection (L-mode). Despite the lack of pre-heating, up to 6MW of ICRF power were coupled to the plasma leading to a transition to H-mode for P_{ICRH}>5MW in most discharges. Heating efficiencies between 0.65-0.85 were achieved as a combination of the low magnetic field adopted (enhanced finite Larmor radius effects) and the deliberate slow rise of the ICRF power, allowing time for a fast ion population to gradually build-up leading to a systematic increase of the wave absorptivity. Although fast ion tails are a common feature of harmonic ICRF heating, the N=2 majority heating features moderate tail energies (<500keV) except at very low plasma densities ($n_{e0}<3x10^{19}/m^3$), where fast H tails in the MeV range developed and fast ion losses became significant, leading to enhanced plasma wall interaction. The main results of these experiments will be reported.

INTRODUCTION

Heating single ion species plasmas at their fundamental cyclotron frequency using the fast magnetosonic wave is extremely challenging [1]: At the cyclotron resonance where the wave absorption takes place the electric field component rotating in the same sense as the ions and responsible for the cyclotron heating vanishes [2]. An easier option is to rely on higher cyclotron harmonic scenarios, which do not suffer from this screening effect [3] and actually work better when large minorities (or majority) resonant ions are present. For example, second harmonic (N=2) Tritium heating is the reference type of ion cyclotron heating chosen for ITER's DT plasmas [4]. Harmonic cyclotron heating is a finite Larmor radius effect ($r_L=v_\perp/w_c$) which means it is only efficient provided the temperature is sufficiently high: The N=2 ICRF heating scales with $|J_1(k_\perp r)|^2$, where J_1 is the Bessel function and $k_\perp$ is the magnitude of the wave vector component perpendicular to the confining magnetic field. At modest temperature $|J_1|^2 \sim (k_\perp r/2)^2$ is simply proportional to the perpendicular energy and thermal ions feature lower ICRF absorptivity than more energetic ones. It can readily be seen, however, that reducing the magnetic field is equally beneficial for cranking up the potential of N=2 heating. For a non-active operation phase of ITER at reduced magnetic field ($B_0 \leq 2T$), N=2 majority hydrogen ICRH is a most suitable heating scenario [5]. As a proof of principle, this heating scheme was explored in JET L-mode plasmas with similar RF settings (B_0=1.8T, f=51.5MHz) during the recent H campaign. The main results are reported in this paper.

[*] See the *Appendix of F. Romanelli et al., Proc. 25th IAEA Fusion Energy Conference, 2014, Saint Petersburg, Russia*

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PRELIMINARY SIMULATIONS

Figure 1 shows the results of N=2 H majority ICRH simulations using the TOMCAT code [6] for typical conditions of the JET experiments: B_0=1.8T, f=51.5MHz, $n_0=3x10^{19}/m^3$ and T_0=2keV. The left subplot depicts the deposition profile of the target (thermal) plasma while the middle figure shows the same but assuming a 2% fraction of fast H ions with effective temperature 100keV. The single-pass absorption (SPA) increases from 40% in the former to 60% in the latter due to the additional absorption of the fast H ions, illustrating the advantage of preheating a subpopulation of the plasma ions for starting this scheme. This can be achieved either by direct NB injection or by gradually building-up the RF-induced ion tails. The right subplot shows the results of the same heating scheme but adopting parameters relevant for ITER's half-field non-activated phase ($n_0=3x10^{19}/m^3$ and T_0=8keV). In view of the higher temperature and of the different machine size, this scenario has a 100% SPA in ITER.

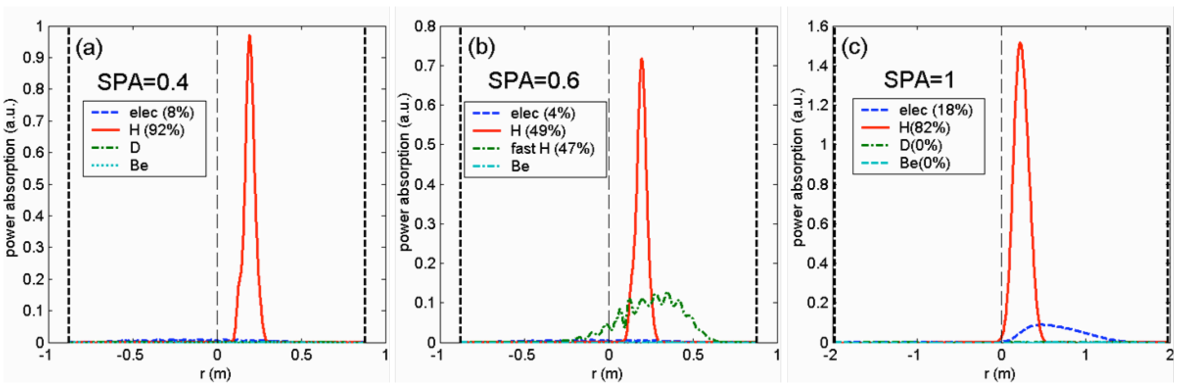

FIGURE 1. ICRF simulations of N=2 H majority ICRH (B_0=1.8T, f=51.5MHz): (a) JET experimental parameters; (b) JET parameters with 2% of fast H ions at 100keV; (c) ITER half-field parameters. Traces of D and Be were also considered in the simulations.

COMPARISON WITH NBI PERFORMANCE

A comparison between the performance of a series of ICRH and NBI heated discharges is given in Fig. 2, where (a) the plasma stored energy, (b) the bulk plasma radiation and (c) the edge W concentration (a.u.) are plotted as function of the auxiliary power applied. The database represents similar plasmas with B_0=1.8T, I_p=1.65MA, $n_{e0}=3x10^{19}/m^3$ and T_{e0}=1-2keV (depending on the auxiliary power level). Most points are for L-mode but some discharges reached H-mode when P>5MW of ICRF heating was applied, provided the plasma density was favourable for the L-H transition [7].

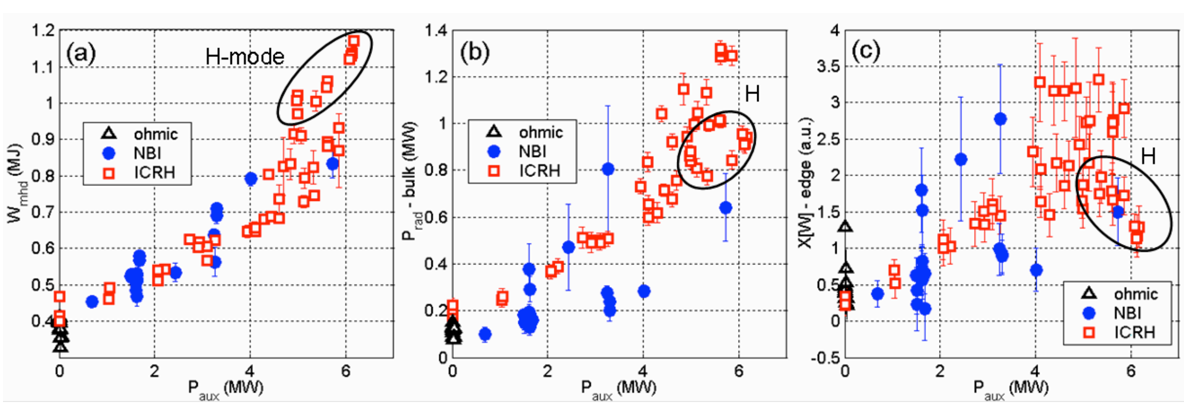

FIGURE 2. Comparison of NBI and N=2 ICRF heating performance in L-mode hydrogen plasmas in JET-ILW: (a) plasma stored energy (EFIT); (b) bulk plasma radiation (bolometer); (c) edge W concentration (VUV spectroscopy).

NBI and ICRF heating show a similar performance and the plasma energy (a) increases from ~0.4MJ (1MW ohmic heating) to 0.9MJ when 6MW of auxiliary power is injected. Due to the improved confinement, the H-mode points lie on a higher cloud reaching up to 1.2MJ for P_{aux}=6MW. The experimental heating efficiencies (inferred from break-in-slope analysis of the plasma energy) were within 0.65-0.85 for both NBI and ICRF heating. Although the heating efficiency itself is good, the confinement at low B_0 is poor, which explains the rather modest energies and temperatures (T_0<2keV) reached despite the relatively high power applied. Generally speaking, ICRH gives rise to higher bulk radiation (b) and W content (c) than NBI heating and both quantities increase linearly with the input ICRF power. The radiated fraction with ICRH is only about 20%, which is comparable to the values observed in N=1 ICRH scenarios in similar conditions [8]. Some NBI points exhibit unusually high radiation and X[W] values and are associated to transient impurity events (see the large error bars). Note that the radiation and W concentration are reduced in H-mode as compared to L-mode for the same input power.

DENSITY SCAN: IMPURITIES, FAST PARTICLES AND PWI

The plasma density has shown to play a key role in the performance of the N=2 H majority ICRH scheme. From Fig. 3, one sees that although the density only weakly affects the plasma energy (a), its effect on the bulk radiation (b) and edge W content (c) is more pronounced: both quantities drop considerably at higher densities and for $n_{e0}>3.5\times10^{19}/m^3$, the bulk radiation fraction is below 15% while the edge W concentration is reduced by a factor of ~4 w.r.t. its value at low density. This is caused by two independent effects: (i) the cooling of the SOL due to higher gas injection (lower sputtering yields) and (ii) the fact that the RF wave absorption in the given conditions is enhanced when the plasma density becomes larger.

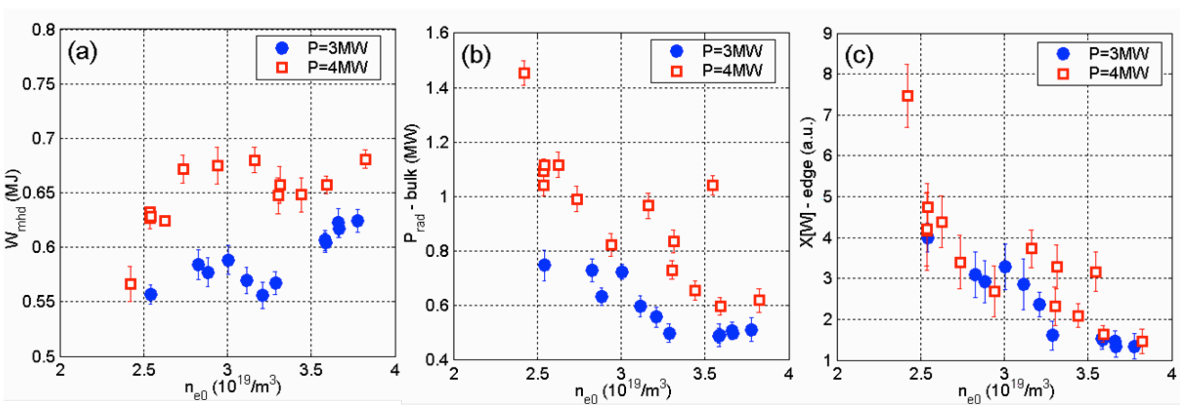

FIGURE 3. Impact of electron density on N=2 H majority ICRH performance: (a) Plasma stored energy; (b) Bulk plasma radiation (bolometer); Edge W concentration (VUV spectroscopy).

As increased ICRH power yields larger impurity levels and higher radiation, and given the fact that these may affect the ICRF heating efficiency itself, it is critical to understand the causal link between these phenomena. The standard interpretation is that the electric fields close to the antenna non-resonantly accelerate ions in the SOL via RF sheath rectification effects and give rise to enhanced first wall sputtering [9]. Alternatively, sputtering can be caused by ICRH induced fast particles that are not confined in the bulk plasma and bombard the wall. The former is often the signature of a weak absorption scheme, while the latter is – quite on the contrary – the result of a heating scheme which efficiently accelerates a small fraction of particles to high energies, such as harmonic ICRH. Fig. 4a shows that there is a critical density for which fast H ion tails become important in the experiments. Below this threshold the fast H flux inferred from NPA measurements rises fast when the density is decreased. At higher ICRH power, this threshold shifts to higher densities. All these observations are consistent with the formation of high-energy H tails via second harmonic heating. In Fig. 4b, one sees that the temperature of the poloidal limiter is closely correlated with the formation of the fast H tails: above the critical density the temperature is crudely constant while below it increases at a rate prescribed by the amount of power applied, reaching dangerously large values even at P=4MW. Interestingly, the beryllium content (Fig. 4c), which typically increases with density due to the larger number of sputtering D ions present in the SOL, also increases when the density is reduced below the threshold, confirming the enhanced plasma-wall interaction (PWI) caused by the fast H ions. The minimum Be level also shifts towards larger densities at higher ICRH power levels.

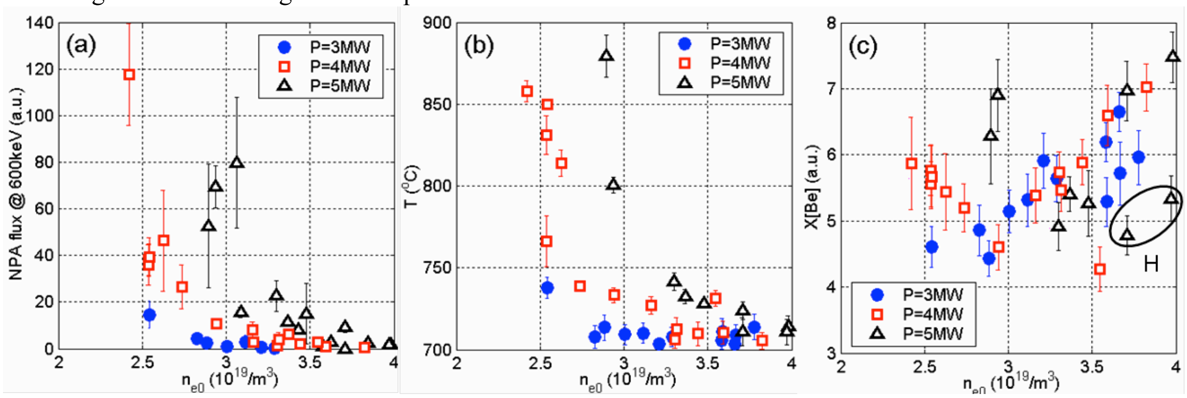

FIGURE 4. Fast ion acceleration and impact on plasma-wall interaction as function of the plasma density for various ICRF power levels: (a) NPA hydrogen flux at E_H=600keV; (b) Poloidal limiter temperature (IR camera); (c) Edge Be concentration (visible spectroscopy).

It has been observed that puffing gas close to the antennas magnetically connected to the hot-spots is beneficial for reducing the above described effect. For typical PWI induced by RF sheath effects, this is believed to be related to the reduction of the poloidal (increased coupling) and parallel (increased electron mobility) components of the RF electric fields near the antenna caused by the local density enhancement [10]. For the PWI induced by fast particle losses described here, the interpretation is less clear and more systematic studies of the gas injection location w.r.t. hot-spots are needed.

SUMMARY

Second harmonic H majority ICRH experiments at low magnetic field were performed in JET. The RF heating efficiency is good and comparable to fundamental ICRH and NBI heating in similar conditions (0.65-0.85). Despite the low radiated power fraction (15-20%), the overall heating performance is modest due to the poor confinement at low field and current characteristic of the L-mode plasmas studied. H-mode was reached in some pulses for P_{ICRH}>5MW and a substantial increase in the energy content together with reduced radiation/impurity fractions is the immediate result. Both the impurity level as well as the plasma radiation drop strongly when the density is increased. Under a threshold density (which is function of the applied power) high-energy H tails are formed. In these conditions, the fast particle losses become important and also contribute to the enhanced PWI typically observed with ICRH at low densities, sometimes leading to strong heating of the poloidal limiters (hot-spots). This ICRH scheme has shown strong potential for heating single-species / low magnetic field plasmas and should be considered if a low-field commissioning phase in ITER takes place.

REFERENCES

1. A. Krasilnikov *et al.*, *Plasma Phys. Control. Fus.* **51(4)** (2009) 044005
2. F. Perkins, *Nucl. Fus.***17** (1997) p.1197
3. T. Stix, *Waves in Plasmas*, AIP Press (1992)
4. D. Van Eester *et al.*, *Nucl. Fus.* **42** (2002) 310
5. E. Lerche *et al.*, IAEA-FEC 2010 (Daejon)
6. D. Van Eester et al., *Plasma Phys. Control. Fus.* **40** (1998) p.1949
7. C. Maggi et al., *Nucl. Fus.* **54(2)** (2014) 023007
8. E. Lerche et al., *Nucl. Fus.* **54** (2014) 073006
9. J. Myra *et al.*, *Nucl. Fus.* **46** (2006) S455
10. E. Lerche *et al.*, *Journal of Nucl. Materials*, PSI (2014) (in press)