Experimental investigation of ICRF heating scenarios for ITER's half-field Hydrogen phase performed in JET

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Abstract. Two ICRF heating schemes proposed for the half-field operation phase of ITER in Hydrogen plasmas - fundamental H majority and 2nd harmonic ^{3}He ICRF heating - were recently investigated in the JET tokamak. Although the same magnetic field and RF frequencies (B_0=2.65T, f=42MHz and f=52MHz, respectively) were used, the density and particularly the plasma temperature foreseen for the initial phase of ITER could not be matched in JET. Modest heating efficiencies (η<0.4) with typically dominant electron heating were found for both scenarios and strong plasma-wall interaction manifested by large impurity content and high radiation losses was observed. This effect is stronger for the ^{3}He ICRF heating case than for the H majority heating case. It was verified that concentrations as high as X[^{3}He]≈20% are necessary to observe significant ion heating in the 2nd harmonic ^{3}He ICRF heating scheme. ICRF accelerated ions up to 50keV in the fundamental H heating experiments and up to 200keV in the 2nd harmonic ^{3}He ICRF heating experiments were detected with NPA diagnostics. While hints of an increase in the heating efficiency as function of the plasma temperature were observed in the H majority case, the He^3 concentration was the main 'handle' for enhancing the heating efficiency in the 2nd harmonic ^{3}He heating scenario.

1. Introduction

The non-active phase of ITER [1] will start with Hydrogen (H) plasmas at reduced magnetic field. In H plasmas and for the designed frequency range of the ICRF heating system in ITER (f=40-55MHz), only fundamental ion-cyclotron heating of H ions (at f≈40MHz) and second harmonic (N=2) ion-cyclotron heating of ^{3}He ions (at f≈53MHz) are feasible for central ion heating at the nominal half-field value of B_0=2.65T. None of the two ICRF scenarios cited above are high performance heating schemes from the RF point of view: The fundamental H majority scenario suffers from the 'adverse' polarization of the RF fields close to the ion-cyclotron layer of the majority H ions ('screening effect') [2] whereas the N=2 harmonic ^{3}He heating scheme requires relatively large fractions of

[*] See the Appendix of F. Romanelli et al., Proceedings of the 22nd IAEA Fusion Energy Conference 2008, Geneva, Switzerland

‘minority’ ions to become efficient. Given the fact that the initial ITER operation relies on every MW of auxiliary heating power that can be injected into the plasma, experiments aiming at assessing the ICRF heating performance of the ITER half-field scenarios in H plasmas were recently performed in JET.

The ICRF parameters of the half-field phase of ITER were closely reproduced in the JET experiments: The fundamental Hydrogen heating scenario was studied at f=42.5MHz / B_0=2.65T and the N=2 ^{3}He ICRH experiments were done at f=51.5MHz / B_0=2.65T. In these conditions, the fundamental ion-cyclotron resonance layer of the H ions is located around R=2.85m whereas the N=2 ion-cyclotron resonance of the ^{3}He ions is located at approximately R=3.15m, respectively. Dipole phasing was used in both experiments and up to 5.5MW of ICRF power was coupled to the plasma. Aside from the different ICRF parameters and the dilution of the H plasmas with ^{3}He in the N=2 ^{3}He ICRH pulses, the plasmas were similar in the two experiments. Both experiments were performed in L-mode and adopted a plasma geometry that favours the ICRF antenna coupling, with antenna plasma distances varying between 9.5-11.0cm (ROG = 4.0-5.5m). Typical central densities of $n_0=3\text{x}10^{19}/m^3$ and central temperatures ranging from Te=2-4keV, depending on the NBI power applied ($0<P_{NBI}<8$MW), were obtained in the experiments.

Since there were no H beams available for the experiments, D beams were used both for diagnostic purposes (charge-exchange, MSE) and to pre-heat the plasma. The D NBI injection angles and energies (mostly ~80keV) were carefully selected to minimize the harmonic ion-cyclotron absorption of the beam deuterons in the two scenarios. The fundamental H majority heating experiments were performed first and no ^{3}He was injected in the machine to avoid spurious ^{3}He absorption / acceleration near the plasma edge. In the second harmonic ^{3}He heating experiments, the injection of ^{3}He was controlled using a PID (proportional–integral–derivative) feedback control on the gas valve actuation based on the real-time measurements of line emission intensities of several ion species by visible spectroscopy [3]. The ^{3}He concentration X[^{3}He], was varied from 5-25% in these experiments.

2. Experimental results

The ICRF heating efficiencies (η = absorbed power / coupled power) for electrons and (bulk) ions obtained by analyzing, respectively, the ECE and charge-exchange signal responses to fast variations in the applied ICRF power [4] are depicted in Fig.1 for the fundamental H majority experiments (left) and for the second harmonic ^{3}He heating experiments (right). In both scenarios the electron absorption is mainly due to fast wave Landau damping and not to collisional damping with ICRF accelerated ions, as is usually the case in minority ICRF heating schemes.

For the H majority case, the electrons absorb typically twice as much RF power as the ions and both absorptivities increase with the bulk plasma temperature, reaching a total heating efficiency of $\eta\approx0.4$ at T_e=2.5keV. The slope of the heating efficiency of the ions is somewhat steeper than the one for the electrons, indicating that the ion-cyclotron absorption of the H ions (rather than the electron absorption) is privileged when increasing the bulk plasma temperature within the studied range. For the 2nd harmonic ^{3}He scenario, the dependence of the heating efficiency with the temperature was minor, but a clear enhancement of the ICRF absorption for higher ^{3}He concentrations was observed. Note that it is the ion absorption that is mainly improved at higher ^{3}He concentrations and that the total heating efficiency reached at X[^{3}He]≥20% is similar to the one obtained for the H majority case ($\eta\approx0.4$). The ion heating at low X[^{3}He] (as initially proposed for ITER) is very small and the total heating efficiency is only about $\eta\approx0.2$ in these conditions.

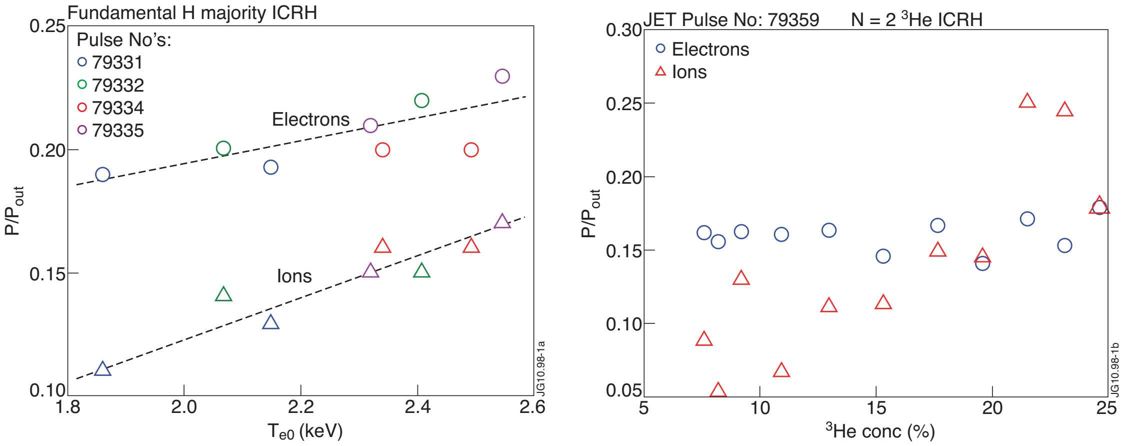

Figure 1: (left) Heating efficiencies obtained for electrons (circles) and for ion (squares) by exponential BIS analysis of the ECE and CXRS signals as function of the plasma central temperature; (right) Heating efficiencies for electrons (circles) and ions (triangles) obtained by the FFT analysis of the central electron and ion temperature signals as function of the ^{3}He concentration.

As mentioned, the low heating efficiencies obtained in both scenarios (compared to typical heating efficiencies of $\eta \geq 0.8$ observed in minority ICRF heating schemes) were actually expected: Fundamental majority ICRF heating suffer from the small values of the left-hand polarized RF field component near the ion-cyclotron layer whereas second harmonic heating scenarios typically require large fractions of the minority species to be efficient. Despite the low efficiencies of these heating schemes, fast H ions up to 50keV and fast ^{3}He ions up to 200keV were detected by the NPA diagnostics in the N=1 H and in the N=2 ^{3}He heating experiments, respectively, when 5MW of RF power was applied. When more than 5MW of NBI was applied together with the ICRF power in the N=2 ^{3}He discharges, RF accelerated D-beam ions in the MeV range (detected with γ-spectroscopy) accompanied by enhanced fast ion losses were observed.

An important consequence of the low ICRF absorptivity of these scenarios is the enhancement of plasma-wall interactions leading to relatively large impurity content and considerable radiation losses in the plasma. This is depicted in Fig.2 (left), where the total radiated power (bolometer) as function of the ICRF power applied is shown for the N=1 H (circles) and the N=2 ^{3}He (triangles) experiments. The data correspond to 0.4s time averaged values sampled throughout the experiments. The density, temperature and NBI power were similar in all the time intervals considered.

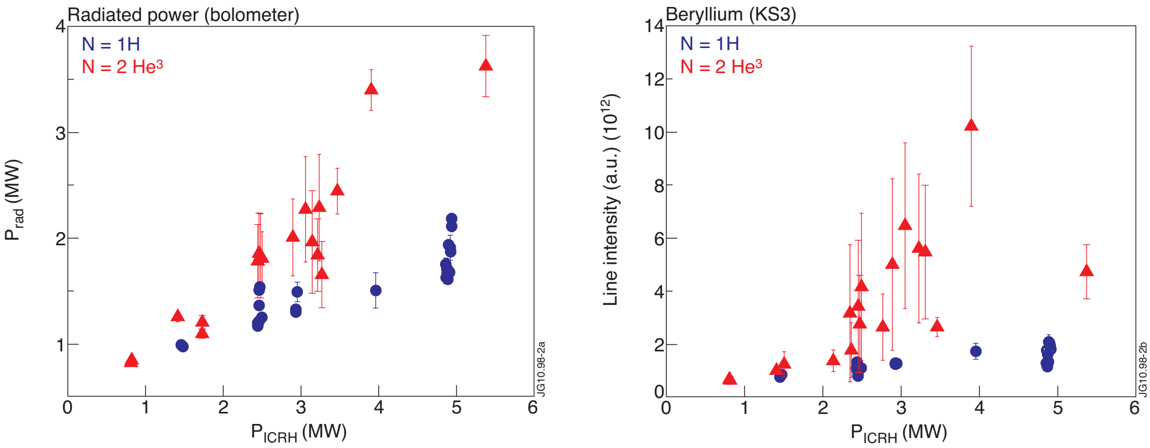

Figure 2: Total radiated power (left) and intensity of Be 527nm line (right) as function of the ICRF power for the N=1 H (circles) and the N=2 ^{3}He (triangles) ICRF heating schemes. The data correspond to 0.4s time averaged values with similar densities, temperatures and NBI power.

The fact that the radiation losses for a given ICRF power are higher for the N=2 ^{3}He case than for the fundamental H majority case is not only due to the presence of relatively large fractions of ^{3}He in the H plasma (higher Z_{eff}), but is related to a stronger RF-induced plasma-wall interaction observed in this case, leading to a higher impurity content in the plasma. This is depicted in Fig.2 (right), where the line emission intensity of the Beryllium measured by visible spectroscopy is shown as function of the ICRF power for the two scenarios. The same time intervals as on the left figure were considered. A similar study for the C^{+6} and C^{+4} spectroscopy measurements (not shown) indicates that most of the additional radiation observed in the N=2 ^{3}He case comes from the plasma edge rather than from the bulk plasma, but a more detailed analysis based on 2D bolometer tomography is still ongoing. The fact that the impurity content is higher for this case than for the fundamental H majority case despite of the similar ICRF heating efficiencies (and similar antenna coupling conditions) is believed not only to be related to the different RF sheath rectification effects at the two distinct operation frequencies but also to the different fast ion losses observed in the two cases. As a matter of fact, in the N=2 ^{3}He experiments, considerable parasitic RF power absorption of NBI deuterons (with 2nd and 3rd harmonic cyclotron resonances in the plasma) was observed when more than 5MW of NBI was applied together with the ICRF power. These ions are accelerated to high energies leading to an enhanced number of fast ion losses when compared to the fundamental H majority heating case (where the parasitic D absorption was practically negligible). Additionally, the fact that the transport / confinement properties of a pure H plasma and of a 10-20% ^{3}He diluted H plasma are different leading to distinct temperature / density profiles can also have a considerable influence on the radiation pattern, particularly near the plasma edge.

3. Summary

Results of JET experiments aiming at studying two ICRF heating scenarios proposed for the half-field phase of ITER in H plasmas (fundamental H majority heating and second-harmonic ^{3}He heating) were presented. The heating efficiencies obtained for the fundamental H majority heating scheme were around η=0.3-0.4 with dominant fast wave electron heating and hints of enhanced efficiency with increasing plasma temperature were observed. For the 2nd harmonic ^{3}He heating scheme, the efficiency varied from below η=0.2 (for low X[^{3}He]) up to η=0.4 when X[^{3}He]$\geq$20% was reached. It was shown that the increase in the heating efficiency with X[^{3}He] is mainly due to enhanced ^{3}He ion-cyclotron absorption, which exceeds the electron absorption at high ^{3}He concentrations. The low ICRF heating efficiencies associated to the rather poor confinement of the H plasmas in the experimental conditions described here lead to relatively strong plasma wall interaction in both scenarios.

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