ICRF heating scenarios in the ITER non-active phase operations

S.H. Kim[1], P. Lamalle[1], B. Beaumont[1], A. Loarte[1], A. Messiaen[2]
[1]*ITER Organisation, Route de Vinon-sur-Verdon, CS90 046, 13067 St Paul Lez Durance Cedex, France*
[2]*Laboratory for Plasma Physics-ERM/KMS, partner in the Trilateral Euregio Cluster, B-1000 Brussels, Belgium*

Introduction Access to H-mode conditions is one important operation milestone in the ITER non-active phase of operations allowing the characterization of plasma behaviour in H-mode at the ITER scale, the commissioning of edge localized mode (ELM) control schemes, and preparation for H-mode scenarios in the active phase with DD or DT plasmas. On the basis of present understanding, access and sustainment of H-mode plasmas in the ITER non-active operational phase will require high levels of auxiliary power even for half-current/half-field (7.5MA/2.65T) plasmas. This requires the use of all available auxiliary heating power including ion cyclotron resonance frequency (ICRF) heating in addition to hydrogen neutral beam injection (H-NBI) and electron cyclotron (EC) wave heating. For half-current/half-field plasmas in the non-active phase operations, the potential ICRF heating schemes are fundamental frequency H majority heating and second harmonic He^3 minority heating in H plasmas and fundamental frequency H minority heating in He plasmas [1-3]. In this work, these ICRF heating schemes are investigated in depth using a full wave ICRF code, TORIC [4]. Multiple ion species heated by ICRF heating and H-NBI are included and a range of background plasma conditions (L-mode/H-mode plasma profiles with varying fast/minority ion concentrations) are considered, in order to address the feasibility of the ICRF heating schemes in the ITER non-active phase operations. In addition, coupling of ICRF power in half-current/half-field He plasmas has been investigated using a semi-analytic antenna code, ANTITER II [5].

ICRF heating scenarios in H plasma operation Fundamental frequency H majority ICRF heating in H plasma at 42MHz (n_ϕ=27, a simple toroidal spectrum assumed in this work as

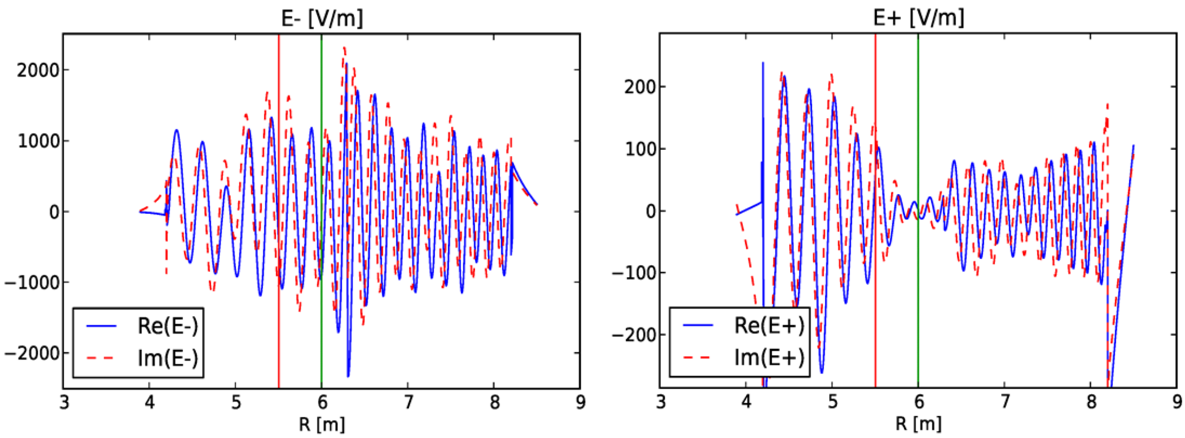

Figure 1. ICRF wave electric field components, E- (left) and E + (right) in the case that fundamental frequency H minority heating (f_{IC}=42MHz) is applied to 7.5MA/2.65T H-mode H plasma.

done in [1]) is first investigated with various assumptions, such as H-mode ($T_e(\rho=0)$=14.5keV, $T_i(0)$=12keV and $n_e(1)=2\text{x}10^{19}\text{m}^{-3}$), L-mode ($T_e(0)$=10keV, $T_i(0)$=8keV and $n_e(1)=1\text{x}10^{19}\text{m}^{-3}$), with/without ICRF heated H ions (peaked profile shape with $T_{fast}(0)$=100keV) and H-NBI fast ions (broad profile shape with $T_{HNBI}(0)$=870keV). These are categorized as four cases, (1) with both ICRF heated H and H-NBI fast ions, (2) with only ICRF heated H ions, (3) with only H-NBI fast ions, and (4) with no fast ions. Simulations performed using the TORIC code have shown that central electron heating is dominant for all four cases with the H-mode/L-mode conditions; implying that multi-pass wave absorption to ions is significant for this scenario [2]. Even in the case with both ICRF heated H and H-NBI fast ions (the ion heating was highest among the cases compared), single-pass wave absorption was not efficient as shown in Figure 1. The ICRF wave absorption has changed little even in the presence of He^3 ions (2.5% added to the H plasma) which has a second harmonic resonance layer far off-axis (R_0+1.6m at f_{IC}=42MHz).

Second harmonic He^3 minority ICRF heating in H plasma (equivalent to second harmonic T minority heating in full-field/full-current (15MA/5.3T) DT operation) is also studied as a potential candidate ICRF heating scenario in H plasma operation. The previous study in JET [2] demonstrated that the efficiency of this ICRF heating scheme can be improved along with He^3 ion concentration. The same assumptions were used for H-mode and L-mode plasma conditions and four cases, (1) with both ICRF heated He^3 and H-NBI fast ions, (2) with only ICRF heated He^3 ions, (3) with only H-NBI fast ions, and (4) with no fast ions, were studied with varying concentration of He^3 ions. Distribution of absorbed ICRF power normalized by the total absorbed power in the case 1 and 4 is shown in Figure 2. The horizontal axis represents the He^3 ion concentration. At low concentration of ICRF heated He^3 ions (<10%), the electron heating fraction was high, while ICRF wave absorption to the He^3 minority ions became high (>50%) as the ICRF heated He^3 ions concentration increased over 10%. however, such high concentration is not foreseen in ITER H operation. Even in this case, however, the wave electric field components were high across the second harmonic He^3 resonance layers implying that multi-pass wave absorption is still significant [1-2].

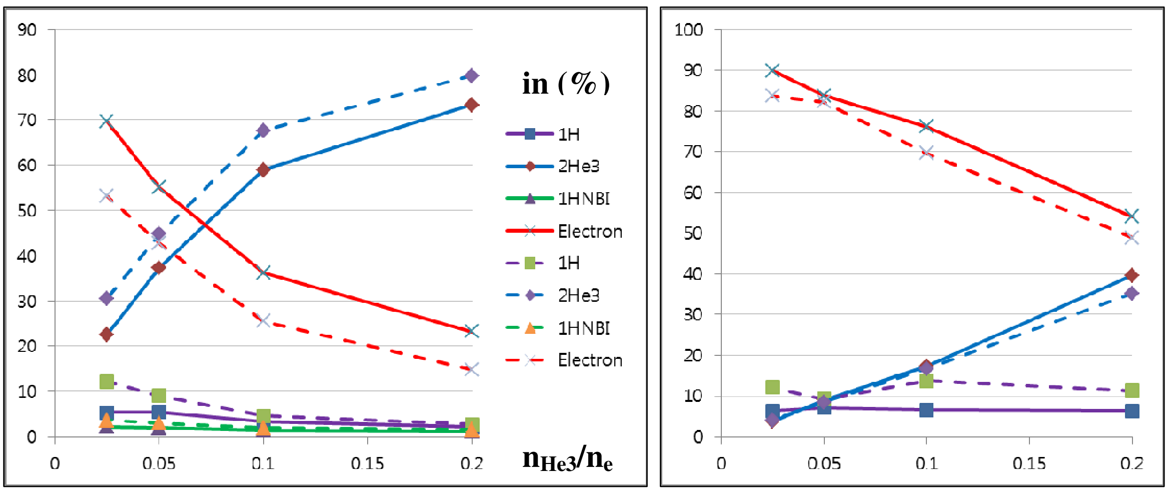

Figure 2. IC wave absorption with second harmonic He^3 minority heating (f_{IC}=52.5MHz) in H-mode (solid) and L-mode (dashed) H plasmas. (Left) Case 1 with ICRF heated He^3 ions and HNBI. (Right) Case 4 with no fast ions.

Fundamental frequency H minority ICRF heating in He plasma The L-H threshold power in He plasma is often found to be lower than that in H plasma. However, high fraction of H minority ions in He plasma (n_H/n_e>20%) can significantly increase the L-H threshold power [6]. In this respect, the fundamental frequency H minority ICRF heating (f_{IC}=42MHz) in He plasma has been investigated with varying the H minority ion concentration. Similarly to the previous studies, the same assumptions were used for H-mode and L-mode plasma conditions and four cases, (1) with both ICRF heated H and H-NBI fast ions, (2) only with ICRF heated H ions, (3) only with H-NBI fast ions, and (4) with no fast ions, have been compared. The fundamental frequency H minority heating was significantly high (70~80%) for a wide range of H ion concentration, in the presence of ICRF heated H ions and H-HNBI fast ions (Figure 3 (left)). In the absence of ICRF heated H ions (case 3 and 4), the fundamental frequency H heating was maximum around 5% H ion concentration with about 60~70% total power absorption. The detailed structure of the wave electric field components in the plasma (shown in Figure 3 (right) for case 4 with 2.5% H ion concentration) shows very good single-pass wave absorption to H minority ions. A comparison of H minority ion heating profiles also showed that the ion heating profile becomes on-axis in the presence of ICRF heated H ions. This requires a further study with realistic fast ion temperature profile peaked at the resonance layer. An additional scan on the plasma density in the absence of fast ions suggested that H minority ICRF heating would be a good candidate heating scheme for low density ITER He plasmas where H-NBI is not favourable due to its shine-though limit.

ICRF power coupling study using ANTITER-II The feasibility of ICRF power coupling to half-field/half-current He plasmas has been investigated using the ANTITER-II code [5]. 10MW ICRF power per antenna (subjected to 45kV design maximum voltage on the IC system) can be coupled to He plasmas with f_{IC}=40MHz and for various antenna phasing conditions. These results showed good agreement with recent TOPICA [7] simulations for a wide range of ICRF frequencies. The potential variation of ICRF coupling power in the

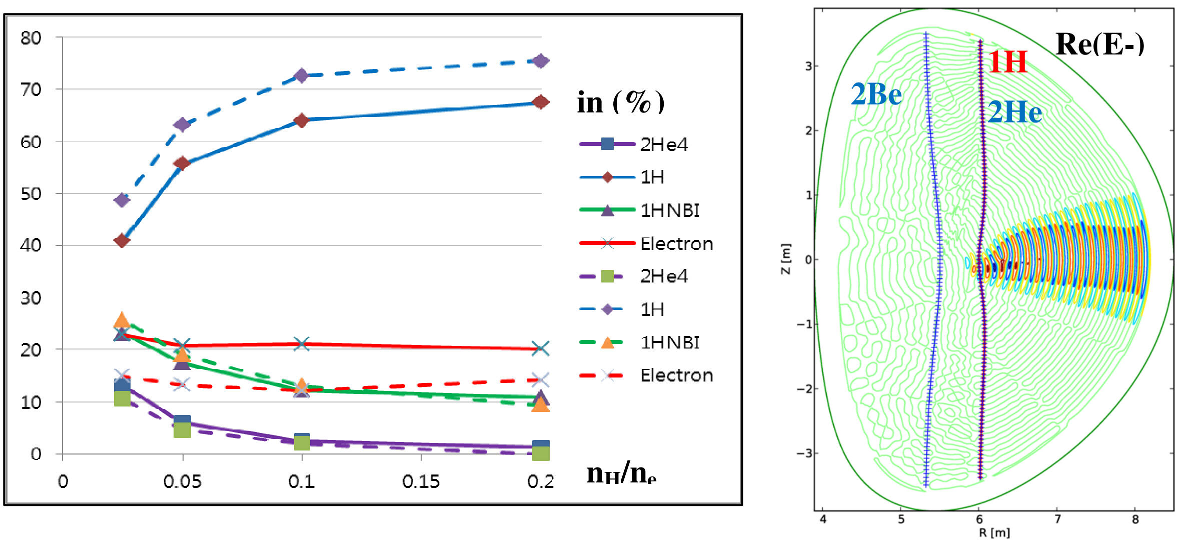

Figure 3. (Left) ICRF wave absorption with fundamental frequency H minority heating (f_{IC}=42MHz) in H-mode (solid) and L-mode (dashed). Case 1 with ICRF heated H and HNBI. (Right) ICRF wave electric field component, Re(E-). Case 4 with no fast ions (H-mode).

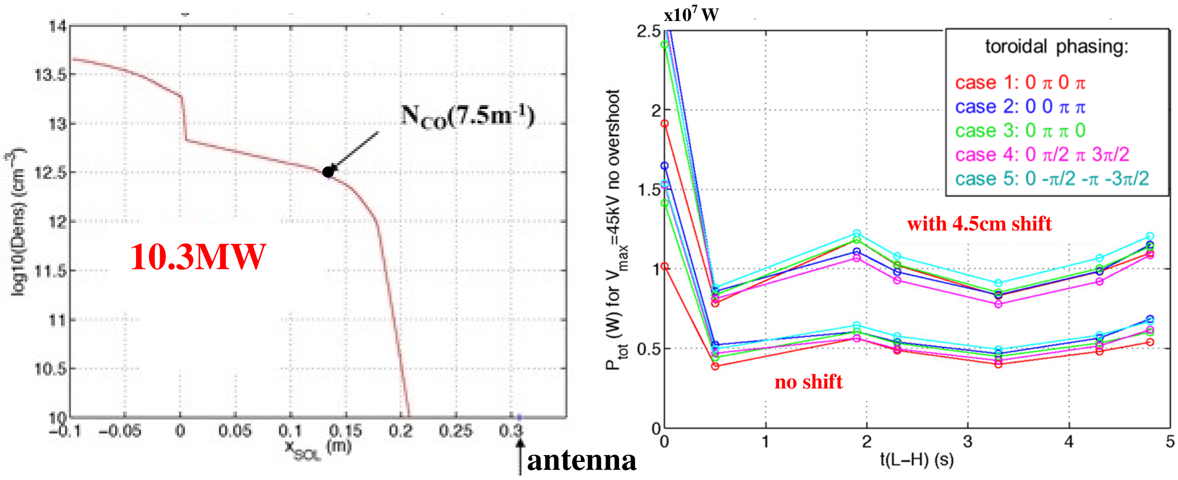

Figure 4. (Left) ICRF coupled power per antenna is reduced from 12.4MW to 10.3MW in the presence of steep density gradient near the separatrix. The distance between antenna and wave cutoff for assumed dipole phasing, $N_{co}(k_{//}=7.5m^{-1})$, is kept constant (18cm), and high far SOL density is assumed. (Right) ICRF coupled power per antenna is reduced to about 8MW (0.5s after the L-H transition), and then 10MW power coupling is recovered at 1s (with 4.5cm separatrix shift closer to the antenna).

presence of a steep density gradient near the separatrix predicted by a physics model [8] has been studied (Figure 4). Up to 20% of the coupled power to the plasma is reduced in the presence of a steep density gradient near the separatrix. However, it is not yet clear that this will be the case in ITER. Variation of ICRF coupling power during an L-H transition has been also studied prescribing the density profile evolution (obtained from a 15MA DT JINTRAC simulation and multiplied by 0.5). As shown in Figure 4 (right), about 10MW of ICRF coupled power per antenna was achievable 1s after the transition in the case that the separatrix is shifted 4.5cm closer to the antenna [9].

Summary and Conclusions ICRF heating scenarios in the ITER non-active operation phase have been studied and good single-pass wave absorption is observed when fundamental frequency H minority ICRF heating is applied to half-field/half-current He plasmas. The feasibility of good ICRF power coupling to He plasmas has been also studied at various plasma and antenna operation conditions.

Acknowledgements The authors thank to Dr. R. Bilato (IPP) and Dr. S. Pinches (IO) for their support for TORIC-5, and also to Dr. D. Milanesio (POLITO) and Eng. F. Durodié (LPP-ERM) for providing TOPICA simulation results. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

References

[1] R.V. Budny *et al.*, 2012 *Nucl. Fusion* **52** 023023
[2] E. Lerche *et al.*, 2011 *Plasma Phys. Control. Fusion* **53** 124019
[3] E. Lerche *et al.*, 2012 *Plasma Phys. Control. Fusion* **54** 074008
[4] M. Brambilla, 1991 *Plasma Phys. and Control. Fusion* **41** 1
[5] A. Messiaen *et al.*, 2010 *Nucl. Fusion* **50** 025026
[6] F. Ryter *et al.*, 2013 *Nucl.Fusion* **53** 113003
[7] V. Lancellotti *et al.*, 2006 *Nucl.Fusion* **46** S476
[8] R.J. Goldston *et al.*, 2012 *Nucl.Fusion* **52** 013009
[9] M. Kocan, *private communication*