ICRF heating scenarios in the ITER non-active phase operations

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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\textsuperscript{3} minority heating in H plasmas and fundamental frequency H minority heating in He plasmas \cite{1-3}. In this work, these ICRF heating schemes are investigated in depth using a full wave ICRF code, TORIC \cite{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 \cite{5}.

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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{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.}
\end{figure}
done in [1]) is first investigated with various assumptions, such as H-mode ($T_e(\rho=0)=14.5\mathrm{keV}$, $T_i(0)=12\mathrm{keV}$ and $n_e(1)=2\times10^{19}\ \mathrm{m}^{-3}$), L-mode ($T_e(0)=10\mathrm{keV}$, $T_i(0)=8\mathrm{keV}$ and $n_e(1)=1\times10^{19}\ \mathrm{m}^{-3}$), with/without ICRF heated H ions (peaked profile shape with $T_{\text{fast}}(0)=100\mathrm{keV}$) and H-NBI fast ions (broad profile shape with $T_{\text{HNBI}}(0)=870\mathrm{keV}$). 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 ($R_0+1.6\mathrm{m}$ at $f_{\text{IC}}=42\mathrm{MHz}$).

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 ($f_{\text{IC}}=52.5\mathrm{MHz}$) 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.](image-url)
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-through 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).
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.

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**References**

[5] A. Messiaen et al., 2010 *Nucl. Fusion* **50** 025026  
[7] V. Lancellotti et al., 2006 *Nucl.Fusion* **46** S476  
[9] M. Kocan, private communication