FEASIBILITY OF MAIN THERMAL ION HEATING BY ICRF WAVES USING A TOP LAUNCHER IN A TOKAMAK WITH DEUTERIUM-TRITIUM PLASMAS

[1]Jungpuyo Lee, [2]Nicola Bertelli, [3]John Wright, [2]Syun'ichi Shiraiwa, [4]Roberto Bilato, and [3]Paul Bonoli.

[1]Hanyang University, Seoul, Republic of Korea
[2]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[3]MIT Plasma Science and Fusion Center, Cambridge, MA, United States of America
[4]Max Planck Institute for Plasma Physics, Garching, Germany

Email: jungpyo@hanyang.ac.kr

1. INTRODUCTION

Main ion direct heating is more efficient than electron heating in achieving the fusion ignition condition for three reasons. First, ion channel transport is likely smaller than that electron channel transport, and the beneficial effects of energetic ions have been observed in many experiments demonstrating good confinement [1]. Second, a higher fuel ion temperature is crucial for increasing fusion reaction rate, as shown in the JET Deuterium-Tritium (D-T) experiments [2]. Lastly, the ion-electron temperature equilibration or the alpha channelling is still unclear especially in mid-size reactors. Although neutral beam injection provides direct fuel ion heating, its penetration into the core plasmas is not straightforward. In this study, we examine the feasibility of main thermal ion heating using ICRF waves in a tokamak, focusing on a launcher positioned at the top of the device.

A main scenario for ICRH, as in ITER, is minority species heating, in which the wave frequency matches the cyclotron frequency of the minority species at the core. This scheme enables efficient heating by avoiding unfavourable wave polarization. However, energetic minority species tend to transfer more collisional energy to electrons than ions. Several studies have investigated direct majority heating, such as second harmonic (n=2) tritium damping [3,4], and deuterium heating in tritium rich or neutral beam plasmas [2, 3, 5], but these methods may be less efficient than the n=1 direct heating using the top launcher in this study. The top launcher has also been proposed for the ICRF current drive applications [6], but its wave frequency intentionally set to avoid direct deuterium heating as this could increase deleterious heating of fusion-born alpha particles. In this study, we focus on direct ion heating, assuming that the primary role of ICRH in future reactors is to initiate burning and reach the ignition temperature, and the heating system needs to be isolated to prevent neutron damage once sufficient ignition is achieved.

2. WAVE POLARIZATION AND ACCESSIBILITY

The favorable wave polarization for cyclotron damping is achieved with a large value of $|E_+/E_y| = |\underline{R}/\underline{S}| \simeq |(15\hat{R}^3 - 13\hat{R}^2 - 10\hat{R} + 8)/(15\hat{R}^3 - 10\hat{R})|$ for D(50%)-T(50%) plasmas, where $\underline{R}$ and $\underline{S}$ are the Stix dielectric tensor components, $\hat{R} = R/R_D$ is the normalized major radius. Here, R_D is the major radius at which the wave frequency matches the Deuterium cyclotron frequency. Thus, the good polarization for the significant cyclotron damping is only obtained within the range $0.75 < \hat{R} < 0.85$ near the ion-ion hybrid resonance layer ($n_{||}^2 = \underline{S} \simeq 0$). To achieve effective central plasma heating, it is beneficial to locate the hybrid resonance layer at the plasma center (e.g. $\omega \simeq 34\ MHz$ for ITER with $B_0 \simeq 5.2$ T and $R_0 \simeq 6.2\ m$). For the optimal access to the hybrid resonance layer via the fast wave propagation path, along with favorable polarization, it is necessary to locate the wave launcher around the top ($\theta = 90, R \simeq 5\ m$) or the bottom of the positive triangularity tokamak. Figure 1-(a) shows the contour plots of E_+ of 34MHz ICRF waves launched from the top, propagating from $R \simeq 5\ m$ toward the low field side. Here, it is worth noting that the wave is propagating between the tritium resonance layer at $R_T \simeq 5\ m$ (red line) and deuterium resonance layer at $R_D \simeq 7.5\ m$ (blue line), and there are the hybrid resonance layer at $R \simeq 6.1\ m$ (yellow line) and the cut-off layer at $R \simeq 6.2\ m$. Figure 1-(b) represents the power absorption profiles, indicating the significant majority species heating (with total power distributed in D:T:e=50:15:35 %).

3. WAVE POWER DAMPING TO IONS

Compared to the simulations of 34MHz in Figure 1, increasing the wave frequency to 36-38MHz results in significantly higher ion power damping, reaching approximately 90% (Deuterium 75%, Tritium 15%). However, the most of the power transfer is deposited at the plasma edge around r/a=0.8, due to the short distance between the top launcher and the hybrid resonance layer. Placing the launcher at 120 degree maximizes the D and T damping, although practically it is more challenging to have the high-field launcher compared to top launcher. The power partitions are investigated in terms of several control parameters such as tritium ratio, temperature, and toroidal mode number. Since the hybrid layer becomes close to the tritium resonance layer in the deuterium-rich plasmas, the tritium damping generally increases as the tritium ratio is reduced. Conversely, in tritium-rich plasmas, the long distance to the resonance layer enhances electron damping, resulting in a more complex dependency.

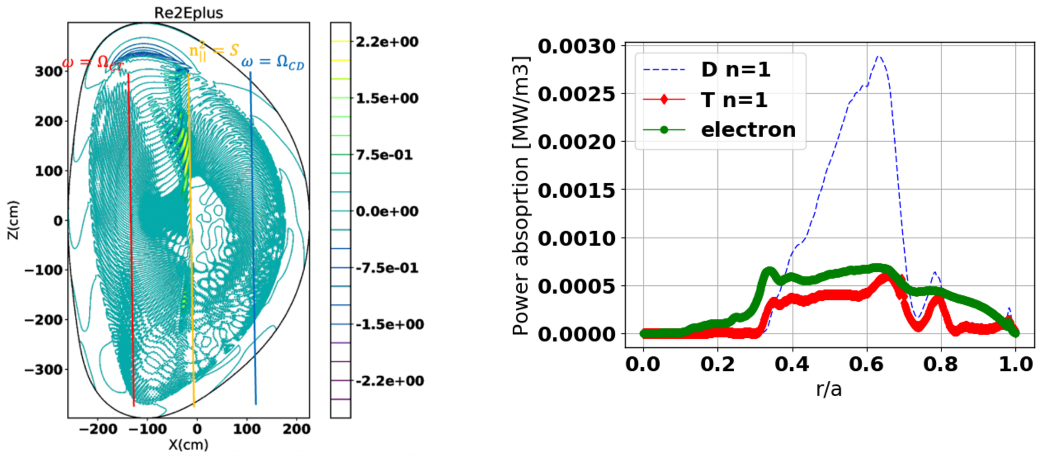

Figure 1. (a, left) Contour plots of $E_+ = E_x + iE_y$ and (b, right) radial power absorption profiles for the ICRF waves of 34MHz $, n_\phi = 27$ with a Top launcher for ITER D(50%)-T(50%) plasmas simulated by TORIC. Here, $n_e = 1.05 \times 10^{20} m^{-3}, T_{e0} = 25\ KeV, T_{D0} = 27.5\ KeV,$ and $T_{T0} = 27.5\ KeV$

4. CONCLUSIONS

A relatively low frequency 34MHz ICRF with a top launcher is proposed to provide a significant fraction (>50%) of thermal deuterium heating, which could be advantageous during the early phase of ignition to raise ion temperatures to the ignition. The top launcher is required to ensure both favorable polarization and adequate accessibility for core damping. Further investigation is necessary to address additional engineering constraints associated with the top launcher and to mitigate alpha particle heating under varying conditions (e.g. different toroidal/poloidal mode number or different plasma density and temperature).

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