# Modelling of ICRF heating in ASDEX Upgrade discharges with pure wave heating relevant to the ITER baseline scenario

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**Introduction** The baseline or reference scenario is one of the basic operational scenarios foreseen for ITER. It is envisaged to deliver fusion power of 500 MW and fusion gain Q~10 using ELMy H-mode discharges at $I_p$ =15 MA, $B_T$ = 5.3 T, normalized plasma pressure $\beta_N$ = 1.8 and normalized confinement $H_{98y2}$ = 1 with a safety factor $q_{95}$ = 3 [1]. Experiments on present-day devices can provide important insights in preparing ITER operation. ITER scenario development on present-day devices has so far mostly been carried out with dominant bulk ion heating with NBI which is strongly coupled with fuelling and momentum injection. This is not representative of the expected conditions of burning ITER baseline plasmas with predominant electron heating by fusion-born alpha particles and small externally applied torque. Recently, it was found that at low torque in the ITER baseline scenario on DIII-D, which is typically prone to low-n tearing modes, there is a strong tendency for m/n=2/1 tearing modes to slow and lock, often resulting in disruption [2]. More studies with ITER baseline plasmas at low torque are thus called for. In this paper we focus on ASDEX Upgrade (AUG) plasmas with pure wave heating, i.e. ICRF and ECRF heating only, that form a part of the development of the ITER baseline scenario on AUG [3, 4]. They are of particular interest because they approach the conditions of burning ITER plasmas with dominant electron heating and low torque.

**Experimental results** We have chosen two representative AUG discharges with pure wave heating for a detailed study. Their main parameters are shown in Table 1. The main plasma ion species is deuterium (D) which is introduced with gas puffing. ICRF power is applied with a frequency of 30 MHz tuned to a hydrogen minority ion resonance at $r/a \approx 0.2$-0.3 on the high-field side (cf. Fig 1). ECRF power is applied using 140 GHz in X3 mode which located the 3rd harmonic resonance around mid-radius at r/a ≈ 0.4 and the 2nd harmonic resonance at the plasma edge at r/a ≈ 0.9 (cf. Fig 1). In both discharges combined ECRF and ICRF heating sustains stable plasma conditions. Discharge 33377 reaches $\beta_N = 1.6$ and $H_{98y2} = 0.85$ which is closer to the ITER baseline reference values $\beta_N = 1.8$ and $H_{98y2} = 1$. However, it has $q_{95}=3.6$ as compared to $q_{95} = 3$ foreseen for ITER baseline plasmas. Discharge 34454 at $q_{95} = 3$ reached $\beta_N = 1.4$ and $H_{98y2} = 0.7$. Figure 2 shows the electron temperature ($T_e$) and density ($n_e$) profiles as measured by Thomson scattering diagnostics for the two discharges. The $n_e$ profiles are flat while the $T_e$ profiles are peaked in the centre.

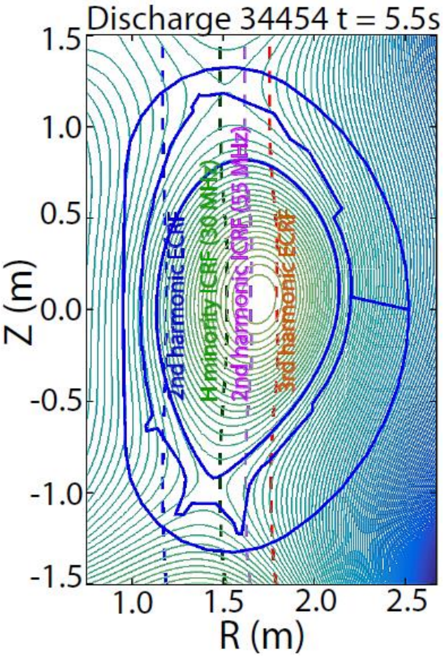

**Figure 1** Plasma poloidal cross section with 3rd and 2nd harmonic ECRF resonance at 140 GHz together with H minority ICRF resonance at 30 MHz. Also shown is an alternative 2nd harmonic H ICRF resonance at 55 MHz.

**Table 1** Main parameters for discharges 33377 and 34454 at t = 5.95 s and t = 5.5 s, respectively.

| **Parameter** | **33377** | **34454** |
|---|---|---|
| $I_p$ (MA) | 0.9 | 1.1 |
| $B_T$ (T) | 1.8 | 1.8 |
| $q_{95}$ | 3.6 | 3.0 |
| $\delta_{upper}$, $\delta_{lower}$ | 0.26, 0.4 | 0.04, 0.4 |
| $T_{i0}$ (keV) | 2.3 | 1.2 |
| $T_{e0}$ (keV) | 2.0 | 1.7 |
| $n_{e0}$ ($10^{19}m^{-3}$) | 8.8 | 8.6 |
| $P_{ICRF}$ (MW) | 3.2 | 3.4 |
| $P_{ECRF}$ (MW) | 2.6 | 1.4 |
| $\beta_N$ | 1.6 | 1.4 |
| $H_{98y2}$ | 0.85 | 0.7 |

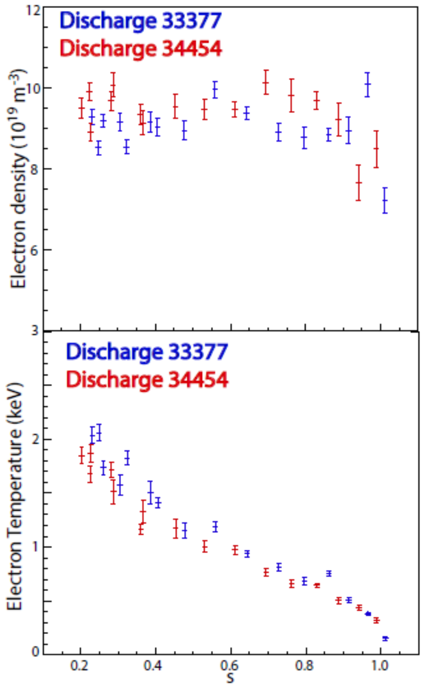

**Figure 2** $T_e$ and $n_e$ profiles as measured by Thomson scattering for discharges 33377 and 34454. Here, s is the square root of the normalized poloidal flux.

**Modelling results** We have modelled discharges with the ICRF code PION [5] and the ECRF code TORBEAM [6]. According to PION, there are three main absorption mechanisms that damp the launched ICRF waves: H minority heating at $\omega \approx \omega_{cH}$, 2nd harmonic heating of D which is the main bulk ion species and direct electron damping of the launched wave via electron Landau damping and transit time pumping.

Assuming a hydrogen concentration $n_H/(n_H+n_D)$ of 5% which is typical in AUG plasmas and a full ICRF toroidal mode number spectrum with a peak around N ≈ 12, we find that H minority damping dominates, absorbing 55-70 % of $P_{ICRF}$, while direct electron damping and 2nd harmonic D damping of the launched ICRF waves are about 25-40 % and 5-10 %, respectively.

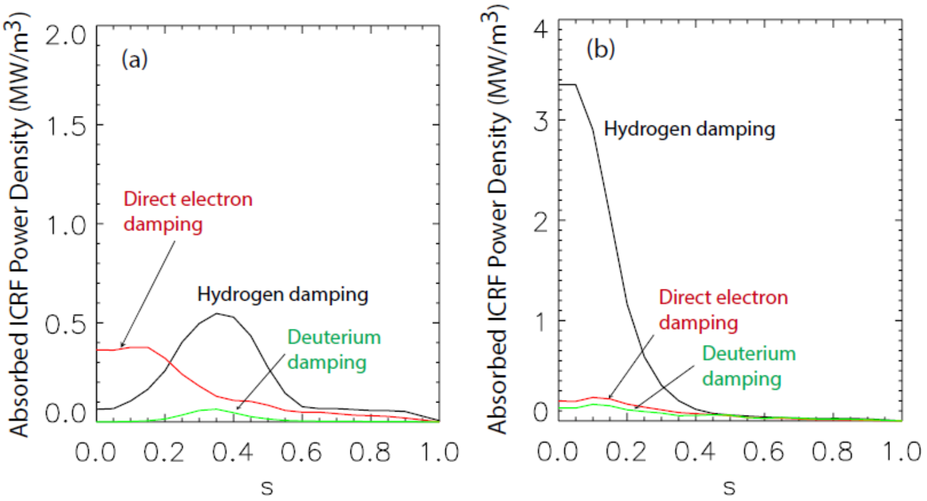

**Figure 3** (a) ICRF power deposition profiles as given by PION for discharge 34454. (b) As (a) but for an alternative ICRF scenario with 55 MHz instead of 30 MHz as used in discharge 34454 (cf. Fig. 1).

Figure 3a shows the radial ICRF power deposition profiles for H minority damping, 2nd harmonic D damping and direct electron damping for discharge 34454 at t = 5.5 s. The H and D damping peak off-axis due to the off-axis ICRF resonance, while direct electron damping peaks in the plasma center. Similar profiles are obtained for discharge 33377. The maximum H and D absorption power density is rather low, i.e. 0.6 and 0.05 MW/m$^3$, respectively. The low power density results in a relatively low average energy of ICRF-accelerated ions. Thus, they prominently heat bulk ions in collisions and the resulting total electron heating, i.e. the sum of direct electron damping of the launched wave and the collisional electron heating by the fast resonant ions, is limited to ~40% of $P_{ICRF}$. The ICRF driven fast ion energy content is about 10 kJ which is about 5% of the thermal D energy content. For reference, adding 3 MW of NBI heating with 59 keV deuterium beams increases the D energy content by about 10%. The ECRF power deposition as calculated with TORBEAM is shown in Figure 4. The 3rd harmonic ECRF absorption depends strongly on the electron temperature at the resonance. In these plasmas $T_e$ is relatively low (cf. Fig. 2) and, consequently, 3rd harmonic damping around mid-radius is relatively weak as compared to 2nd harmonic damping at the edge plasma around r/a ≈ 0.9. This results in strong ECRF absorption around r/a ≈ 0.9 as shown in Figure 4. The ECRF power deposited within r/a = 0.6 is ~30-35% of $P_{ECRF}$.

Finally, we have used PION simulations to study ways to improve electron heating by ICRF waves beyond the ~40% of $P_{ICRF}$ obtained in discharges 33377 and 34454. Stronger electron heating by ICRF could lead to a higher $T_e$ which could improve ECRF power deposition in the core plasma. We find that there are several possible ways to achieve this. First, one could operate at a lower $n_e$, which would also reduce collisional coupling between electrons and ions. By reducing $n_e$ by 30% from 8.8 $x10^{19}/m^3$ to $6.2x10^{19}/m^3$, while keeping all the other parameters the same, the electron heating by ICRF waves increases from ~40% to ~55% of $P_{ICRF}$. Second, one could operate at a slightly higher toroidal magnetic field of 1.95T. It would provide more central power deposition by moving the ICRF resonance to the plasma center. This would increase electron heating by ICRF from ~40 % to ~50% of $P_{ICRF}$ due to a higher energy of resonant ions given the higher power per resonant particle with a central resonance. However, this is not a viable option in combination with ECRF heating because it will move the ECRF deposition further off-axis. Third, one could use an ICRF frequency of 55 MHz to place the 2nd harmonic H resonance in the plasma center. This yields to a higher average energy of fast hydrogen ions that favors strong electron heating (up ~70% of $P_{ICRF}$) with a central power deposition as shown in Figure 3b. The resulting ICRF driven fast ion energy content would be about 15% of the thermal D energy content. In the forthcoming experiments on AUG, we plan to use polychromatic ICRF heating with 30 and 55 MHz, i.e. adding 2nd harmonic H heating with central deposition using 55 MHz to H minority heating using 30 MHz with off-axis deposition, in ITER relevant baseline plasmas.

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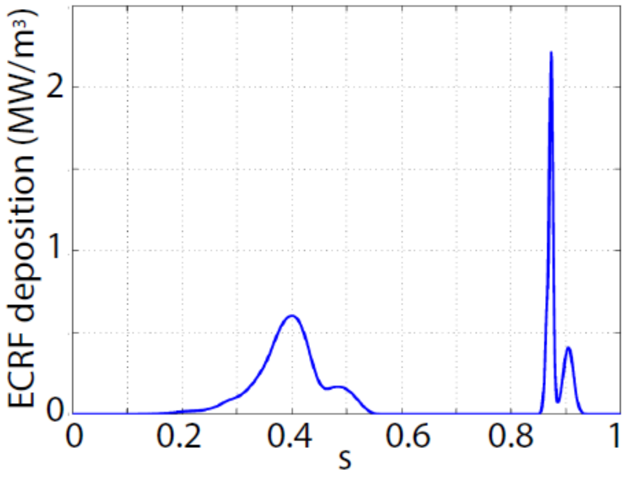

**Figure 4** ECRF power deposition profile as calculated with TORBEAM for AUG discharge 34454.