Modelling of dual-frequency ICRF heating in ASDEX Upgrade discharges relevant to the ITER baseline scenario

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The baseline scenario is one of the standard operational scenarios foreseen for ITER. It is envisaged to deliver fusion power of 500 MW and fusion gain $Q \approx 10$ using ELMy H-mode discharges at $I_p = 15MA$, $B_T = 5.3T$, normalized plasma pressure $\beta_N = 1.8$ and normalized confinement $H98y2 = 1$ with a safety factor $q_{95} = 3$ [1]. Experiments on present-day devices can provide important insights in preparing ITER operation. In earlier works [2, 3], we explored the viability of pure wave heating to simulate heating by fusion-born alpha particles in ITER baseline relevant plasmas on ASDEX Upgrade (AUG). As a first step, fundamental hydrogen (H) minority heating was selected to maximize core electron heating. We concluded that central second harmonic ICRF heating of H minority in combination of ECRF heating could potentially improve core electron heating when applied alone or in combination with standard hydrogen minority ICRF heating [3]. Based on these results, as part of the recent Medium-Size-Tokamak (MST1) campaign at ASDEX-Upgrade (AUG), several deuterium discharges were conducted to explore the performance of central second harmonic H minority heating when applied alone and in combination of off-axis H minority heating, as compared to pure off-axis H minority heating. In this paper, we have chosen two such discharges for a detailed study, and show that, as predicted, the new heating schemes boost electron heating in the plasma core.

In both discharges, performed at $I_p = 1MA$ and $B_T = 1.8T$ ($q_{95} \approx 2.95$), ICRF waves were applied at a frequency of 30 MHz and 55 MHz, corresponding to the fundamental and second harmonic H minority resonances, respectively, complemented by a constant 140 GHz ECRF power in X3 mode. In 36144, 4.1 MW of Deuterium NBI is applied throughout the discharge to ensure stable plasma conditions, while in discharge 37936 NBI is used only during the ramp-up phase and short periodic blips for diagnostic purposes, providing a pure wave heating scenario during most of the discharge. The main parameters of discharge 36144 are shown in Figure

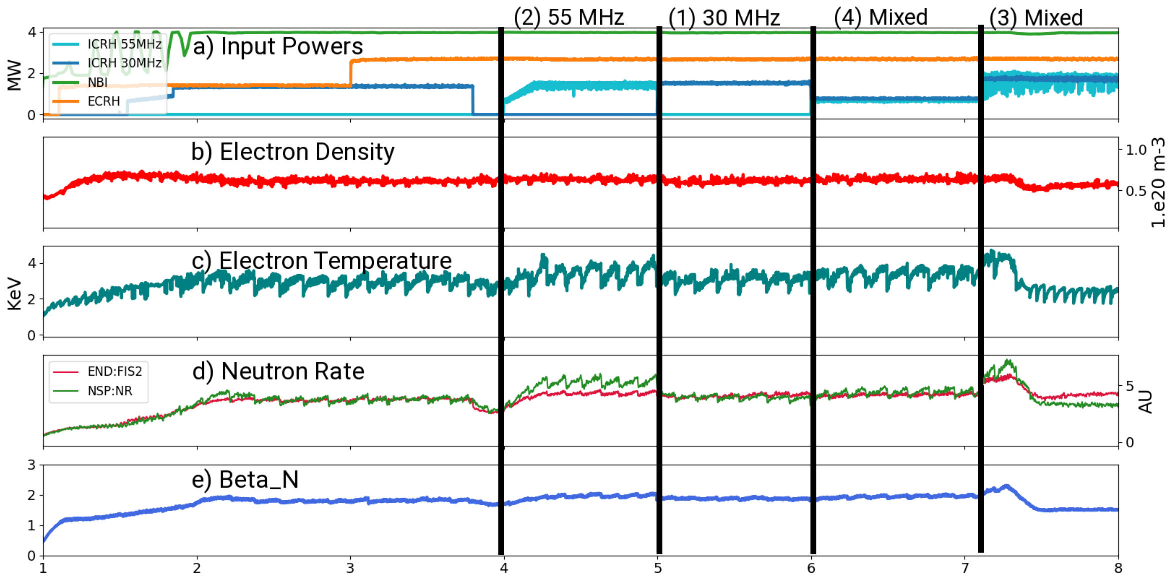

Figure 1: *Time evolution of main plasma parameters for discharge 36144. In descending order, the plots show a) Input power (ICRH, NBI, ECRH), b) electron density, c) electron temperature, d) neutron yield (not absolutely calibrated), e) normalised plasma Beta.*

1. Both 36144 and 37936 present three distinctive heating phases, where the plasma is heated respectively by (1) 1.5 MW of H fundamental heating alone, (2) 1.5 MW of second H harmonic heating alone, and (3) 1.5 + 1.5 MW of mixed heating. Additionally, 36144 has an alternative mixed phase (4) where the power is halved in both ICRH antennas to have 1.5 MW total ICRH power as in the non-mixed phases (1) and (2). Unfortunately, we do not have an equivalent phase in 37936 and therefore we will prioritise (1),(2),(3) in our results.

We have modelled these discharges using the ICRF code PION [4] which we have upgraded to allow multiple frequencies as in [5]. NBI depositions are modelled with the RABBIT code [6], and are taken into account in PION to include NBI+ICRF synergy [7]. As one can see in Figure 2, the 30 MHz ICRF wave places the fundamental H harmonic slightly off-axis in the high-field side, which produces low absorption of the IC waves through direct ion damping. Our simulations show almost half of the wave power is absorbed through direct electron damping, which is precisely why this scenario was considered in our past attempts to recreate alpha-heated plasma conditions [3]. On the other hand, the 55 MHz ICRF heating places the 2nd harmonic H resonance in the plasma center. Central heating naturally produces a more peaked power deposition than the off-axis fundamental H resonance. As a result, most of the power is absorbed by minority ions and the average energy of fast H ions is increased (see Figure 2). Although direct electron heating is reduced, overall electron heating is maintained since collisional energy transfer to electrons is favoured by highly energetic ions. Figure 3 shows electron heating (direct

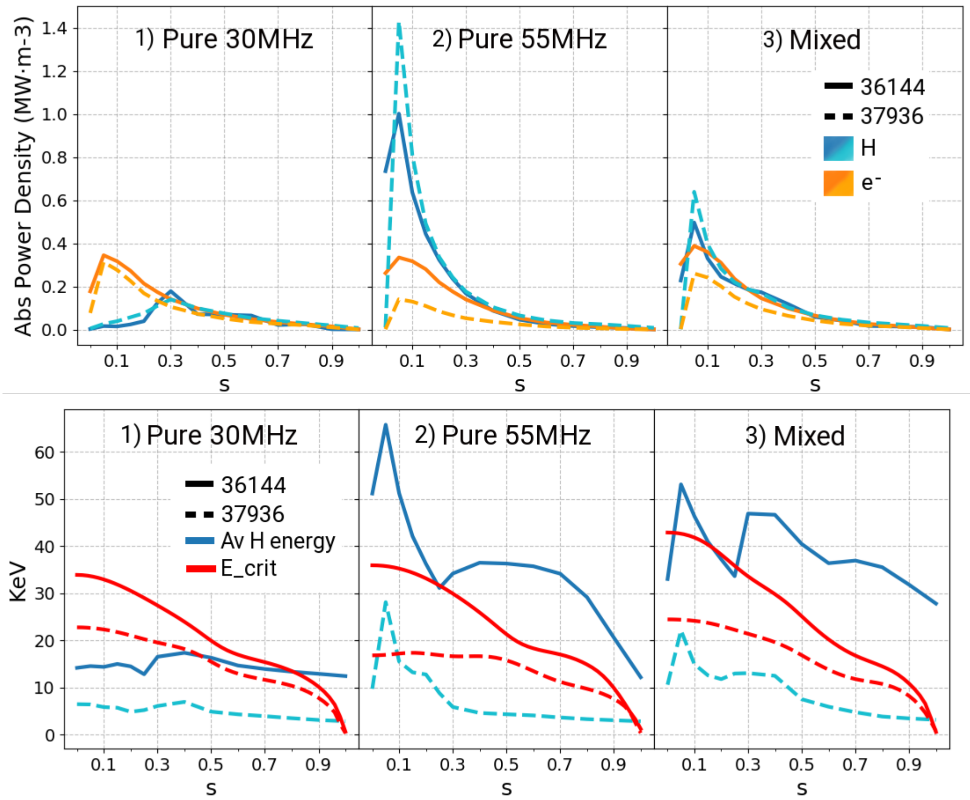

Figure 2: ***(Top)*** *Normalized ICRF wave absorption profiles comparison (as a function of the normalized poloidal flux) for discharges 36144 (full lines, ICRH + NBI) and 37936 (dashed lines, pure wave heating). Blue and orange lines show respectively H minority direct damping and direct electron damping.* ***(Bottom)*** *Average H energy and Stix critical energy profiles (as a function of the normalized poloidal flux) comparison for discharges 36144 (full lines, ICRH + NBI) and 37936 (dashed lines, pure wave heating).*

e^- damping + power transfer by fast ions to e^-) distribution for the three heating schemes. The second harmonic scheme (2) provides equal (with NBI) or slightly reduced (pure wave heating) total electron heating w.r.t. (1), but increased core electron heating in both cases. This can be observed experimentally in Figure 1 (c), and also results in increased neutron rate (d) since core ion heating is also enhanced. The mixed scheme (3) shows an increase in both total and core electron heating of around 10%. Overall, we see that the new schemes (2) and (3) favour core electron heating as intended, specially in the pure wave heating scenario. NBI allows for a slightly higher total electron heating, but moves some of the heating further off-axis.

In this paper, we have studied recent experiments in the ASDEX Upgrade tokamak which tested the performance of a mixed scheme using second harmonic hydrogen resonance to boost the performance of the previously-tested fundamental hydrogen scheme. We have showed the proposed ICRH schemes are, at the very least, of comparable performance to the fundamental

Integrated e- heating: Total / Below s = 0.5	(1) 30MHz	(2) 55MHz	(3) Mixed (Relative increase wrt (1))
36144 (RF + NBI)	2.4 MW / 0.7 MW	2.4 MW / 0.84 MW	4.0 MW / 1.44 MW (13%, 7%)
37936 (RF only)	0.7 MW / 0.33 MW	0.55 MW / 0.38 MW	1.6 MW / 0.9 MW (7%, 8%)

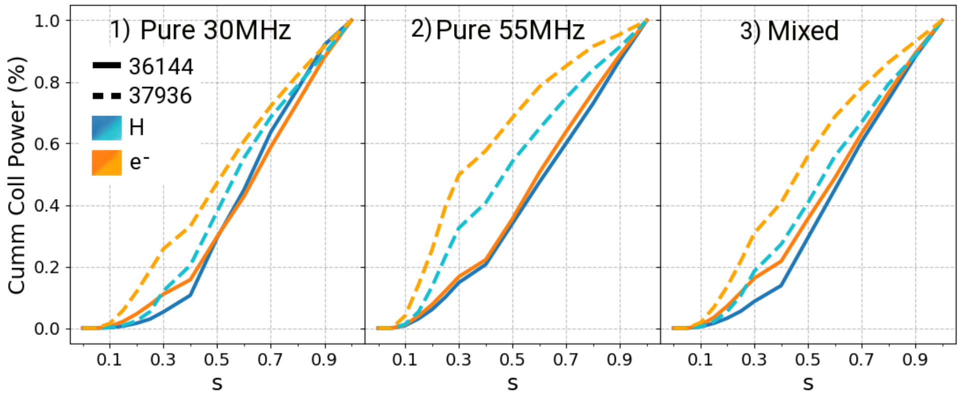

Figure 3: ***(Top)*** *Integrated power going to electrons (direct damping + collisional), both total* ($0 < s < 1$) *and core (taken arbitrarily to be* $0 < s < 0.5$) *heating. Relative values are also given in (3) wrt (1) to address the change in ICRH power.* ***(Bottom)*** *Normalized integrated power deposition profiles (as a function of the normalized poloidal flux) comparison for discharges 36144 (full lines, ICRH + NBI) and 37936 (dashed lines, pure wave heating). Blue and orange lines show respectively collisional heating to ions and electron heating (direct damping + collisional to electrons).*

hydrogen resonance scheme both with and without complementary NBI heating. The second harmonic H resonance scheme (2) shows greatly improved core electron and ion heating, although can have slightly reduced total electron heating. The mixed scheme (3) shows the overall best performance, with increases of around 10% in both total and core electron heating w.r.t the fundamental H scheme (1). Considering the fundamental H minority scheme had already been selected to maximize core electron heating, these improvements (although small) are quite significant.

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