ICRF H-MODE AND $2\Omega_{CH}$/D(H)-MINORITY HEATING ON ASDEX

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INTRODUCTION

ICRH experiments in the ASDEX divertor tokamak have now been operated in the $2\Omega_{CH}$ regime and D(H)-minority mode. This paper presents the status of these investigations and compares some of the most interesting features of the RF scenarios with neutral beam heating (NI) in the same machine under optimized and reproducible plasma parameters. The achievement of the H-mode with ICRH alone is reported. Considerations on possible synergetic effects of the combination of ICRH with NI /1/ and impurity studies during ICRH /2/ are presented separately.

$2\Omega_{CH}$ (67 MHz) and D(H)-heating (33.5 MHz) experiments are being routinely conducted in excess of 2 MW launched power for pulse lengths of up to 1 s. In addition to the combined scenarios of NI + ICRH, pure $2\Omega_{CH}$ and D(H) heating up to maximal power have now been applied in extensive studies of diverted discharges and in the case of carbonised walls /3/.

EXPERIMENTAL RESULTS

Electron and ion heating properties of both RF scenarios are compared in Figs. 1 and 2. Direct central electron heating (Fig. 1) measured via the initial slope of the sawteeth is clearly higher in the minority mode than at $2\Omega_{CH}$. The electron heating efficiency, $\bar{n}_e \, \Delta T_e(0)/P^{IC}_{dep}$ of about 4.0 and $1.8\cdot10^{13}$ eV/kW cm^3, for D(H) and $2\Omega_{CH}$ (H-plasma), respectively, is also higher in the minority case ($n_H/n_e \sim 0.05$), which, however, was partly due to the better confinement properties of deuterium plasmas. Figure 2 presents the ion heating at RF power below 1 MW: The minority regime exhibits an efficiency as high as the NI H-mode ($4.2\cdot10^{13}$ eV/kW cm^3, $H^o \rightarrow D^+$) /4/, which is consistent with the good confinement observed at that RF power level (see Figs. 4 and 5).

Now to the global heating efficiencies of the various scenarios: Recent investigations on $2\Omega_{CH}$-heating and its combination with NI gave rather promising results /5/. When combining ICRH with NI, an important question is whether the RF heating efficiency becomes improved with increasing T_i (target) or by coupling of the IC wave to the fast beam particles. In the case of carbonised walls where heating is not degraded by deleterious impurity radiation, the increase of T_i due to NI preheating (Fig. 3)

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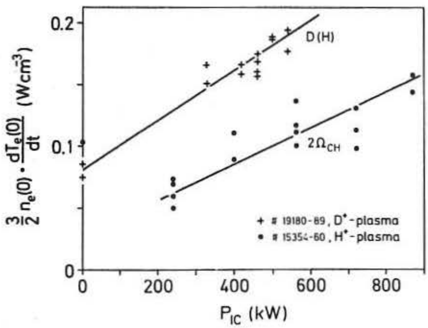


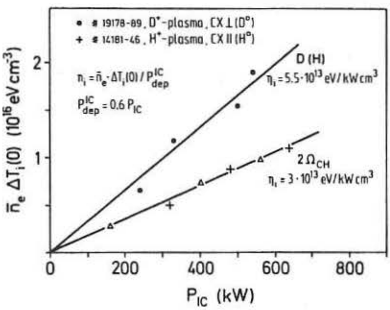
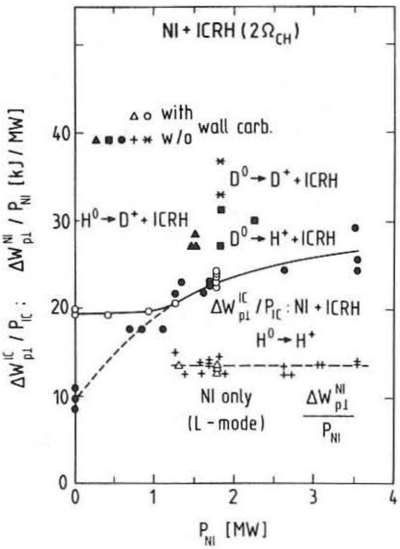


Fig. 1: Direct e-heating of $2\Omega_{CH}$ and D(H) scenarios.

Fig. 2: Ion heating for both ICRF regimes.



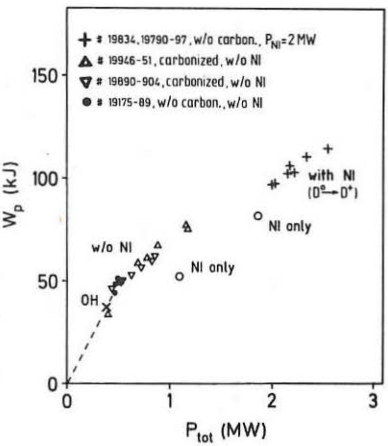


Fig. 4: Plasma energy versus total heating power for D(H), NI and NI+D(H) heating

Fig. 3: Heating efficiencies of $2\Omega_{CH}$, NI and NI+$2\Omega_{CH}$

improves the IC efficiency only by about 25 % from about 20 kJ/MW (w/o NI, $T_i \sim 0.5$ keV) to 25 kJ/MW at $P_{NI} = 3.5$ MW ($T_i \sim 2.2$ keV). Coupling of the IC wave to the beam is in fact observed in CX-spectra, but obviously to an extent which is not sufficient enough to improve the heating: On comparison of ICRH discharges with additional $H^o \rightarrow D^+$ or $D^o \rightarrow H^+$ (Fig. 3) the RF efficiency turns out to be independent of the beam species. Owing to the isotope effect on confinement $2\Omega_{CH}$-heated discharges in deuterium and helium with a small amount of hydrogen ($n_H/n_e > 10$ %) show even better efficiencies ($D^o \rightarrow D^+$ + ICRH in Fig. 3). No heating at the fourth IC harmonics of D^+ and $^4He^{2+}$ could be noted.

As a general feature, energy and particle confinement of ICRH-heated plasmas are systematically better than those of the NI L-mode but appear still within the combined error bars. The plasma energy for minority heating at low power scales as well as the ohmic phase (Fig. 4). With increasing RF power W_p bends towards an L-mode behaviour, staying, however, at a slightly higher level than NI. In combination with NI, W_p and thus τ_E' are improved, too, a feature also observed at $2\Omega_{CH}$ /5/. The energy confinement times of $2\Omega_{CH}$, D(H) and NI(L) modes normalized to the ohmic values are presented in Fig. 5. Careful experimental investigations on the RF power absorption lead to $\alpha = 0.6$ and 0.7, without and with beam preheating respectively. For pure NI heating $\alpha = 0.8$ to 0.9 was found, in good agreement with the beam deposition calculations. As shown for various $2\Omega_{CH}$ regimes, carbonisation strongly reduces the central radiation /2, 3/, thus improving the confinement. At high power ($P_{IC} \sim 5\ P_{OH}$) both RF scenarios reach about equal τ_E' ($\sim 0.6\ \tau_E^{\Omega}$) while below 700 kW the D(H)-confinement still remains as good as the ohmic one. Assuming equal global heating efficiencies ($\sim$ 20 kJ/MW) for the D(H) and 2Ω modes, but with W_p^{OH} (D(H), D^+-plasma) > W_p^{OH} ($2\Omega_{CH}$, H^+-plasma) the superior confinement of D(H) at low power in comparison to $2\Omega_{CH}$ can be explained.

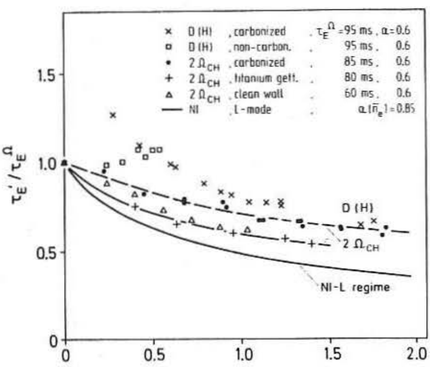


Fig. 5: Normalized confinement times versus launched RF power for various heating scenarios.

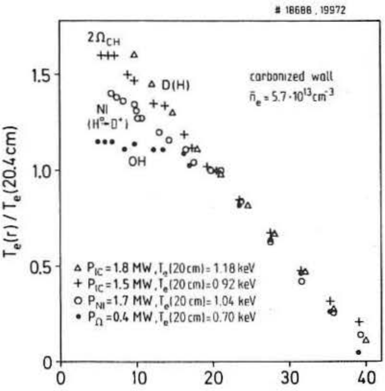
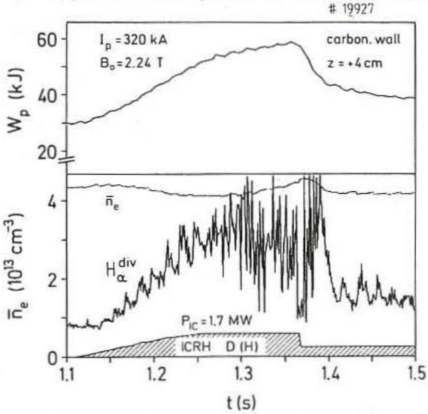


Fig. 6: Normalized T_e profiles of OH, NI, $2\Omega_{CH}$ and D(H)

Rather narrow power deposition profiles are expected theoretically for ICRF heating. In fact, ICRH is accompanied by T_e profiles strongly peaked on axis (Fig. 6) confirming a rather local power deposition. Well outside the $q = 1$ zone, however, the profiles of OH, ICRH (2Ω, D(H)) and NI appear to be almost invariant if normalized to T_e at $r \sim a/2$ indicating a 'profile consistency' within the so-called confinement zone /6/. When the IC resonance layer is shifted from the plasma centre to half radius, the T_e profile does not vary much while the global heating is maintained with slightly reduced sawteeth amplitude.

ICRF H-mode studies have been performed with and without NI. In combination with NI under optimized conditions the additional ICRF power can switch the plasma into the H-mode. For the first time, the H-mode has been achieved with ICRH alone in the D(H)-minority regime at an absorbed RF power of about 1.1 MW. The H-mode is marginally reached showing all characteristic signatures of rising n_e and W_p, and frequent ELMs (Fig. 7). The typical development of an edge electron temperature pedestal is also



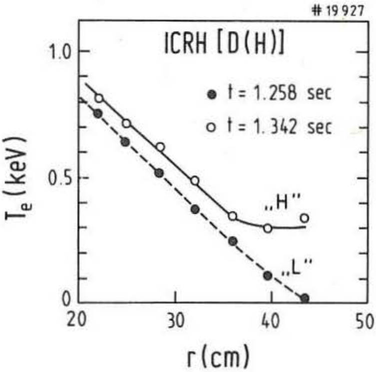


Fig. 7: Transition into the H-mode of an ICRF-heated plasma.

Fig. 8: Development of the edge T_e profile in the ICRH L and H-phase.

observed (Fig. 8) which is rather similar to the behaviour found with NI heating /7/. The occurrence of a short ELM-free H-phase (see Fig. 7 at t = 1.365 s) gives rise to a shrinking of the scrape-off-layer and changes the antennae coupling to such an extent, however, that in all cases one of the RF generators terminates operation by voltage breakdown in the vacuum line when operating at the RF power limit. To keep the H-mode with ICRH somewhat higher RF power than available at present appears to be necessary.

CONCLUSIONS

Global heating and confinement of $2\Omega_{CH}$ and D(H)-regimes are found to be almost equal at high RF power and appear to be well comparable to or even somewhat better than the NI L-mode. For the first time ICRH has now shown the potential to access the H-mode.

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