# COMPARING HIGH POWER ION CYCLOTRON RESONANCE FREQUENCY HEATING WITH NEUTRAL INJECTION IN ASDEX UPGRADE : DIFFERENCES, SIMILARITIES AND SYNERGIES

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**Abstract**

By using 3 dB couplers, ICRF heating has become much less sensitive to changes in coupling. High power regimes with strong ELMs could thus be investigated. Comparison with NI then allows effects specific to the heating schemes to be investigated. Large differences were observed on the central plasma, in particular on the sawteeth. With ICRF heating, the central electron temperature is higher and the sawtooth amplitude larger than with NI. No difference was seen on the ELM behaviour (frequency, effect on edge $T_e$) between NI and ICRF. The combination of NI and ICRF results in stabilization of the 3,2 neoclassical mode, under conditions where it is unstable with NI alone.

## 1. INTRODUCTION

High power regimes have usually been investigated - on tokamaks with divertors - to a large extend with neutral injection (NI) heating. High power ion cyclotron resonance frequency (ICRF) heating has been hampered by the sensitivity of the ICRF coupling to the plasma parameters in the edge. Specifically in divertor machines, where large powers frequently lead to type I ELMy H-modes and thus to large variations in the edge parameters, it was harder to access the high power regime with ICRF. Consequently, most of the high power data include inherently NI specific features such as the coupling between power and refueling, a broad and density dependent power deposition profile, fast particle effects and often rotation. Many of those features may not be present in future large machines, as $\alpha$-particle heating is only in certain aspects comparable to present heating methods, significantly different in other aspects.

With ICRF, heating can be separated from refueling; further, by using different heating scenarios, fast particle effects can be isolated, the deposition can be targeted to ions or electrons, and the narrow power deposition can be localized indepedently of density. Thus, high power ICRF and its comparison with NI permit in principle to separate the effects specific to the heating methods.

The recent installation of 3 dB couplers [1, 2] on ASDEX Upgrade, has effectively shielded the RF generators from the changes in coupling (even from those due to type I ELMs, despite their high frequency and strong variation on a short time scale) allowing them to operate on an almost constant load. Significant increases [3] in the maximum ICRF power to the antennas (up to 5.7 MW) and in the power routinely attainable for standard scenarios (4 MW) could thus be achieved. Direct comparison of ICRF and NI at significant power levels and thus differentiation of the characteristics due to heating mode has become possible in ASDEX Upgrade.

## 2. RESULTS

We used for ICRF heating a H minority in D, with a central position of the resonance layer, f = 30 and 31.6 MHz ($B_t$ = 2.1 T, $I_p$ =1 MA, R = 1.65 m, a = 0.5 m, b = 0.8 m), and for NI : 60 keV D, injection angle 19° with respect to perpendicular at the plasma center (corresponding to a beam tangency radius of 0.53 m). At 5 MW, we are typically 3 times above the H-mode threshold. With 0.4 MW/m$^3$, the resulting average power density exceeds by a

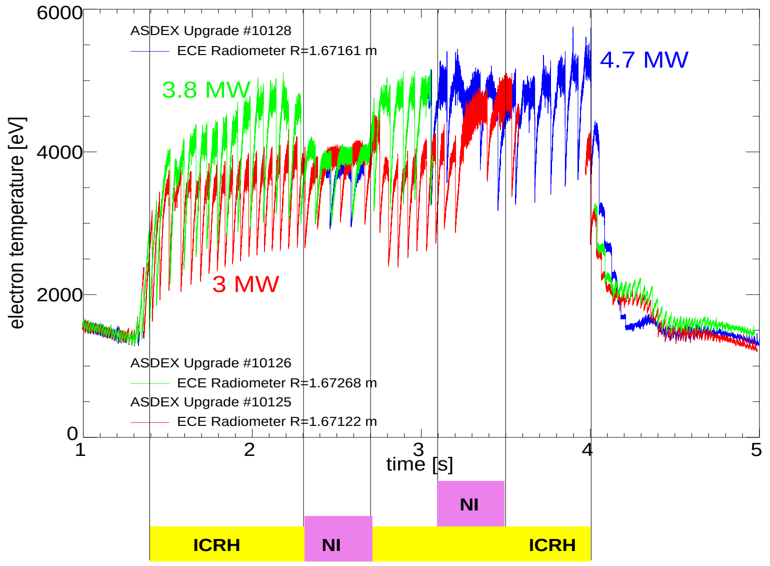


FIG. 1. *Central electron temperature for three discharges, with increasing levels of ICRF power (3 MW, 3.8 MW, 4.7 MW). Each discharge has during the indicated times 5 MW NI (in the first phase alone, in the second phase in combination with ICRF).*

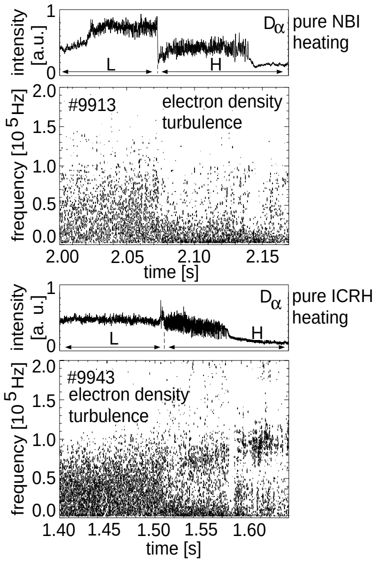


FIG. 2. *Frequency spectrum of the fluctuation in the electron density near the H-mode threshold for NI and ICRF heating.*

factor 3, the maximum achievable in JET for a comparisons between NI and ICRF. The power per plasma surface area is similar.

### 2.1. Differences

Differences were observed in the density and temperature profiles, and in the sawtooth behaviour between ICRF and NI, reflecting the distinctions in refueling and power deposition. The differences in the profiles are larger at the top of the sawteeth. At the same line averaged density (typ. $5\times10^{19}$ m$^{-3}$), the density profile is flatter with ICRF (and increasingly so with higher density) indicating refueling from the edge. The maximum central electron temperature is higher with ICRF (5.5 keV versus 4 keV for NI, see Fig. 1) and the profile more peaked : the ratio $T_{e\ ICRF}/T_{e\ NI}$ decreases from 1.4 centrally, to 1.25 at r/a = 0.4, and is close to 1 at r/a = 1. At the bottom of the sawteeth, the differences are smaller.

The higher average electron temperature and sawtooth amplitude with ICRF exist simultaneously with a shorter sawtooth period (82 ms versus 120 ms with NI). This is not only due to faster initial central heating rate (58 eV/ms versus 22 eV/ms), but also due to a shorter period during which the electron temperature is saturated. For minority heating, the sawtooth period increases with increasing power (from 48 ms at 3 MW to 82 ms at 4.7 MW). When the position of the resonance layer is varied, a more central position of the resonance layer result in a longer sawtooth period. This indicates competing mechanisms : on the one hand localization of the electron heating and resultant change in current profile and on the other hand a stabilizing effect of fast particles. The latter can be separated by using mode conversion heating ($He_3$ in H) : the power goes mainly to the electrons and no stabilizing effect due to fast particles occurs; under certain conditions then the sawtooth period can even be made to decrease with increasing ICRF power and the influence of the localization of the power can be analyzed [4].

Differences are observed between ICRF and NI in the edge near the H-mode threshold (Fig. 2) : at the L-H transition, the fluctuation in the electron density for purely ICRF heated plasmas do not show a complete broad band suppression as is observed with NI heating, but only a suppression at the frequencies 50$\pm$30 kHz, leaving a high frequency fluctuation at around 100 kHz in the ELM free H phase. Differences are also observed during type I ELM phases : whereas for NI, the fluctuations near an ELM increase slowly and end abruptly, the opposite is the case for ICRF (Fig 3).

On TEXTOR [5], adding ICRF heating prevented accumulation of high-Z impurities. Ex-

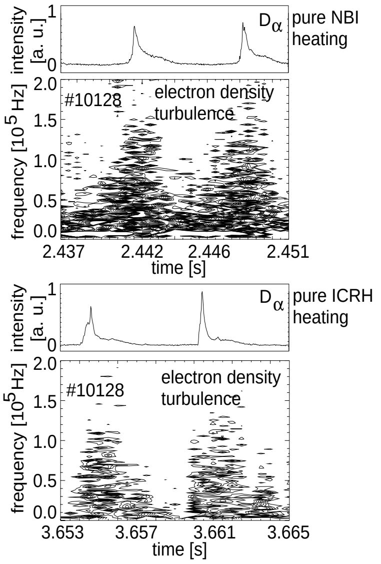


*FIG. 3. Frequency spectrum of the fluctuation in the electron density during type I ELM periods for NI and ICRF heating.*

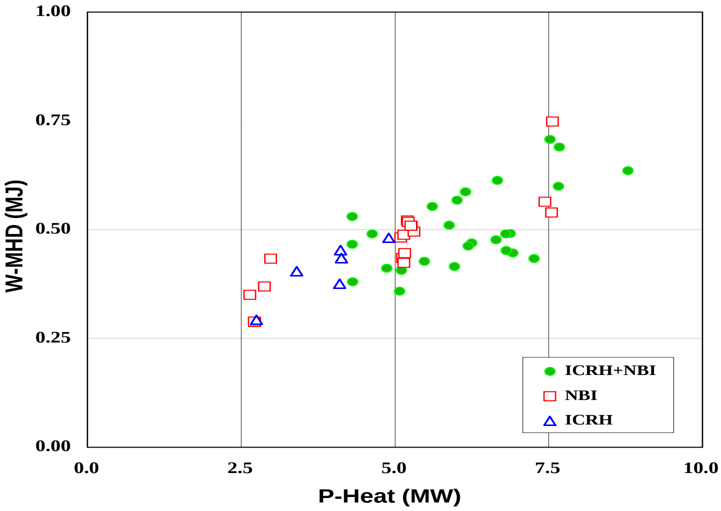


*FIG. 4. Plasma energy content (from equilibrium) versus power. For ICRF the power to the antenna was used (losses in the antenna < 10 % ), for NI the injected power corrected for shine-through (less than 3 % ) Conditions were : ELMy H-mode, 1.85 T < $B_t$< 2.35 T, 0.8 < $I_p$<1.2 MA, 4×$10^{19}$ $m^{-3}$ < $\overline{n}_e$ < 10×$10^{19}$ $m^{-3}$).*

periments with repetitive laser ablation (providing, with the observed identical ELM behaviour, a constant impurity source at the edge) on AUG, confirm a difference in the inward transport of the impurities during NI heated and ICRF heated periods. However, under conditions where, with NI, a strong central mode is present, the decay of the central impurity concentration can be faster.

## 2.2. Similarities

In contrast to circumstances where the local effects play a role and differences are seen, often no differences are observed on global parameters. The overall heating efficiency for example (Fig. 4) is independent of the heating method. The global (bulk + divertor) bolometric radiation in unseeded plasmas is similar for ICRF and for NI ($P_{rad}/P_{tot}$ = 0.7), as is the concentration of O and C impurities.

In JET, large differences were observed in the frequency and amplitude of the ELMs between ICRF and NI heating [6]. In ASDEX Upgrade, for powers ranging from 2.5 to 5 MW, with the plasma far into the H-mode (1.5 to 3 times the threshold power, clear type I ELMs), no differences were observed in the ELM frequency, despite the observed differences in the frequency spectrum of the fluctuations in the electron density during the type I ELM periods (Fig. 3). Not only is the ELM frequency identical, but the average edge $T_e$ (near the separatrix $0.95 < \rho_{pol} < 1.05$) and the amplitude of the variation of $T_e$ due to the ELMs is the same for ICRF and NI heated plasmas (see Fig. 5). The occasional somewhat larger temperature excursion in the case of ICRF is due to the larger heat pulse of the sawteeth propagating to the edge (consistent with the larger amplitude of the sawteeth in the center).

## 2.3. Synergies

Local effects can affect the discharge globally. Synergetic effects of ICRF and NI have already been observed in AUG [7] and other machines. Indications of the avoidance of neoclassical modes [8] by using a combination of NI and ICRF [9], as compared to NI alone is shown in Fig. 6. The discharge with NI alone (#10560) shows near t = 3.2 s, the appearance of a neoclassical 3, 2 mode. The electron temperature and the plasma energy then collapse. The discharge with the combination NI and ICRF (#10531) shows at about the same time, a change in sawtooth behaviour, but no collapse, until at t = 4 s, the ICRF is replaced by NI. Subsequently a 2, 1 mode locks and the discharge collapses.

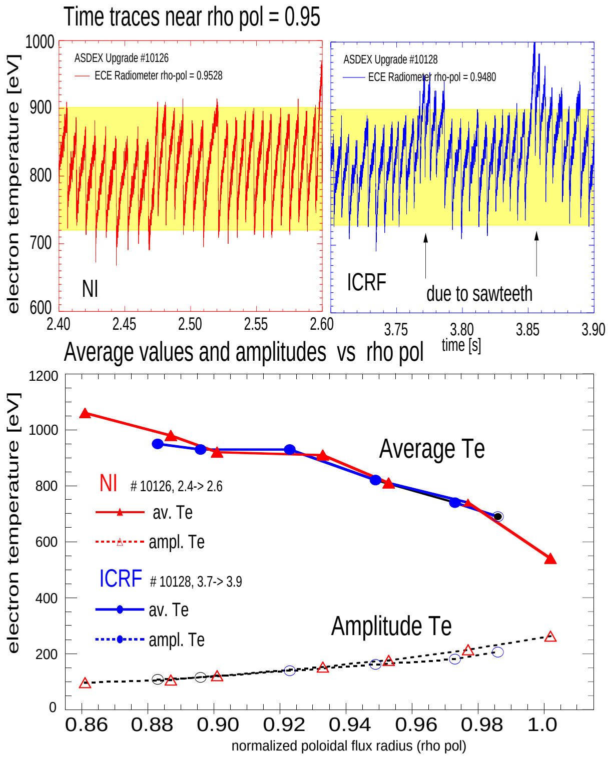


*FIG. 5. Top : time traces of the edge electron temperature with NI and ICRF near the separatrix : the ELM frequency, and electron temperature variation due to the ELMs is the same for NI and ICRF. Bottom : average temperature and amplitude of the variation due to ELMs in the neighbourhood of the separatrix. Triangles for NI, circles for ICRF.*

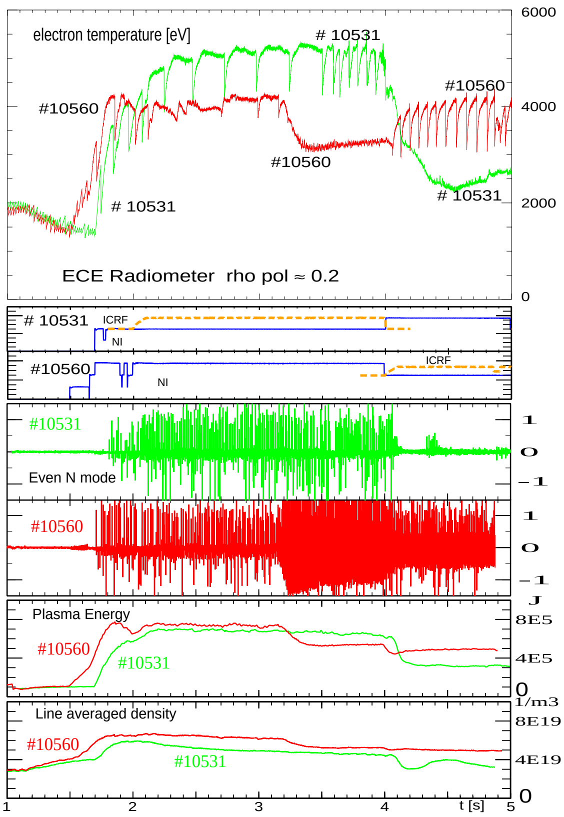


*FIG. 6. Stabilization of a 3, 2 neoclassical mode with a combination of ICRF and NI. Discharge 10531 has between t = 2 and 4 s, 5 MW NI + 2.5 MW ICRF, after 4 s NI alone (7.5 MW). Discharge 10560, has 7.5 MW NI alone in the first part of the discharge.*

## 3. SUMMARY

The use of 3 dB couplers on ASDEX Upgrade has permitted operation in regimes previously almost inaccessible with ICRF in divertor machines. Sufficiently large differences are observed with NI heating that efforts should be intensified to differentiate, in existing and future high power data, the effects specific to the heating methods.

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