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## ABSTRACT.

The objective of the present study is to find out the range of the IIHR layer radial position within which the plasma confinement in conventional *L-mode* regime may be improved. The recent ICRF-MC heating experiments on JET (RF power dominated  $D(^3He)$ -discharges,  $P_{RF}/(P_{tot}-P_{RF}) \approx 2.0$ ) were analyzed. The RF power coupled into plasma in the ICRF-MC scenario improved confinement properties of discharges with respect to the (*OH+NBI*)-phase at the central locations of IIHR ( $|r_{ii}/a_{pl}| < 0.3$ ) with the best result (up to ~60% improved confinement) closer to axis and at dipole antenna phasing. A shift of IIHR towards the plasma edge ( $|r_{ii}/a_{pl}| > 0.4$ ) resulted in degradation of confinement. An analysis of plasma confinement based on plasma diamagnetic and thermal energy content, and results of modeling of the absorbed power at ICRF-MC are discussed.

## 1. INTRODUCTION

The control of plasma heating efficiency and local transport are the principal goals for the achievement of enhanced tokamak operation. ICRF Mode Conversion (ICRF-MC) in plasma containing two ion species has a potential to solve the mentioned problems due to efficient local heating of electrons [1] and possibility to generate ponderomotively driven local toroidal/poloidal flow near the ion-ion hybrid resonance (IIHR) [2].

The objective of the present study is to find out the limits of the IIHR layer radial position within which the plasma confinement in conventional *L-mode* regime may be improved. The recent ICRF-MC heating experiments on JET ( $D(^3He)$ -discharges in the RF power dominated regime,  $P_{RF}/(P_{tot}-P_{RF}) \approx 2.0$ ) were analyzed. Magnetic configurations with the single-null divertor and toroidal magnetic field / plasma current ratio of 3.44T/1.35MA, 3.34T/2MA and 3.7T/2MA were used in the experiments. Up to 5 MW of the RF power was applied at frequencies of 33.8 or 37.2MHz using four A2 ICRF antennas [3] powered at  $\pm 90^\circ$ , dipole ( $0\pi 0\pi$ ) or ( $00\pi\pi$ ) phasing. By applying  $^3He$  -puff of variable gas injection rate before the RF power, the concentration of  $^3He$  ions was varied. As a result, the location of IIHR moved from the  $\omega_{cHe3}$  layer towards the  $\omega_{cD}$  resonance as the  $^3He$  concentration was increased. For the analyzed shots, location of the IIHR layer across the plasma was varied in the range  $-0.75 \leq r_{ii}/a_{pl} \leq 0$  by changing the  $^3He$  concentration in deuterium plasma in the wide range  $0 < n_{He3}/n_e < 0.35$ . The enhancement confinement factor FH98m defined as a total energy confinement time normalized to the ELMy H-mode confinement scaling IPB98(y,2) [4] was used to analyze plasma confinement as a function of the IIHR layer position. Since the concentration of the 3 He ions in deuterium plasma reached relatively high values (up to ~35%) in the experiments, the confinement scaling IPB98(y,2) was corrected following an established mass-dependence:  $\tau_{E-IPB98(y,2)} \propto (\sum A_i n_i / \sum n_i)^{0.19}$ . Here index  $i$  refers to  $^3He$  and  $D$  ions, respectively. However, in terms of total coupled power, the scaling was *not corrected* for plasma radiation. The analysis was done for both, RF and non-RF phases of discharges. The latter was possible after demonstration of reasonably good correlation between the  $^3He$  concentration deduced from the edge spectroscopic data and the  $^3He$  concentration deduced from the measured electron power deposition due to ICRF-MC in  $D(^3He)$ - plasmas [1]. Modeling of RF power absorbed at ICRF-MC with the TOMCAT 1 D code [5] was used to analyze the plasma heating efficiency.

## 2. EXPERIMENTAL RESULTS

Figures 1 and 2 show time traces of the main plasma parameters in discharges performed in two different magnetic configurations with the similar RF power applied at  $f=33.8$  MHz with antenna  $+90^\circ$  and dipole phasing, respectively. In both discharges, the position of IIHR was located very close to axis,  $r_{ii}/a_{pl} \approx -0.4$  at  $n_{He3}/n_e \approx 1.4\%$  (Fig.1) and  $r_{ii}/a_{pl} \approx -0.12$  at  $n_{He3}/n_e \approx 25\%$  (Fig.2). Heating of electrons is clearly seen in both cases, which indicates established ICRF-MC conditions: FW launched by LFS antennas convert near IIHR into short-wavelength plasma waves absorbed by electrons. The change in the stored diamagnetic energy per MW of RF power coupled was about of 1.7 times higher in the discharge with antenna dipole phasing (Fig.2) suggesting more efficient absorption of RF power in the plasma. As a result, the enhancement confinement factor FH98m (here based on the diamagnetic energy content) was higher in this case (Fig.2). Note, however, that the presence of fast deuteron populations with energies above the maximum beam injection energy of 135 keV was registered by the gamma-ray emission spectroscopy in the latter case [1]. Further assessments of the plasma confinement properties versus  $^3He$  concentration and, consequently, versus IIHR radial location were undertaken in terms of the total plasma diamagnetic energy content  $W_{dia}$  and thermal energy content  $W_{th}$  deduced from measured plasma densities and temperatures, respectively. The result of such analysis for discharges with the ICRF-MC conditions in the 3.44T/1.35MA and 3.34T/2MA magnetic configurations is shown in Figure 3. Several features may be stressed: (i) some decrease in the FH98m factor (here without mass-correction) on increasing the  $^3He$  concentration during both, RF and non-RF phases of discharges, (ii) a minor improvement in the confinement within the concentration range  $n_{He3}/n_e \approx 13-17\%$  corresponding to central locations of ICRF-MC (Fig.3c), (iii) a noticeable difference in confinement properties based on  $W_{dia}$  and  $W_{th}$  energy content during the RF+NBI power on phases of discharges. The main difference seems to be at low  $^3He$  concentration (Fig.3b,3c), at which He3 minority damping may give rise to some non-thermal population. Trends in the plasma confinement properties in terms of the FH98m factor (based on  $W_{th}$  energy content and mass-corrected) versus the IIHR radial position are shown in Figure 4. It is clearly seen that an improved confinement with respect to the (OH+NBI)-phase of discharges was only observed at the central ICRF-MC locations ( $|r_{ii}/a_{pl}| < 0.3$ ). The best result (up to  $\sim 60\%$  improved confinement at  $r_{ii}/a_{pl} \approx -0.12$ ) was achieved so far in the 3.7T/2 MA magnetic configuration with antenna dipole phasing (star symbols in Fig.4). As it was mentioned before, the ICRF-MC heating efficiency was higher with dipole phasing than with  $+90^\circ$  phasing. It resulted in larger  $T_{e0}$  increase (Fig.2) and better confinement. A shift of MC layer towards the HFS edge ( $|r_{ii}/a_{pl}| > 0.4$ ) resulted in degradation confinement (Fig.4).

## 3. MODELLING OF ICRF-MC ABSORBED POWER

To investigate the tendencies in the confinement/heating properties of the ICRF-MC heated plasmas, an analysis of absorbed power using modeling with TOMCAT 1D RF code was undertaken. The code solves the twelfth-order wave equation system for the three electric field components written in variational form using the finite-element approach [5]. In its variational form, the wave equation is closely related to the power balance equation. The obtained absorbed power density per guiding

centre orbit (used as the independent variable) is a strictly positive quantity. The absorbed power (total, by electrons, minority  $^3\text{He}$  and majority  $D$  ions) per full (double) transit over the plasma for two reference magnetic configurations, 3.44T/1.35MA and 3.70T/2.0MA was modeled. Figure 5 shows how the absorption varies as a function of the toroidal wave mode numbers  $n_{||}$  for the given (Figs.1, 2) plasma parameters and the A2 antenna  $k_{||}$ -spectrum [6]. Here vertical dashed and dot-dashed lines note the widths and positions of maxima of the antenna spectra. For the case of better ICRF-MC performance (Fig.2), the code predicts efficient central ( $r/a_{pl} \approx -0.15$ ) absorption of the mode-converted power by electrons (>90% of total absorbed power) in the  $n_{||}$ -range corresponding to the width of spectrum launched with dipole phasing (Fig.5(a)). Relatively low absorption ( $P_{\text{tot}} \leq 20\%$  with roughly equal distribution between electrons and  $^3\text{He}$  ions) was predicted in the  $n_{||}$ -range corresponding to the antenna spectrum launched at  $+90^\circ$  phasing (Fig.5(b)). This is the antenna spectrum that gave somewhat poorer performance with the central ICRF-MC location (Fig.1) than dipole spectrum. However, a series of calculations for this case show that the absorption by electrons may be increased by  $\approx 80\%$  and be comparable with the best-analyzed case (Fig.2) if dipole instead of  $+90^\circ$  launched spectrum is used. Figure 6(a) shows the predicted absorption by electrons as a function of the  $^3\text{He}$  concentration calculated for the experiment shown in Fig.2. A reasonable correlation of the calculated power (Fig.6(a)) with the measured central electron temperature (Fig.6(b)) was found for the measured plasma density (curve 1, Fig.6(b)) and for that one increased by 10% (curve 2). The absorbed power as a function of  $n_{||}$  and the  $^3\text{He}$  concentration reveals an oscillation nature which makes difficult the comparison with experiment. Small ( $\pm 10\%$ ) variations in plasma density (curves 2, 3 with respect to curve 1, Fig.6(b)) resulted in the radial shift of max and min positions of the oscillations thus indicating sensitivity to the conditions of the computation. The present study shows that the plasma confinement properties in discharges with ICRF-MC conditions are related to the electron heating efficiency which depends on the IIHR location and the antenna launched  $k_{||}$ -spectrum.

## ACKNOWLEDGEMENTS

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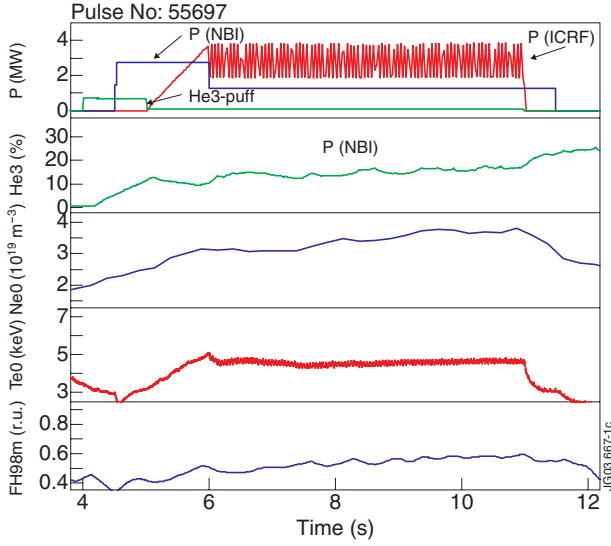


Figure 1: ICRF-MC performance at  $B_T = 3.44T$ ,  $I_p = 1.35MA$ ,  $Z_{eff} \approx 3.2$ ,  $P_{rad}/P_{tot} \approx 40\%$ , A2 antennas powered at  $+90^\circ$  phasing,  $f=33.8MHz$ .

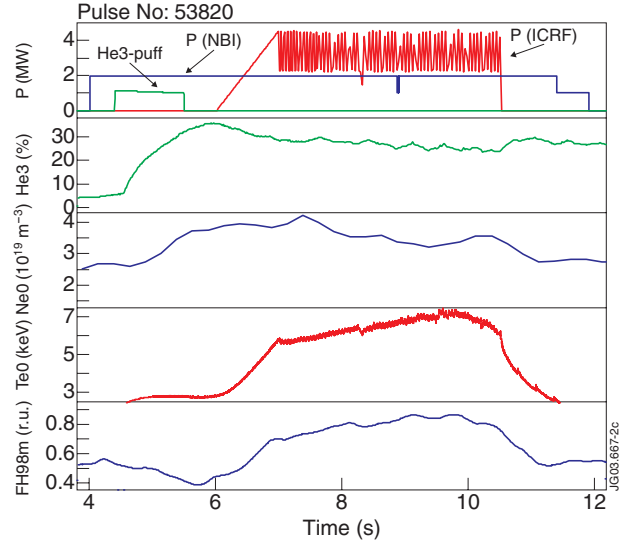


Figure 2: ICRF-MC performance at  $B_T = 3.70T$ ,  $I_p = 2.0MA$ ,  $Z_{eff} \approx 2.5$ ,  $P_{rad}/P_{tot} \approx 36\%$ , A2 antennas at dipole ( $0\pi0\pi$ ) phasing,  $f=33.8MHz$ .

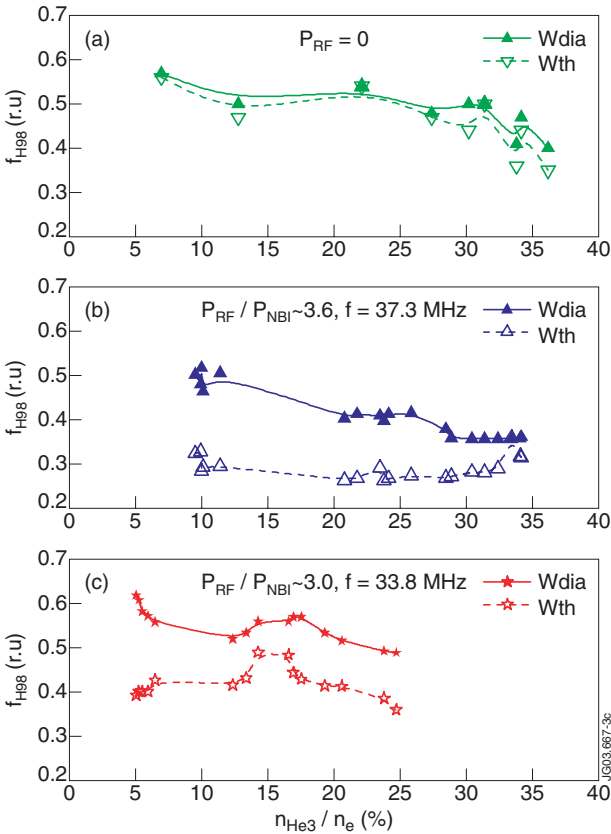


Figure 3: Comparison of confinement in discharges with ICRF-MC: (c) at  $B_T=3.44T$  with  $+90^\circ$  phasing, Pulse No's: 55394, 55398, 55403, 55410, 55695, 55697; (b)  $B_T=3.34T$ , ( $00\pi\pi$ ) phasing, Pulse No's: 55708-7.

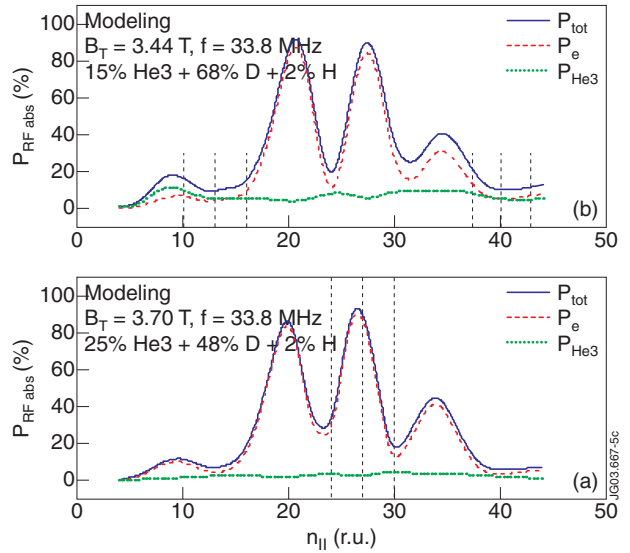


Figure 4: Trends in plasma confinement versus IHR radial location for the shots mentioned in Figures 1–3.



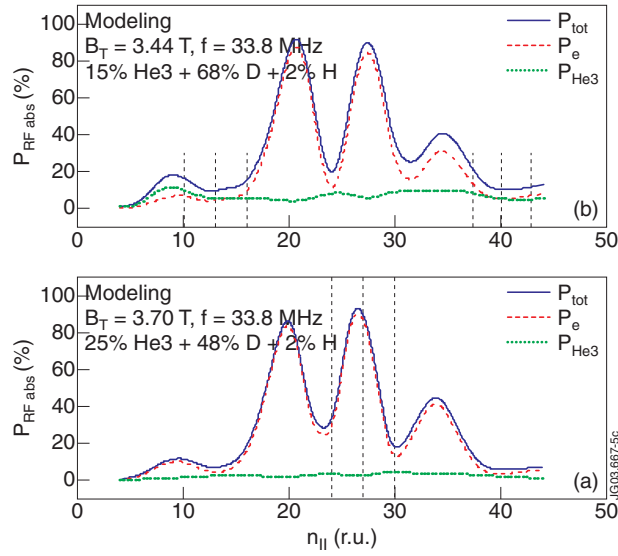


Figure5: Calculated absorption in % of the incoming power versus the toroidal mode number  $n_{||}$ : (a) - for the shot Pulse No: 53820 (Fig.2); (b) for the Pulse No: 55697 (Fig.1 );  $n_{e0} = 3.21 \times 10^{19} \text{ m}^{-3}$ .

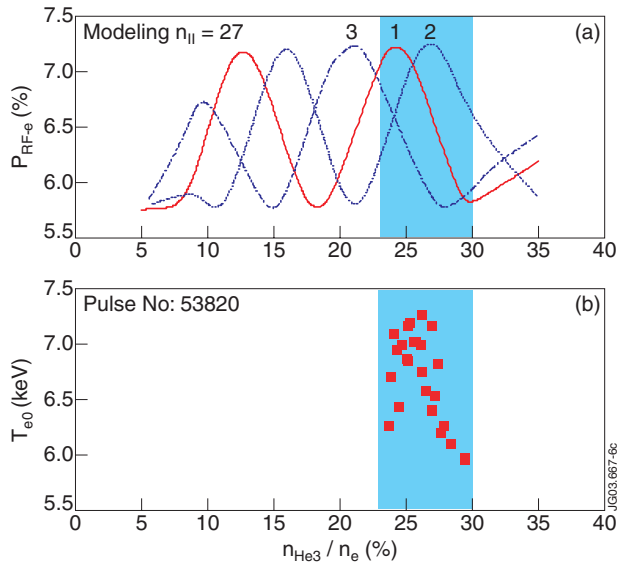


Figure 6: Calculated  $P_e$  absorption (a) and  $T_{e0}$  measured in the Pulse No: 53820 (b) versus  $\text{He}_3$  concentration: curve 1 -  $n_{e0} = 3.2 \times 10^{19} \text{ m}^{-3}$ ; curve 2 -  $n_{e0} = 3.5 \times 10^{19} \text{ m}^{-3}$ ; curve 3 -  $n_{e0} = 2.9 \times 10^{19} \text{ m}^{-3}$ .