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# ICRF coupling and edge density profile on Tore Supra

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## Introduction

Analysis of the power coupling between the plasma and ICRF antenna requires the knowledge of the behaviour of the fast magnetosonic waves (FW) near the edge. Because the wavenumber spectrum of the RF antenna is mostly in the range where vacuum propagation is impossible, the FW is not propagating below a given density. Beyond the cut-off density the wave is evanescent. The FW cut-off, located at the outer part of the plasma, is not only a function of the generator frequency ($\omega_0$) and the cyclotron frequency of majority ionic species (i) in front the antenna ($\Omega_{ci}$) but also depends on the parallel wave number ($k_{//}$) given by antenna geometry.

$$\mathbf{n}_{\mathbf{e}}^{\mathbf{cut-off}} \approx \frac{\mathbf{A}_{\mathbf{i}}}{\mathbf{Z}_{\mathbf{i}}}\left[\frac{\boldsymbol{\Omega}_{\mathbf{ci}}}{\boldsymbol{\omega}_{\mathbf{0}}}\left(\frac{\boldsymbol{\Omega}_{\mathbf{ci}}}{\boldsymbol{\omega}_{\mathbf{0}}}+\mathbf{1}\right)\left(\mathbf{k}_{//}^{2}-\mathbf{k}_{\mathbf{0}}^{2}\right)\right] \qquad \mathbf{(1)}$$

However, the evanescent zone is shorter than the perpendicular wavelength so that part of the wave tunnels through it. The coupling capabilities are then closely related to antenna matching and the quality of the wave injection is characterised by the antenna loading resistance (Rc). The RF power ($P_{ICRF}$) launched from the antenna to the plasma is proportional to the coupling resistance and the current density (J) feeding the straps : $P_{ICRF} \propto Rc \times J^2$.

This work accounts for the experimental evidence of the relationship between the RF coupling resistance the edge density profile and allows a precise description of the dependence of the RF loading and the distance between the antenna and the characteristic FW cut-off layer.

## Experimental conditions

The position of the RF cut-off density has been determined experimentally from the edge density profile measured by reflectometry. On Tore Supra, an X-mode fast sweeping heterodyne reflectometer [1], located beside the antenna, allows density measurements from 0 to approximately $1.2\times10^{19}$ $m^{-3}$. The ICRH antennas of Tore Supra are made of two straps and the $k_{//}$ spectrum depends on the spacing between the strap and the phasing between them. All the results presented here have been obtained during hydrogen minority heating scheme with dipole phasing configuration (the currents flowing along the straps are in opposite phase). The launched ICRH frequency equals 48 MHz. The maximum of the current spectrum occurs at $k_{//max} = \pm 14$ $m^{-1}$. The RF cut-off density is evaluated at this wavenumber value to characterise the distance between the ICRH antenna and the plasma. It is equal to about $ne_{RF}=9.1\ 10^{18} m^{-3}$. A collection of results of ICRF coupling have been obtained for various experimental plasma conditions, with very different boundary conditions, such as : plasma detachment, density ramping or ergodic divertor (ED) configuration and also a comparison between different filling gas (He or D2).

## Results

From equation (1), the FW cut-off density values do not depend on the type of gas used between He and D2 since the A/Z ratios are equivalent. However, it seems that D2 plasmas are apparently more efficient in coupling ICRF power than He for comparable experimental conditions i.e. same volume average density (Fig. 1). Differences occur on the plasma boundary and from reflectometry data one can observe dramatic differences in the edge density profiles (Fig. 2). Different recycling conditions [2] take place between these gases, since the plasma-wall interaction is governed by their ionisation potentials that are very different. As a consequence, the integrated data such as the volume average density cannot account properly for the density boundary conditions. From edge profile measurements it is then possible to draw more precisely the relationship between the RF coupling and the distance between the antenna and the RF density cut-off (Fig. 3).

The effect of the heating onto the plasma may evolve towards complicated interactions due to subtle action/reaction physical processes. An aspect of this interaction is the fact that the injection of RF power can strongly affect the edge density due to some power deposition at the plasma boundary inducing consecutive antenna outgassing. On Tore Supra, the average density generally increases as soon as the ICRH is turned on. This phenomenon is especially remarkable for D2 plasmas. In the following example (Fig. 4) the density increase due to additional input power triggers a plasma detachment that in turn degrades the coupling efficiency of the ICRF heating to the plasma until the RF power is turned off by an automatic security system. The measurement of the evolution of the edge density profile (Fig. 5) during the heating phase allows to plot (Fig. 6) the dependence between the RF coupling and the distance between the antenna and the plasma edge. By comparing the relationship between the coupling with respect to the plasma-antenna distance during a density ramp up experiment, it exhibits the same dependence (Fig. 6) for both experiments.

On Fig. 7 is a synthesis of a collection of 40 plasma discharges that summarises many different density regimes. It demonstrates the primary role of the distance between the RF cut-off and the antenna as one relevant parameter for the ICRF coupling efficiency. Moreover, by using the Ion Cyclotron ANTenna (ICANT) code [3], computations were made with fast wave surface impedance from BRAFFA code, using measured density and temperature parameters. Thus a calculation of the exponential decay ($Rc \sim \exp(-2k_{//}d)$) of the coupling resistance leads to a comparable calculated exponential factors ($\mathbf{k_{//}^{ICANT} \approx 8.2m^{-1}}$) with the measured one ($\mathbf{k_{//}^{EXP.} \approx 8.35m^{-1}}$). Efforts still need to be done to recover for the absolute values of Rc.

The cut-off / antenna distance is not the only parameter governing the ICRF coupling. By increasing the RF frequency from 48 to 57 MHz, the RF cut-off density is decreased to $7.4\ 10^{18} m^{-1}$. However, a better coupling efficiency for identical plasma conditions is found (Fig. 8). To account for this discrepancy, an additional dependence of about the square of the injected ICRF heating frequency ($Rc \sim F^2$) is found for the coupling resistance. This tendency is recovered by the ICANT code but not the exact dependence ($Rc \sim F^{1.3}$).

### References

[1] F. Clairet et al. : ppcf 43, 429 (2001).

[2] B. Meslin et al. : 24th EPS Conf. on Controlled Fusion and Plasma Physics vol 21 A-I, p194 (Berchtensgaden, Germany 1997).

[3] S. Pécoul et al. "Numerical modeling of the coupling of an ICRH antenna with a plasma with self-consitent antenna currents" computer physics communications (to be published).

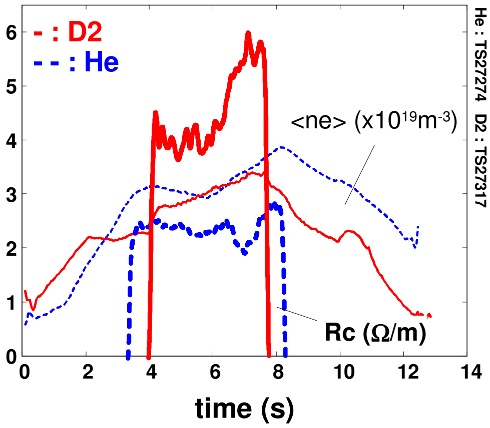

**Figure 1 : While average densities are comparable, a higher ICRF coupling efficiency is measured for the D2 plasma compared to the He plasma.**

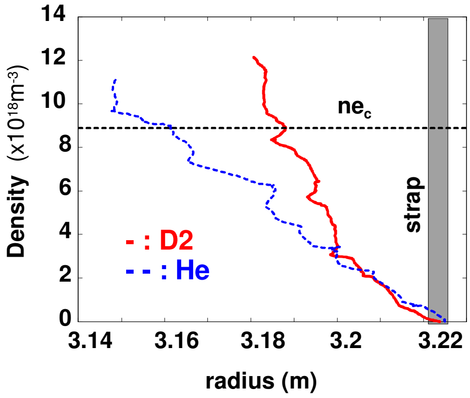

**Figure 2 : density profiles measured by reflectometry show a higher edge density for the D2 plasma and consequently a shorter distance between the antenna and the RF cut-off density ($ne_{RF} = 9.1\ 10^{19} m^{-1}$).**

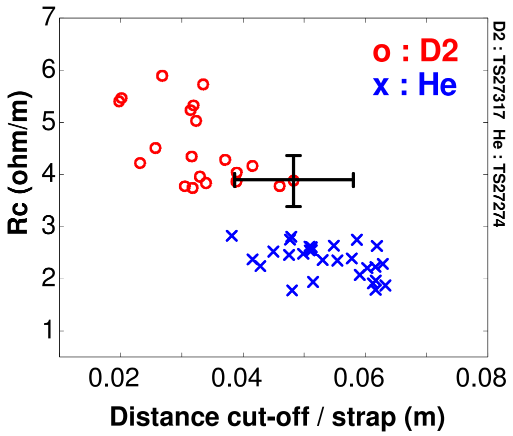

**Figure 3 : Dependence between the RF coupling resistance and the distance between the cut-off and the antenna. Each point correspond to one density profile measurement.**

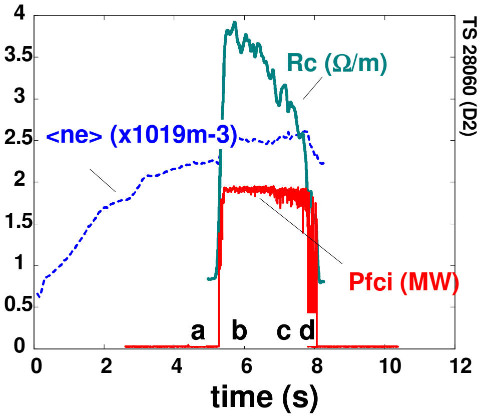

**Figure 4 : As the RF power is turned on the density increases and the coupling efficiency decreases dramatically.**

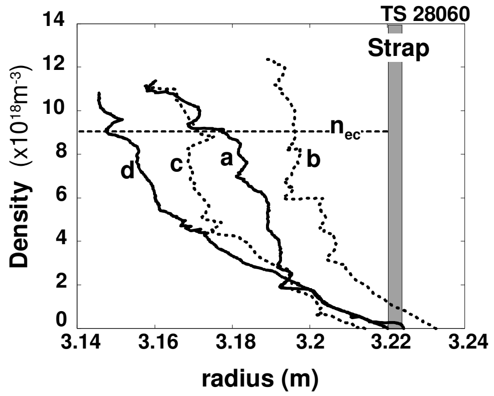

**Figure 5 : Density profiles are ploted at four different time (see Fig. 4) : the additional RF power increase the density (a to b) that in turn trigger a plasma detachement where a collapse of the edge density occurs (c-d).**

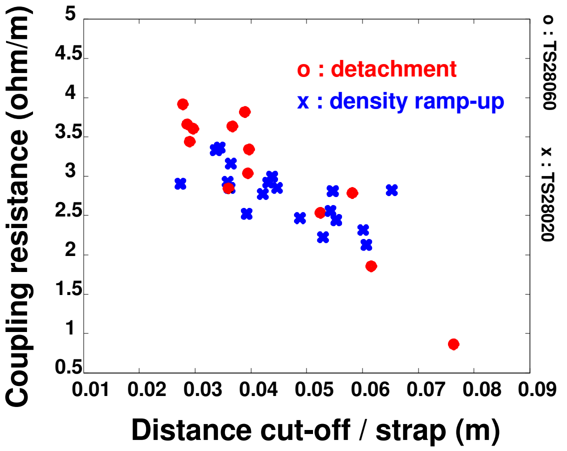

**Figure 6 : Comparison of the RF coupling dependence during a plasma detachement (see example Fig. 4) and a plasma with density ramping.**

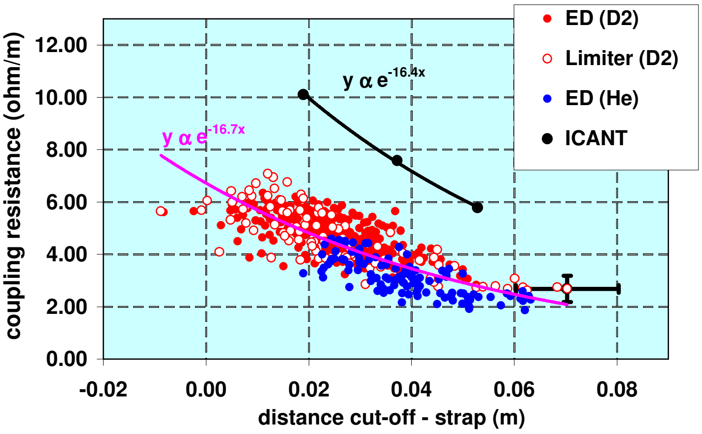

**Figure 7 : Synthesis of the dependence of RF coupling resistance vs. the plasma-antenna distance for a collection of 40 discharges over numerous density regimes. Expected dependence of Rc ~ exp(-2k$_{//}$d) from theory leads to k// = 8.35 m$^{-1}$ comparable to wavenumber calcutad from ICANT simulations (~ 8.2 m$^{-1}$).**

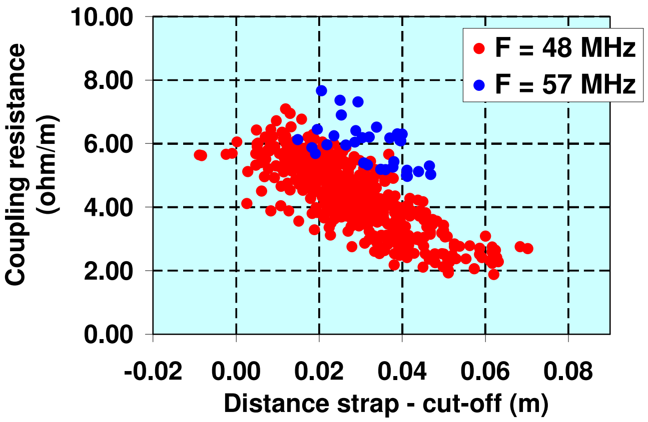

**Figure 8 : Additional square dependence of the coupling resistance is found with respect to the injected RF frequency.**