ELSEVIER

Journal of Nuclear Materials 278 (2000) 117–122

journal of nuclear materials

www.elsevier.nl/locate/jnucmat

Interaction of ICRF power and edge plasma in Tore Supra ergodic divertor configuration ☆

F. Nguyen *, A. Grosman, V. Basiuk, D. Fraboulet, B. Beaumont, A. Bécoulet, Ph. Ghendrih, L. Ladurelle, B. Meslin

Association Euratom-CEA sur la Fusion Contrôlée, CEA-Cadarache, F-13108 St. Paul-lez-Durance, France

Received 18 May 1999; accepted 15 July 1999

Abstract

The coupling of ICRF power to plasma is a crucial problem in Tore Supra for high power and long pulse operations and depends greatly on the edge parameters, in particular on the edge density. Conversely, the behaviour of the bulk plasma is related to the edge conditions and the injection of RF power also induces major modifications on the edge plasma. Moreover, the Ergodic Divertor (ED) of Tore Supra imposes a complex configuration at the edge due to the presence of the magnetic perturbation. Several diagnostics are available to study the interaction of ICRF power with the edge plasma: Langmuir probes on the ED modules, infra red (IR) cameras, charge exchange neutral analysers. In minority heating scheme, the edge density is very sensitive to any perturbation in the high recycling regime which is always found in the ED configuration for relevant plasma parameters. Partially detached regimes, with or without inhomogeneities of density and temperature induced by the flux tubes of the laminar layer, are obtained for high resistance coupling values. The coupling is then not very robust and feedback control or antenna automatic matching techniques are developed. In fast wave electron heating scheme with ED, various fast wave absorption mechanisms (minority heating, Mode Conversion, Alfven resonance) are present at the plasma edge due to the large size of the plasma. The ICRF coupling is difficult due to the low fast wave direct electron damping, even with high hydrogen minority scheme. An increase of the injected ICRF power could improve this situation.

1. Introduction

The coupling of ICRF power to plasma is a crucial problem in Tore Supra for high power and long pulse operations. The coupling of ICRF power depends greatly on the edge parameters, in particular on the edge density. Conversely, the behaviour of the bulk plasma is related to the edge conditions and the injection of RF power also induces major modifications on the edge plasma not only by increasing the heat and particle fluxes coming from the central confined plasma, but also by depositing directly power at the edge and by imposing RF fields in the scrape-off layer. Moreover, the Ergodic Divertor (ED) of Tore Supra imposes a complex configuration at the edge due to the presence of the magnetic perturbation. Several diagnostics are available to study the interaction of ICRF power with the edge plasma: Langmuir probes on the ED modules, infra red (IR) cameras, charge exchange neutral analysers. In the present paper, two ICRF heating schemes in the ED configuration are studied, namely minority hydrogen heating and fast wave electron heating (FWEH). The first scheme was well developed and it will be shown that the requirements of adequate density at the antenna are difficult to reach in view of the sensitivity of the density regimes in the high recycling mode which is used. The

☆ This paper was presented at the Thirteenth International Conference on Plasma–Surface Interactions in Controlled Fusion Devices, San Diego, California, USA, May 18–22, 1998, whose Proceedings are published in J. Nucl. Mater. 266–269 (1999).

* Corresponding author. Tel.: +33-4 42 25 78 09; fax: +33-4 42 25 62 33.

E-mail address: fnguyen@cea.fr (F. Nguyen).

0022-3115/00/$ - see front matter
PII: S0022-3115(99)00216-0

second scheme imposes specific requirements in terms of location of ion cyclotron resonant layers : their necessary exclusion to promote the electron deposition contradicts the large plasma size in ED configuration. A large hydrogen minority is then used to diminish the ion absorption but parasitic edge absorptions then competes with the FWEH seriously.

2. Ergodic divertor configuration and ICRF minority heating scheme

In the ED configuration, a laminar layer is surrounding the central confined plasma [1]. When studying the relations linking the densities on both sides of this layer, three regimes have been identified in ohmic phase [2,3] in Deuterium plasmas depending on the averaged density: a linear regime, a highly recycling regime and finally detachment. In ^{4}He plasmas, only the linear and highly recycling regimes have been observed up to $\langle n_e \rangle \sim 8 \times 10^{19}$ m^{-3}.

The injection of RF power strongly affects the edge density as many of the parameters controlling it are modified such as possible antenna outgassing, thermal and particle fluxes entering the laminar layer [4], physics of the electrostatic sheath, edge impurity content and thus radiated power, etc... Therefore, on Tore Supra the average density generally increases as soon as ICRF power is injected, especially in deuterium plasma. Conversely, any modification of the edge density perturbs the loading resistance of the ICRF antenna and thus its coupling capability. It should be stressed that the variations of the edge density are very large even with small evolution of average density (generally, the control parameter for gas injection in Tore Supra) making the power injection difficult even if an automatic matching is implemented as in Tore Supra. The three Tore Supra ICRH antennas are compact resonant double loop structures with incorporated capacitors, and the matching is obtained by adjusting in real time the two internal capacitors located at the end of each current straps [5].

Though the injection of RF power likely modifies also the dependencies of edge density evolution, the classification in terms of various density regimes still remains, and it can be illustrated by comparing the evolution of the coupling efficiency as a function of central and edge parameters. The ICRF coupling resistance R_c, which characterises the coupling efficiency, is plotted in Fig. 1(a) versus the average density $\langle n_e \rangle$ for ED configuration in minority heating scheme. The general tendency is that R_c increases with $\langle n_e \rangle$ but with a large dispersion. A saturation is observed in deuterium above $\langle n_e \rangle = 4 \times 10^{19}$ m^{-3}.

The ED modules are equipped with Langmuir probes that provide electron temperature and density at the outer side of the laminar layer. These measures give an estimate of the edge density [3] that regulates the coupling resistance.

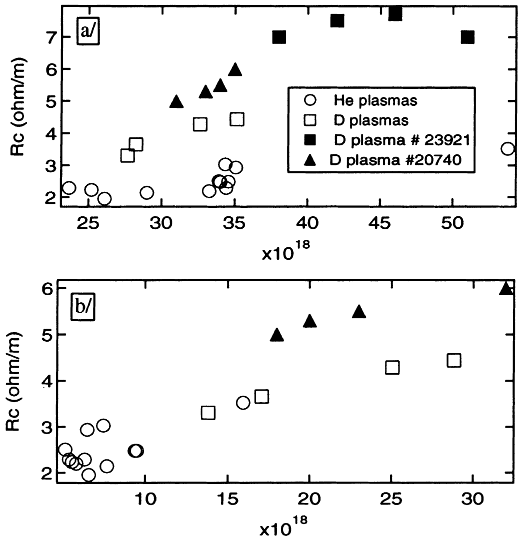

Fig. 1. Coupling resistance in minority heating with ED as a function of (a) average density and (b) edge density.

In Fig. 1(b), the same coupling resistances are plotted versus this edge density and a common trend appears. Note that the small dispersion is likely due to different radial position of the antenna with respect to the divertor modules. The antenna protection tiles were located 1 cm behind the ED modules in the shot #20740 and at the same radial position in the other shots. The saturated regime for R_c (black squares in Fig. 1(a)) has been obtained for shot #23921 with a slow rise of $\langle n_e \rangle$ during the shot. The evolution of the edge parameters is a clue to the shot fate. It should be stressed that there are strong inhomogeneities in the Langmuir probes measurements for some shots: for instance on shot #23921, the density on one ED modules finally drops when the temperature is around 10 eV but on other ED modules, the edge density still rises to very large values ($4–5 \times 10^{19}$ m^{-3}). The edge density value in front of the ICRF antenna is decorrelated from these measurements and a partial detachment occurs locally. Since no measurements are available at the antenna, this shot is not included in Fig. 1(b). The different regimes for edge density could be identified: the R_c saturated regimes correspond to partially detached plasma with strong local inhomogeneities (e.g. #23921) and the R_c evolution at lower density corresponds essentially to attached plasmas.

Since the evolution of the edge density [3,6] acts on the coupling resistance, up to now for high power injection, the edge density was such to naturally evolve in a high recycling regime. These regimes are very unstable either because of the possible triggering of radiative instabilities, or because of the natural unstable character of the thermal parallel transport equation when radiation is significant but also because of the sensitivity to changes in the coupled power.

A specific concern is related to the initial coupling of RF power, as it may prevent or possibly trigger the detachment. Two similar shots in a series are compared hereafter; the experimental scenario involved an important density change just before and during ICRH power injection. The triangles in Fig. 1(b) show different R_c values of the shot #20740. The average density and the density at the ED module no. 3 (the Langmuir probes of the different ED modules give similar evolution for electron temperature and density) are displayed in Fig. 2(a). The coupling resistance (Fig. 2(b)) increases with $\langle n_e \rangle$ and the edge density. The edge temperature (Fig. 2(c)) remains larger than 20 eV and no detachment occurs. On the contrary, the shot # 20733, also displayed on Fig. 2, presents different evolution of the edge density due to the smaller preceding average density (which resulted in a larger gas injection feedback response see Fig. 2(d)): consequently, no ICRF power is injected as plasma detaches very early and the edge temperature drops to 10 eV (Fig. 2(c)). The edge density drops also but the average density still increases to reach the same value of the #20740 density.

The detachment may prevent coupling of ICRH in the early phases but also may stop it at any time then. This has led to the implementation of feedback techniques on the detachment parameter. IR cameras allow to measure and record the surface temperature T_s of the ED neutraliser plates. As they are coated with B_4C, the surface temperature is directly related to the conducted heat flux. As the base temperature is about 160°C, the heat flux is about $(T_s - 160) \times 10^4$ W/m^2. Maximum, and average values of the temperature along one neutraliser plate for shot #23896 are plotted in Fig. 3(b). The average density, the ICRF power and the edge density (ED module no. 5) are given in Fig. 3(a). The ED module no. 5 is also equipped with a Langmuir probe having a fast acquisition rate: the latter measure of density is also given in Fig. 3(a). At the application of the ICRF power ($t = 4.1$ s), a small drop of density first occurs. This is certainly the type of initial detachment hereabove quoted. Note that the heat flux strongly decreases at the same time. The drop of ICRF power at $t = 4.6$ s is also correlated with a density drop that is clearly seen with fast acquisition (line in Fig. 3(a)). A plasma detachment finally occurs at $t = 5.2$ s and the drop of edge density is again visible (by a factor of ten). This large drop of edge density induces a safety switch off of the ICRF power. In fact, the conducted flux (Fig. 3(b)) shows the same accidents at 4.1, 4.6, 5.2 s and is then a very good indicator of an edge event influencing the coupling resistance. Just before 5 s (Fig. 3(b)), such an edge event happened but the ICRF power 'survived'. The flux profile also evolves during the RF pulse (beginning of RF, steady state, edge events, final crash). This plasma is partially detached: the edge temperature

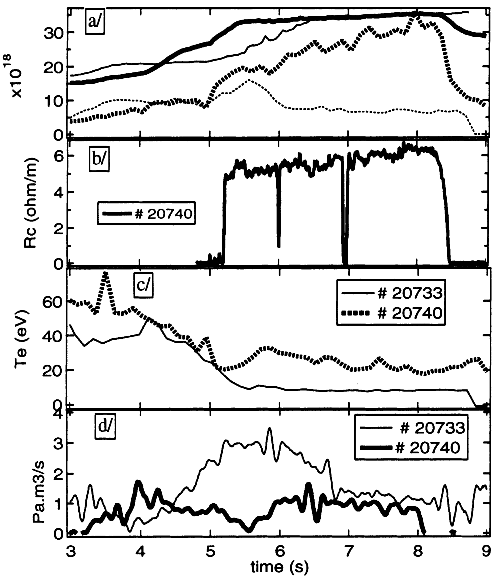

Fig. 2. (a) Average density of #20740 (bold line), #20733 (line), density of Langmuir probe ED no. 3 for #20740 (dot dash line), #20733 (dash line), (b) R_c of Q5 antenna, (c) electronic temperature of Langmuir probe ED no. 3 d/D gas injection.

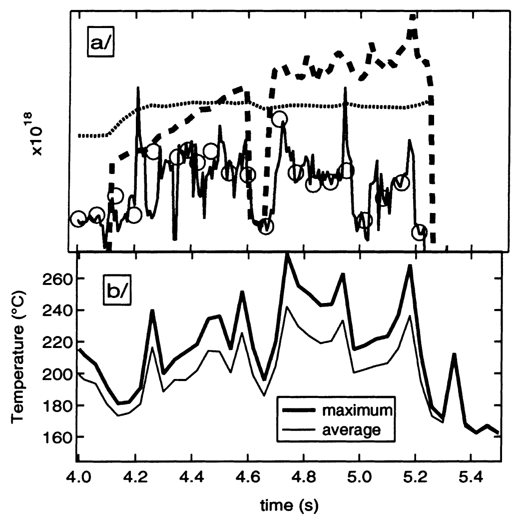

Fig. 3. (a) Pulse #23896 ICRF power (MW) multiplied by 1e19 (bold dash line) average density (dash line) density of Langmuir probe ED no. 5 (circle) fast acquisition density of Langmuir probe ED no. 5 (line), (b) Surface temperature on an ED module.

given by the fast acquisition fluctuates with minimum values around 13 eV. This partial detachment is the cause of the appearance of edge instabilities that may ($t = 4.7$, 5.2 s) or may not ($t = 4.9$ s) affect the ICRF power. The conducted flux provides an estimation of $P_{tot} - P_{rad}$ and is a good indicator for radiative edge instability.

The presence of RF waves at the edge is also a perturbation that could enhance these kinds of phenomena. The electron heating (FWEH), to be developed in the next section, is characterised by a much smaller absorption. The level of RF field is thus larger at the edge. Consequently, while in minority heating scheme only the ED Langmuir probes directly connected to a neighbouring antenna (i.e. on a toroidal distance less than $\Delta\varphi = 2\pi/12$) are affected, such effects are generalised in the FWEH scenario. The involved perturbations include strong increase of the floating potential so that the saturation current of the Langmuir probe is not reached any more.

ELMs (in other devices such as JET), large pellet injection or monster sawtooth crash may also produce large perturbations of the plasma edge and no mechanical rapid displacement of the antenna can cope with fast coupling perturbations then induced. For future experiments, new matching concepts are required to ensure that the maximum power can be transferred continuously to the plasma, even during transients [5]. These perturbations can lead to over voltages in the feedthrough or in the lines and induce arcs. Consequently, the power is switched off on any increase of the standing wave ratio to avoid heavy damages generated by arcs. These transients should generally only lead to power limitations. But these perturbations are not discriminated from arcs and power trips occur in any case. So an arc detector [7] not based on reflected power measurement would be of great interest in order to avoid inopportune power trips. The FWEH scheme by avoiding monster sawtooth may be a solution to this kind of problem and the application to the ED configuration is detailed in the following section.

3. Ergodic divertor configuration and FWEH scheme

The FWEH scheme has proved to be an excellent candidate for advanced tokamak scenarios in limiter plasma in Tore Supra, and high β_p values have been obtained [8]. The main competing fast wave damping mechanisms, due to the fundamental and second harmonic hydrogen cyclotron absorptions located on the high (HFS) and low field side (LFS), have been excluded by a proper choice of the toroidal magnetic field and of a smaller minor radius plasma located on the HFS. The exclusion of these cyclotron layers has been monitored with the neutral fluxes [8] measured by charge exchange neutral analysers.

Yet, the Ergodic Divertor imposes several operational constraints. In order to have an unperturbed core plasma, the ED magnetic perturbation has a sharp radial decrease thanks to its multipolar coil shape. The consequence is that the plasma should lean on the ED coils on the LFS, to have a non-negligible stochastic layer thickness. The stochasticity of the magnetic field lines also requires a resonance condition which, in usual operation, translates into a safety factor value about 3 at the ED coils location. As the scenario for FWEH constrains the toroidal magnetic field, the value of the plasma current is bounded. The large size of the plasma makes the exclusion of the ion cyclotron layers difficult. In addition, the magnetic field ripple is very important on the LFS (7%) corresponding to a radial excursion of 20 cm of the field lines for the considered parameters. The initial experiments of FWEH with ED at 2.1 T, having the second cyclotron harmonic of hydrogen located in the plasma, on the LFS just in front of the ICRF antenna were not favourable. Further experiments at a larger toroidal field (2.6 T), to exclude this 2H layer out of the plasma even with the ripple effect, found the fundamental H cyclotron layer entering the plasma from the HFS. A strategy of high minority has been tested as the position and the strength of the cyclotron absorption of the fast wave by the hydrogen depend on the ratio of hydrogen to deuterium concentrations. A high concentration of hydrogen reduces the ion absorption favouring the electron absorption. A scan in the ratio hydrogen to deuterium concentrations has been performed with an ED configuration ($I_{plasma} = 1$ MA, $R_0 = 2.43$ m, $a = 0.73$ m, different currents in the ED coils) with the 1H layer 25 cm inside the plasma. The various ion absorptions and the isotopic ratio H/D are estimated with charge exchange neutral analysers. On the LFS, no fast particle (H or D) is detected. On the HFS, no fast D particle has been measured. Fast H ions are present for ratio H/D between 5% and 25–30%. The queue of fast H ions disappears only for very large injection of hydrogen for which the ratio H/D is of the order of 45%. Fig. 4 displays the traces for two typical shots: #23531 ($I_{DE} = 0$ kA, $P_{ICRF} = 5$ MW peak, no hydrogen injection) and #23539 ($I_{DE} = 25$ kA, $P_{ICRF} = 4$ MW and large hydrogen injection). In Fig. 4(a), the hydrogen neutral fluxes are plotted for ohmic and RF phases. The H/D ratio is around 15–20% for #23531 (no H injection) and 40–50% for #23539 (see Fig. 4(b)). The gas injections are displayed in Fig. 4(c). Different values of current in the ED coils (0–15–25 kA) have been tested in the range H/D$\sim$25–30% and the flux of fast H ions on the HFS is similar. The degree of ergodization then does not influence this ion absorption. The important parameters for the creation of fast ions seems to be the deepness in the plasma of the H cyclotron layer and the

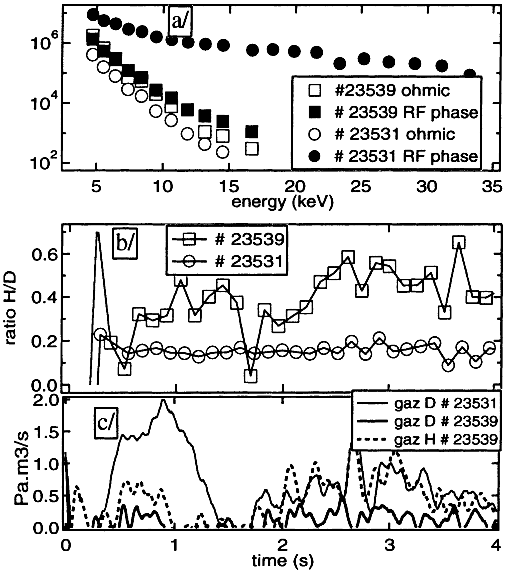

Fig. 4. (a) H fluxes from the HFS measured by the charge exchange neutral analyser, (b) ratio H/D, (c) gas injection.

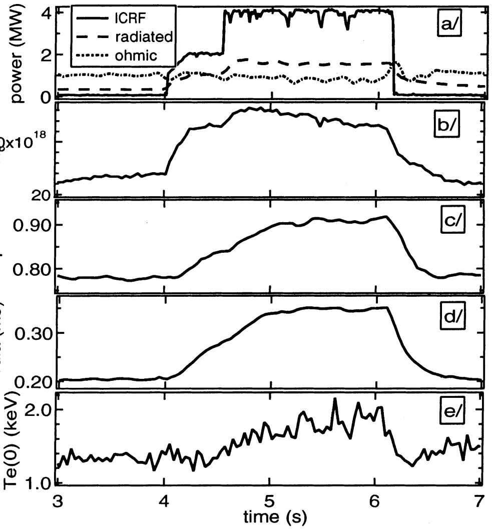

Fig. 5. Time evolution of shot #23534 (FWEH in ED configuration) (a) powers, (b) average density, (c) β_p + li/2, (d) energy contents W_{dia}, (e) central electron temperature.

isotopic ratio H/D. Indeed, a limiter configuration with smaller plasma shifted on the HFS ($I_{plasma} = 0.8$ MA, $R_0 = 2.45$ m, $a = 0.7$) m with the 1H layer 14 cm inside the plasma has the same behaviour, namely, there are fast H ions for H/D = 10% but they vanish for H/D ~ 20%.

For all these shots, there is a very sharp increase of the average density with the injection of ICRF power. When the H/D ratio is large and then no fast H ions are detected, there is almost no increase of electron temperature (although there are few shots in the database). When fast ions are detected, there is a slow increase of the electron temperature. In Fig. 5, time dependencies of shot TS #23534 ($I_{DE} = 25$ kA, H/D ~ 25–30%) are plotted. In Fig. 5(b), one can see the large rise of the average density from 2.4×10^{19} to 3.2×10^{19} m^{-3} with 2 MW of ICRF injected power. Starting at $t = 4.7$ s, there is an evolution at constant energy contents (see the diamagnetic measurement of the energy content W_{dia} in Fig. 5(d)) towards a reduction of $\langle n_e \rangle$ (Fig. 5(b)) and an increase of $T_e(0)$ (Fig. 5(e)). The evolution of $\beta_p + \mathrm{li}/2$ is similar to the energy contents (Fig. 5(c)). Note that the neutral flux due to fast H ions on the HFS is constant during this period. The power partitioning on electrons and ions and the location of the deposition is very important in this scenario. Various simulations of the power deposition have been carried out. The 2D full wave ALCYON code [9] has been used to study the influence of the high minority strategy on power partitioning. When considering a dipole spectrum for the Tore Supra antenna, as expected the percentage of power deposited on H ions decreases when the isotopic ratio H/D increases: 82% (res. 90/93) on electrons and 18% (reps. 10/7) on H for plasma mixture 10% H–90% D (res. 30–70/50–50).

Nevertheless, a very important effect in this kind of scenario, namely the mode conversion of the fast wave, is not included in this simulation. The 1D full wave code VICE [10] has been used to address the influence of this phenomenon for three plasma mixtures: (a) 5% H–95% D, (b) 25% H–75% D and (c) 50% H–50% D. Again, the power deposited on H ions decreases when the H concentration increases. In the three cases, the location of mode conversion power deposition occurs at the edge on the HFS and is not favourable for obtaining peaked central electron temperature. Alfven resonances have also been detected by the VICE code on the HFS in some cases but have not been taken into account in the above simulations. All this means that the power deposition is very difficult to simulate for these shots due to the various edge phenomena, but that there are clearly some non-negligible power deposition at the edge. These results, when convoluted with the actual antenna spectrum in dipole phasing gives the global power partitioning:

(a)	D: 11.2%	H: 38.8%	FWEH: 38.5%	Mode Conversion: 5.2%
(b)	D: 7.9%	H: 15.8%	FWEH: 66.4%	Mode Conversion: 12.6%
(c)	D: 14.3%	H: 11.3%	FWEH: 66.4%	Mode Conversion: 8.1%

The single pass absorption (SPA) on electron has been estimated with the SINGLE code [10,11] and ranges from 4% at the beginning ($T_e(0) = 1.4$ keV) and 7% at the end ($T_e(0) = 2$ keV) of the RF phase (#23534 in Fig. 5). These low values explain the large influence of parasitic absorptions at the edge. Note that the single pass absorption varies with B^{-3} and that the FWCD experiments carried out at lower magnetic field (2.1 T) were more favourable to FWEH. Such a regime of low central absorption and non-negligible edge absorption is not favourable for the coupling of power. As noted in the preceding section, the Langmuir probe measurements are much more perturbed (this is clearly seen on the saturation current measurement) by the injection of ICRF power (only the probes of two ED modules could be used) than in minority heating scenario where only the probe in direct magnetic connection on the neighbouring antenna is perturbed. Probably, much more RF power is travelling in the edge plasma in this configuration than in minority heating scheme. The density and the coupling resistance are very well correlated and present a chaotic time behaviour.

During these experiments, the amount of metallic impurities (Fe, Cu, Ni) increases during the RF phase and together with the large density leads to a fast rise of radiated power. If the injected RF power becomes lower than the radiated power, the plasma disrupts: one should then impose a rise of the power faster than the increase of the radiated power when shaping the RF pulse to avoid this effect.

4. Conclusion

In minority heating scheme with ED, the coupling of ICRF power depends on the edge density. The latter is very sensitive to any perturbation in the high recycling regime which is always found in the ED configuration for relevant plasma parameters. The coupling resistance increases with the edge density but detachment instability perturbs the edge plasma at high values of densities. Partially detached regimes, with or without inhomogeneities of edge density and temperature induced by the flux tubes of the laminar layer, are obtained for high resistance coupling values. The coupling is then not very robust and feedback control or antenna automatic matching techniques are developed. In FWEH scheme with ED, various fast wave absorptions mechanisms (minority heating, Mode Conversion, Alfven resonance) are present at the plasma edge. The ICRF coupling is then difficult due to the low Fast Wave direct electron absorption. Large plasmas at a current around 1 MA require more ICRF power to obtain large electron temperature that favours the direct electron damping against the edge parasitic absorptions. Experiments at larger injected power are then scheduled to alleviate these coupling difficulties.

References

[1] F. Nguyen, Ph. Ghendrih, A. Grosman, Nucl. Fusion 37 (6) (1997) 743.
[2] B. Meslin, Ph. Ghendrih, A. Grosman et al., Proc. 24th Eps conference, Europhysics Conference Abstract 21A-I (1997) 197.
[3] B. Meslin, T. Loarer, Ph. Ghendrih et al., J. Nucl. Mater. 266–269 (1999) 318.
[4] Y. Sarazin, Ph. Ghendrih, X. Garbet, Proc. 24th Eps conference, Europhysics Conference Abstract 21A-I (1997) 193.
[5] L. Ladurelle, G. Agarici, B. Beaumont et al., Fusion Technology 1996, in: Proceedings of the 19th SOFT, vol. 1, 1996, pp. 593–596.
[6] A. Grosman, J. Gunn, E. Laugler et al., J. Nucl. Mater. 266–269 (1999) 189.
[7] F. Braun, Th. Sperger, Fusion Technology 1996, in: Proceedings of the 19th SOFT, vol. 1, 1996, pp. 601–603.
[8] Equipe Tore Supra, Plasma Phys. Control. Fusion 36 (1994) B123–B132.
[9] D.J. Gambier, A. Samain, Nucl. Fusion 25 (1985) 283.
[10] D. Fraboulet, Université J. Fourier Grenoble I, Ph.D. thesis, 1996 and report EUR-CEA-FC-1595, 1996.
[11] D. Fraboulet, A. Bécoulet, Phys. Plasmas 4 (12) (1997) 4318.