

# ERGODIC DIVERTOR EXPERIMENTS WITH FAST WAVE ELECTRON HEATING IN TORE SUPRA

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## 1. Introduction

The Fast Wave Electron Heating (FWEH) scheme has proved to be an excellent candidate for advanced tokamak scenarios in limiter plasma in Tore Supra: high  $\beta_p$  values and bootstrap current have been obtained with this good electron heating scheme [1]. Such a scheme is very attractive for long pulse operation on Tore Supra but the operational constraints of Ergodic Divertor (ED) configuration should be addressed. Experimental results and power deposition calculations are presented.

## 2. Ergodic divertor configuration and FWEH scheme

In FWEH scheme, the main competing Fast Wave damping mechanisms, due to the ion cyclotron resonances 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 small minor radius plasma located on the HFS [1]. The ED configuration imposes several operational constraints. In order to have an unperturbed core plasma, the ED magnetic perturbation has a sharp decrease radially thanks to its multipolar coil shape and, in consequence, 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, depending on the value of  $\beta_p + l_i/2$  [2]. As the scenario for FWEH constrains the toroidal magnetic field, the value of the plasma current is bounded (1 MA in Deuterium plasma in what follows). 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 penetration of 20 cm of these resonance layers for the considered parameters.

## 3. Experiments at 2.1 T

Initial experiments of FWEH with ED have been done at 2.1 T: the 2nd cyclotron harmonic of Hydrogen (2H) and the 4th cyclotron harmonic of Hydrogen (4D) are then located in the plasma, on the LFS just in front of the ICRF antenna. The time dependencies of a shot in this configuration (#19473) are displayed on Fig. 1. There is a strong increase of average density with the injection of ICRF power. The central electron temperature first increases then decreases slowly. The charge exchange neutral analyzers [3] measure no flux of fast ions from the HFS and large fluxes of fast H and D from the LFS indicating ion damping on the LFS. The presence of fast ions in this region is not favorable to the couplers. In particular, large amount of Fe is detected by spectroscopy. However, the electron pressure, density and temperature profiles (see Fig. 3) are comparable with those obtained with 3 MW of ICRF power in limiter configuration without resonance layer at the edge (#22938 with  $B_0 = 2.1$  T).

#### 4. Experiments at 2.6 T

Further experiments have then been carried out at a larger toroidal field (2.6 T) to exclude this 2H layer out of the plasma even with the ripple effect. Of course, the consequence is then that the 1H layer enters the plasma from the HFS (25 cm). A strategy of high minority has been tested as the position and the strength of the cyclotron absorption of the FW by the minority species depends on the ratio of Hydrogen to Deuterium concentrations. A lower ion absorption should be favorable to the electron absorption. The isotopic ratio H/D is estimated with charge exchange neutral analyzers [3]. 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% (e.g. #23534). 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% (e.g. # 23540). The configuration has been tested with different values of current in the ED coils (0-15-25 kA) in the range H/D~25-30 % and the flux of fast H ions on the HFS are similar. The degree of ergodization then does not influence this ion absorption. The Fig. 2 displays the traces for two typical shots in ED configuration ( $I_{DE} = 25$  kA) with different isotopic ratios: # 23534 (H/D~25-30%) and #23540 (H/D~45%). For these shots, there is again a very sharp increase of the density with the injection of ICRF power: the average density rises from  $2.4 \cdot 10^{19} \text{ m}^{-3}$  (resp.  $2.5 \cdot 10^{19} \text{ m}^{-3}$ ) to  $3.2 \cdot 10^{19} \text{ m}^{-3}$  (resp.  $3.7 \cdot 10^{19} \text{ m}^{-3}$ ) with 2 MW of ICRF power for #23534 (resp. 23540). In minority heating (#23534), starting at  $t=4.7$  s, there is an evolution at constant energy contents (see the energy content  $W_{dia}$  on Fig. d/) towards a reduction of  $\langle n_e \rangle$  (Fig. 2 b/) and a increase of  $T_e(0)$  (Fig. 2 e/). The evolution of  $\beta_p + li/2$  is similar to the energy contents evolution (Fig. 5 c/). Note that the neutral flux due to fast H ions on the HFS is constant during this period. On the contrary, when the H/D ratio is large and then no fast H ions are detected (#23540), there is no increase of electron temperature (Fig. 2e/) but the average density rises higher up to  $4.2 \cdot 10^{19} \text{ m}^{-3}$  (Fig. 2b/). These differences of electron density and temperature could also be seen on the normalized profile plotted on Fig. 3. The electron pressure profiles are almost similar for #23534 and #23540, the large density compensates the low temperature for # 23540. However, the energy content (Fig 2d/) and  $\beta_p + li/2$  (Fig. 2c/) becomes larger with minority heating on the HFS (#23534). 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.

#### 5. Power partitioning

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 [4] 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, one finds as expected that the percentage of power deposited on H ions decreases when the isotopic ratio H/D increases: 82% (resp. 90/93) on electrons and 18% (resp. 10/7) on H for plasma mixture 10% H-90% D (resp. 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 [5] has been used to address 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. The mode conversion occurs in the three cases. The location of mode conversion power deposition is at the edge on the HFS (see Fig. 4) and is not favorable for obtaining peaked central electron temperature. Alfvén 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 [5, 6, 7] 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 on Fig. 4). These low values are explained by the large influence of parasitic absorption at the edge. Note that the single pass absorption varies with  $B^{-3}$  and that the experiments carried out at lower magnetic field (2.1 T) were more favorable to FWEH (maximum of SPA of 17% at 2 keV for #19473, see Fig. 4). Such a regime of low central absorption and non negligible edge absorption is not favorable for the coupling of power.

## 6. Conclusion

In ED configuration, the FWEH scheme presents ion damping at the edge, either on the HFS (2.6 T with minority heating) or the LFS (2.1 T with 2H and 4D damping) leading to the creation of spurious fast ions at the edge. In addition, mode conversion occurs also at 2.6 T behind the minority layer on the HFS. A high minority strategy has been tested. At 2.6 T with minority heating, a favorable increase of temperature appears with a corresponding density decrease. With high minority strategy, the temperature does not increase but the density is higher, leading to a similar pressure profile. At 2.1 T with 4 MW, the pressure profile is somewhat larger but is comparable with a FWEH pulse in limiter configuration at 3 MW without cyclotron layer at the edge. More experiments at higher ICRF power are scheduled.

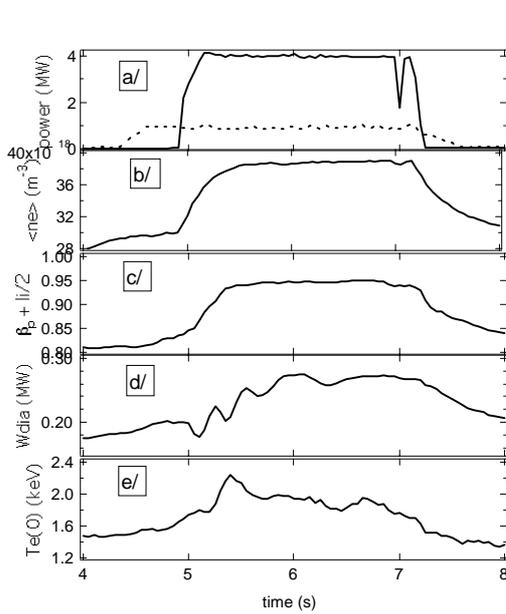
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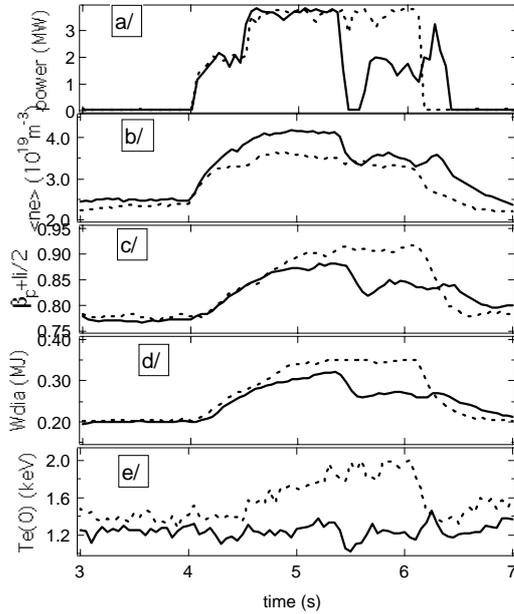
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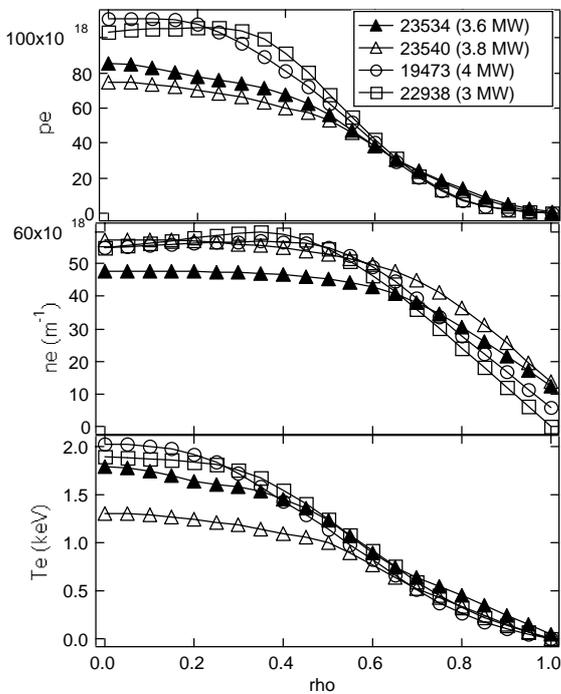
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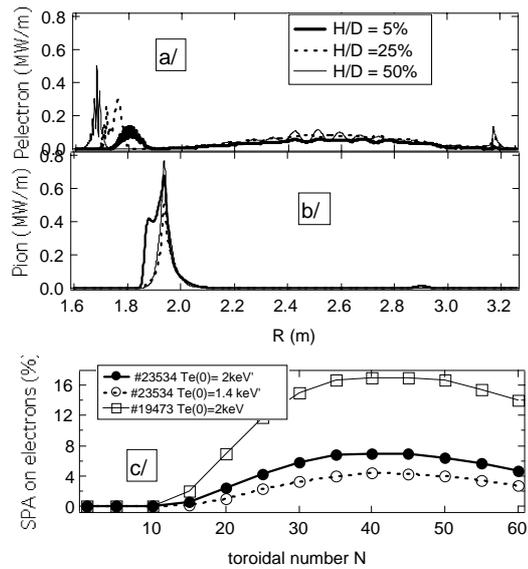
**Fig. 1.** Time evolution of shot #19473 a/ ICRF power(-), LH power (- -) b/average density c/  $\beta_p + li/2$  d/ energy contents Wdia e/ central electron temperature



**Fig. 2.** Time evolution of shot #23534 (- -) and 23540 (-) a/ ICRF power b/average density c/  $\beta_p + li/2$  d/ energy contents Wdia e/ central electron temperature



**Fig. 3.** Normalized profiles of electronic pressure, density and temperature at  $I_p=1$  MA



**Fig. 4.** Power deposition with the VICE code a/ on electrons, b/ on ions H and D, c/ Single Pass Absorption on electrons