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Ergodic Divertor experiments in Tore Supra above the Greenwald density limit with ICRF power at low magnetic field

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1. Introduction

Steady state scenarios in magnetic fusion meet two conflicting requirements: on the one hand, current drive favours low-density scenarios, on the other hand, relevant power extraction by the divertor is only achieved at high density. Generation of a large fraction of bootstrap current is a means to overcome these difficulties by lowering the contribution of the externally driven current. A test of this line of thought has been achieved on Tore Supra with the Ergodic Divertor (ED) with low field (B_0 = 1.3 T and B_0 = 1.6 T) and low plasma current (I_{plasma}~0.76 MA) target plasmas, where an increase of β_p has a significant impact on bootstrap current. Working gas was deuterium, with typically 4-8% fraction of Hydrogen.

2. FWEH at B_0=1.3 T in Ergodic Divertor configuration

At the lower field (B_0=1.3 T), Fast Wave Electron Heating (FWEH) was expected due to the strong dependence on magnetic field of the single pass electron absorption (ELD+TTMP). Indeed, no fast ion was detected, but the density rises (n_l=3.2 -> $5.10^{19}\,m^{-2}$) with a constant electron temperature. The impurity levels rose (Fig. 3), and the pulse ended in disruption (TS # 28260, I_{plasma}=0.6 MA). Parasitic edge absorption competes with FWEH, since the resonance layer of the third cyclotron harmonic of hydrogen (3H) lies in the plasma in front of the ICRF antennas (see Fig. 1), due to the strong magnetic ripple modulation on the low field side. Since it is necessary to operate with a large minor radius plasma lying on the ED coils on the low field side, due to the operational constraints of the ED configuration, it is difficult to exclude the ion cyclotron resonance layer at the edge [1] (contrary to dedicated FWEH scenarios in limiter configuration [2]).

3. FW2HH at B_0=1.6 T in Ergodic Divertor configuration

3.1. Ion heating at cyclotron second harmonic

At higher magnetic field (B_0=1.6 T), the 3H resonance layer is pushed behind the antenna current straps (see Fig. 2). Clear evidence of Hydrogen heating from second cyclotron harmonic resonance (FW2HH) located almost on axis has been found with charge exchange [3] (on parallel and perpendicular analysers with behaviour comparable to standard minority heating D(H) on axis, see Fig. 4) and ion ripple losses [4] diagnostics. The isotopic ratio $n_H/(n_H+n_D)$ calculated from charge exchange measurements rises from 4

% to 8% during the pulse TS # 28265 (5 s to 8 s). A preliminary analysis with the Fokker-Planck PION code [5] shows that in this pulse, with 4.7 MW coupled to the plasma, 4 MW are deposited on H ions via FW2HH and 0.7 MW directly on electrons.The fast ion energy content (0.05 MJ) reaches 20% of the total energy content. One obtains during 3 s a poloidal beta β_p = 0.5, T_e~1.4 keV and W_{dia}~0.25 MJ. The ion temperature was directly measured by charge exchange spectroscopy (C^{6+} + D -> C^{5+} + D^+ + hν), using a modulated diagnostic beam [6]. The ion temperature profile is very close to the electron temperature profile in the measurement region (see Fig. 5). Figures 3 display a comparison of FWEH at B_0 = 1.3 T (TS#28260) and FW2HH at B_0 = 1.6 T (TS#28265): the level of impurities rises much more for FWEH (in particular for Fe and Ni) even for a coupled power lower by a factor of 3, due to parasitic FW absorption at the edge. The new lateral antenna protections [7] have a very satisfactory behaviour, since a steady state is reached with a maximum temperature below 400°C for 4.7 MW of coupled RF power (TS # 28265, see Fig. 3).

3.2. Ergodic Divertor resonance condition

The increase of β_p in FW2HH modifies the resonance condition of the ED [8] : the safety factor at the edge for ED resonance is an increasing function of β_p+li/2. By increasing the poloidal beta, one then modifies the safety factor needed at the edge and this allows to lower the plasma current (to I_{plasma}=0.66 MA in pulse TS # 28265), with the toroidal magnetic field kept constant. The bootstrap current increases with β_p and then this reduces the requirement for non inductive current drive in view of steady state scenarios. In pulse TS#28265, the bootstrap current fraction is 13 % for β_p = 0.5, which is comparable at given β_p to the bootstrap fraction obtained in Fast Wave minority heating D(H).

3.3. Confinement

The electron energy content reaches W_e~0.135 MJ and follows the Rebut-Lallia-Watkins scaling law. The global thermal energy (i.e. the suprathermal contribution calculated by the PION code having been substracted) follows exactly the Tore Supra L-mode scaling law [9] even if the confined plasma has a reduced volume due to the presence of the stochastic and laminar layers at the edge produced by the resonant magnetic perturbation of the ED coils [10-11].

3.4. Greenwald density factor

Pulse TS # 28265 exhibits a large density (volume averaged density above 3.10^{19} m^{-3}) favourable to power and particle extraction. This corresponds to a record Greenwald density factor of $f_{Greenwald}$~1.1 (note that the pulse in FWEH, TS#28260, also exceeded $f_{Greenwald}$~1 before disruption (see Fig. 6)). This large density was sustained without gas injection during the heating phase (3s). This shots remains attached all the time. This performance should be compared to the maximum of $f_{Greenwald}$~0.6 achieved in ED operation at 1.5 MA with 4.1 MW of FW minority heating and 1 MW of ohmic power (TS # 28076, $\langle n_e \rangle$~4.10^{19} m^{-3} at B_0 = 3.14 T) or $f_{Greenwald}$~0.59 with ohmic power only (2MW, TS # 28269, $\langle n_e \rangle$~$3.8.10^{19}$ m^{-3} at B_0 = 3.13 T, 1.5 MA) with non zero gas injection in a detached D plasma when $\langle n_e \rangle \geq 3.10^{19}$ m^{-3}.

4. Conclusion

FWEH at low magnetic field (B_0 = 1.3 T) in the ED configuration proves to be difficult due to the presence of parasitic resonance cyclotron layers at the edge ; as it has already been seen at larger field [1, 12].

On the contrary, Fast Wave heating at the second cyclotron harmonic of Hydrogen (FW2HH) is an efficient heating scenario leading to a significant increase of β_p, allowing to lower the plasma current to meet the ED resonance condition, and therefore alleviate the non inductive current requirement. The bootstrap current is comparable to that of minority heating D(H) pulses. One obtains almost equipartition since the ion and electron temperature profiles are very close in the region of measurement. A record Greenwald density factor of 1.1 has been sustained in this scenario without gas injection for the 3 s of the RF heated period (TS#28265), and without energy confinement degradation.

5. References

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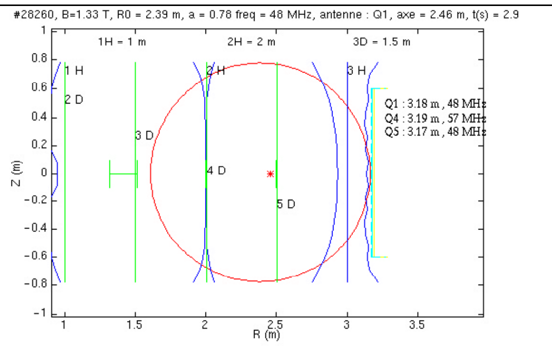

Fig. 1 : TS # 28260 (B_0=1.3 T) ion cyclotron resonance layers

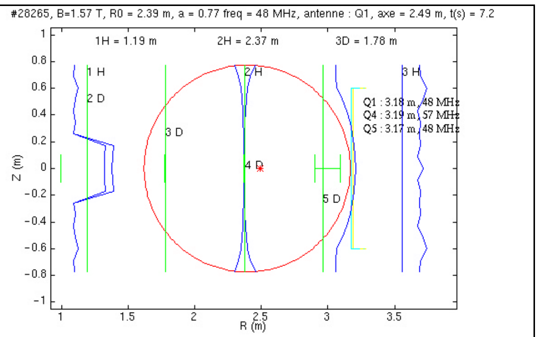

Fig. 2 : TS # 28265 (B_0=1.6 T) ion cyclotron resonance layers

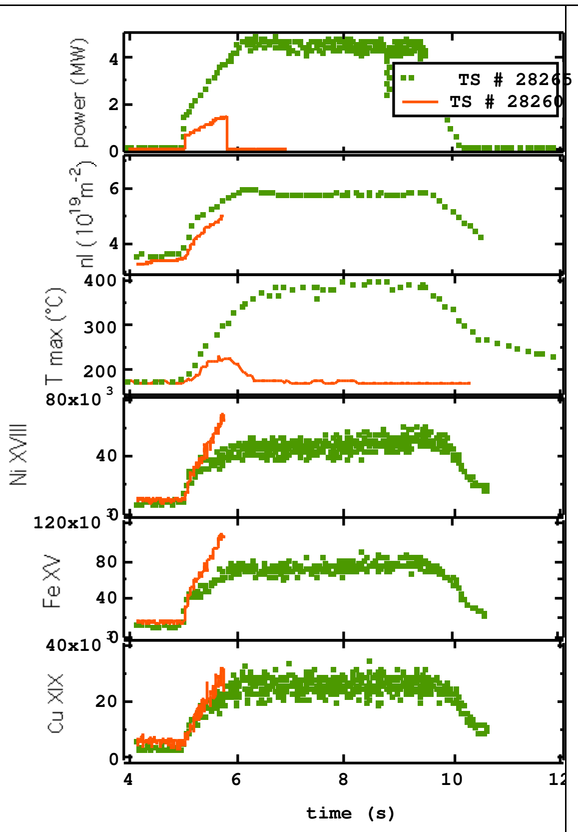

Fig. 3 : comparison of pulses TS#28260 and TS#28265 for coupled power, lineic density, maximum temperature on the antenna protection, Faraday screen and septum, impurity (Ni XVII, Fe XV and Cu XIX

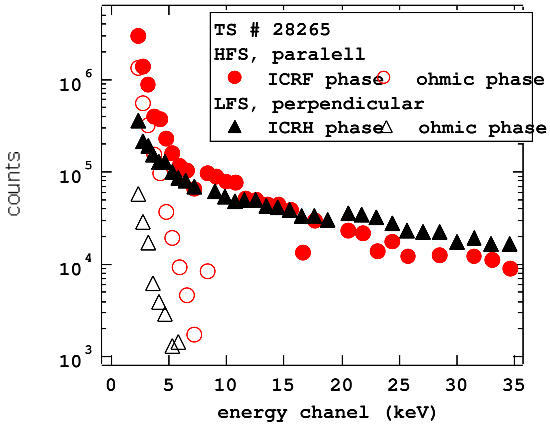

Fig. 4 : TS # 28265, charge exchange measurement on parallel (High Field Side) and perpendicular (Low Filed Side) analysers.

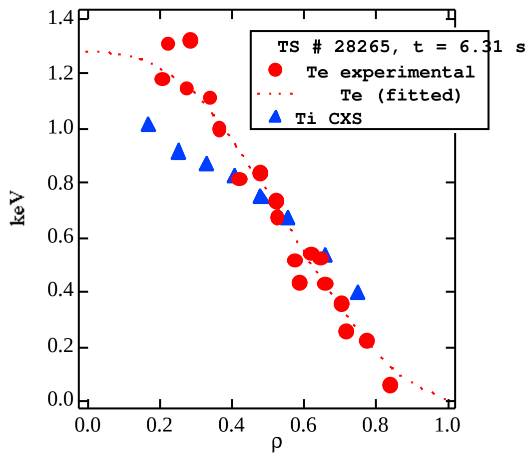

Fig. 5 : ion and electron temperature profiles for pulse TS # 28265 (t=6.31 s).

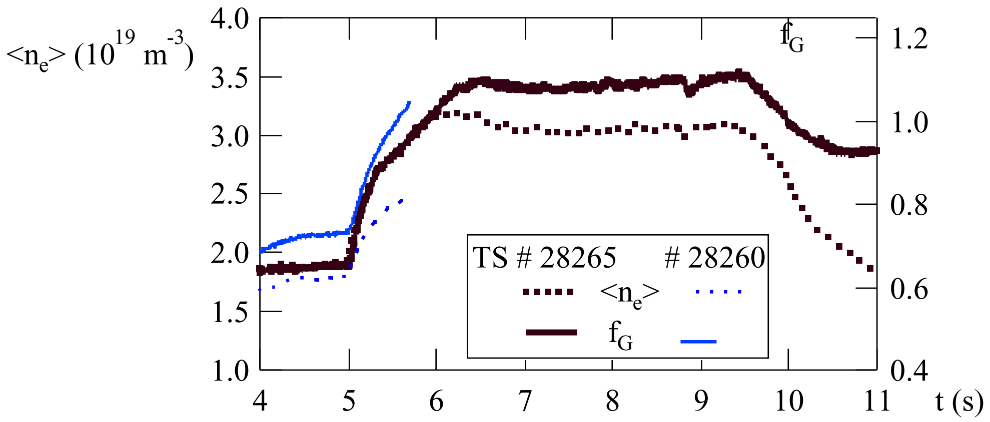

Fig. 6 : TS # 28265 & TS # 28260, average volumic density and Greenwald density factor