*34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-1.147 (2007)*

Fast ion behaviour during ICRH experiments on Tore Supra

M.Goniche, T.Aniel, J.F.Artaud, V.Basiuk, L.Colas, P.Devynck, R.Dumont, A.Ekedahl, D.Elbeze, L.-G.Eriksson, C.Fenzi, G.T.Hoang, P.Lotte, D.Mazon, L.Manenc, P.Monier-Garbet, O.Meyer, F.Rimini, M.Schneider, F.Turco

Association EURATOM-CEA, CEA/ DSM / DRFC
Centre de Cadarache, 13108 Saint Paul-lez-Durance, France

The 2006 experimental campaign of Tore Supra was mainly devoted to the study of high RF power (6-10 MW) stationary (~30s) discharges obtained by combination of Ion Cyclotron Range of Frequency (ICRF) heating and Lower Hybrid Current Drive. All these discharges were performed with the minority (hydrogen) heating scheme in deuterium plasmas with H concentration, measured from the charge-exchange diagnostic, varying between ~3 and ~20%. Due to the strong magnetic ripple of Tore Supra (5.5% at the plasma frontier), fast ion losses are expected either by ripple well trapping (downwards on Tore Supra) or by banana orbit drift (by collisionless stochastic transport). We investigate in this paper, the effect of the minority species concentration on the confinement of the fast particles but also of the thermal particles.

1) Energy and fast particle confinement. The global confinement quality is estimated from the diamagnetic energy normalized to the Tore Supra L-mode scaling which is very close to the H89 scaling. In these discharges, with plasma current I_p=0.9MA, LH power varies between 0.9 and 3.2MW, ICRH power between 0.9 and 6.5MW. The energy content increases by ~30% when the isotopic ratio n_H/n_D increases from ~3 and 8-10% and then decreases for larger concentrations (Figure 1). As expected, this improvement is maximized for discharges with a low fraction of LH power (P_{LH}/P_{ICRH} <0.3, red closed points) and is weaker when LH power is large (P_{LH}/P_{ICRH} >0.5, blue open points). A similar trend is found at lower plasma current (I_p=0.6MA).

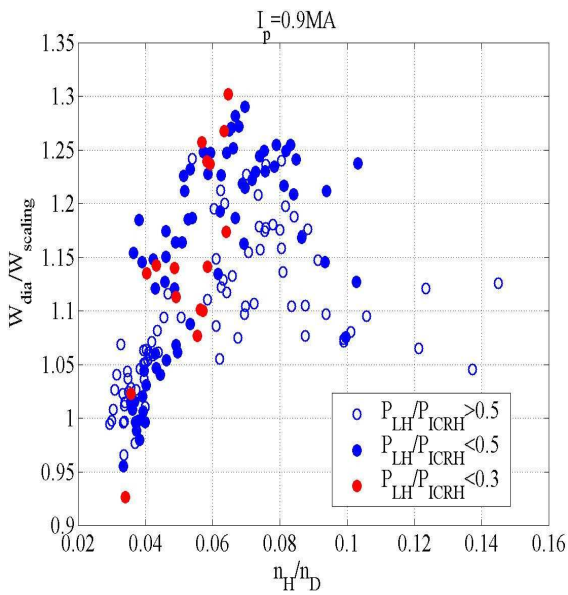

Figure 1. Diamagnetic energy normalized to the L-mode scaling versus the isotopic ratio n_H/n_D

The energy balance between electrons and ions is examined for a series performed with exactly the same additional RF powers at high density ($\overline{n_e}$ =4.1±0.1×$10^{19}m^{-3}$, Z_{eff}=2.4) and medium plasma current (I_p=0.9MA, q_a=5.3). For these discharges $W_{dia}/W_{scaling}$ as the poloidal beta β_p (Figure 2) increase with n_H/n_H+n_D by 10% and 6% respectively and are both maximum for a ratio of ~7%.. The normalized pressure of the fast ions β_{fast} can be estimated from $\beta+l_i/2-\beta_p \sim -\beta_{fast}/2+\beta_{fast\text{-}el}/2\text{-}+l_i/2$, where $\beta_{fast\text{-}el}$ is the β of LH driven fast electrons. This quantity varies by less than 0.05 for the series at constant LH power (2.85MW). Polarimetry and MSE measurements indicate no detectable variations of the current profile (Δl_i<0.05).Variation of $\beta_{fast\text{-}el}$ can be neglected. From the uncertainty on these diagnostics, we conclude that β_{fast} varies by less than 0.1. Electron temperature profile is measured from the Thomson scattering and ECE diagnostics, ion temperature from the charge exchange diagnostic, electron density from IR interferometers and reflectometers. Thermal ion and electron energies, W_e and W_i, computed from these profiles, vary by less than 20%. W_e seems to be maximum for n_H/n_H+n_D~7% and slightly decrease for larger concentration. The ion energy, which is about half of the electron energy, has a lower accuracy because of the lack of measurements for r/a>0.6 and the uncertainty on the deuterium concentration. W_{fast} (=W_{dia}-W_e-W_i) is estimated to vary between 15% and 25% of the total plasma energy. Under-estimate of W_i by 20% would lead to 10<W_{fast}/W_{dia}<15%. This is consistent with a variation β_{fast}<0.1.

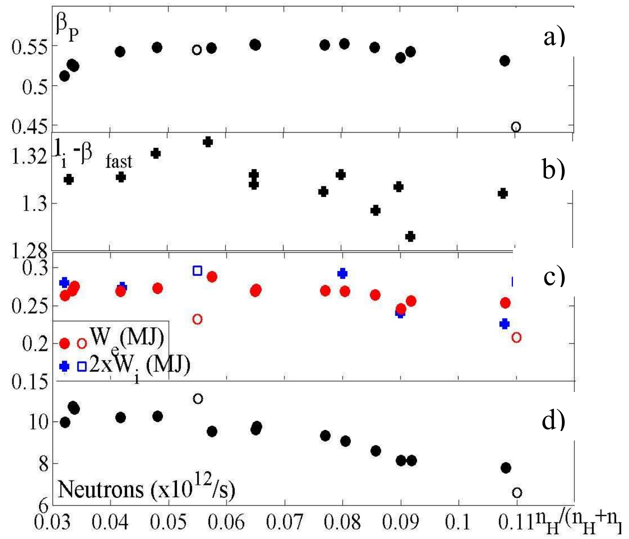

Fig. 2. β_p, l_i-β_{fast}, W_e, W_i, , neutron rate vs. $n_H/(n_H+n_D)$. Two shots, with lower LH power (~1 MW) are in indicated with opened symbols

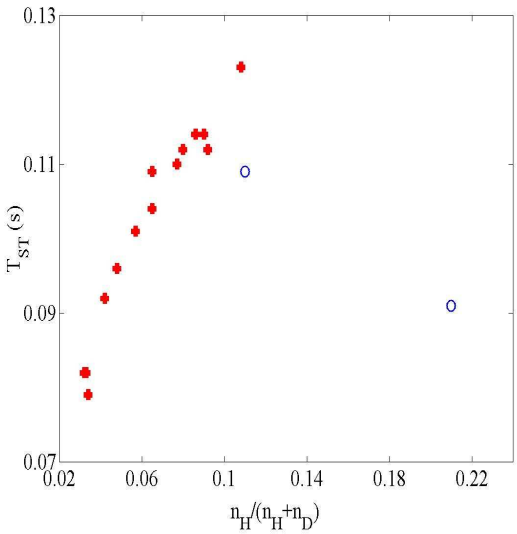

Fig.3. Sawtooth period vs. $n_H/(n_H+n_D)$. Two shots with lower LH power (~1 MW) are in indicated with opened symbols.

Regarding the central ion temperature $T_i(0)$, all these shots indicate a value between 2.2 and 2.7keV and a ratio $T_i(0)$,/$T_e(0)$~0.6. In comparison, pulses achieved with only ~1MW of LH power (open symbols of figure 2) have a higher $T_i(0)/T_e(0)$ ratio (~0.75) for medium and high H concentrations and consistently higher W_i with respect of W_e. Interaction of the LH wave with the fast ions [1] is expected to increase the energy of these particles which could in one hand increase β_{fast} and in other hand enhance the loss channel (larger banana orbits).
In all these discharges, the m/n=1 MHD mode (sawtooth) is triggered when ICRH is applied to the LH-heated plasma. Fast ions are known to be stabilizing with respect of this mode and the q=1 radius is an essential parameter [2].The q-profile reconstructed from the CRONOS code indicates a central q(0)=0.75 and a q=1 normalized radius r/a=0.20 for all these discharges. When the H concentration increases from 3 to 11%, the sawtooth period increases from 80ms to 125ms (Figure 3). This could be understood as an effect of the reduction of the banana orbit of the trapped ions when the concentration increases and therefore to an increase of β_{fast} inside the q=1 surface. This result is consistent with the concentration dependence of β_{fast} (figure 2.b). For very high concentration (~21%), the sawtooth period is shortened to 90ms, suggesting that the wave is partially mode-converted and/or RF power absorption decrease. Indication of RF power absorption is provided by the level of pick-up on the RF measurements. This was found to be minimum for $4\%<n_H/n_H+n_D<10\%$ and to increase sharply for concentration below 4% and smoothly above 10%. Such an effect of the minority concentration is consistent with the calculation of single-pass absorption (METS code) when a temperature of the tail of the proton distribution of ~10keV is considered. The weaker absorption at low concentration (<4%) is confirmed by the increase of the FeXV and CuXIX brightness [3]. Although these results indicate a smaller β_p for very low concentration, the neutron emission rate decreases monotonously by ~30% when the concentration increases from 3% to 11%. Very high concentration (~21%) leads to a further reduction of the neutron rate (~$4\times10^{12}s^{-1}$). Taking into account the error bar of Z_{eff}, the weak reduction of neutron rate between 3% and 6% can be attributed to dilution effect. When increasing n_H/n_H+n_D from 6-to 11%, the lower neutron flux can be computed assuming a reduction of T_i by 10%. This reduced flux is correlated to higher losses on the plasma facing components (see below) but is not consistent with the increase of β_{fast} (fig;2c) and β_{fast} inside q=1 surface(fig.3).

2) Fast ions losses on the plasma-facing components. During ICRF experiments, heat deposition on the three ICRF and two LH antennas, located on the low field side of the machine, are clearly attributed to the loss of fast ions by banana orbit drift [4, 5]. These losses are measured by infra-red thermography and by calorimetry of the actively cooled RF antennas. They increase when the plasma current and/or the plasma density decrease and the heat flux can locally exceed $1MW/m^2$ [5]. From calorimetric measurements, global fast ion losses are estimated to be 4-6% of the ICRF power at high density ($\overline{n_e}=4\times10^{19}m^{-3}$, $T_e(0)=4.5keV$). This could be an over-estimate if significant un-coupled power would be absorbed by the antennas. Although no energy measurements of these deconfined ions are available, the heat pattern on the antennas indicates that most of these ions have energy above 500keV. When the minority concentration is varied, the heat flux varies significantly (factor ~1.5-2) and is minimum for n_H/n_H+n_D= 6-7%. We may assume that no spurious effects from a weaker absorption are expected between 4 and 10% and the slow increase of LH antenna temperature with decreasing minority concentration is attributed to the larger banana orbits (higher energy for the ions). For high concentration (for n_H/n_H+n_D= 10-11%), the increase of fast ions impinging on the antennas seems correlated to the reduction of neutron productions, as already mentioned. It has to be noted that, for this H scan, the variation of plasma collisionality ($\sim n_e/T_e^{3/2}$) is estimated to be less than 10% and is negligible.

3) Conclusion. For ICRH heated plasmas, significant effect (up to 30%) of the minority (H) concentration on the total plasma energy is measured with an optimum concentration $n_H/n_H+n_D\approx7\%$. Sawtooth period indicates that β_{fast} inside the q=1 surface increases continuously when H concentration increase from 3 to 11%. This result is consistent with total β_{fast} from magnetics when error bars and dilution are taken into account. However, lower neutron emission rate at high n_H/n_H+n_D is not fully consistent with β_{fast} measurements. This lower neutron rate is correlated to enhanced fast ion losses at the edge and further investigation, like experiments with lower (or higher) LH power, is needed.

References

[1] D.Testa, Plasma Phys.Control.Fusion, **41** (1999) 507
[2] F.Porcelli, Plasma Phys.Control.Fusion, **33** (1991) 1601
[3] O.Meyer et al., this conference
[4] A.Ekedahl et al., Journal of Nuclear Materials **363-365**, 1329 (2007).
[5] M.Goniche et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA