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Effect of Toroidal Rotation Generated by ICRF Waves on Core Energy Confinement

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Introduction

Fusion reaction depends strongly on the ion temperature. Thus, it is important to choose an auxiliary heating scenario providing an efficient ion heating. Using the Ion Cyclotron Resonance Heating (ICRH) in minority scheme is one of potential candidates for such heating in fusion reactors. Significant fraction of ion heating has been demonstrated in many tokamak experiments (CMOD[1], JET[2], Tore Supra[3]) by optimizing the concentration of minority ion concentration. Previous H-minority heating experiments in Tore Supra indicated that the bulk ion and electron heating are very close to each other for high concentration ($n_H/n_e \approx 6\%$), whereas the electron heating dominates strongly for the low concentration case ($n_H/n_e \approx 2.5\%$). Furthermore, the high minority concentration discharges exhibited a good energy confinement with strong toroidal rotation in co-current direction[4]. This work reports the recent experiments performed in Tore Supra (CIEL configuration), with injected ICRH power of up to 8 MW, at $I_p = 0.8 - 1.2$ MA and $n_e(0) = 5 - 7\times10^{19}$ m^{-3} corresponding to a Greenwald fraction of up to 0.8. Furthermore, an analysis of the micro-stability performed with the linear electrostatic gyrokinetic code KINEZERO[5] is presented.

Experimental Setup and Results

In the experiments reported here, toroidal rotation and ion temperature have been measured by X-ray spectroscopy and the new charge exchange recombination spectroscopy (CXRS) system installed on Tore Supra. High-resolution, time-resolved iron X-ray spectra have been acquired using a Johan-type cylindrically curved crystal spectrometer[6]. The averaged (differential) central toroidal velocity $<\Delta v_\phi(0)>$ and the ion temperature are inferred from the *w* Doppler shifted resonance line (1s2p $^1P_1$ - 1s^2 $^1S_0$). Time and space resolved CVI line emission spectra at 5290 Å have been measured along height lines of sight which intersect the plasma cross section in the equatorial plane at major radius locations R = 2.35, 2.45, 2.53, 2.61, 2.67, 2.74, 2.80 and 2.87 m. The ion heating was optimized by varying the concentration of minority ions. The ion temperature was close to the electron temperature: $T_e(0)$ and $T_i(0)$ reached about 4.5 keV. In addition, the energy confinement exceeded the standard L-mode value and was as good as Elmy H-mode. As shown in Fig. 1, the stored plasma energy (including fast ion effects) exceeds the L-mode by a factor of 1.4 - 1.7. This improvement of the confinement correlates with the plasma toroidal rotation. Improved core confinement is found to be strongly correlated with an acceleration of the plasma in the toroidal co-current direction, which correlates well with the central ion pressure normalized to the plasma current.

Fig. 2 shows a discharge with 7 MW of total injected power (6MW of ICRH and 1MW of LHCD). The ion temperature, measured at approximately r/a = 0.2 by X-ray spectroscopy, is very close to the electron one. The electron energy content exceeds the L-mode scaling by a factor of 1.4. Also, the total energy enhancement factor, with respect to the total ITER-L mode prediction (including fast particle contribution) is increased by a factor of 40%. Interpretative analyses performed with the integrated package code CRONOS, including the PION code for ICRH, indicate that about half of the RF power is coupled to the thermal ions (n_H/n_D = 14%). During the improved confinement phase, an toroidal acceleration of the plasma is observed in the plasma current direction, and we estimate $\langle v_\phi(0) \rangle$ to be between 80 km/s -100km/s with an error bar of 20 km/s due to the uncertainty in the ohmic value which is not measured. Note that usual L-mode plasmas heated by ICRH rotate with $\langle v_\phi(0) \rangle$ around 40 km/s in the opposite direction, i.e. counter-current. The dramatic change in the rotation velocity observed at t = 9s is not well understood at present. It could be due to a redistribution of the suprathermal ions, or thermal particle losses. In Tore Supra, the ripple amplitude reaches about 7 % on the low field side. However, thermal particle losses estimation using P. N. Yushmanov[7] analytical calculation shows that a factor of two in the measured central ion temperature would be needed here to account for a possible bifurcation (co-current / counter-current) in the rotation.

Fig. 3 shows the typical ion temperature and toroidal rotation profiles measured during a similar discharge (but with no bifurcation observed in the rotation) with well defined OH and ICRH phases. It is worth stressing here that the central temperature and velocity are in agreement with X-ray spectroscopy measurements. When the RF power is applied, it is clear that both rotation and ion temperature profiles are more peaked. In this discharge, micro-stability analyses have been performed with the linear electrostatic gyrokinetic code KINEZERO, using measured rotation profiles. As reported in Fig. 4, TEM and ITG modes inside *r*/*a* = 0.6 could be stabilized by strong toroïdal rotation through E×B shear, which is consistent with experimental observations.

Conclusions

New experiments performed on Tore Supra with the H-minority heating scenario exhibit toroidal rotation velocity up to 90km/s in the co-current direction. There is a strong correlation between the increase in the plasma stored energy induced by ICRF heating and the rotation. Rotation and ion temperature profiles measured with the new CXRS diagnostic show that the profiles are more peaked when the RF in applied. Micro-stability analyses indicate that such measured rotation velocities are consistent with stabilization of TEM and ITG modes inside *r*/*a* = 0.6.

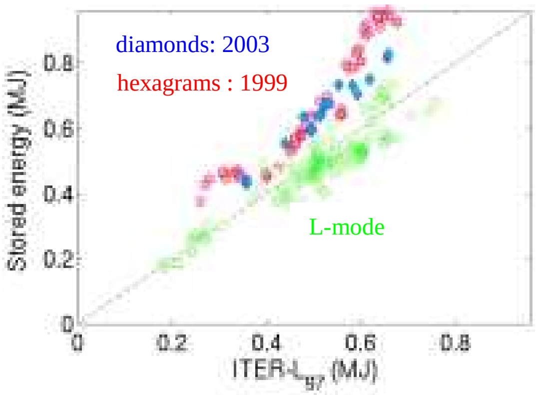
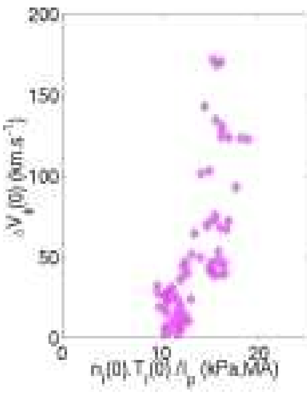
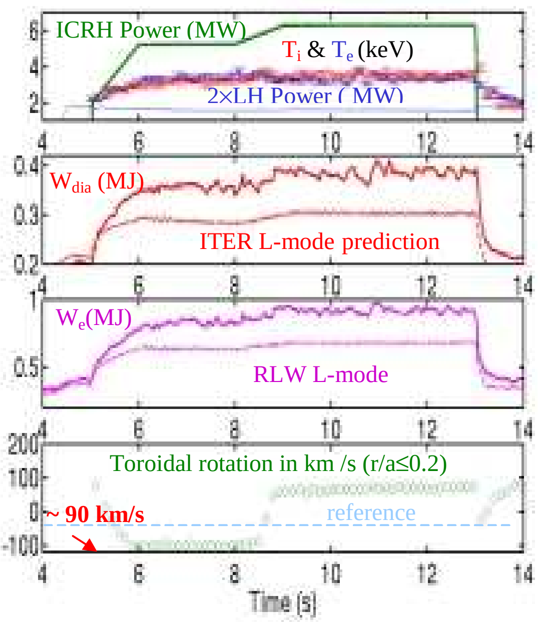


Fig. 1 : Total energy versus thermal ITER L-mode predicton (left) and ion pressure scaling (right)





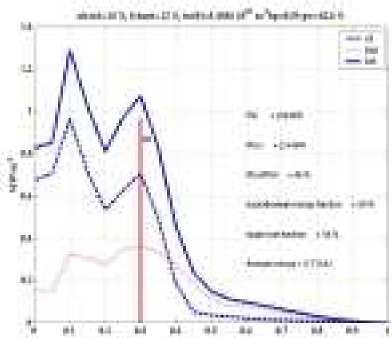


Fig. 2 : Improved confinement discharge with combined LHCD and ICRH (#TS32187). A negative / positive variation in the toroidal rotation corresponds to a change in the direction parallel/anti-parallel to the plasma current direction.

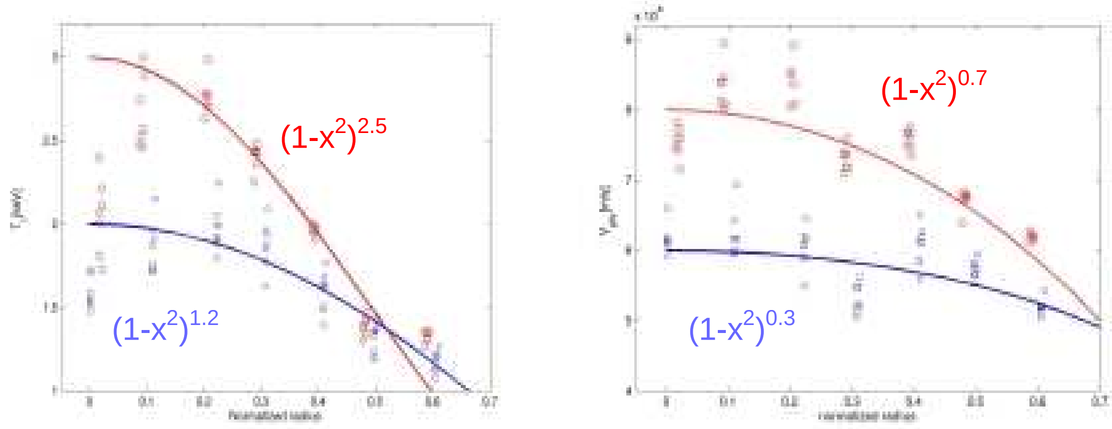
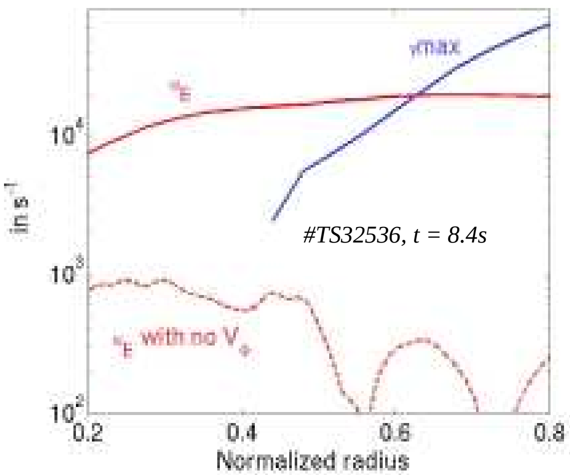


Fig. 3: Ion temperature (left) and toroidal rotation (right) profiles measured by CXRS during ICRH (hexagrams) and OH (squares) plasma phases (#TS32536). Simple fits are shown.



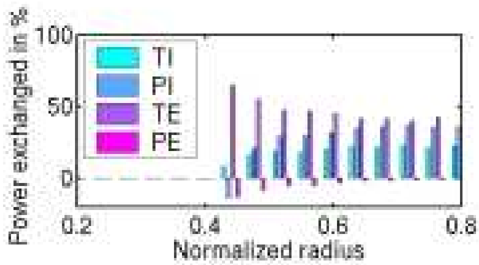


Fig. 4: Left, radial profile of the growth rate of ITGs and TEMs (γ_{max}) and radial profile of the E×B shearing rate (ω_E) calculated with the measured V_ϕ, and calculated without V_ϕ(dashed line). Top right, radial profile of the nature of the power exchanged by the unstable modes TI (Trapped Ions), PI (Passing Ions), TE (Trapped Electrons) and PE (Passing Electrons). One can see that the unstable modes are a mixture of TI, PI and TE.

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