Studies of Confinement and Turbulence in FTU High Field High Density Plasmas

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Abstract. The Frascati Tokamak Upgrade (FTU) is an high field and high density device in which confinement and transport issues relevant for the next generation of tokamaks can be studied. In this paper we present the results of a study on the role of density, temperature and q profiles on confinement and transport. Peaking of the electron density profile in pellet fuelled discharges has been found to enhance the energy confinement time to values as high as 120 ms at densities of the order of those expected in ITER. Experiments designed to further improve the confinement by injecting pellets at higher densities show the existence of a second threshold for saturation of confinement. Reflectometry measurements show turbulence suppression in pellet injected discharges (as predicted by microstability analysis) and give insight on the change in turbulence in e-ITB plasmas. Finally particle transport and turbulent pinch have been investigated in experiments with full LHCD.

1. Introduction

Confinement and transport issues relevant for Tokamaks designed to reach high values of Q (ratio between fusion and input power) are investigated in existing high field, high density machines such as the Frascati Tokamak Upgrade (FTU), in which the toroidal field (up to 8 T) and the plasma density (line average density up to $4x10^{20}$ m^{-3}) are close to those foreseen for next generation devices. FTU is a limiter machine with dominant auxiliary electron heating (up to 1.6 MW of ECRH and 2.5 MW of LH): in the following, results on confinement and turbulence will be presented for ohmic and improved scenario plasmas (pellet enhanced confinement and e-ITB). In section 2 results on the scaling of confinement with density are presented, data refer to a density scan experiment on ohmic discharges and pellet injected discharges. In section 3 reflectometry measurements and the microstability analysis of pellet fuelled discharges are shown. Section 4 addresses the issue of turbulence stabilization in transport barrier formation. Finally in section 5 FTU results on particle transport studies are discussed.

2. Confinement in gas-fuelled and pellet-fuelled ohmic discharges

In FTU ohmic discharges the dependence of the confinement time (τ_E) on the line-averaged density shows the well known behaviour of linear ohmic confinement (LOC) and saturated ohmic confinement (SOC) phases [1]. The result of a density scan (performed at B_t=7.2 T by varying the plasma current between 0.5 MA and 1.4 MA) is presented in *FIG. 1*. The central line-averaged density is in the range $0.4\text{-}3.3\times10^{20}$ m^{-3}. For any given plasma current the transition from LOC to SOC occurs at a threshold value of the line-averaged density which is about half the Greenwald limit. The confinement time in the SOC phase is independent of plasma current and for FTU standard ohmic plasmas at B = 7.2 T this characteristic τ_E is found to be about 55 ms, in agreement with the ITER97-L scaling). In [1] it is shown that the roll-over of τ_E at the threshold is due to the electron conductivity reaching its lowest value while ion heat conductivity increases bringing a change in the character of the heat transport from electron dominated transport below $n_e = 1.5\times10^{20}$ m^{-3} to ion dominated transport at higher density. Pellet fuelled discharges which exhibit enhanced confinement above the ITER-97 scaling, qualitatively recover the linear dependence of τ_E on the line-averaged density (neo-Alcator type scaling); this effect is also shown in *FIG.1* with the inclusion of post-pellet enhanced confinement times in discharges at different currents.

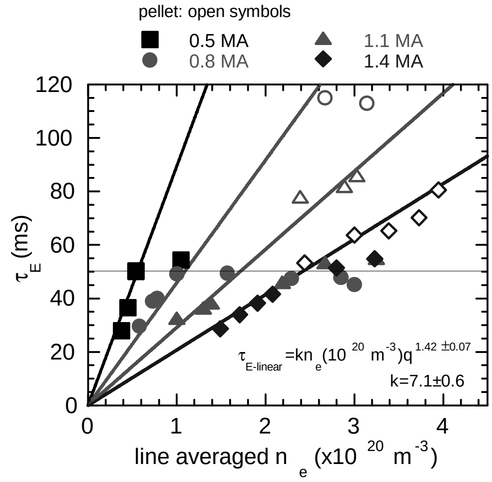

FIG. 1. Effect of pellets (open symbols) on energy confinement time: the linear scaling with density is recovered in multiple-pellet fuelled discharges (pellet τ_E data are averaged over 50 ms). The horizontal line represents the saturated ohmic confinement time in FTU.

In new experiments during the 2004 campaign, pellets have been injected on plasma targets above 2×10^{20} m^{-3} at 0.8 and 1.1 MA with the aim of exploring the pellet induced linear regime of confinement at even higher densities. Preliminary analysis of discharges at 0.8 MA, *FIG. 2*, indicate that a second threshold for confinement saturation arise at about 110 ms, this result is in agreement with the observations done in Alcator C [2]. Saturation of confinement with pellet is not observed in discharges at 1.1 MA where a line-averaged density above 4×10^{20} m^{-3} would be needed to reach the threshold. The linear scaling of confinement is confirmed for the 1.1 MA discharges below the density threshold.

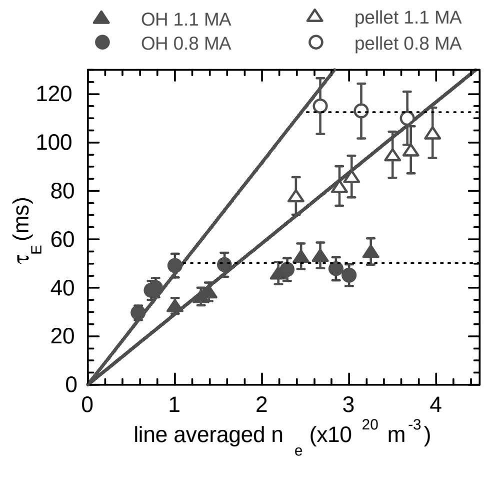

FIG. 2. Saturation of the confinement in pellet enhanced plasmas is observed at 0.8 MA

Transport studies show that pellet enhanced plasmas have the same level of electron heat conductivity found in SOC phase but ion conductivity is down to neoclassical level [1]. In the next section, the mechanisms leading to enhancement of confinement from pre to post pellet phase are investigated, in particular the change in turbulence from pre to post pellet phase is studied through microstablity analysis.

3. Turbulence analysis of pellet discharges

Turbulence measurements on FTU are carried out using a two-channel poloidal correlation reflectometer [3] which can work either in O-mode, for low density plasmas, or in X-mode, for high density ones. The typical spectrum of the reflected E field has a low frequency component (LF) between 0 and 20 kHz, a quasi-coherent component (QC) between about 50 and 250 kHz and a broad band (BB) component up to 500 kHz.

The effect on turbulence of pellet injection on FTU shot #25371 is shown in *FIG 3.* The reflectometer works in X-mode with a cut-off density, for a toroidal field of 7.2T, of about 2.5×10^{20} m^{-3}. The first pellet produces a sharp reduction in the QC component of the fluctuation spectrum. After the second pellet this reduction is not observed. The low level of turbulence corresponds to enhanced particle and energy confinement time.

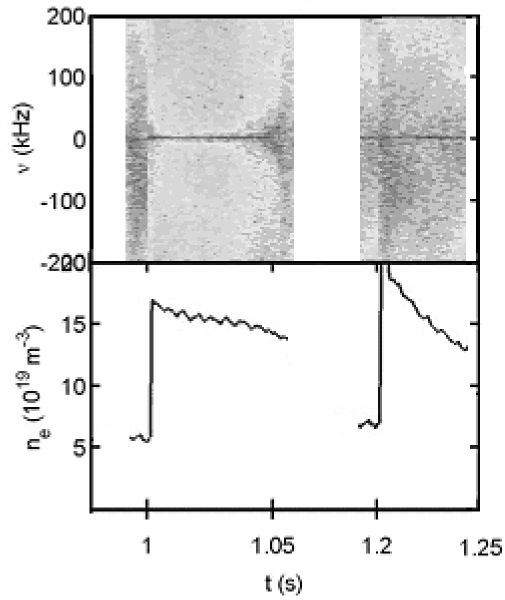

FIG 3. FTU shot 25371. Reflectometer measurements: two time windows around the injection of pellets in FTU. First pellet produces the enhancement of confinement (PEP) while the second does not produce the effect.

In order to identify which modes are stabilized by pellet injection, we have calculated the linear growth rates of microinstabilities using the linear electrostatic gyrokinetic code Kinezero [9]. This code does not include finite collisionality effects, so in order to analyze the highly collisional FTU discharges, we have assumed all electrons to be de-trapped and switched off the TEM; the validity if this assumption has been checked by comparing the results of Kinezero with those from GS2 [4] which include collisionality effects. The linear growth rates are calculated for wave numbers $k_\theta \rho_i$ ranging from the ITG to the ETG part of the spectrum and for radial position $0.2 < r/a < 0.8$. Two time slices of FTU discharges #12744 and #12747 have been chosen for the analysis: immediately before the injection of the first pellet (t = 0.58 s, τ_E= 50 ms) and after the second injection (t = 0.77 s, τ_E = 70 ms, τ_E = 120 ms respectively). In *FIG. 4*, it is shown the maximum growth rates on the ITG part of the spectrum ($k_\theta\rho_i$ < 2) and the ExB shearing rate for the pre and post-pellet plasma phases. In [4] the impact of the density profile has been isolated by running a study case in which we used all pre-pellet profiles but the density, replaced by the post-pellet density profile. The peaking of the density profile is stabilizing in the region 0.5 < r/a < 0.8. In this region, the ExB shear is almost unchanged by the steeper density. On the contrary, for 0.2 < r/a < 0.5, the ExB shear is sensibly enhanced.

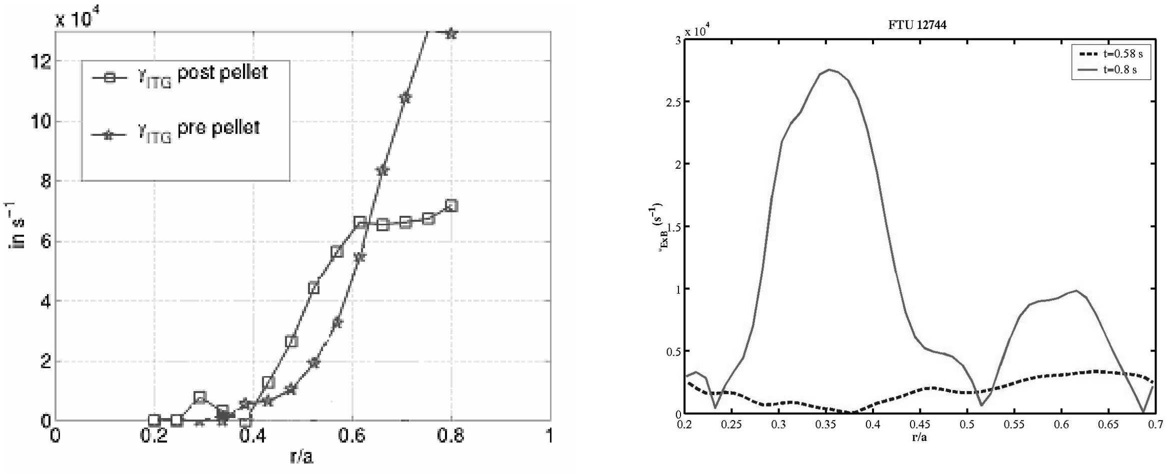

Fig 4. Maximum growth rates of ITG modes (left figure) and ExB shearing rate (right figure) before (t = 0.58 s) and after the injection (t=0.85 s) of two pellets in shot #12744.

The change in temperature gradients from pre- to post-pellet is destabilizing in the region inside r/a ~ 0.7 for both ITG and ETG, while at r/a = 0.8, where the normalized temperature gradient decreases in the post pellet phase, the new temperature profiles are suppressing ETG and stabilizing ITG. There is also a slight stabilizing effect due to the small increase of the magnetic shear. Nevertheless, adding to these effects, the density peaking brings a large stabilization on both ITG and ETG: 40% on ETG peak growth rate and 20% on ITG peak growth rate. It is important to stress here that the stabilization of turbulence due to density peaking on ITG is possible thanks to the high collisionality of FTU, in a lower collisionality plasma with TEM, the density peaking would have been destabilizing and no enhancement of the confinement would have been observed without the appearing of other factors such as a larger change of the magnetic shear. From the above analysis it is seen that the experimental profiles of the post pellet phase, although stabilizing, do not appear to suppress completely the ITG turbulence, as it would be expected from transport analysis where ion temperature evolution in the post pellet phase is well described by the neoclassical transport coefficient. Further stabilization is expected from electromagnetic effects: although the α parameter (α=-$R_0q^2\beta$') is small in FTU (0.1 < α <0.2) it is important to note that electromagnetic effects (shear Alfven waves) which are stabilizing on ITG and ETG can be important [5]. As it is shown in *FIG. 5.* a clear trend of χ_e decreasing with α is observed; pellet discharges (lowest values of χ_e) do have α within $0.25\times\alpha_{crit}$ (where α_{crit} is a threshold for the onset of AITG and varies between 0.34 and 0.46 in the set of discharges analyzed). This result suggests that further stabilization might be achieved by heating pellet fuelled discharges (assuming the density profile unchanged) so to push α close to the critical value.

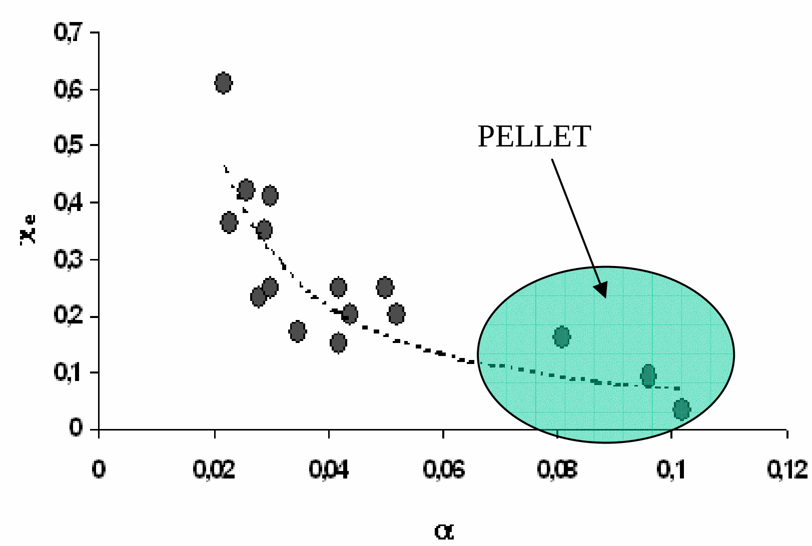

Fig 5. Electron conductivity Vs α in the 0.8 MA, 1.1 MA density scan discharges, including pellet injected plasmas (within the circle). Pellet discharges have α of the order of $0.25\alpha_{crit}$.

4.Turbulence stabilization in e-ITB plasmas

Electron internal transport barriers (e-ITB) are obtained on FTU by LH and ECRH heating [6] at densities up to 10^{20} m^{-3}. The change in character of the turbulence before and after barrier formation is investigated using fluctuation measurements and microstability analysis. Reflectometer data of FTU shot #19739, *FIG. 6*, show the presence of a 150 kHz mode in the pre-barrier phase which is stabilized during the barrier phase.

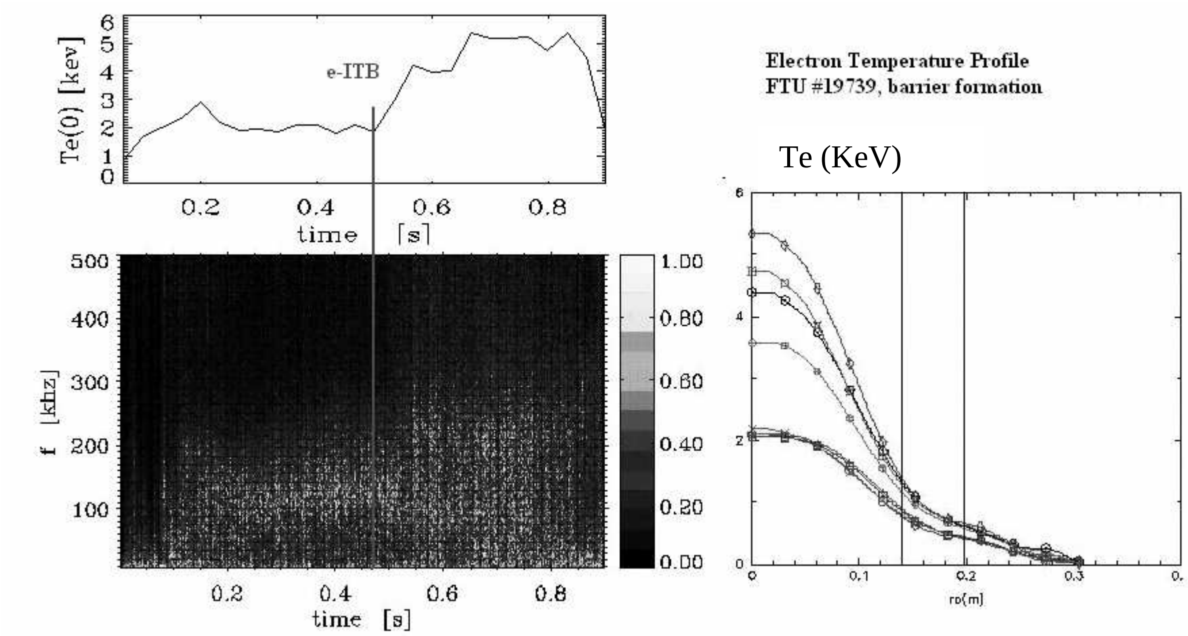

Fig 6. Central electron Temperature related to the spectrogram at r/a=0.5. On the right electron temperature profile featuring the barrier formation (the vertical lines indicate the region sampled by the reflectometer).

By cross correlation analysis it is found that the mode has poloidal and toroidal wave numbers respectively m=60, n=30 and from the angular velocity of the mode $k_\theta\rho_i$ =0.7 is obtained, which is in the range of the dissipative trapped electron modes [7]. Microstability analysis carried out with Kinezero shows ITG-TEM stabilization in the region of plasma outside the barrier, together with ETG suppression all over the plasma radius. More detailed reflectometer measurements together with the possibility of using a new version of Kinezero including collisions are envisaged in the next FTU campaign.

5. Particle confinement

Understanding particle transport and confinement is of crucial importance for predicting the density profiles in future burning plasma experiments.
Density profiles with peaking factors (n_{e0}/<n>) around 2 are routinely observed on FTU in all variety of discharges. Recent experiments aiming at investigating particle confinement have shown that the density profile inside mid radius is controlled by convective Ware pinch, as reported in *FIG. 8*.

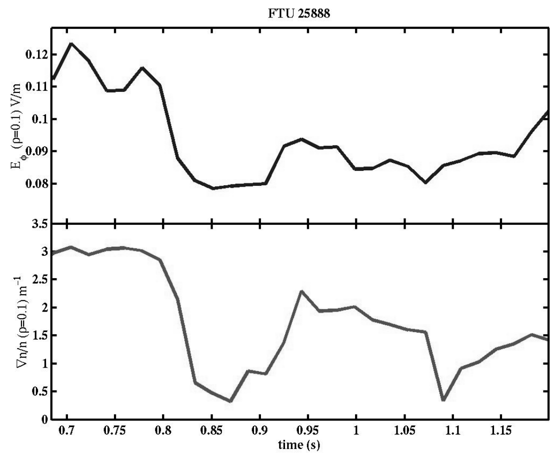

Fig 8. Toroidal electric field and density gradient scale length measured at minor radius r=0.1 m

The analysis of discharges where the inductive electric field is brought to zero via LH current drive have shown that the density profile remains peaked. Transport models predict particle pinch to be driven by electrostatic turbulence, ITG and TEM, through the temperature gradients and magnetic shear (the latter effect is due to the drift of trapped particles). The dependence of the convective pinch responsible of the residual peaking on $\nabla T_e/T_e$ and $\nabla q/q$ has been studied on a set of LHCD discharges (ν^*=0.1-0.4), as reported in *FIG.9* and *FIG. 10*. The results are in agreement with those reported in Tore Supra [8], namely inward thermo-diffusion in the inner part of the plasma (r<0.1 m) and outward in the outer part; inward magnetic curvature pinch is observed for r>0.1 m.

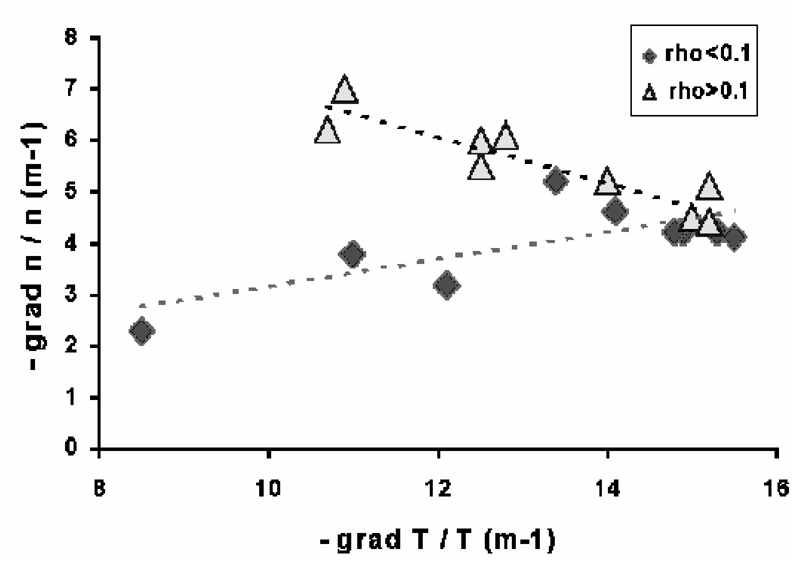

Fig 9. Density gradient scale length Vs temperature gradient scale for a series of full LHCD discharges.

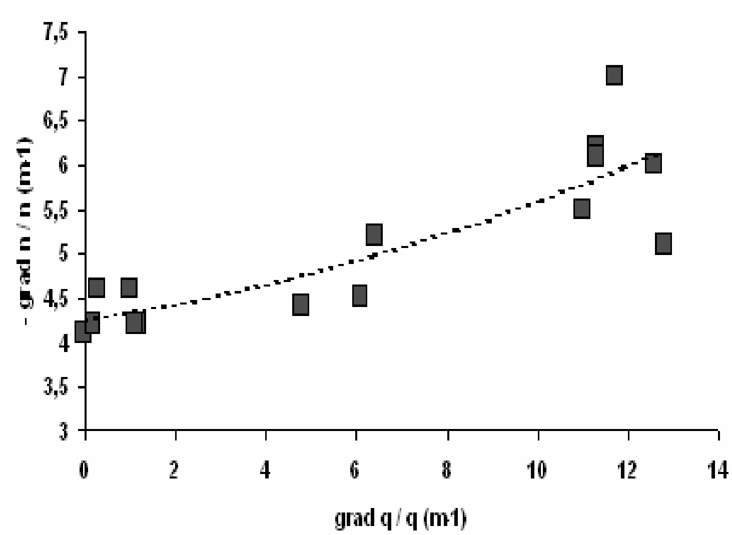

Fig 10. Density gradient scale Vs magnetic shear scale for a series of full LHCD discharges (r>0.1)

In the plasma conditions described above, the density profiles around (r = 0.1 m) appear to be related to the profiles of $1/\sqrt{q}$.

Conclusion

FTU discharges exhibit a significant energy confinement improvement following pellet injection. The reduction of electron thermal conductivity at high density (line averaged density above 3×10^{20} m^{-3}) together with a reduction of ion thermal conductivity down to neoclassical level are responsible for the improvement of confinement. Microstability analysis carried out with the gyrokinetic electrostatic code Kinezero show stabilization of both ITG and ETG modes due to peaking of the density profile at high collisioinality. At the highest densities TEM are found to be stable due to lack of trapped particles. The stabilization of drift wave turbulence is found experimentally with reflectometer measurements, both in pellet fuelled discharges and in e-ITB plasmas. Turbulent particle pinch is observed on FTU full LHCD discharges.

Reference

[1] ESPOSITO, B., et al., Plasma Phys. Control. Fusion **46**(2004), 2793.
[2] PARKER, R. R., et al., Nuclear Fusion **25**(1985), 1127
[3] VERSHKOV, V. A., et al., Rev. Sci. Instr., **70** (1999).
[4] ROMANELLI, M, et al., Physics of Plasmas **11**(2004), 3845.
[5] ZONCA, F., Physics of Plasmas **6**(1999), 1917
[6] PERICOLI-RIDOLFINI, V., et al., Nuclear Fusion **43**(2003), 469-478
[7] VERSHKOV, V., 31st EPS Conf. on Plasma Phys. London, ECA **28B**(2004) , O-2.06
[8] HOANG, G. T., et al., Physical Review Letter **93**(2004)
[9] BOURDELLE, C., et al., Nucl. Fusion, **42**(2002), 892