

Confinement and turbulence study in the Frascati Tokamak Upgrade high field and high density plasmas

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Received 10 December 2004, accepted for publication 9 January 2006

Published 17 February 2006

Online at stacks.iop.org/NF/46/412

Abstract

The Frascati Tokamak Upgrade (FTU) is a high field and high density device which allows one to study confinement and transport at plasma parameters generally not accessible to other tokamaks and is relevant to next generation experiments (ITER). In this paper we study the effect of different density, temperature and q profiles on confinement and transport in various types of plasmas including ohmic, externally heated and pellet-fuelled discharges. Peaking of the electron density profile in pellet-fuelled discharges has been found to enhance the energy confinement time on FTU to values as high as 120 ms at densities of the order of those expected in ITER. Experiments designed to further improve confinement by injecting pellets at higher densities show the existence of a second threshold for saturation of confinement when the local electron heat conductivity corresponds to the same order of the local ion neoclassical conductivity in the region of maximum temperature gradient. Reflectometry measurements show turbulence suppression in pellet-injected discharges (as predicted by microstability analysis) and give insights to the change in turbulence in electron internal transport barrier plasmas. Finally, particle transport has been studied in experiments with full LH current drive.

PACS numbers: 52.55.Fa, 52.55.Dy

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A study of confinement and transport issues relevant to tokamaks designed to reach high values of Q (the ratio between fusion power and input power) can be carried out in existing compact 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 $4 \times 10^{20} \text{ m}^{-3}$) are close to those foreseen for next generation devices. Operations at high field and high density allow one both to study plasmas with ρ^* (the ratio between ion Larmor radius and plasma minor radius) close to those foreseen for large scale devices and to address issues related to the actual value of the magnetic field, density and temperature, such as the coupling of auxiliary heating, impurity penetration, pellet

penetration and profiles control. FTU is a limiter, circular tokamak with a major radius of 0.93 m and minor radius of 0.3 m, with dominant electron heating (up to 1.4 MW of ECRH and 2.1 MW of LH coupled to the plasma). In this paper, the results of the study of confinement and turbulence are presented for ohmic and advanced scenario plasmas (pellet-enhanced confinement and electron internal transport barriers (e-ITB)). In section 2 the results of the scaling of confinement with density are presented: data refer to a density scan experiment in ohmic and pellet-fuelled discharges. In section 3 reflectometry measurements and the microstability analysis of pellet-fuelled discharges are reported. Section 4 addresses the issue of turbulence stabilization in the transition to an electron transport barrier. Finally, in section 5 the effect of different density and q profiles on particle transport is discussed.

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

The scaling of confinement time with plasma density as well as the effect on confinement of different fuelling methods and plasma profiles has been addressed in various tokamaks as reported in [1, 2]. In FTU ohmic, gas fuelled discharges the dependence of energy confinement time (τ_E) on the line-averaged density shows the well-known behaviour of linear ohmic confinement (LOC) followed by a saturated ohmic confinement (SOC) phase [3]. 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 and central line-averaged density in the range $(0.4\text{--}3.3) \times 10^{20} \text{ m}^{-3}$ ($T_{e0} = 1.0\text{--}2.0$ keV) was shown in figure 11 of [3]. In the SOC phase, τ_E is independent of the density and plasma current (I_p) and for FTU standard ohmic plasmas at ($B_T = 7.2$ T) it is found to be ~ 50 ms. As shown in [3] the confinement time of FTU ohmic discharges in the SOC phase is on average 92% of the confinement time predicted by ITER97-L scaling $\tau_{E, \text{ITER97}} = 0.023 I_p^{0.96} B_T^{0.03} R^{1.83} (R/a)^{0.06} \kappa^{0.64} \bar{n}^{0.40} M_{\text{eff}}^{0.20} P^{-0.73}$, (note that ITER97-L describes on average the scaling of confinement time of ohmic plasmas in the SOC phase and the explicit dependence on density and current is compensated by the dependence on the same variables of the ohmic power in the formula as discussed in [1, 2]). In [3] it was shown that flattening of τ_E above the saturation threshold density ($n_{\text{threshold}}$, depending on I_p) is due to the change in the character of the heat transport from electron-dominated transport below $n_{\text{threshold}}$ to ion-dominated transport at higher densities. In the SOC phase the electron conductivity (χ_e) saturates at its lowest value $\sim 0.2 \text{ m}^2 \text{ s}^{-1}$ (the saturation value found for χ_e is still larger than the ion neoclassical level), while the ion heat conductivity (χ_i) increases to values up to eight times its neoclassical value [3]: in this paper all conductivity values are taken at the radial position corresponding to the maximum pressure gradient, approximately $r/a \sim 0.3$. Two pellet injectors are currently available on FTU: a horizontal injector for low-field side fuelling, shooting 3 mm in diameter cylindrical deuterium pellets (10^{21} particles) at a maximum speed of 1.3 km s^{-1} , and a vertical injector located at the same toroidal position injecting deuterium pellets of the same size from the high-field side and at a reduced speed of 500 m s^{-1} . Pellet penetration depends on the temperature of the target: in the experiments analysed here pellets have been injected on plasma targets with a central temperature in the range 1.5–2.0 keV and the ablation is found to occur at about one-third of the plasma minor radius [4, 5] ($r/a \sim 0.3$, which in these plasmas corresponds approximately to the position of the $q = 1$ resonant surface). Pellet-fuelled discharges, which exhibit enhanced confinement above the ITER97-L scaling, qualitatively recover the linear dependence of τ_E on the line-averaged density (neo-Alcator type scaling $\tau_E = kn_e q^{1.42}$, and $k = 7.1$); this effect was also shown in [3] with the inclusion of post-pellet enhanced τ_E in discharges at various currents. In pellet-fuelled discharges χ_i becomes neoclassical reaching values between 0.1 and $0.2 \text{ m}^2 \text{ s}^{-1}$ at $r/a \sim 0.3$ (transport analysis is performed using the JETTO code in interpretative mode for the electron temperature and density; the current profile is evolved assuming neoclassical resistivity and the ion temperature profile is evolved using a model neoclassical conductivity

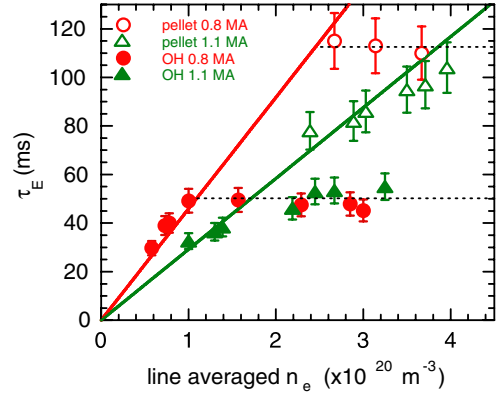


Figure 1. Saturation of the confinement in pellet-enhanced plasmas is observed at 0.8 MA.

times an anomaly factor [3]) while the electron conductivity is found to be everywhere higher than the ion conductivity $\chi_e \geq \chi_i$ indicating that heat transport in FTU PEP mode plasmas is controlled by electron losses. In new experiments performed during the early 2004 campaign, pellets have been injected on plasma targets above a line-averaged density of $2 \times 10^{20} \text{ m}^{-3}$ 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, figure 1, indicates that a second threshold for τ_E saturation arises at ~ 110 ms: this result was also found in Alcator C [6]. At 1.1 MA the linear scaling of τ_E in pellet discharges is confirmed below the second density threshold (no data are so far available to study the second saturation region at this value of I_p). From the results at 0.8 and 1.1 MA it can be concluded that, in the pellet-induced linear regime of confinement, heat transport is controlled by electron losses: while χ_i is at its neoclassical level [3], χ_e decreases by increasing the density remaining above χ_i . Saturation is observed when the electron heat conductivity reaches the ion neoclassical value (values in the range of $0.1 \text{ m}^2 \text{ s}^{-1}$). Further improvement of confinement could be obtained by stabilizing the residual electron turbulence (e.g. electromagnetic turbulence) that keeps the electron transport anomalous. Experiments on FTU aimed at achieving full neoclassical transport in the central region of the plasma are under investigation. In the next section, the mechanisms leading to enhancement of confinement from pre- to post-pellet phase are studied, in particular the change in the turbulence is studied through microstability analysis.

3. Turbulence analysis of pellet discharges

Turbulence measurements on FTU are carried out using a two-channel poloidal correlation reflectometer [7] 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 (LF) component 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 measurement of turbulent fluctuations using reflectometry on FTU PEP modes is by no means simple. For a 7.2 T plasma the maximum cut-off density that can be reached for X-mode propagation is $n_e = 2.7 \times 10^{20} \text{ m}^{-3}$. This density,

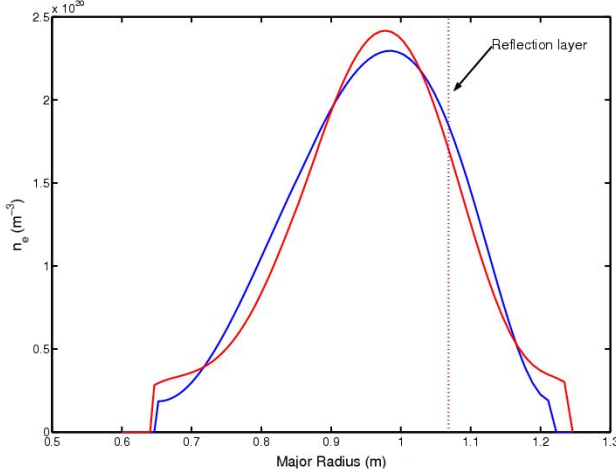


Figure 2. Density profiles for FTU shot 25371 at $t = 1.04$ s and $t = 1.22$ s, reflection surface ($\cdots$).

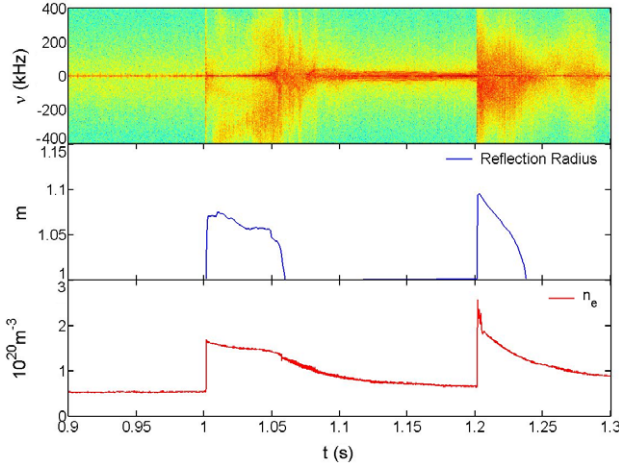


Figure 3. Turbulence spectrogram for FTU shot #25371 showing the injection of two pellets, including reflection radius and line average density. The spectrum exhibits a lower level of turbulence for frequencies in the range 20–200 kHz and a higher level of turbulence for the LF component of the spectrum in the 50 ms following the first pellet ($t = 1.03$ s, PEP mode) as compared with the same spectrum during the second pellet ($t = 1.23$ s, no PEP).

for the best performance discharges, is usually located in a peripheral region (r/a in the range ~ 0.7 – 0.8) where no turbulence suppression is observed. However, if the pre-pellet target density is sufficiently low, we can make observations in a more interesting region ($r/a \leq 0.5$) as in the case of shot #25371, figure 2. The effect on turbulence of two consecutive pellets injected in shot #25371 ($B_T = 7.2$ T, $I = 500$ kA, $T_{e0} = 2$ keV) is shown in figure 3. The reflectometer works in the reflective regime when the reflection radius is greater than about 1 m. The first pellet produces a regime of improved particle confinement as is evident by looking at the evolution of the line average density in the first 50 ms following the injection ($t = 1.0$ s– 1.05 s, last section of figure 3), while the particle confinement time is not enhanced by the injection of the second pellet ($t = 1.2$ – 1.25 s). The reflectometer data indicate that the different particle confinements during the two consecutive pellets, are correlated to a lower level of turbulence for frequencies in the range 20–200 kHz and higher level of

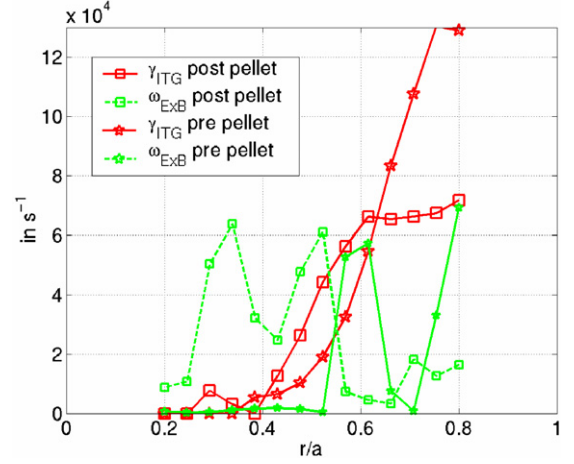


Figure 4. Maximum growth rates of ITG modes and $E \times B$ shearing rate before ($t = 0.58$ s) and after the injection ($t = 0.85$ s) of two pellets in shot #12744.

turbulence for the LF component of the spectrum following the first pellet as compared with the same spectrum during the second pellet (e.g. at $t = 1.21$ s).

It is clear that the improvement in the confinement in PEP mode discharges is due to the suppression of the mechanisms responsible for anomalous transport. The best candidate is plasma turbulence and indeed reflectometry measurements show that improved confinement plasma have a reduced level of fluctuations. In order to identify which small scale modes are stabilized by pellet injection, we have used the linear electrostatic gyrokinetic code Kinezero [13]. This code does not include finite collisionality effects; therefore, in order to analyse the highly collisional FTU discharges, we have assumed all electrons to be de-trapped and switched off the TEM; the validity of this assumption has been tested by comparing the results of Kinezero with those of GS2 [8] which includes 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 the discharge #12744 ($B_T = 7.2$ T, $I = 800$ kA, $T_{e0} = 1.5$ keV) have been chosen for the analysis: two pellets have been injected in the above discharge; we have studied the stability of the profiles immediately before the injection of the first pellet ($t = 0.58$ s, $\tau_E = 50$ ms) and after the second injection ($t = 0.77$ s, $\tau_E = 120$ ms). In figure 4 are shown the maximum growth rates on the ITG part of the spectrum ($k_\theta \rho_i < 2$) and the $E \times B$ shearing rate for the pre- and post-pellet plasma phases. The main stabilizing mechanism in the central region of the plasma ($0.2 < r/a < 0.5$) is the increased $E \times B$ shearing rate which becomes dominant over the linear growth rate. From an analysis of the effects produced separately on γ_{lin} by temperature gradients, q profiles and density profiles, it is found that [8]: (a) the change in temperature gradients from pre- to post-pellet leads to an increase of the γ_{lin} in the region inside $r/a \sim 0.7$ 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 suppress ETG and stabilize ITG; (b) the small increase in magnetic shear produces a slight stabilizing effect; (c) the density peaking

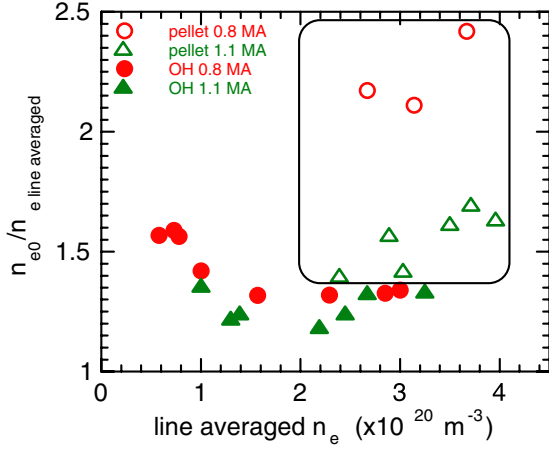


Figure 5. Density peaking versus line average density in the density scan experiments, including pellet-fuelled discharges.

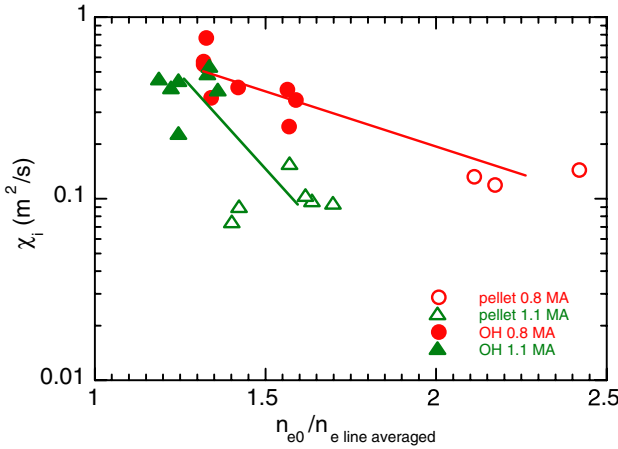


Figure 6. Ion heat conductivity at maximum temperature gradient ($r/a = 0.3$) versus density peaking, including pellet-fuelled discharges.

brings large stabilization to both ITG and ETG in the outer region ($0.5 < r/a < 0.8$, where the $E \times B$ shear is almost unchanged): 40% decrease on ETG peak growth rate and 20% decrease on ITG peak growth rate. Transport analysis carried out with JETTO shows that ion conductivity decreases to ion neoclassical values from the pre-pellet to the post-pellet phase in a region between the centre of the discharge and $r/a = 0.7$. According to Kinezero analysis the stabilization up to mid-radius can be ascribed to the increased $E \times B$ shearing rate in this region (due to peaking of the pressure profile) above the linear growth rate of the most unstable modes. The linear analysis also shows that, due to high collisionality, the increase in density gradient stabilizes in the region $r/a > 0.5$. The dependence of the density peaking versus line density and of ion heat conductivity versus density peaking at the radial position of the maximum temperature gradient are reported in figure 5 and figure 6, respectively. 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. Further stabilization of drift wave turbulence is expected from electromagnetic

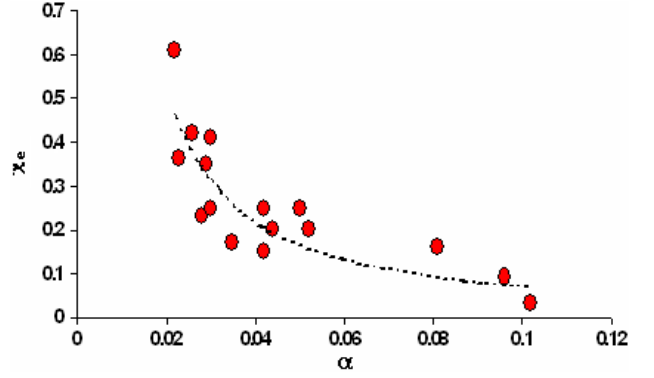


Figure 7. Electron conductivity versus α in the 0.8 MA and 1.1 MA density scan discharges, including pellet-injected plasmas. Pellet-discharges have the larger values of α , of the order of $0.25\alpha_{\text{crit}}$.

effects: although the α parameter ($\alpha = -R_0 q^2 \beta'$, where $R_0 = 0.937$ m is the major radius, q is taken at $r/a = 0.3$ and is typically about 1, and the radial derivative of β is of the order of 10^{-1} m^{-1} in the same radial position) is small in FTU ($0.1 < \alpha < 0.2$) it is important to note that the electromagnetic effects (shear Alfvén waves) which stabilize on ITG and ETG can be important [9]. As shown in figure 7 a clear trend of χ_e decreasing with α is observed (in plotting the electron thermal conductivity versus α we have treated these quantities as independent, without taking into account the amount of convolution between the variables); pellet-fuelled discharges (lowest values of χ_e) do have α within $0.25 \times \alpha_{\text{crit}}$ (where α_{crit} is the threshold for the onset of AITG and varies between 0.34 and 0.46 in the set of discharges analysed). This result suggests that further stabilization might be achieved by heating pellet-fuelled discharges (assuming the density profile remains unchanged) so as to push α close to the critical value.

4. Turbulence analysis of e-ITB discharges

Electron internal transport barriers (e-ITB) are obtained on FTU by LH and ECRH heating [10] at densities of up to 10^{20} m^{-3} and turbulence is investigated by reflectometer measurements taken in a region close to the foot of the barrier and by a microstability analysis code. As described in [10] transport barriers on FTU are not characterized by a sharp change in the electron heating conductivity and in the electron temperature gradient at the foot of the barrier the location of which is determined by the criteria $\rho^* > 0.014$. As a consequence a change in the character of the turbulence at the transition to the e-ITB is observed in a region which often extends up to few centimetres outside the foot of the barrier.

By analysing the reflectometer spectra of the set of e-ITB discharges described in [10] at plasma current 500 kA we observed that the transition to the transport barrier triggered by LH is often characterized by the stabilization of a mode around 120 kHz and consequent spreading of the energy at neighbouring frequencies. Reflectometer data of FTU shot #19739 at reflection radius $0.5 < r/a < 0.6$ ($B_T = 5.3$ T, $I = 500$ kA, $T_{e0} = 2\text{--}5$ keV, $P_{\text{LH}} = 1.5$ MW, $P_{\text{ECRH}} = 1.0$ MW), are presented in figure 8 while in figure 9 the density and temperature profiles at two time slices before ($t = 0.3$ s) and after the barrier formation ($t = 0.7$ s) are

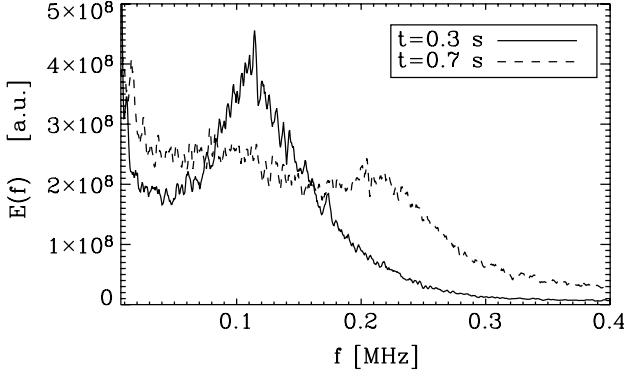


Figure 8. FTU #19739. Spectra measured by an O-mode reflectometer at $r/a = 0.5$, $t = 0.3$ s before (—) and $t = 0.7$ s after barrier formation (---).

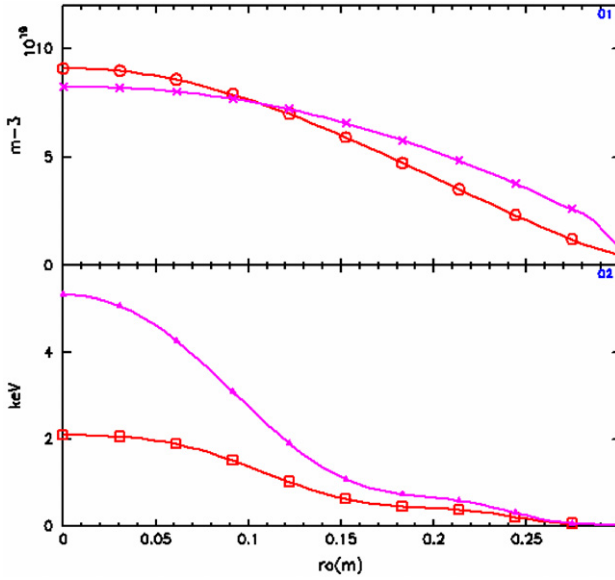


Figure 9. Density and temperature profiles of shot FTU #19739 at $t = 0.3$ s ($\circ$ and $\square$) and $t = 0.7$ s ($\times$ and $\triangle$), respectively, in the pre-barrier and barrier phase. The reflection radii are located at $r = 0.15$ m ($t = 0.3$ s) and $r = 0.18$ m ($t = 0.7$ s), respectively. The foot of the barriers ($\rho^* > 0.014$) is at $r = 0.16$ m ($t = 0.7$ s).

shown. According to the criteria mentioned above, the foot of the e-ITB is located at $r/a \approx 0.53$. Due to the increase in density during the LH phase, the reflection radius moves about 2 cm outwards; therefore, a strict comparison of the spectra at the same location is not possible; however, we neither consider the displacement of the reflection radius to be the cause of the observed evolution of the spectrum, since similar shifts of the reflection radius in plasmas without the barrier are found to leave the turbulence spectrum nearly unchanged, nor can the modest change in the poloidal rotation produce such turbulence reduction. Moreover the localization of the measurement is of the order of a few wavelengths ($\lambda = 0.5$ cm) and the error in the position of reflection radius is much larger, related to the error bar on the density. By cross correlation analysis of the reflectometer signals it is found that the high frequency mode observed at $t = 0.3$ s and $r/a = 0.53$ has poloidal and toroidal wave numbers, $m = 60$ and $n = 30$, respectively, and from the angular velocity of

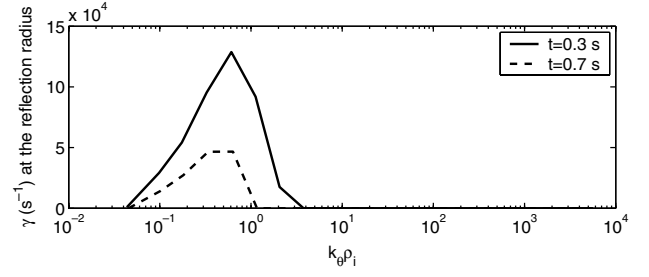


Figure 10. Microstability analysis (Kinezero) of pre-barrier profiles and profiles during the e-ITB showing stabilization of modes with $k_\theta \rho_i$ around 0.7 at the reflection radius.

the mode $k_\theta \rho_i = 0.7$ is obtained, which is in the range of the dissipative trapped electron modes [11]. Microstability analysis carried out with Kinezero for the plasma profiles taken at $t = 0.3$ s and $t = 0.7$ s shows ITG-TEM ($k_\theta \rho_i \leq 1$) stabilization at the reflection radius in agreement with the measurements, together with ETG ($k_\theta \rho_i \gg 1$) suppression all over the plasma radius (figure 10). The growth rate of the most unstable modes with $k_\theta \rho_i \leq 1$ is found to decrease at $t = 0.7$ s as compared with the growth rate at $t = 0.3$ s between $0.4 < r/a < 0.7$. In particular the code predicts that the most unstable mode at reflection radius corresponds to $k_\theta \rho_i \approx 0.7$, and its linear growth rate decreases in the barrier phase, in agreement with the experimental observation. Reflectometer measurements and the result of the numerical analysis suggest that local stabilization of turbulence in the range of dissipative electron modes ($k_\theta \rho_i$ around 0.7) could be related to the barrier formation in FTU. Dedicated experiments to investigate the change of fluctuations in plasmas having the same level of input power but different transport properties (with and without an e-ITB) together with the possibility of using a new version of Kinezero including collisions are envisaged for the next FTU campaign.

5. Particle confinement

Understanding particle transport and confinement is of crucial importance for predicting the peaking of the density profiles in future burning plasma experiments. Particle transport is controlled by diffusive and convective fluxes. The dominant neoclassical (collisional) convective flux is driven by the Ware pinch proportional to the toroidal electric field, while other collisional fluxes are negligible compared with turbulence driven flows (both types of fluxes are proportional to the diffusion coefficient and turbulent diffusivity is well above neoclassical diffusivity). It is widely accepted that operations in a fusion reactor and in future large scale tokamaks (ITER) should rely on a large fraction of the plasma current being non-inductively driven. In the above conditions the Ware pinch will be negligible and the density profile will either be flat or will be controlled by turbulent transport only. It is therefore of interest to assess the existence of a turbulent pinch and its dependence on the gradients of temperature and current. Turbulent transport models predict that particle pinch will 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) [14].

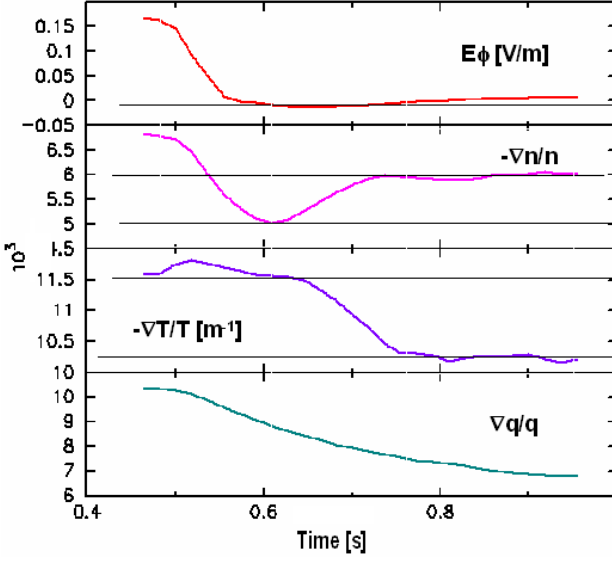


Figure 11. FTU #26481. Toroidal electric field, normalized density, temperature and q profile gradients (in m^{-1}) taken at minor radius $r/a = 0.4$.

Moderately peaked density profiles with peaking factors ($n_{e0}/n_{\text{line-average}}$) around 1.5 are routinely observed in FTU in all varieties of discharges. In order to study the turbulent pinch on FTU we have carried out experiments in which the inductive current and, therefore, the toroidal electric field is brought to zero using LH full current drive. The time evolution of the toroidal electric field, as calculated by JETTO transport analysis, normalized density, temperature and safety factor gradients taken at $r/a = 0.4$ are shown in figure 11 for shot FTU #26481 ($B_T = 7 \text{ T}$, $I = 500 \text{ kA}$). This is an LH heated discharge (1.5 MW of LH at $t = 0.5 \text{ s}$) with full LH current drive reached at $t = 0.6 \text{ s}$. The toroidal electric field decreases from $t = 0.5 \text{ s}$ due to the switching on of the LH system. A change in the normalized density gradient is observed in the time interval corresponding to the electric field descent. In figure 11 one can also see that the normalized temperature gradient (turbulent pinch) does not change during the same interval bringing us to the conclusion that in this phase the variation of the normalized density gradient is mainly due to a change in the Ware pinch. The residual peaking of the density profile as well as profile changes observed after $t = 0.6 \text{ s}$ are correlated with the normalized temperature gradient. The persistency of a peaked density profile in the absence of a Ware pinch is confirmed by the analysis of a set of FTU discharges of the type described above.

The dependence of the convective pinch responsible for the residual peaking on $\nabla T_e/T_e$ and $\nabla q/q$ as estimated on a set of LHCD discharges ($v^* = 0.1\text{--}0.4$) is reported in figures 12 and 13. The scaling of density peaking with ∇T_e is in agreement with Tore Supra results [12], namely outward thermo-diffusion in the outer part of the discharge ($0.3 < r/a < 0.5$); no clear conclusion can be drawn for magnetic curvature pinch because of the small variation of ∇q at constant ∇T_e in the set of discharges analysed. Further experiments designed to investigate the particle pinch on FTU in controlled experimental conditions have been performed in the 2004 campaign.

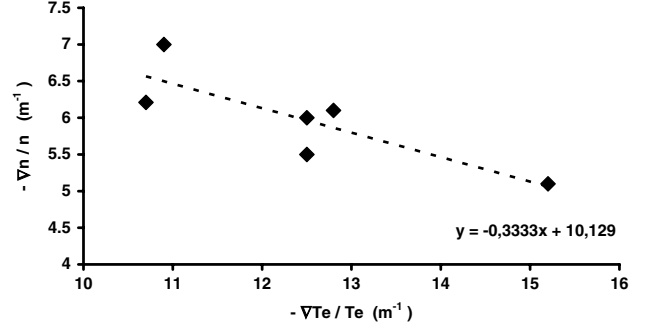


Figure 12. Density gradient scale length versus temperature gradient scale for a series of full LHCD discharges. The values are taken for r/a ranging between 0.3 and 0.5.

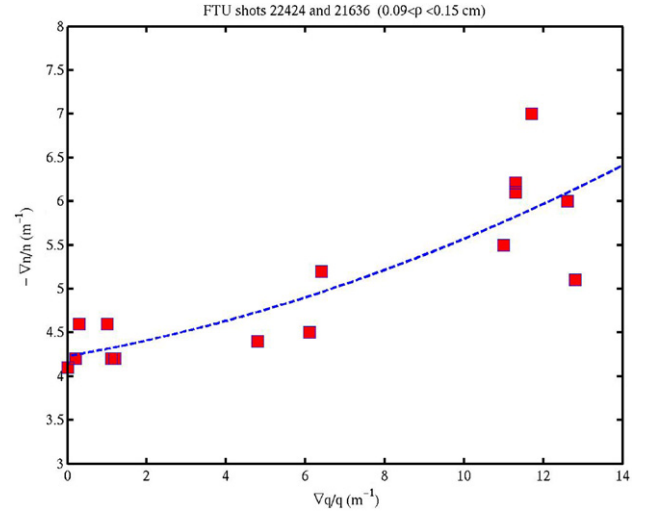


Figure 13. Density gradient scale length versus safety factor gradient scale for a series of full LHCD discharges. The values are taken for r/a ranging between 0.3 and 0.5.

6. 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 $3 \times 10^{20} \text{ m}^{-3}$) together with a reduction of ion thermal conductivity to the neoclassical level are responsible for the improvement of confinement. Microstability analysis carried out with the gyrokinetic electrostatic code, Kinezero, shows stabilization of both ITG and ETG modes due to peaking of the density profile at high collisionality. At the highest densities TEM is found to be stable due to full de-trapping of the particles. The stabilization of drift wave turbulence is measured experimentally with a reflectometer, both in pellet-fuelled discharges and in e-ITB plasmas. The study of density profiles in full LHCD stationary discharges, where both the Ware pinch and particle sources are absent, shows the persistency of density peaking which can be explained in the framework of turbulent transport with a particle pinch depending on local temperature and q gradient scale length. The result of the analysis is in agreement with previous studies carried out on Tore Supra.

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