Steady improved confinement in FTU high field plasmas sustained by deep pellet injection

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Abstract. High density plasmas ($n_0 \approx 8 \times 10^{20}$ m^{-3}) featuring steady improved core confinement have been obtained in FTU up to the maximum nominal toroidal field (8 T) by deep multiple pellet injection. These plasmas also feature high purity efficient electron–ion coupling and peaked density profiles sustained for several confinement times. Neutron yields in excess of 1×10^{13} n/s are measured, consistent with the reduction of the ion transport to neoclassical levels.

1. Introduction

High field high density scenarios are possible candidates for a burning plasma experiment providing basic information on the physics of alpha particle heating, instabilities and related confinement properties. The full potential of this approach is developed when peaked density profiles are sustained by an appropriate fuelling method: in this case, the core thermal losses are reduced and the total fusion reaction rate is optimized with respect to the input power due to particle concentration in the well confined hot core.

Deep pellet injection (e.g., pellets penetrating beyond $q = 2$ and possibly up to the $q = 1$ surface) in Alcator C had already shown the capability to enter such a regime in high field ohmic discharges and in a transient mode by the injection of a single pellet [1]. JET with the PEP mode and other machines [2] have shown the possibility of obtaining benefits from single and multiple pellet injection, typically at low toroidal fields.

In FTU ($R = 0.93$ m, $a = 0.3$ m), the possibility of sustaining improved confinement and peaked density profiles by the injection of a second pellet at 6 T/0.7 MA and edge $q = 4.7$ has already been demonstrated [3]. The new results reported in this article refer to operations at 7 T/0.8 MA ($q = 4.7$) and 8 T/1.2 MA ($q = 3.3$) in which a steady pellet improved scenario has been demonstrated; of particular interest is the 8 T discharge, corresponding to the maximum nominal FTU toroidal field. This discharge was fuelled by the injection of five pellets at intervals of 100 ms for the entire duration of the current plateau, without major adverse MHD events and no impurity accumulation (an outflow of iron is observed following the injection). The density increases while the temperature oscillates around a constant value.

Transport analysis predicts transition to an improved confinement regime characterized by neoclassical ion transport and high neutron yield lasting more than three energy confinement times. High plasma purity ($Z_{eff} < 1.3$), deep penetration and sawtooth stabilization are the main features of this regime.

Pellets are delivered by a pneumatic single stage multibarrel injector [4], built at the Risø laboratories, capable of firing up to eight pellets with a typical velocity of 1.3 km/s and a mass of the order of 10^{20} deuterium atoms. Plasma electron density is measured by a five chord DCN and a two chord CO_2/HeNe interferometer: the first instrument loses fringes during pellet injection while the second is able to follow very fast phenomena. Use of Thomson scattering measurements is needed to reconstruct the density profiles in the post-pellet phase. The electron temperature profile is measured by an ECE Michelson interferometer and an ECE polychromator, with the results being in agreement with the Thomson scattering data. The radiation losses are measured by a 16 channel bolometer array. The average value of the ion effective charge Z_{eff} is derived from the visible bremsstrahlung emission along a central chord. The neutron yield is measured by an NE213 scintillator and ^{235}U fission chambers.

2. Results

In the last campaign, FTU has been operated up to its nominal design toroidal magnetic field (8 T) and plasma current (1.6 MA) in order to investigate the effect of deep multiple pellet injection in plasmas with high magnetic field and strong ohmic electron heating (<2 MW m^{-3}). The experiments at 1.6 MA corresponding to $q = 2.6$ are at an early stage of analysis and will not be discussed here. We mention only that two pellets have been injected in such a discharge producing a remarkable density increase without any disruption: this is an encouraging result for further investigation. In the following we present results in the range 7–8 T and 0.8–1.2 MA. As already reported [5], two kinds of plasma response to deep pellet injection are observed in FTU:

(a) At high edge q and low plasma density, pellet induced perturbations are quite strong and pellet penetration is short due to high electron temperature; there is no reheating and the central density decays in less than 100 ms; the sawtooth activity is stopped and replaced by an $m = 2$ instability that can terminate the discharge in a disruption.

(b) At lower q and high density, a fast reheating phase in which the sawtooth is either suppressed or slowed down is observed; the central density remains high or even increases for several confinement times, giving rise to a substantial increase of the energy content.

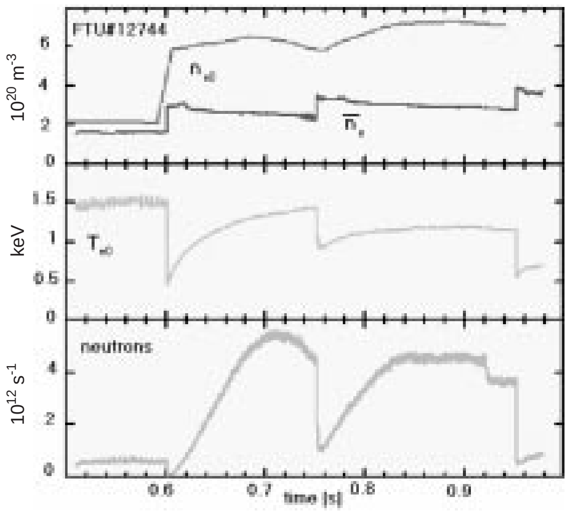

Figure 1. Time traces of the most significant parameters of discharge FTU 12744, $B = 7$ T, $I = 0.8$ MA, $q = 4.7$. Pellets were injected at 0.65, 0.75 and 0.95 s.

In this article, we concentrate on the behaviour of type (b) discharges at high toroidal field. In Figs 1 and 2 time traces of the most significant parameters of discharges FTU 12744 and FTU 18598, respectively, are shown. The launched pellets had a speed of 1.2–1.4 km/s and contained (0.9–1.2) $\times 10^{20}$ deuterium atoms. In both cases the injected particles were lost very slowly while a relatively fast central reheating took place: this produced a significant increase of central pressure and neutron yield.

A strong peaking of the electron density profile is observed in discharge FTU 12744 (Figs 3, 4) following the injection of the first pellet with a significant particle deposition in the central part of the discharge (see curve δn_e in Fig. 3); profiles are available only 17 ms after the injection, so the density profile evolution cannot be assessed during this time interval.

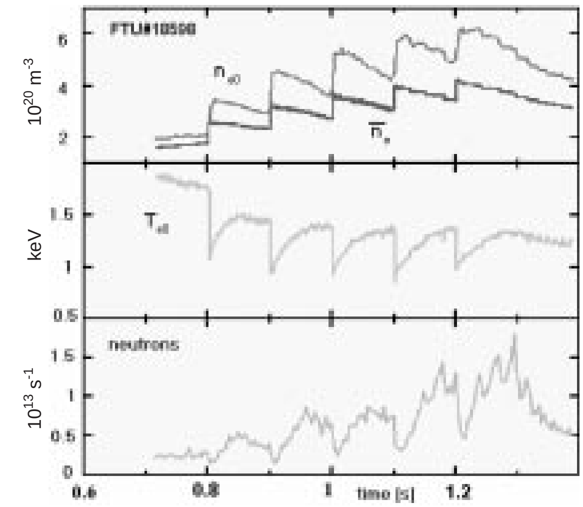

Figure 2. Time traces of the most significant parameters of discharge FTU 18598, $B = 8$ T, $I = 1.23$ MA, $q = 3.3$. Pellets were injected from 0.8 s at 100 ms intervals.

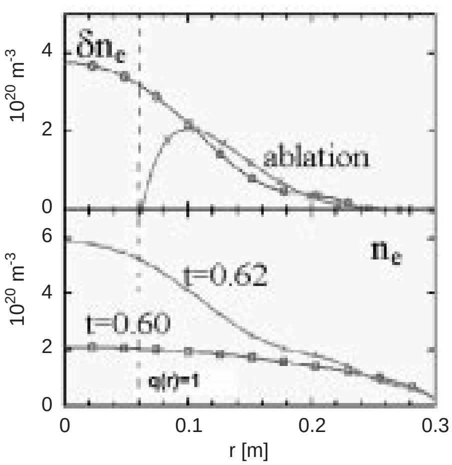

Figure 3. Density increase and ablation profile followed by density profiles before and after the injection of the first pellet for discharge FTU 12744.

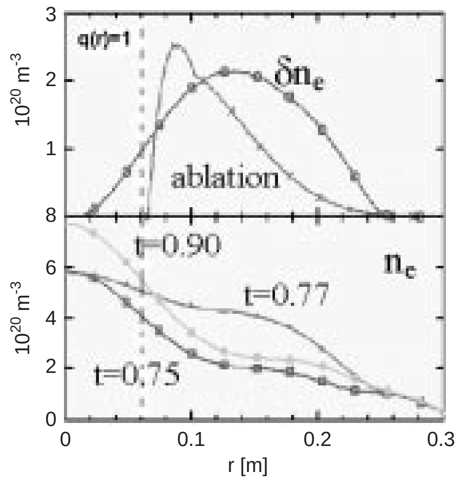

Figure 4. Density increase and ablation profile followed by density profiles before and after the injection of the second pellet for discharge FTU 12744.

Following the injection of the second pellet the central density is not much affected (see curve δn_e in Fig. 4), possibly due to the already existing strong density gradient, but a particle inward pinch appears on a longer timescale as shown by the profile at 0.90 s, i.e. 150 ms after the injection.

Simulations of pellet ablation have been performed by means of a neutral gas and plasma shielding (NGPS) code already validated on a large number of experimental data including FTU [6]. Results are shown in Figs 3 and 4 and they are in agreement with the density perturbation deduced from fast ECE temperature measurements assuming adiabaticity to be valid on the pellet ablation timescale ($\sim$100 μs). Both pellets, in the case we are examining, are completely ablated at 7 cm from the centre ($r/a \approx 0.25$), confirming the need of a fast particle pinch to explain the strong density peaking following the first pellet. In Figs 3 and 4 the position of the $q = 1$ surface is also shown: it refers to the pre-pellet phase and is deduced from the sawtooth inversion radius. The temperature profiles are flattened or only slightly affected after the reheating while they show a significant drop at the centre on the timescale of the pellet flight time ($\sim$100 μs): this fast response in a region where pellets are not supposed to penetrate could be associated with a transient ergodization of the field lines that cools the centre via parallel transport.

Transport in these discharges has been analysed using the time dependent EVITA code [7]. The code solves the magnetic field diffusion equation and the electron ion energy balance equations which are linearized at each time step and integrated by a finite difference method. Most quantities can be taken from experimental data or simulated on the basis of given models. We present here interpretative runs in which the measured electron density and temperature profiles are used. The Spitzer resistivity is chosen since it adequately reproduces the measured loop voltage. The ion heat conductivity is assumed as neoclassical multiplied by an anomaly factor which

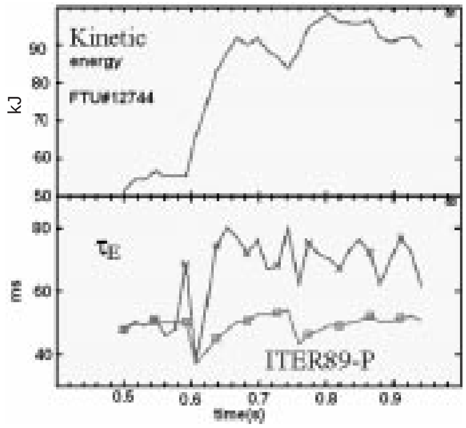

Figure 5. Evolution of the internal energy and confinement time as compared with the ITER-89P values for discharge FTU 12744.

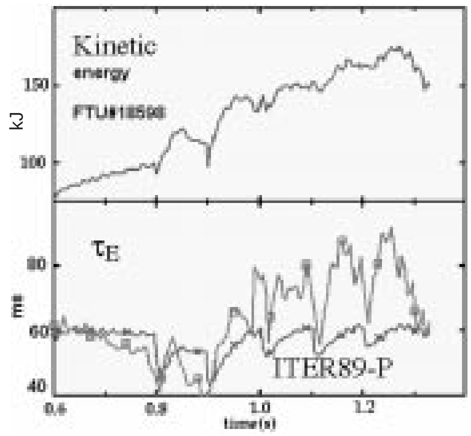

Figure 6. Evolution of the internal energy and confinement time as compared with the ITER-89P values for discharge FTU 18598.

is adjusted in order to simulate the experimental neutron yield. The plasma geometry is given by the equilibrium reconstruction.

Transport analysis shows that after pellet injection the ion conductivity must be reduced to the neoclassical level in order to reproduce the large neutron yield, while in typical gas fuelled discharges it is 5–7 times larger. The ion and electron temperatures are similar, as expected in high density plasmas. Evaluation of core electron transport is affected by several uncertainties mainly due to the reconstruction of the radiation losses profile and local ohmic power deposition. In the gradient zone, which lies between 10 and 15 cm, an upper bound for χ_e of 0.2 m^2/s can be estimated. When sawteeth are completely suppressed, deep in the central region this value drops below the ion conductivity, which becomes the dominant loss channel. Even in terms of global confinement, we observe an improvement with respect to the ITER89-P scaling law, usually quoted for L mode operation, by a factor $H_{89P} = 1.3$–1.5 (Figs 5 and 6). Our observations indicate a substantial agreement with the ITERL-97P scaling, which already includes a favourable dependence on density that overestimates the trend of the usual saturated ohmic regime.

The fusion parameter $n_{i0}\tau_E T_{i0}$ of these discharges is around 0.6×10^{20} m^{-3} s keV, which, in this respect, is the record performance of FTU. The improved performance lasts more than three confinement times and is recovered after repeated pellet injection: this feature, which already defines in many regards a steady state, opens the route to a further extension of this regime. As regards the q profile evolution, only marginal modifications are observed which are within the uncertainties of the simulation: in particular the code gives no clear evidence of transition to a reversed shear q regime, which has been observed in other experiments [2, 8, 9], and this is consistent with the persistence of a marginal or slower $m = 1$ activity.

3. MHD and impurity accumulation

Discharges FTU 12744 and FTU 18598 show significant differences with respect to MHD behaviour and impurity accumulation due to a different pellet penetration and perturbation of the target plasma parameters. NGPS simulations show a slightly shallower penetration in the 8 T discharge as expected from its higher temperature. Moreover, in this case, the relative perturbation of the density and of the central temperature is weaker than that in the 7 T discharge. As a result in the latter discharge the sawtooth is completely stopped and never reappears, while it is only progressively slowed down in the 8 T discharge. The confinement improves substantially when the sawtooth is suppressed but then a slow impurity accumulation takes place after the second pellet: at time slices with the same electron temperature, the difference in soft X ray emissivity is so large that it cannot be justified by the central electron density increase. On the contrary, in the 8 T discharge, the soft X ray channels do not show any average increase in spite of the fact that the density is constantly growing (Figs 7 and 8). There is evidence, from spectroscopy, that in this case heavy impurities are expelled from the centre.

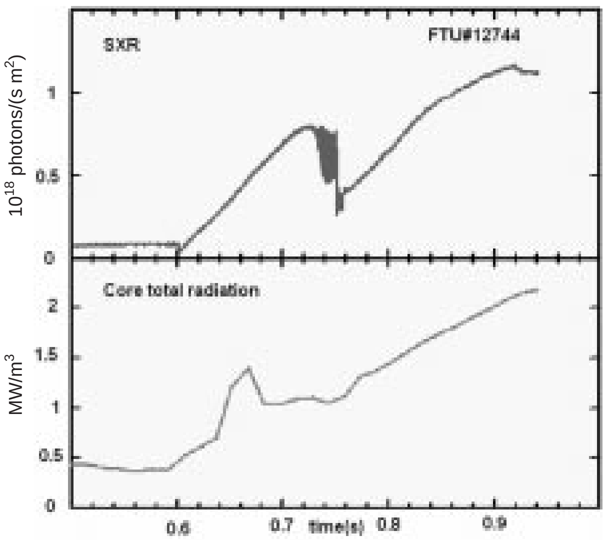

Figure 7. Soft X ray emission along a central chord and total core radiation in discharge FTU 12744.

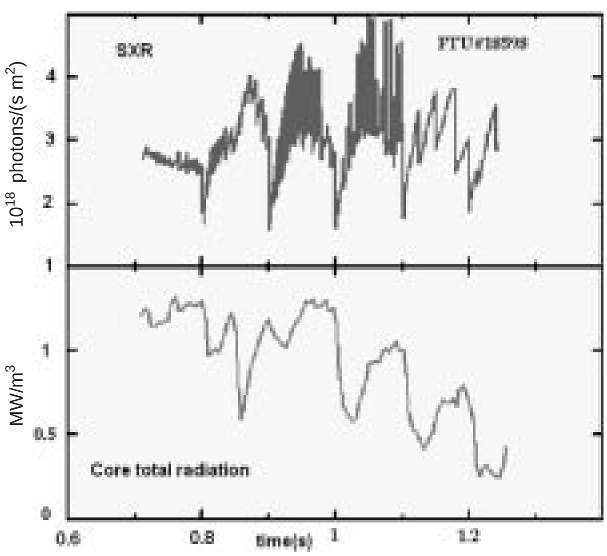

Figure 8. Soft X ray emission along a central chord and total core radiation in discharge 18598.

Possibly for the above reason, the discharge remains stable during the injection of five pellets, the only limitation being the duration of the current plateau.

We believe that a slowly sawtoothing post-pellet phase is crucial for establishing a steady regime without loosing the good confinement performance associated with peaked density profiles. The time intervals between the pellets and tuning of their masses and velocities can be the tools for obtaining this result.

4. Conclusion

An improved core confinement regime has been established on FTU at high field (7–8 T) and high current (0.8–1.2 MA, $q = 4.7$–3.3) by multiple pellet injection. The enhanced performance, clearly marked by a large increase of the neutron yield ($\sim 10^{13}$ s^{-1}), lasts for more than three confinement times. At 8 T, where slow sawtooth activity persists, there is no evidence for major adverse MHD events, and an impurity outflow is observed. The central temperatures are in the range 1.1–1.4 keV and the peak densities are in the range (6–8) $\times$ 10^{20} m^{-3}: the ion diffusivity is reduced to neoclassical levels. It should be noted that this regime, which brings about a steady average fusion triple product of 0.6×10^{21} m^{-3} s keV, is obtained in a clean plasma ($Z_{eff} < 1.3$) at low q with no direct ion heating and good electron–ion coupling. All these features are relevant for a burning plasma experiment even if in hotter plasmas the difficulty of achieving deep penetration must be overcome. Moderate central temperatures (10–13 keV) and peaked temperature profiles, as foreseen in the high field approach to the burning condition [10, 11], together with new injector technology and non-conventional injection schemes, can help in this effort. High speed (up to 4.5 km/s) single barrel injectors are now available [12], and this technology can easily be extended to a multibarrel device [13]. On the other hand, pellets injected from the high field side, taking advantage of the radial particle drift, have proven to be more efficient than those injected from the external equatorial direction [9, 14]. A burning plasma experiment might be designed with especially dedicated access to allow this solution to be compatible with the required high speed.

Further investigation on FTU, in addition to operation at the maximum nominal current of 1.6 MA, will concentrate on the possible synergy of pellet injection and additional heating.

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