Steady Improved Confinement in FTU High Field Plasmas
Sustained by Deep Pellet Injection

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Abstract. High density plasmas ($n_o \sim 8\times10^{20} m^{-3}$) featuring steady improved core-confinement have been obtained in FTU at the maximum nominal toroidal field (8 T), and lower, by deep multiple pellet injection. These plasmas featured also 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 bringing basic information on the physics of alpha particle heating, instabilities and related confinement properties. The full potentiality of this approach is developed when peaked density profiles are sustained by an appropriate fuelling method: in this case, 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 in Alcator C high field had already shown in the past the capability of entering such a regime in 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 shown [3]. The new results reported in this paper 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 FTU maximum nominal toroidal field. The above discharge has been fuelled by the injection of five pellets at 100 ms interval 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 shows 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 multi barrel injector [4], built at the RISO laboratories, capable to fire up to eight pellets with a typical velocity of 1.3 Km/s and a mass of the order of 10^{20}D atoms. Plasma electron density is measured by a 5 chord DCN and a two chord CO_2/HeNe interferometers: the first one, during pellet injection loses fringes while the second is able to follow very fast phenomena. Use of the Thomson scattering measurements is needed for reconstructing the density profiles in the post pellet phase. The electron temperature profile is measured by an ECE Michelson interferometer and an ECE polychromator and the results are in agreement with the Thomson scattering data. The radiation losses are measured by a 16 channels 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 U235 fission chambers.

2. Results

In the last campaign, FTU has been operated up to its design nominal 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 MWm^{-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 2 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 kind of plasma responses to deep pellet injection are observed in FTU: (i) at high edge q and low plasma density, pellet induced fluctuations are considerably 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; (ii) 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 stays high or even increases for several confinement times giving rise to a substantial increase of the energy content.

In this paper, we concentrate on the behavior of type (ii) discharges at high toroidal field.
In *FIG. 1, 2* time traces of the most significant parameters of shots FTU#12744 and FTU#18598 are shown. In both cases the injected particles are lost very slowly while a relatively fast central reheating takes place: this produces a significant increase of central pressure and neutron yield.

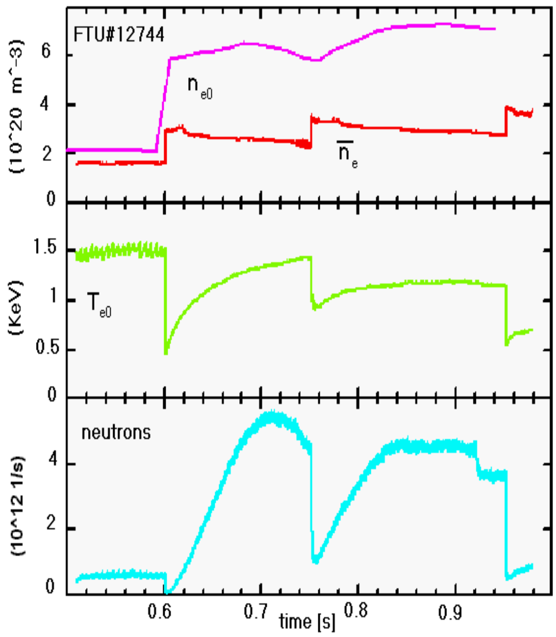

FIG 1 shot #12744, B=7T, I=0.8MA, q=4.7. Pellets at 0.65, 0.75 and 0.95 s.

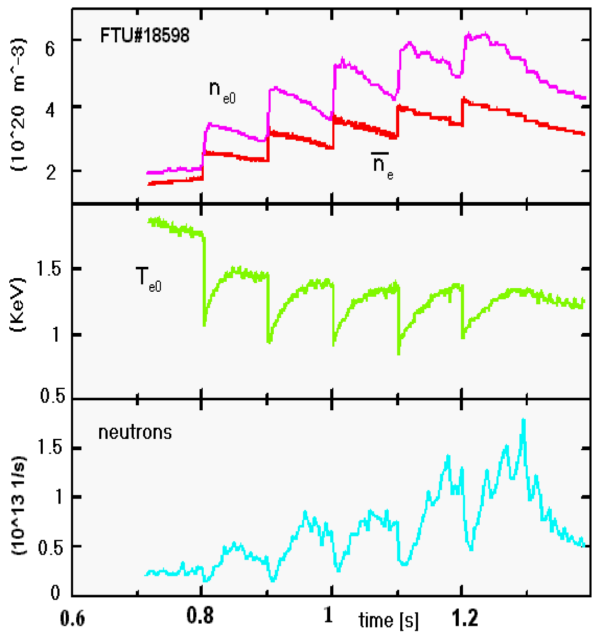

FIG 2 shot #18598, B=8T, I=1.23 MA, q=3.2. Pellets from 0.8 s at 100 ms intervals.

A strong peaking of the electron density profile is observed in shot #12744 (*FIG. 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 we cannot say anything about the deposition of particles during this time interval.

Following 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 time scale 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 [6]. Both pellets, in the case we are examining, are completely ablated at 7 cm from the center (r/a ~0.25) confirming the need of a fast particle pinch to explain the strong density peaking following the first pellet (*particle deposition is reported in FIG 3, 4 ablation curves*). The temperature profiles are flattened or only slightly affected after the reheating while they show a significant drop at the center on the time scale of the pellet flight time (~ 100 µs): this fast response in a region where pellets are not supposed to penetrate could be associated to a transient ergodization of the field lines that cools the center via parallel transport, further investigation is needed.

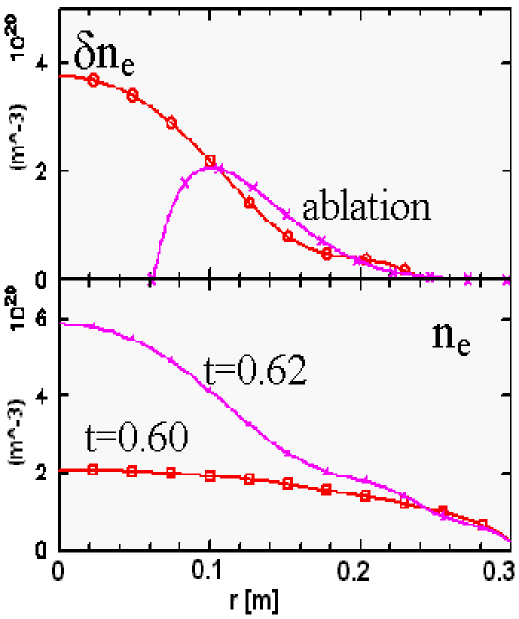

FIG 3 #12744, density increase and ablation profile followed by density profiles before and after the injection of the first pellet.

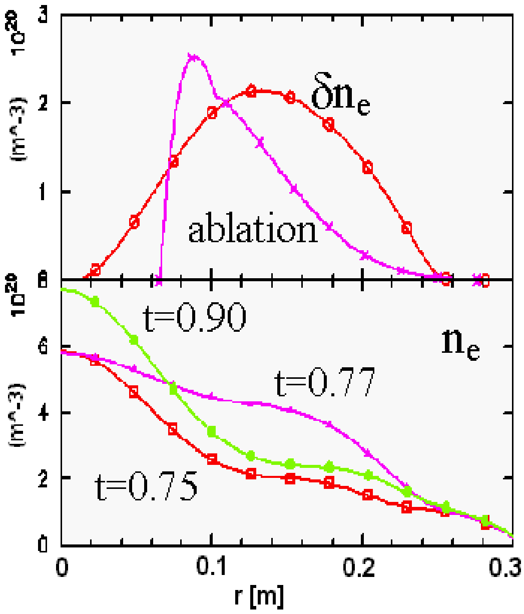

FIG 4 #12744 density increase and ablation profile followed by density profiles before and after the injection of the second pellet

Transport in these discharges have been analyzed 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 is adjusted in order to simulate the experimental neutron yield. The plasma geometry is given by the equilibrium reconstruction.

Transport analysis shows that, after the 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. 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 the sawtooth is completely suppressed, in the very 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 (*FIG 5, 6*). Our observations indicate a substantial agreement with the ITERL-97P scaling which already includes a favorable dependence on density that overestimates the trend of usual saturated ohmic regime.

The fusion parameter $n_{io}\tau_E T_{io}$ of these discharges is around $0.6\times10^{20} m^{-3}$skeV which, in this respect, is the record performance of FTU. The improved performance lasts more than 3 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.

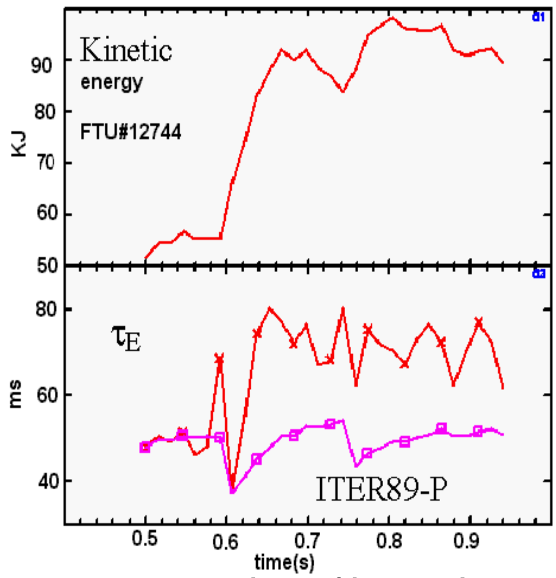

FIG 5 FTU#12744 evolution of the internal energy and confinement time as compared to ITER-89P

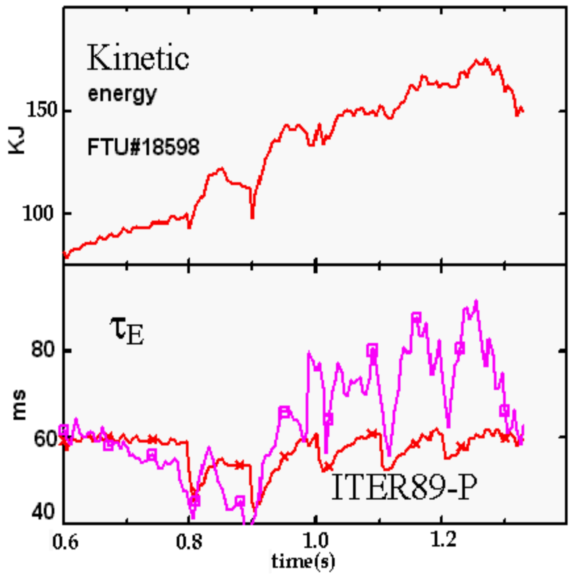

FIG 6 FTU#18598 evolution of the internal energy and confinement time as compared to ITER-89P

3. MHD and impurity accumulation

Shots FTU#12744 and FTU#18598 show significant differences with respect to MHD behavior 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 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 shot. 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 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 (*FIG 7, 8*). There are evidences from spectroscopy that in this case heavy impurities are expelled from the center. 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 performances associated with the peaked density profiles. Timing between pellets and tuning of their masses and velocities can be the tools for obtaining this result.

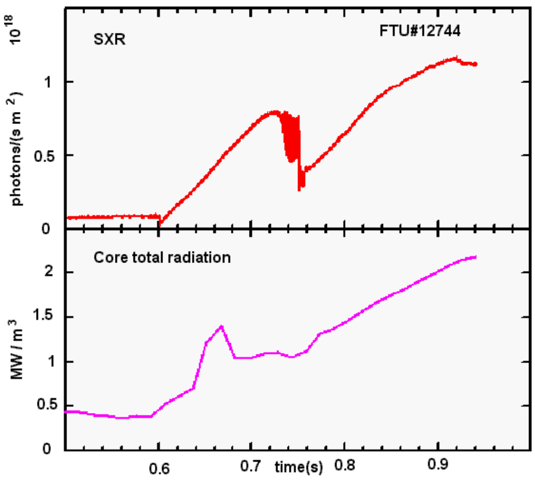

FIG 7 Soft X-ray emission along a central chord shot #12744.

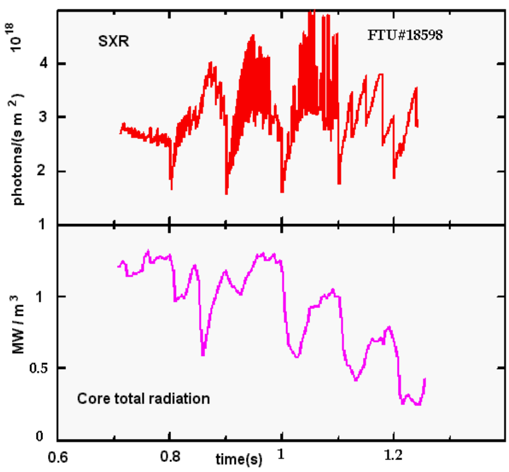

FIG 8 Soft X-ray emission along a central chord shot #18598.

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 (~$10^{13}s^{-1}$), lasts for more than 3 confinement times. At 8 T, where a slow sawtooth activity persists, there is no evidence for major adverse MHD events and an impurity outflow is observed. Central temperatures are in the range of 1.1-1.4 KeV, peak densities are in the range of 6 - $8\times10^{20}m^{-3}$: both electron and ion diffusivities are 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}sKeV, is obtained at low q, with no direct ion heating, good electron-ion coupling and in a clean plasma (Z_{eff} < 1.3). All these features are relevant for a burning plasma experiment. Further investigation, 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.

References

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