High field, high performance operation in FTU with multiple pellet injection

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1. Introduction

FTU tokamak has successfully been operated at its maximum nominal toroidal field (8T) and plasma current (1.6 MA). Very high densities have been achieved by fuelling the plasma with multiple pellet injection and, when the sawtooth is stabilized, these discharges show enhanced particle and energy confinement properties. The pellet improved performance in FTU is similar to that observed on Alcator C, JET and other machines but it is new since it combines high field, high density operation with quasi-steady behaviour [1, 2]. This regime, obtained in a clean plasma, at low q and high density with a good electron-ion coupling and no direct ion heating, simulates, in many regards, burning plasma conditions to be attained in future experiments. In this paper we present, in addition to a general description of the improved performance, an analysis of the sawtooth behaviour in the post-pellet phase, some considerations about particle confinement and, finally, a description of the impurities role.

2. Experimental set-up

FTU is a circular tokamak (R=0.93m ; a=0.3m) with a molybdenum toroidal limiter placed at the high field side. In addition to ohmic heating, which can be in excess of 2.5 MW, about 2 MW of LH, 1 MW of EC and 0.5 MW of IBW are also available. Pellets are delivered by a pneumatic, single stage multi-barrel injector, 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 five chord DCN and a two chord CO_2/HeNe interferometers: the first one loses fringes during pellet injection while the second is able to follow very fast phenomena. Use of 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, a fast ECE polychromator and by the Thomson scattering system which can now provide a profile every 17 ms. The radiation losses are measured by a 16 channels bolometer array. Impurity lines are analysed by visible and UV spectrometers. 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 a NE213 scintillator and U235 fission chambers. A multicollimator has recently come into operation which, under the conditions considered here, can yield the neutron emissivity profile with an integration time of 50-100 ms.

3. Results

Main performances obtained with multiple pellet injection are summarized in table 1. At 8T up to 5 pellets have been fired into a single discharge at time interval of 100 ms covering the entire duration of the current flat-top . We consider here only Ohmic discharges: for combination with ECRH see ref. [3].

TAB.1 FTU RECORD DISCHARGES

SHOT	B [T]	I [MA]	$\bar{n}$ $[10^{20}\,m^{-3}]$	T_o [keV]	neutrons $[10^{13}s^{-1}]$	τ_E [ms]	H89P	H97P	$n_0 T_0 \tau_e$ $[10^{20}\,m^{-3}\,KeVs]$
11612	6	0.7	2.1	1.5	0.2	80	1.6	1.0	0.4
12744	7	0.8	3.0	1.3	0.5	90	1.6	1.2	0.9
18598	8	1.2	4.0	1.4	1.3	80-100	1.4-1.7	1.0-1.2	1.0

In all cases, improved confinement is associated with the suppression or stabilization of the sawtooth activity: post pellet fast reheating combined with slow density decay increases the plasma energy content while the ohmic input power stays around the pre-pellet level. The improved phase lasts several energy confinement time and survives the injection of other pellets thus reaching a quasi-steady regime. Total sawtooth suppression seems to occur when the q=1 surface leaves the plasma. Figure 1 shows the comparison between two similar shots : the sawtooth disappears when the central q becomes larger than the value computed by the code at the inversion radius in the pre-pellet phase which should correspond to the real q=1. Both suppression and slowing of sawtooth activity, takes place only if pellets penetrate deeply enough. Fig 2 shows the post-pellet sawtooth period versus the pellet penetration length normalized to the distance between the inversion radius and the edge: the period starts to increase when the normalized penetration is larger than 0.7. Sawtooth free discharges also occur in the same domain [4].

Particle transport has also been investigated. It is apparent that particles are rapidly transported well beyond the pellet penetration point predicted by a Neutral Gas and Plasma Shielding (NGPS) [5] code and confirmed by fast ECE measurement. Indeed the density profile perturbations, deduced by ECE under adiabatic assumption on the ablation time scale (~100μs) agree with the code prediction, on the low field side while a deeper deposition is observed on the high field side. This observation is systematic and is not due to diagnostic spurious effects (fig 3). The topology of an m=1 rotating island, transferred to the ECE diagnostic toroidal location which is 90º away from the pellet, might explain the observed asymmetry. Nevertheless, it is clear from the temperature drop that particles reach the center on a time scale too fast for any diffusive process. After the end of the ablation, we observe a central density decay time longer than neoclassical prediction, including the ware pinch: fig 4 shows that, across the r=16 cm surface, within which no particle source can be present after the ablation, the experimental particle losses are lower than the net computed neoclassical flux. If the neoclassical value is regarded as a lower limit for radial diffusivity, an anomalous inward pinch is required to explain the experimental observation.

The plasma impurity content plays an important role for the evolution of the discharge after the strong pellet perturbation. In some cases, hollow temperature profiles are produced usually leading to a major disruption when a further pellet is injected. This happens when the density is raised close to a critical value determined by the power balance at the center between ohmic heating and radiation losses from molybdenum.

4. Conclusion

A quasi steady improved confinement regime has been obtained 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. Improved performance is associated with sawtooth stabilization which occurs when the pellet penetrates close to the inversion radius. Fast ECE T_e profiles show strong low-high field side asymmetries during the ablation process: under the adiabatic assumption this implies also asymmetries in the final particle deposition. Fast inward particle transport, beyond the penetration point, possibly due to the presence of MHD structures might explain the observation. After the ablation, an anomalous inward pinch is needed to explain the observed central density decay which is longer than neoclassical prediction. The presence of metallic impurities sets a limit to the achievable central density: a clean target plasma and a persistent slow sawtooth activity are the best condition for achieving high performances without impurity accumulation. Further investigation are in progress regarding impurity control and combination with additional heating.

References

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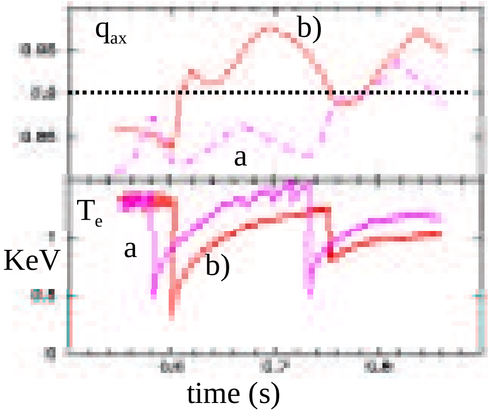

Fig1: two discharges with different post pellet MHD behaviours. The upper traces show the q on axis simulated by JETTO while the dashed line indicates the pre-pellet value at the inversion radius . a) #12747 b)#12744.

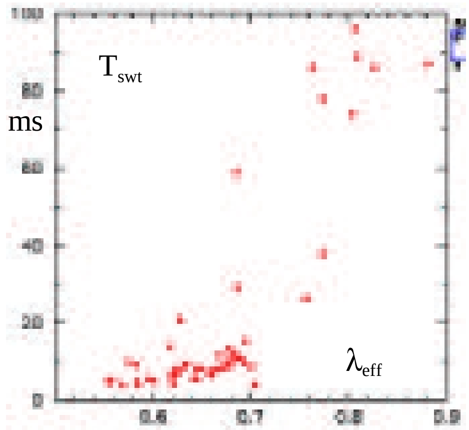

Fig 2: post pellet sawtooth period versus the penetration length normalized to the distance of the q=1 surface from the edge

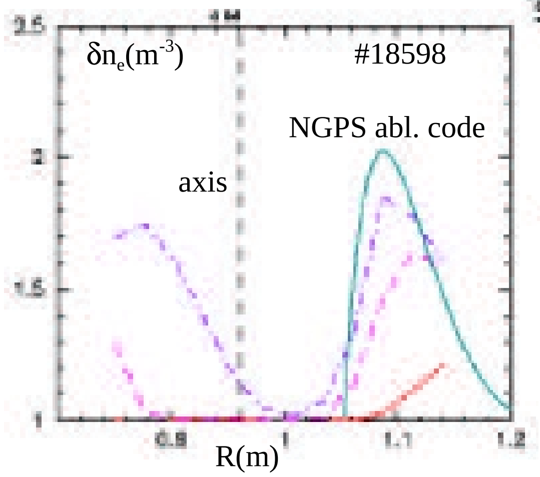

Fig 3. Particle deposition deduced from fast ECE (nT=cost.). Times from ablation start: 50; 100;150µs. Results from NGPS simulation are also shown.

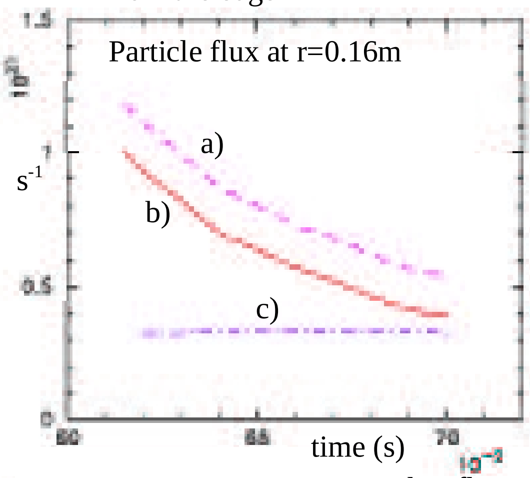

Fig 4 #12744 . Particle fluxes integrated on the 0.16 m flux surface: a) neocl. diffusion; b) neocl. diff. minus ware pinch; c) experimental

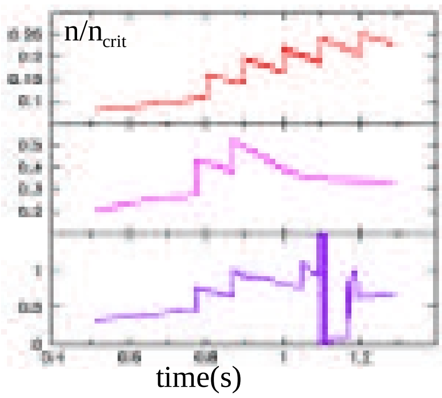

Fig 5: line average density normalized to the estimated critical density for central radiation collapse (from top #18598; 19553; 19568). Only shot 19568 reaches the critical density and eventually disrupts.