Investigation of High Density Regimes in FTU by Pellet Injection and Impurity Seeding

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Abstract. High field pellet fuelled discharges in FTU have achieved good energy and particle confinement properties in ohmic quasi-steady regime. Peak densities close to $1 x 10^{21}$ m^{-3} have been obtained, showing a post pellet decay time of several energy confinement times. Experiments aimed at obtaining Radiative Improved Modes (RIM) at high field have also been carried out using Neon injection. We have observed an increase of average density with respect to the reference discharge, which cannot be explained by the contribution of Neon. The neutron yield increases also by a factor 3-6 and the energy confinement time increases by a factor 1.4

1. INTRODUCTION

High density regimes with peaked profiles are known to yield many advantages in tokamak operation especially in view of a future burning plasma experiment. In these regimes the plasma effective charge can be kept close to one, the electron-ion coupling is more efficient and some turbulence can be stabilized like for instance the one driven by the ion temperature gradient (ITG). Indeed, an improved confinement is typically observed, together with a much more efficient neutron production due to the fact that most particles are in the hot plasma core. This scenario is however difficult to obtain, especially in steady state, first because it needs deep fuelling tools hardly available for high temperature plasmas, and secondly because impurity accumulation, driven by the steep density gradient itself, needs to be avoided. An intensive campaign, using repetitive pellet injection, has been performed on FTU to deal with these problems: the results are quite encouraging since a quasi-steady high confinement regime has been obtained in which also impurity accumulation can be avoided by an optimized timing of the pellet sequence and a proper preparation of the plasma target [1]. A detailed analysis of the confinement properties of these discharges is presented in this paper, with a deeper insight into particle and impurity transport. Preliminary results of simulation of turbulence by a gyrofluid code, in qualitative agreement with reflectometric measurements are also illustrated.

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The so called radiation improved (RI) [2] mode has also been investigated. One of the main advantages of this regime is that it could in principle yield a plasma with high and peaked density profiles, improved confinement together with a significant amount of radiated power which would alleviate power exhaust problems. Results obtained using this technique, at high field, without momentum injection and/or internal fuelling will also be presented in this paper.

Details about FTU (R=0.93 m; a=0.30 m, B<8T, IP<1.6 MA, molybdenum limiter), diagnostics and the pellet injector, can be found in ref. [1].

2. PELLET INJECTION

The pellet improved performance (PEP) is now highly reproducible in FTU provided some optimized condition are met. The target plasma needs to be very clean to avoid central radiation collapse, pellets must penetrate close or beyond the q=1 surface, and the pellet repetition rate must be of the order of one energy confinement time. These discharges show enhanced particle and energy confinement properties that have now been further analyzed. Figure 1 shows a new example of this regime, in which the repetitive injection of pellets produces a large increase of the neutron yield and an improvement of the energy confinement time with respect to a similar gas fuelled discharge. The H factor referred to ITER97_thermal scaling goes from 0.8 to about 1.1. The peaking of the density profile (n_o/n_{vol}~ 2.0) also contributes to the observed neutron yield jump so that the relevance of the performance is only partially described by the improved global confinement alone. In the power balance reported here, performed both with JETTO and EVITA codes, which give similar results, the ion diffusivity is assumed neoclassical multiplied by an anomaly factor. The latter, which is adjusted in order to reproduce the measured neutron yield, is about three in the pre-pellet phase, while drops to one after the pellets, thus indicating an improvement in the ion confinement.

As already anticipated, in order to enter this improved regime, pellets need to interact with the q=1 surface in order to stabilize sawteeth. However, the optimized condition seems to be the one in which sawteeth crashes persist but with a repetition rate lower than usually observed in the pre-pellet phase. In ref. [1] we had already reported the different post-pellet evolution of two discharges, both of them showing high neutron yield and good confinement performances. In one of them (#12744) the sawtooth is immediately stopped and the core soft-x ray emission, marking the presence of heavy impurities, keeps increasing in spite of the density and temperature remaining almost constant . In the other one (#18598) the sawtooth is only partially stabilized as seen from the progressive increase of its period, and the level of soft-x emission remains on average constant in spite of the increase of the density. The role of impurities in the evolution of these discharges has been investigated now using the technique of impurity emission analysis by an impurity transport code. The average Z_{eff} measured by visible Bremsstrahlung, the UV

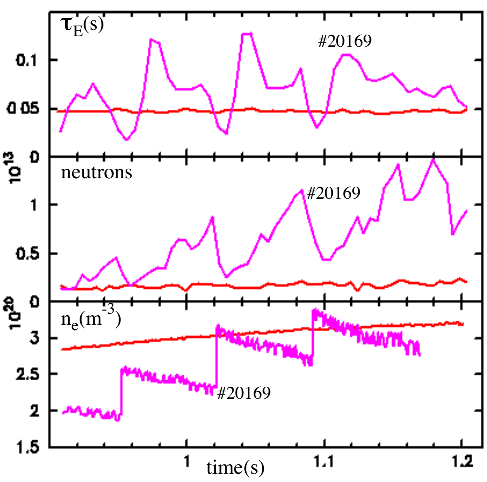

Fig.1: pellet fuelled discharge compared with a reference gas fuelled one at same density

spectra obtained by a SPRED spectrometer, the radiated power and soft X-ray emission profiles are simulated by the code [3], assuming, before injection, as usual for FTU [4], a diffusion coefficient $D_{\perp} = 0.5\ m^2 s^{-1}$ and a peaking factor S = aV(r)/2D, where V(a) = 5 m/s. The density and the relative importance of the intrinsic impurities is estimated by simulating the experimental UV line brightnesses and the global soft X-ray emission, and by comparison with the effective charge given by visible Bremsstrahlung. In the first discharge, the simulated impurity profiles after pellets are consistent with an impurity accumulation scenario, typical of a convective transport regime, but with an inward convection velocity in the plasma core (0<r<10 cm) two orders of magnitude higher than the one expected in a neoclassical regime (fig 2). The impurity densities are one order of magnitude higher after pellet injection. In the second discharge, the impurity profiles before and after pellets are reproduced by the same diffusion parameters, which means that the average effect of sawteeth maintains the impurity transport basically unchanged. As a result, the impurity content remains almost constant after pellet injection. Yet, due to the high purity of these plasmas, even during the accumulation, the contribution of impurities to the central density remains totally irrelevant.

As far as particle transport is concerned, one should first remark that the pellet fuelling efficiency in FTU is typically close to 90-100% if the pellet penetrates close to the q=1 surface. No outward radial drift of the ablated material is observed differently from what reported by other devices [5]. On the contrary, as shown in fig. 3, already 20 ms after the injection, when the first experimental density profile is available, the central density turns out to be higher than the off-axis peak value expected from a simulation with a NGPS ablation code [6]. From post pellet density profiles given by fast ECE Te signals plus adiabatic assumption, which essentially confirm what expected by the code, it's seen that the central density response is within few milliseconds. A possible explanation for this fast inward transport of particles beyond the penetration point is the interaction of the pellet with an m=1 island which is observed to grow just after the injection [7]. On a longer time scale, the particle balance analysis shows that the experimental particle flux, in the post-pellet phase, is lower than neoclassical, thus implying the presence of an anomalous inward pinch .

The CUTIE gyrofluid code [8] has been used to predict the turbulence behavior in one of these discharges. Starting from pre-pellet plasma conditions, we have simulated the injection of a pellet by switching on for 80 μs, which is the typical ablation time, a localized gaussian

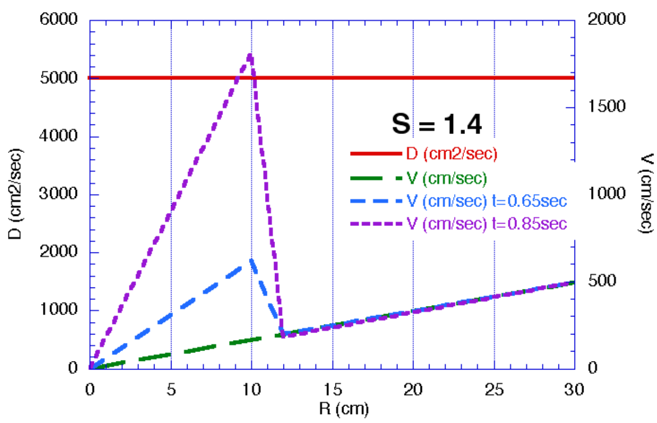

Fig.2: #12744. diffusion coefficient and inward velocity needed to simulate the ipurity content at different times

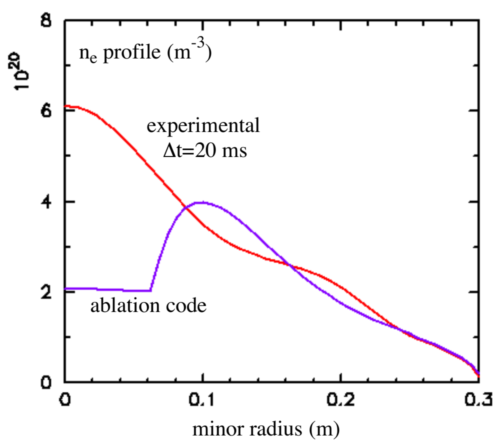

Fig.3: experimental density proifile 20 ms after pellet injection compared with the profile given by a code just after ablation

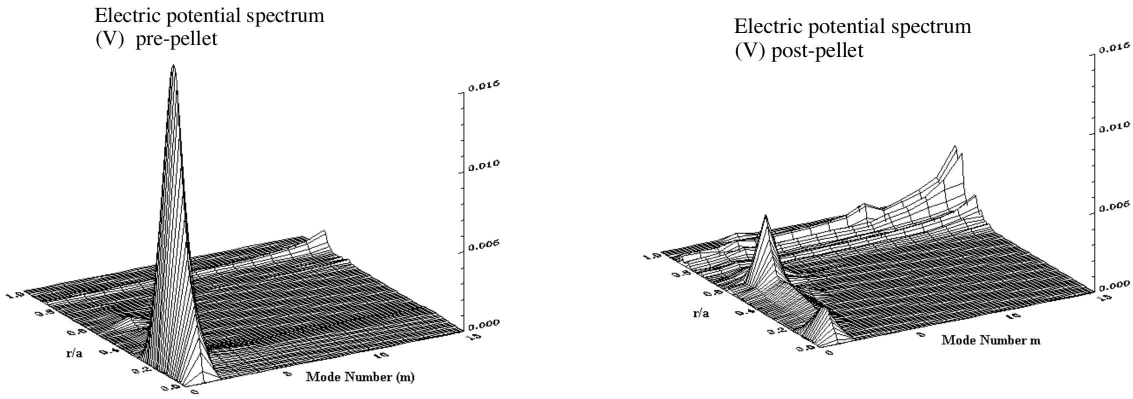

Fig. 4 turbulence spectra simulated by the CUTIE code before the pellet (left) and imediately afterwords (right).

shaped particle source. Preliminary results show that CUTIE predicts the same qualitative behavior of the plasma parameters following the injection of the pellet as observed in the experiment, together with the suppression of low m number perturbations which were present in the pre pellet phase (fig 4), and a general decrease in the transport coefficients. Reflectometry measurements of density fluctuations also show an increase of the m poloidal mode number where the electron thermal diffusivity is reduced.

3. PRELIMINARY IMPURITY SEEDING EXPERIMENTS

Following the results obtained in many Tokamaks (TEXTOR, ISX-B, DIII-D, ASDEX, AUX, etc.) which achieved an improved energy confinement regime when injecting light impurities into the plasma (Radiative Improved mode), an experimental campaign has begun in FTU to find the signatures of a RI mode. The peculiar interest of doing that in FTU is that the target is a particularly clean, high density, high field plasma with equal ion and electron temperatures as required in a burning experiment. Neon was chosen as the proper light impurity to be injected in this case.

The plasma target itself was chosen with the following parameters: at B_T=6T a plasma current of 0.8-0.9 MA was set up to avoid the onset of marfees; operation was done at an electron density (D_2) larger than 10^{20} m^{-3}, in order to be well in the saturated ohmic confinement regime (SOC). The plasma column leaned onto the inner toroidal limiter. The external deuterium flow was stopped at the beginning of the current flat-top (0.45 sec) , just before the injection of a short Ne puff (10-30 ms duration) is programmed. Experiments were performed both just after boronization of the vacuum chamber (boron coating with glow discharge with a mixture of 90% He and 10% dyborane, B_2H_6) [11], and a few weeks far away, in a well conditioned machine (impurity content dominated by metals). The shots with fresh boronized walls had the advantage of low radiation power fraction (30-40%), compared with the usual FTU level ≥ 60%, and thus with a longer Ne gas puff possible, but with the disadvantage of contamination with hydrogen particles released from the Boron film (up to 60% of the total fuel content). The essential phenomenology obtained by Ne injection does not differ appreciably in the two cases. The Ne concentration into the plasma is monitored by a UV SPRED spectrometer (Ne VII line at ~ 10.6 nm) and the brightness of different Ne lines analyzed by a Schwob-Fraenkel grazing incidence spectrometer. Figure 5 shows the effect of Ne injection at 0.5 s on line average density, radiated power and neutron yield, compared with a reference discharge, at 6T and 0.9 MA. The average density of the reference discharge

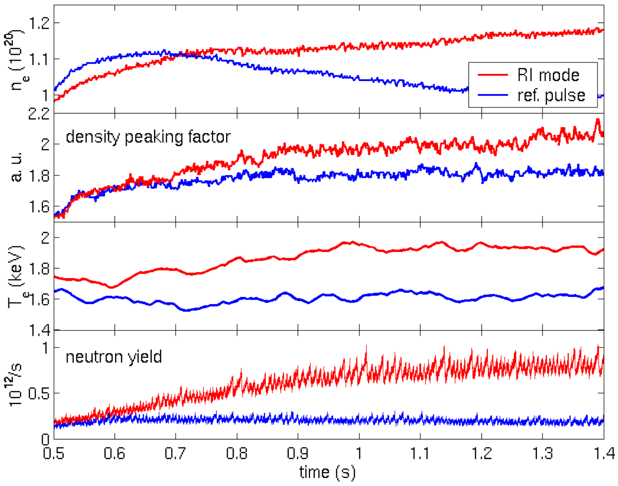

Fig 5: FTU20913 with neon seeding compared to a similar reference discharge (FTU20905)

decreases slowly because no D_2 gas puffing is present after 0.45 sec, and the recycling coefficient is less than 1. The density of the discharge with Ne puff increases for the whole duration of the pulse: this increase cannot be attributed to Ne only, since the Ne concentration, estimated by the variation of Zeff (from 1.4 to 2) is not sufficient to account for the density difference. Radiated power reaches up to 85% of the ohmic power at the end of the pulse. Neutron yield increases by a factor of about 4. Metallic impurities (Mo and Fe) are observed to decrease after Ne injection: indeed the conducted/convected power through the last closed magnetic surface decreases substantially, and therefore we can expect a corresponding decrease of the SOL temperature (in spite of a smaller particle flux) and a smaller sputtering yield for the limiter and wall material. Density and electron temperature profiles are measured, while the ion temperature profile is deduced by using the 1-D transport code EVITA in the interpretative mode. The transport coefficient χ_i is taken to be $\alpha\chi_{ineocl}$. In order to reproduce the enhancement in the neutron yield for the discharge with Ne puff, the anomaly factor α must be decreased by at least a factor 2. Typically, in ohmic discharges in the SOC regime, α is about 3. The energy confinement time is larger in the Ne puffed discharge. The improvement factor is 1.4 at 1.2 sec, i.e. of the same order as the ratio of the density to the critical density for SOC regime, which is 1.5 in this case.

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