Transport analysis of FTU plasmas with multiple pellet injection using neutron-derived T_i profiles and high-resolution n_e profiles

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INTRODUCTION

Previous studies on the energy confinement time (τ_E) of multiple pellet-fuelled discharges in FTU were performed using the JETTO transport code (run in interpretative mode) by modelling the ion transport as a multiple of neoclassical transport with the multiplier adjusted to match the total neutron rate [1]. By injecting up to five pellets in plasmas with line averaged electron density $\bar{n}_e$>1×10^{20} m^{-3} an increase of τ_E up to 120 ms was obtained and the linear ohmic confinement (LOC) phase was found to be extended above the ohmic saturation density values. Indication of a second saturation with $\bar{n}_e$ arose from the analysis of 0.8 MA pellet discharges [2]. In this paper, based on new pellet discharges at 0.8 and 1.1 MA of the 2005 experimental campaign, the behaviour of τ_E in high-density conditions (post-pellet $\bar{n}_e$~4.4×10^{20} m^{-3}) is investigated. For the first time in the JETTO simulations the ion temperature profile (T_i) is not modelled as in [1,2], but T_i derived from the neutron emissivity profiles measured by the FTU neutron camera (spatial resolution at the plasma centre ~3 cm, time resolution during pellet discharges ~80 ms [3,4]) is now used together with n_e profiles from a new high time and space resolution (43 μs, 1 cm) scanning interferometer [4].

EVALUATION OF T_i AND n_e PROFILES

The T_i profiles used as inputs for the JETTO simulations were evaluated by means of a recursive algorithm based on the relation

$$Y_n(t) = \int_V S(\vec{r},t)d\vec{r} = \frac{1}{2}\int_V n(\vec{r},t)^2 \langle \sigma v \rangle_{T_i} \, d\vec{r} \qquad (1)$$

expressing the neutron total production rate Y_n (integral of the local 2.45 MeV DD neutron emissivity S over the plasma volume V) as a function the ion density (n) and the Maxwellian reactivity for the D(d,n)^{3}He reaction (<σv>) [5]. Y_n is measured by the BF_3, NE213 and fission chamber detectors of the FTU neutron yield monitor system [4], while the ion density is obtained as the product of a dilution factor (estimated through the relative content of impurities from spectroscopy and Z_{eff} from visible bremsstrahlung) by n_e; the T_i parameterisation of the reactivity is given in [6].

The S and n_e profiles were deduced from the line integrated measurements provided by the neutron camera and the scanning interferometer using an ad hoc implemented asymmetric Abel inversion algorithm based on the actual FTU magnetic surfaces (surfaces of constant poloidal magnetic flux ψ). For a given equilibrium configuration, a set of N (normally 50) uniformly distributed magnetic surfaces covering the whole plasma and M fictitious lines of sight (normally the $2N$ lines between adjacent magnetic surfaces plus the line passing through the magnetic axis) are selected and the following linear system is built:

$$b_j = \sum_{k=0}^{N} A_{j,k} e_k \;\; j = 1, M \quad \rightarrow \quad \underline{b} = A\,\underline{e} \tag{2}$$

The b_j coefficients represent the integrated measurements along the j-th chord, e_k the local quantity (emissivity/density) between surfaces k and k-1 and A_{jk} the length of the segment of the j-th chord between surfaces k and k-1.

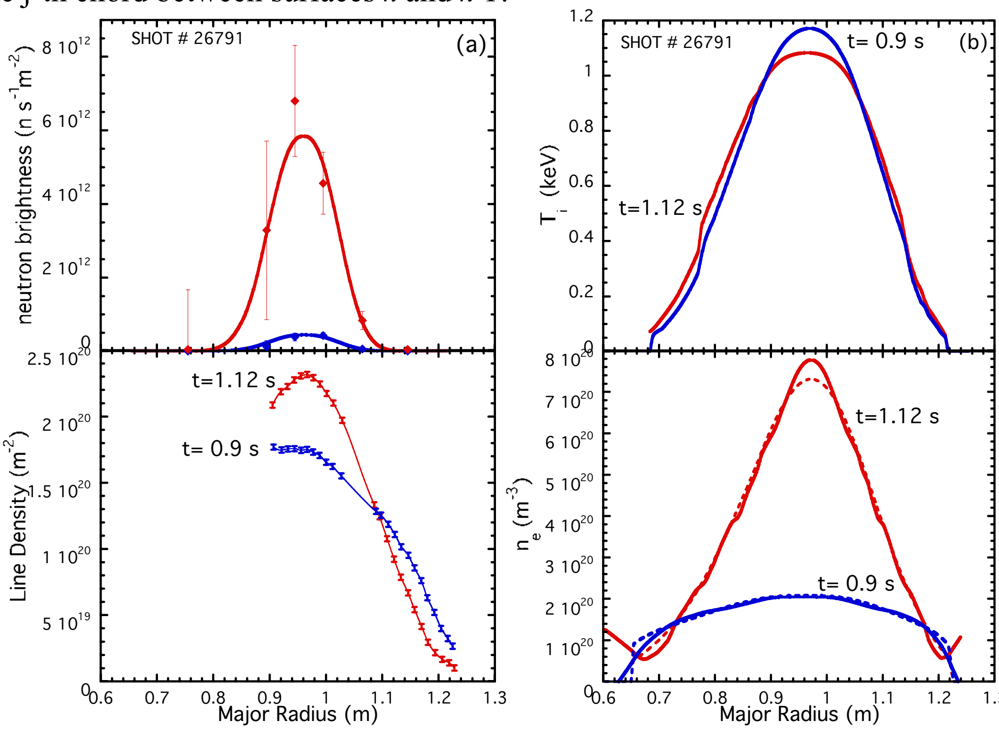

Fig1: (a) Line-integrated density interpolated data and neutron brightness fitted data before pellet injection (t=0.9s) and during a pellet phase (t=1.12s) for shot #26791. (b) Inverted n_e and T_i profiles; dotted density lines represent the n_e profiles obtained with the standard FTU inversion based on the Cormack technique [7].

Due to the low number of chords of the neutron camera (six chord with uneven spacing) the neutron b_j values were obtained from a weighted fit of the raw brightness data using the Poisson uncertainty as error term. The fitting function was chosen in order to have low χ^2 and a low number of free parameters: the 2-parameter generalized parabola $B = B_0(1-\psi^{1.2})^{\alpha}$ was found to be a satisfactory compromise for FTU plasmas. On the other hand, since the scanning interferometer can acquire more than 30 chords, the density b_j values were obtained directly from the raw data by interpolation without any fitting (Fig.1a). A modified Thikonov regularization of the linear system (2) was used in order to deal with noisy input data [8]: instead of searching for a least squares solution by solving the associate system $A^T \underline{b} = A^T A \underline{e}$, a solution was searched for the system $A^T \underline{b} = (A^T A + \alpha R^T R)\underline{e}$ where R is a regularization operator used to smooth the S and n_e gradients and α is a regularization parameter (Fig1b). Typically a single inverted S profile was evaluated for the pre-pellet phase and for each of the pellet phases: normalizing S to Y_n (t) the time evolution of S and therefore of T_i is obtained.

TRANSPORT ANALYSIS

Transport analysis using the JETTO code has been performed for FTU discharges #26793, 26794, 26806, 26812 (1.1 MA) and for discharges #26791 and 26820 (0.8 MA) in which 4 or 5 horizontal pellets have been injected obtaining increasingly higher $\overline{n}_e$ up to about 4.4×10^{20} m^{-3}. The measured T_i profiles (Fig. 2) have been used to evaluate χ_i profiles: during pellet phases measurements show T_i (r) ~ T_e (r) for all discharges confirming the high coupling between ions and electrons produced by pellet injection; errors on χ_i profiles result smaller during the pre-pellet phase due to the fact that, in this phase, the difference T_i - T_e is normally much higher than the uncertainty on the single measurement (~15%).

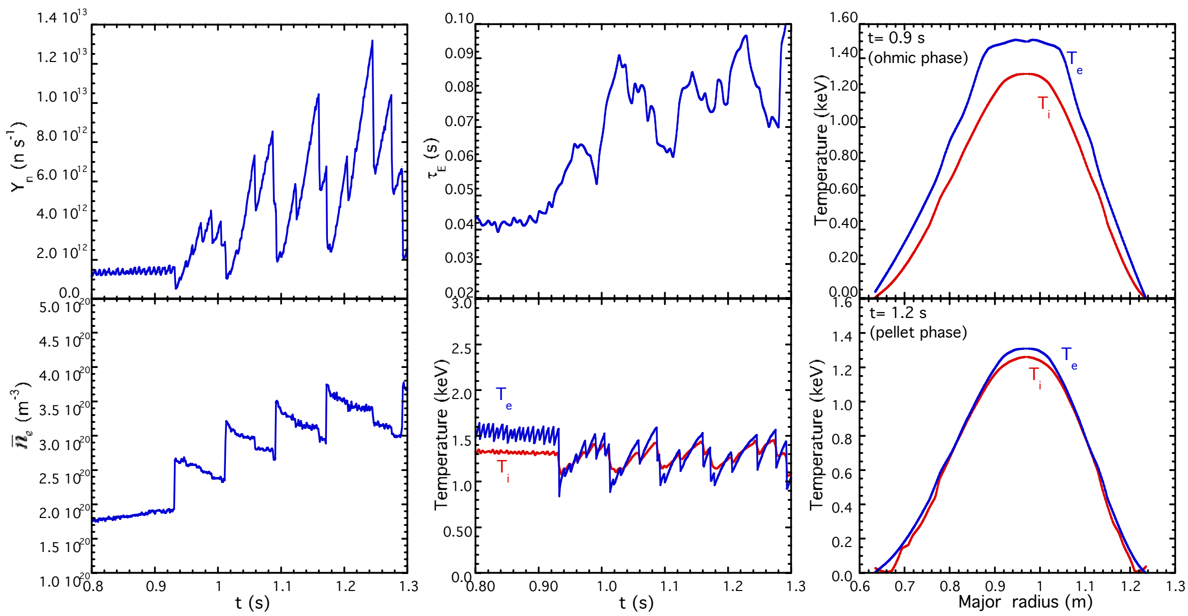

Fig2: Time evolution of $\overline{n}_e$, neutron rate from NE213, $T_e(0)$ from ECE, $T_i(0)$ from neutron camera and τ_E for shot #26794. T_i and T_e profiles before pellet injection and during a pellet phase are also shown.

The JETTO runs based on measured T_i show a decrease of ion transport produced by pellet injection, with a reduction of χ_i to neoclassical values (in the range 0.1-0.2 m^2s^{-1}at r/a ~ 0.3) (Fig. 3). The presence of a second saturation of τ_E with $\bar{n}_e$ arising at about 110 ms is confirmed for I_p=0.8 MA; for I_p=1.1 MA τ_E is approaching the second saturation at the maximum density reached in this series of discharges (~ 4.4×10^{20} m^{-3}) (Fig. 4). A more detailed analysis of the present data is needed to investigate the reasons of this second saturation.

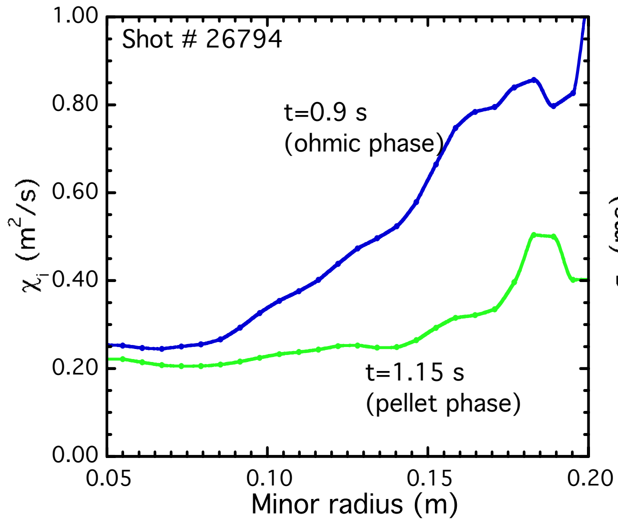

Fig3: χ_i radial profiles in pre-pellet phase compared to post-pellet phase for shot #26794.

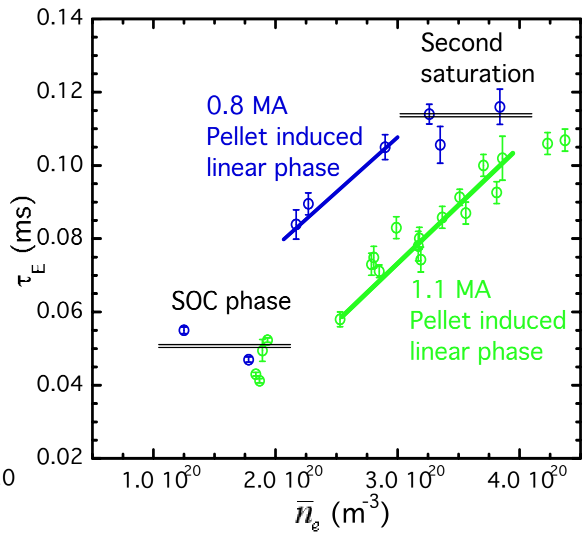

Fig. 4: τ_E (time-average during plateau of ohmic and pellet phases with associated standard error) vs. $\bar{n}_e$ for the six discharges analyzed.

REFERENCES

[1] B. Esposito et al., Plasma Phys. Control. Fus. 46 (2004) 1793

[2] M. Romanelli et al., *Confinement and Turbulence Study in the Frascati Tokamak Upgrade High Field and High Density Plasma*, poster IAEA 2004, submitted to Nucl. Fus. (2005)

[3] B. Esposito et al., Proc 24th EPS Conf. Controlled Fusion and Plasma Physics, Berchtesgaden, Vol. 21A (1997) 1165.

[4] O. Tudisco et al., Fusion Science and Tech. 45 (2004) 402

[5] B. Wholle, Pys. Report 312 (1999) 1

[6] A. Peres J. Appl. Phys. 50 (9) (1979) 5569

[7] C.Mazzotta et al., *Study of Plasma density profiles evolution using the new scanning interferometer for FTU*, this conference

[8] J.P.Holloway et al., Journal of Quantit. Spettr. & Radiat. Transf. 68 (2001) 101