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# Electron temperature evolution in the plasma core of the TJ-II stellarator during and after cryogenic and TESPEL pellet injection

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## Introduction

Pellet injection is widely used in magnetically confined plasmas for core fuelling and impurity transport studies. When an injected cryogenic pellet enters the plasma, it is ablated by background plasma particles and the resultant ablated material forms a cloud of neutral and partially ionized particles that shields the pellet thereby giving rise to a self-regulated process [1]. Pellet databases [2] show that while penetration is dependent on electron density as well as on pellet mass and velocity, it is most sensitive to plasma electron temperature,  $T_e$ . In this work, made in the TJ-II stellarator, comparative studies using cryogenic and tracer-encapsulated solid pellets (TESPEL's) highlight perturbations in core  $T_e$  during and after both types are injected into microwave (ECRH) and/or neutral beam (NBI) heated plasmas. The implications of such perturbations for pellet penetration are discussed.

## Experimental set-up

The TJ-II is a 4-period heliac-type stellarator with a major radius of 1.5 m, a bean-shaped plasma cross-section, with an average minor radius of  $\leq 0.22$  m and a magnetic field  $B(0) \leq 1$  T. It is designed to explore a wide rotational transform range ( $0.9 \leq \iota(0)/2\pi \leq 2.2$ ) in low, negative shear configurations ( $\Delta\iota/\iota < 6\%$ ) [3]. Plasmas, created with hydrogen, are heated using 2 gyrotrons operated at 53.2 GHz, the 2<sup>nd</sup> harmonic of the electron cyclotron resonance frequency ( $P_{\text{ECRH}} \leq 600$  kW,  $t \leq 300$  ms), so central electron densities,  $n_e(0)$ , and temperatures,  $T_e(0)$ , up to  $1.7 \times 10^{19} \text{ m}^{-3}$  and 1 keV, are attained, respectively. In addition, two neutral beam injectors (NBI's) are operated and provide up to 1 MW ( $E_{\text{beam}} \leq 32$  keV) for  $\leq 100$  ms. As a result, plasmas with  $T_e(0) \leq 400$  eV and  $n_e(0) \leq 5 \times 10^{19} \text{ m}^{-3}$  can be attained.

A pipe-gun type cryogenic pellet injector (PI) was developed and built at the laboratories of the Fusion Energy Division of Oak Ridge National Laboratory, Tennessee, USA before being installed on TJ-II. It consists of a gun box, in which up to 4 pellets are created, equipped with a gas propellant system for pellet acceleration. In this way, pellets, containing between  $5 \times 10^{18}$  and  $4 \times 10^{19}$  hydrogen atoms, achieve velocities between 800 and 1200 m/s [3]. Closer to TJ-II, the injection lines are equipped with a) light emitting diodes and light

sensitive diodes (light gates) and b) a microwave cavity detector ( $\mu\text{wC}$ ). These provide timing signals while the  $\mu\text{wC}$  produces a mass dependent signal that allows particle accountability.

During a recent TJ-II experimental campaign, a cryogenic pellet formation pipe and its gas propulsion system were removed from the PI gun box to allow the direct rear-end coupling of a TESPEL system to it, thereby taking advantage of the PI in-line timing, gas expansion and vacuum systems [4]. For this, TESPEL's with outer and inner diameters of  $\sim 300\ \mu\text{m}$  and  $100\ \mu\text{m}$ , respectively, were injected using an independent gas propulsion system (velocities from 125 to 300 m/s were achieved). Aluminium was selected as the tracer material so particle amounts were  $6.7 \times 10^{17}$  atoms (of both carbon and hydrogen) from the polystyrene shell plus  $3.2 \times 10^{16}$  aluminium atoms (providing  $4.4 \times 10^{18}$  and  $4.1 \times 10^{17}$  electrons from the shell and tracer, respectively). Some empty TESPEL's were also injected. Note: all injections are from the low magnetic field side of the plasma.

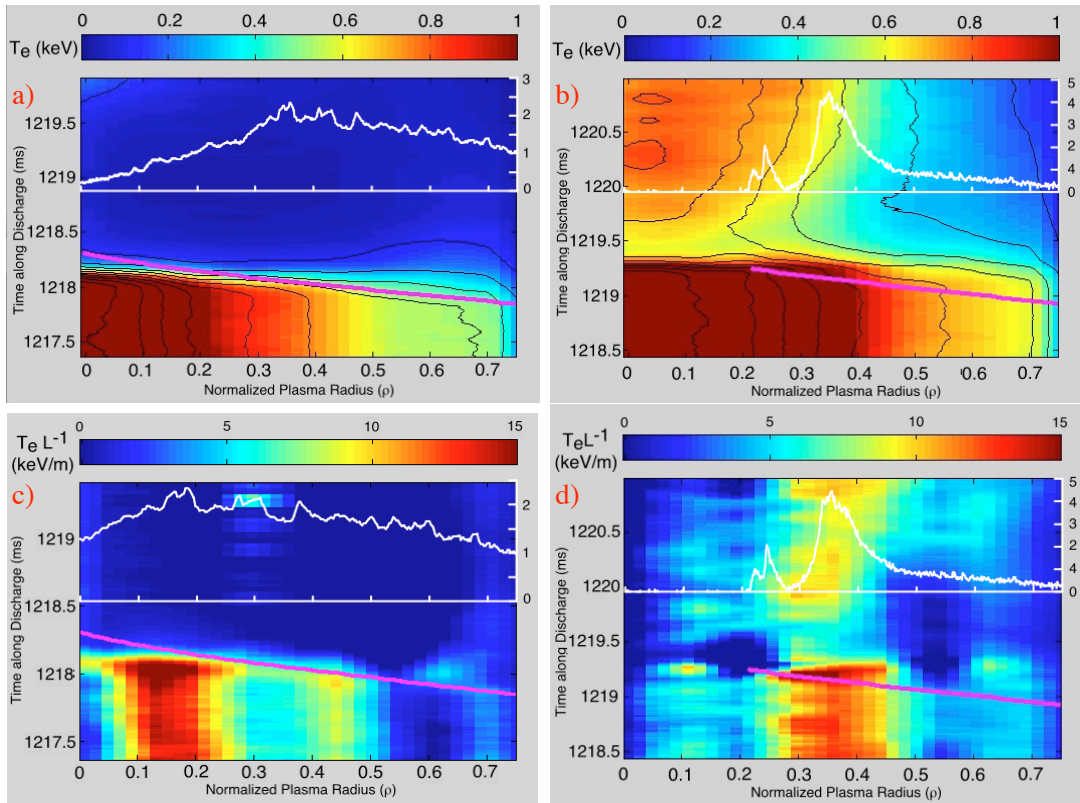


Figure 1:  $T_e$  profile evolution before and after TESPEL injection for discharges a) 40383 and b) 40506. c) and d):  $T_e$  gradients for same discharges.  $H\alpha$  light ( $10^{20}$  photons/s), which is proportional to ablation rate, along the plasma normalized radius is shown (white). Continuous lines represent TESPEL position as a function of time.

Plasma and TESPEL parameters are similar for both cases. Constant value contours are in black.

In order to follow pellet ablation across the plasma minor radius, Balmer  $H\alpha$  ( $\lambda = 656.28$  nm) and/or Al I ( $\lambda = 400$  nm) light, emitted from the neutral cloud surrounding a pellet, is recorded using optical fibre based diagnostic systems installed outside nearby upper (TOP) and rear (SIDE) optical viewports. Other plasma parameters are followed using a range of

diagnostics that includes Thomson Scattering (TS), a microwave interferometer, and an 11 channel Electron Cyclotron Emission (ECE) system (both with 10  $\mu\text{s}$  resolution), located 180°, 90° and 145° toroidally, respectively, from the PI.

## Results

In TESPEL injections into low-density plasmas created with on-axis ECRH, and the standard magnetic configuration (100\_44\_64), a cooling front travels ahead of the slow 300  $\mu\text{m}$  TESPEL if the outer  $T_e$  gradient,  $T_e L^{-1}$ , is  $<\sim 5$  keV/m, *i.e.* the plasma core cools before the TESPEL reaches it. See Fig. 1. Typically, this cold front travels at  $\sim 400$  m/s in front of the ablating TESPEL. In contrast, when  $T_e L^{-1} >\sim 5$  keV/m for  $\rho > 0.5$ , *e.g.* for off-axis ECRH (at  $\rho = 0.35$ ), plasma cooling coincides with, or is delayed with respect to, TESPEL radial position. Similar cooling waves have sometimes, but not always, been reported in other devices [5, 6]. Therein, the plasma/experimental conditions that give rise to such a wave were not identified. Here, the main consequence of such a cooling wave is to provoke a strong central  $T_e$  collapse that extends significantly the TESPEL penetration depth, *i.e.* to beyond the TJ-II plasma centre, see Fig. 1. At present, the underlying physics remains to be determined.

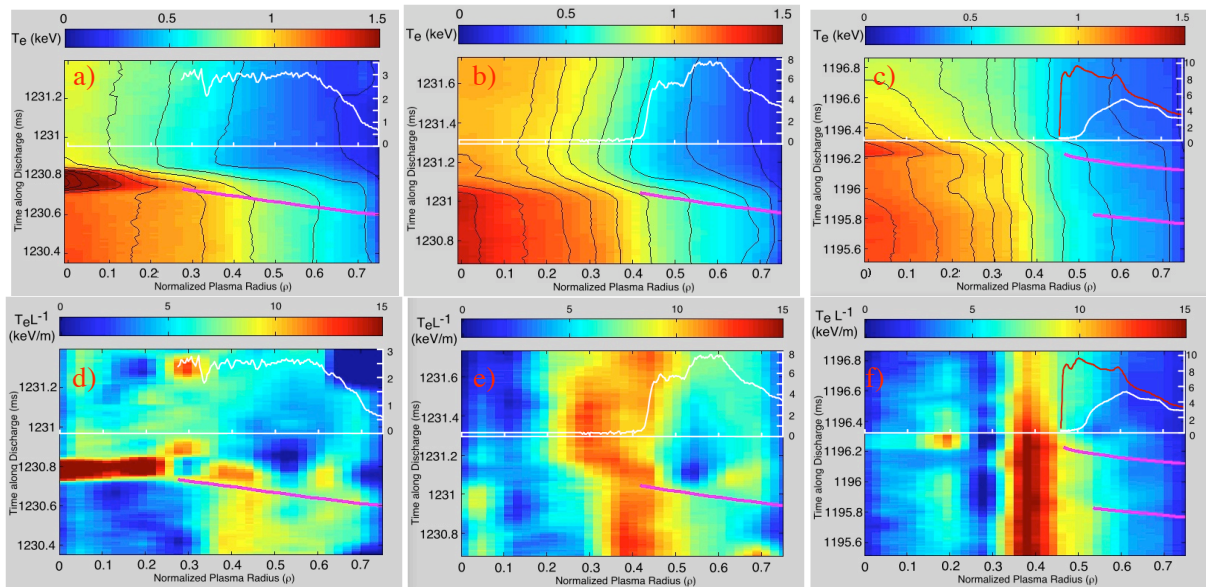


Figure 2:  $T_e$  profile evolution before and after pellet injection for discharges a) 41008, b) 41002 and c) 40231. d), e) and f):  $T_e$  gradient evolution for the same discharges. In c) and f) 2 pellets are injected. The  $H\alpha$  light collection rate ( $10^{20}$  photons/s), proportional to ablation rate, across the plasma normalized radius is shown (white & maroon). Continuous lines represent pellet position as a function of time. Plasma and pellet ( $5 \times 10^{18}$  H) parameters are similar for all, except for the 2nd pellet in c) ( $9 \times 10^{18}$  H). Constant value contours are in black.

In the case of the fast cryogenic pellets ( $\leq 1200$  m/s) a cold front is not observed (the high pellet speed could be masking this effect). Rather a transitory ( $\leq \sim 100$   $\mu\text{s}$ ), but significant, rise in core  $T_e$  is observed immediately after the pellet has travelled towards the plasma centre in some (Fig. 2a & 2c), but not all (Fig. 2b), of the ECRH plasma reviewed to date. Moreover, closer examination of Fig. 2, reveals that this perturbation begins close to  $\rho = 0$  and moves

outwards. A similar  $T_e$  rise is seen in some TESPEL injections, even if the TESPEL is preceded by an inward moving cold front. From Fig. 2a and similar discharges, it is noted that a strong core  $T_e$  rise is triggered when a pellet penetrates beyond  $\rho = 0.3$ , *i.e.* inside the region  $\rho = 0.35$  to  $0.5$  where  $T_e L^{-1}$  is largest. However, for shallower pellet penetrations, it is not so obvious. In some cases, this core  $T_e$  increase is not seen. See Fig. 2b and the 1<sup>st</sup> pellet of Fig. 2c. In contrast, for the 2<sup>nd</sup> pellet in Fig. 2c, which is large and penetrates to  $\rho = 0.45$ , a small but significant core  $T_e$  occurs even though  $T_e L^{-1}$  is larger than in the other cases. It should also be noted that during short time period the bulk plasma density remains unchanged as pellet particles remain local to the injection sector [3], while the ECE diagnostic is located 145° toroidally from the PI. Thus, it appears that  $T_e L^{-1}$  and pellet penetration are involved in this second effect. Finally, the development of core  $T_e$  spikes was observed in previous TJ-II experiments that involved edge-cooling pulses (nitrogen gas injection) [7].

## Discussion

The implication of a pre-cooling front on pellet penetration and central  $T_e$  collapse has been observed. Its trigger appears to be linked to  $T_e$  gradient, though the physical background remains unclear. In contrast, a significant, but transitory ( $\leq 100 \mu\text{s}$ ), rise in core  $T_e$  is noted during and immediately after injection under certain ECRH plasma conditions. Although at present the trigger mechanism is unclear, it is postulated that pellet injection may temporarily improve electron energy confinement: a local increased radial  $T_e$  gradient caused by ablation leads to a more positive radial electric field ( $E_r$ ). Thus the plasma may move deeper into Core Electron Root Confinement, a regime of reduced neoclassical transport [8]; the associated larger  $E_r$  shear could also contribute to reduce electron energy turbulent transport [9]. This improvement of confinement could cause the temporary observed  $T_e$  rise. However, since the  $T_e$  gradient is not sustained (see Fig. 2a), it reduces and the core  $T_e$  collapses quickly.

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