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SPONTANEOUS IMPROVEMENT OF TJ-II PLASMAS CONFINEMENT

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Abstract. Spontaneous improvements in particle and energy confinement have been recently observed in some TJ-II plasmas. Their energy content increases up to a factor 1.4. The transport analysis indicates substantial (~50%) reductions of the thermal and particle diffusivities around the region of steepest pressure gradients. For a series of ~300 kW ECRH discharges in which a systematic reduction of the gas puffing rate has been carried out, the phenomenon is observed until the gas puffing rate is too low. Therefore, the gas puffing control and hence the fuelling rate on the discharge, seem to be critical in the achievement of the transition. The results here shown add to stellarator confinement phenomenology.

Introduction. An improved particle confinement regime, in most magnetic configurations and with different heating powers, has already been described for TJ-II plasmas[1]. This regime can be accessed/abandoned via particle source control, which requires good wall conditioning and a careful design of the waveform of the puffing rate. Apparently, there is a threshold in averaged density over which a better particle confinement regime can be accessed. It is suggested that the transport into the confinement region may be playing the dominant role. In the referenced transitions there are no clear changes in energy, although the density changes notably.

The purpose of this paper is to present results concerning sudden improvements in both particle and energy confinement –to be referred as transitions- using the fuelling rate from the wall as the only external knob. First, we describe briefly a series of discharges that show similar improvements in integral quantities, after a rise in thermodynamic profiles, starting from quasi-steady state conditions. Then, a typical discharge is chosen to perform interpretative transport analysis.

Experimental Characterization. Typical TJ-II[2] (R = 1.5 m, a_{eff} = 0.2 m), discharges operate under Electron Cyclotron Resonance Heating (ECRH) and are characterized by low line averaged density $\langle n_e \rangle = (0.7\text{-}1.2\ 10^{19}\ m^{-3})$. The plasmas are limited by the vacuum chamber, which acts as a helical limiter. The phenomena of spontaneous confinement enhancement in TJ-II, as reported here, were obtained with a nominal 300 kW of ECRH, where the typical energy and particle confinement times are of the order of 1 ms and 10 ms respectively. The densities fall into the range $\langle n_e \rangle = (0.6\text{-}0.7)\ 10^{19}\ m^{-3}$ before the transition. A post-transition steady state cannot be reached due to the ECRH cut-off density ($n(0) \sim 1.7\ 10^{19} m^{-3}$). The iota values ($i(0) \sim 1.68$, $i(a) \sim 1.76$) correspond to vacuum magnetic configurations that exclude large magnetic islands inside the confinement region. The description of the diagnostics used in this work can be found in Ref. [3].
The discharge to be analysed belongs to a series in which only the gas-puffing rate was reduced shot by shot. Fig. 1 shows the corresponding pressure profiles at the transition time (dashed lines) and at the time of maximum plasma energy (solid lines).

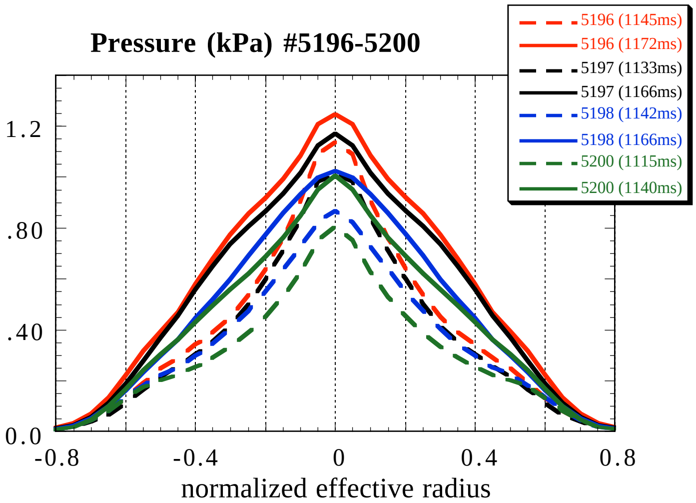

Figure 1: pressure profile before (dash line) and after (solid line) the transition. The gass-puff was reduced shot by shot.

These plasmas, prior to the transition, show typical TJ-II density and temperature profiles. The pre-transition pressure profiles for ρ > 0.6 are similar for all the discharges. The major changes in plasma pressure are obtained inside mid-radius after the transition.

Figure 2 presents some time traces of global and edge parameters for discharge #5196 of the previous series. The spontaneous transition to an improved regime is identified by a sudden increase in the electron temperature and the Soft-X-Rays (SXR) line emission, especially in the larger pressure gradient region (Fig.2a shows a SXR line for ρ = 0.5, and two ECE channels).

The central ion temperature also increases from 90 to 110 eV (not shown in figure). The $<n_e>$ rapidly rises after the transition (Fig.2b) and the diamagnetic energy of the plasma increases up to 50% after the transition (Fig.2c). Note that there is factor of two disagreement between the measured diamagnetic and calculated stored energies in TJ-II plasmas. In the enhanced phase, the electron temperature profile becomes broader, showing the maximum increase in temperature about mid-radius while the density rises in ρ < 0.8. At the same time, the temperature and density measured by Langmuir probes at the limiter drop (T_e at limiter is in fig.2a). The magnetic fluctuations (Fig.2c), present before the transition and attributed to ELM-like phenomena[4], are reduced in the enhanced confinement phase. The almost grassy ELM events just before this transition are very short and cause minor energy losses. The ELM-free period is accompanied by an enhancement of the particle confinement as indicated by a constant H_α-signal together with the rapid increase of the line averaged density, so that the rate ($H_\alpha/<n_e>$) is reduced after the transition[2]. Finally, the enhanced mode is terminated because of the density cut-off for the ECR heating (t=1200 ms, not shown in Fig. 2).

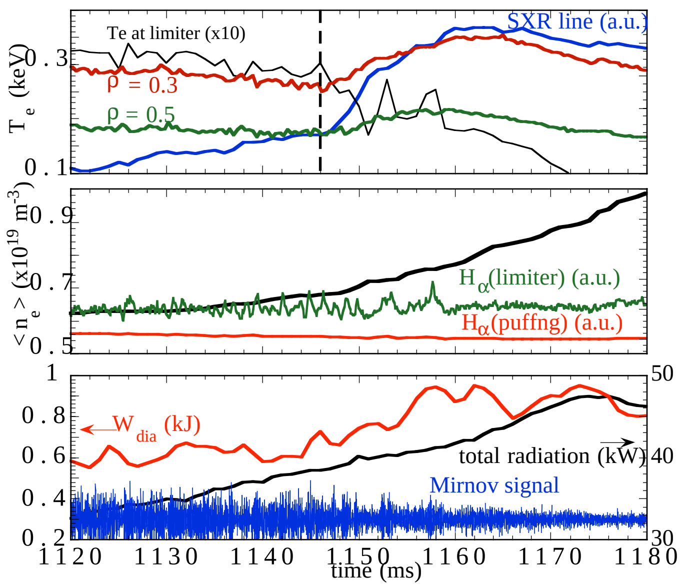

Figure 2. Time evolution of different plasma parameters across the transition n shot #5196. See text for explanation.

The sign of the induced plasma current in TJ-II (bootstrap, possibly) is such that it decreases the iota value, especially in the plasma centre. In magnetic configurations whose vacuum iota profiles lie just above a low order rational this effect can introduce the rational surface inside the confinement region. It has been also described that the ELM-like instabilities are triggered by these induced low m,n modes[5]. To date, the transitions to an enhanced confinement phases have been observed in this kind of magnetic configuration: pre-transition ELM-like instabilities are present and, in this case, the (m, n)=(3, 5) mode may have entered the plasma confinement region.

Transport analysis: The analysis has been performed with the transport shell ASTRA[5] to estimate the changes between confinement phases. According to the experimental data (see Fig. 2), there is a sudden -as compared to typical transport time scales- change in confining properties at t=1145 ms when both n_e and T_e start increasing, until t=1165ms. The drop in T_e causes W_{dia} to no longer increase after t=1165 ms. In doing the analysis, both particle and heat sources have been assumed to remain constant. In the case of the particle source this is supported by the H_α-signal (Fig. 2b) monitored at the gas puffing valve cross-section, although the neutral distribution is uncertain. The evolution of the electron energy density has been modelled with experimental radiation losses, electron-ion heat exchange, convective heat flux and an interpretative transport coefficient, $\chi_e = Q_e / V' n_e \nabla T_e$, where Q_e stands for all electron heat sources and V' is the volume radial derivative, thus forcing T_e to follow the experimental profiles. The particle density evolves with a fixed parabolic shaped transport coefficient (~ 0.1 $m^2 s^{-1}$) and direct losses due to ECRH pump out (core region) and magnetic ripple in the outer region.

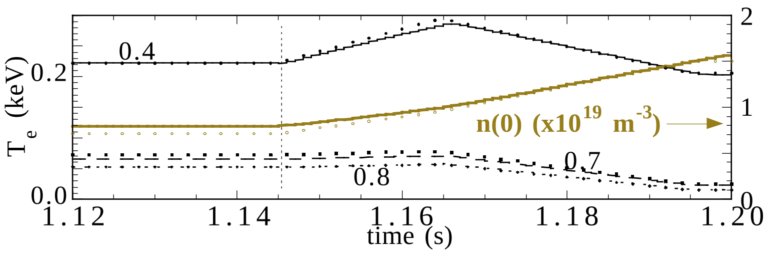

Figure 3: Experimental traces (dots) and code simulation (solid lines) in the time interval of the transition for shot #5196.

Since we are dealing with a dynamical state, the changes in transport have been evaluated by adjusting the experimental profiles in equilibrium at t=1145 ms and taking this state as initial condition. Hereafter, the experimental evolution has been found to be reasonably reproduced (see Fig. 3) by a sudden decrement (factor 0.35) in the particle diffusivity at the transition time (vertical line) accompanied by a fourfold reduction in pump out losses. It must be pointed out, however, that the effect of reducing the particle diffusivity has been found much more relevant than the reduction in direct losses from the plasma centre. The rise in particle density (shown at the magnetic axis with solid line) follows closely the experimental trace (dots). Assuming, as done, Q_e constant in this time interval, the calculated T_e traces (shown at effective radii 0.4, 0.7 and 0.8 with dashed lines) can match their experimental counterparts (markers) only by decreasing noticeably the thermal transport.

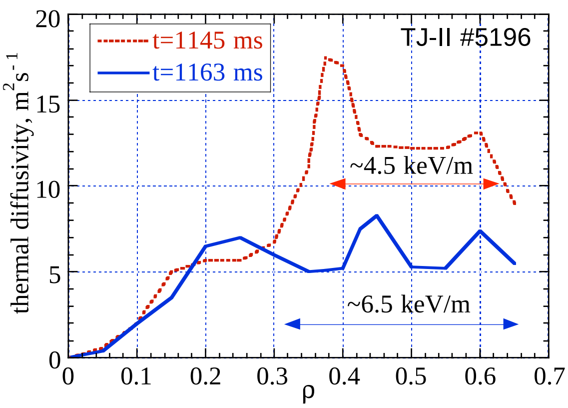

Figure 4: Heat transport coefficient profiles, before (red line) and after (blue line) the transition

Fig. 4 gives χ_e in the confinement region at the relevant times; the extension of steepest pressure gradients is indicated with double arrows labelled by the average gradient in the extension (see also Fig. 1). Aside from the aforementioned reduction in particle diffusivity and direct losses, the experimental profiles are explained through a 50% reduction in thermal transport. The concomitant change in plasma integral values is summarized in Table 1. This analysis provides first-hand estimates of some relevant plasma parameters.

<u>Table 1</u>. Values of calculated stored energy, W; and particle, τ_p, and energy, τ_E, confinement times at the transition time and when Wdia is maximum for TJ-II discharge #5196.

Comment	**time (ms)**	**W (J)**	**τ_p(ms)**	**τ_E(ms)**
pre-transition	≈1145	310	13	1.7
max. W	≈1163	440	20	2.5

Summary and conclussion. Spontaneous transitions to improved particle and energy confinement (from 13 to 20 ms and 1.7 to 2.5 ms, respectively) have been recently observed in TJ-II plasmas. They happen, for a fixed suited waveform of the gas puffing, above a minimum puffing rate although the trigger is unknown. The transition starts with a same pressure profile for $\rho > 0.6$ (Fig. 1) and leads to major changes inside that radial position: both density and temperature profiles broaden thus giving rise to higher stored energy. Several transport related signals (soft X-rays, T_i, T_e, $\langle n_e \rangle$, H_α, etc) change trends significantly after the transition and the magnetic activity (which is related to ELM activity, see H_α) is reduced (Fig. 2).

There is an initiation point for the ECE time traces in agreement with what one would expect from a local change in electron thermal transport. Therefore, and since the transport analysis points to this same direction, further work shall be directed towards understanding possible mechanisms of transport reduction, like changes in neoclassical transport roots (probably triggered by some non linear means), the effect of current induced modifications of iota profiles –since TJ-II is a very low magnetic shear machine, any shear dependent instability can be greatly affected by even low currents- or mode stabilization with thermodynamic gradient thresholds. Further work needs to be done to explore iota ranges and scenarios in which this transition occurs.

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