Peaking of the electron density profiles and enhanced particle confinement in TJ-II ECRH plasmas


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1. Introduction
The global particle confinement of ECRH plasmas in the TJ-II stellarator (R=1.5m, a < 0.22m, B0 < 1 T) has been recently investigated for a series of magnetic configurations, heating powers, electron densities and gas species (H and He). A continuous degradation of this parameter with the injected ECRH power, normalised to the averaged electron density has been found, thus evidencing the “pump out” effect as reported in similar ECR heated plasmas. Under some conditions however, a spontaneous transition to a highly peaked density profile mode has been observed. The transition leads to a decay of the electron density at the LCMS and the edge region, and to an increase of total particle content, corresponding to an enhancement of the global particle confinement of a factor up to 3. Values of the central to edge density ratio ne(0)/ne(a) up to 30 are obtained, ultimately limited by the ECRH cut-off. This mode has many features in common with other enhanced confinement modes reported in the literature, most of them related with the direct heating of the plasma edge. In the present paper, a description of these findings is given, and testing of some hypothesis used to explain the transition in other stellarators is made.

2. The enhanced particle confinement (E.P.C.) mode
The behaviour of some typical plasma parameters during the rise of the electron density by external puffing is displayed in figure 1. Two different cases are shown for H plasmas, corresponding to the same line averaged density value at t ≥ 1200 ms, same heating power (300 kW) but slightly different puffing waveforms. In both examples, the electron density at the LCMS, deduced from the Li beam, shows an initial increase following that of the interferometer trace, but it reaches its maximum at t~1130 ms. A similar behaviour is seen in other edge diagnostics, as the Hα monitors and the Langmuir probes. At this time the average density shows a plateau, followed by a further increase, even when the puffing rate is not increasing. An increase of the peaking factor can be deduced, although the e-folding length for the electron density remains constant. Also, a near zero value of the floating potential and a reduction of the fluctuations levels in the probe signals is seen at that moment.
#3656, a strong oscillation of the edge H\(\alpha\) signal and the saturation current at the limiter probes takes place at the onset of the transition, which corresponds to the ELM activity in TJ-II\(^6\). An increase of \(\tau_p\) at the transition of a factor \(~3\) is found. In shot 3687, by comparison, there is a higher electron density at the limiter position and a weaker peaking.

![Fig.1. Typical traces for H plasmas with strong (left) and weak (right) peaking of density profile.](image)

Effect were recorded. Interestingly, no differences are seen in the electron temperature profiles in both types of discharges for \(t>1100\) ms, as displayed in figure 1. The evolution of central parameters during the transition has been monitored through the Thomson Scattering and Multichannel Soft X Ray systems. Both diagnostics confirm the presence of the peaking effect. The radial profile of the soft X-ray emissivity together with bolometry indicate no impurity accumulation during the density rise phase after the transition, although the situation is strongly modified after switching-off the gas.

To date, the features corresponding to the E.P.C. mode have been found under most of the magnetic configurations (1.7> \(\text{iota}\) > 1.5) and heating powers (starting from \(P_{\text{ECRH}}\ > 300\) kW, one or two gyrotrons, ref 7) in the case of H plasmas. Under the wall conditions used in the reported campaign (all metal scenario), the external requirements to be fulfilled seem to be restricted to a critical value of the electron density of \(n_e\sim0.65\times10^{19}\\text{ m}^{-3}\), together with a given puffing waveform. The critical density is basically constant for all heating powers and magnetic configurations.

As a general rule, no transition is observed in He plasmas for constant heating power. Due to the high recycling characteristics of He on the stainless steel walls, density rising by sequential puffing is harder to achieve and the critical density is typically reached with a smooth
evolution of edge parameters. The situation changes when a second gyrotron, also tuned for central heating, is added at plasma densities near the critical one. Under these conditions, a sudden increase of the Hα signal, due to the H desorbed from the walls\(^8\), takes place initially, being followed by the same features at the edge as those reported above for pure H plasmas.

3. Effect of the fuelling waveform

In order to clarify the impact of the external parameters, a systematic scan on the puffing waveform was undertaken. Two examples are shown in figure 3. For the setting displayed in the left figure, characterised by a sharp peak followed by a constant or declining fuelling rate, the transition is always produced, provided the density reaches the critical value. This was verified by moving the time of the gas injection with respect to the beginning of the discharge. The transition then closely follows the gas injection, showing no sensitivity to other plasma parameters that might be evolving in the mean time. On the contrary, no transition is observed for the waveform displayed in the right figure, characterised by a broader, linearly decaying, gas fuelling rate. As seen, even when the critical density is achieved, no change on its time derivative is seen. The decay times of density and Hα at the limiter closely follow each other under those conditions.

Also, the injection of a small gas pulse during the enhanced mode has been tested. It can reverse the confinement to its previous state provided its intensity is high enough. The insertion of the two poloidal limiters into the plasma edge was also performed. It was found that the transition takes place even for insertion of the limiters up to 3 cm beyond the nominal LCFS. However, in interpreting these results, it must be kept in mind that the poloidal limiters in TJ-II have a fairly restricted poloidal coverage and further experiments with other geometries, more tightly adapted to the boundary plasma are in preparation.
4. Discussion:
The characteristics of the EPC mode here described have many points in common with other enhanced modes reported in the stellarator community. Thus for example, ECRH heating at the edge led to enhanced particle confinement in the Heliotron E\(^{3}\), at similar electron densities, while edge reheating has been claimed for the enhanced mode in CHS\(^{5}\), upon interruption of the puffing. Highly peaked profiles have been reported in W7-AS\(^{4}\) when off-axis heating is performed. All the observations report on the critical role of the puffing rate in the achievement of the transition, but several interpretations of its effect together with edge heating on the edge characteristics (electric field, poloidal currents, edge radiation) have been proposed. In that respect, some of the observations here reported can shed some light in the interpretation of these modes. First of all, and contrary to all previous reports, it must be recalled that no significant absorption of ECRH power is predicted for the peripheral region of TJ-II plasmas\(^{9}\), and no asymmetries in the floating potential between the two poloidal locations of the probes are seen in these plasmas, in contrast with the Heliotron-E observations\(^{3}\). The time behaviour of the electron density and H\(\alpha\) signal for the He plasmas with sequential heating can be interpreted in accordance with the pump-out/enhanced mode transition scheme observed in Heliotron E. In fact, the desorption of H from the walls by the enhanced particle flux due to the pump-out effect would act as the short, intense gas pulse typically required in H plasma in order to produce the transition. The lack of this effect at the critical density corresponding pure He, low power, would prevent from achieving the EPC mode.

In relation to the changes in edge transport associated to the transition, it is worth noting that no changes in the particle e-folding lengths and edge temperature are observed in the enhanced mode, thus implying a constant value for the \(D_{\text{SOL}}\) diffusion coefficient during all the discharge duration. Therefore, depletion of the density at the LCFS in the EPC mode must be associated to a reduction of the fluxes from the inner plasma. Whether this implies a decrease of the diffusion coefficient at some critical location or the development of some type of inward pinch still remains an open question. Code calculations of the transport characteristics of these plasmas are presently underway.