

Plasma Edge Studies and Particle Control in the TJ-II Stellarator

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I. Introduction: The TJ-II stellarator¹ is a medium size device ($R=1.5$ m, $B_T=0.95$ T and average minor radius $a<0.23$ m), presently under operation in Madrid. In the experimental campaigns here reported, plasmas have been produced and heated by electron cyclotron resonance (≈ 300 kW, 53.2 GHz). Central electron temperatures up to 1 keV are achieved in this way, while electron densities are restricted to the cut-off limit of $1.7 \times 10^{19} \text{ m}^{-3}$. The plasma is naturally limited by part of the vacuum vessel, acting as a toroidal belt limiter², or, alternatively, by two mobile poloidal limiters³. These two poloidal limiters are symmetrically spaced and they carry a set of Langmuir probes embedded in them. Only stainless steel components have been exposed to the plasma in this occasion, as the expected local thermal loads are low. A set of H α detectors has been used to study particle recycling at selected locations of the vessel. Spectroscopic measurements, absolutely calibrated manometers and a residual gas analyser have also been used for the particle balance studies. Profiles of plasma boundary parameters have been obtained by using a reciprocating Langmuir probe .

II. Edge Topology of TJ-II: The geometry of the TJ-II vacuum chamber and flux surfaces makes the magnetic connection length in the SOL to be strongly dependent on the radial distance to the last closed magnetic surface (LCMS). To calculate the connection lengths, a field line is integrated many turns around the torus, keeping track of the sequence of points on the line. A confining volume is defined considering the vacuum chamber geometry and the location and size of mobile limiters. When a point is outside this volume but the successive ones are inside, it is considered as the starting point of a whole field line section staying in the interior of the confining volume. The section ends when a point goes out of this volume. The length of the section is approximated by the sum of straight line segments joining its points. A toroidal resolution of 0.5 degrees gives an upper bound of about 2cm for the length of the partial straight segments and appears to be a good estimate for the length of the field line sections.

Given a TJ-II configuration, defined by the currents flowing through the external coils, a set of field lines are integrated. For any of them the connection length is calculated as a half the average length of the confined line sections. Different length distributions are obtained for field lines outside the LCMS, which interact with the vacuum chamber and for field lines only interrupted by the mobile limiters. In the first case there are many line sections with lengths between 2 and 15m., with a few going up to about 60m., and some shorter than 2m. As the field line approaches the LCMS, the small lengths disappear and larger field sections are present, rapidly increasing its average value. Insertion of limiters reduces the connection length

because they split some of the line sections in two parts, but its effect is unimportant on these field lines out of the LCMS.

In the second case, the shortest lengths are typically of the order of 20m, but there are some lengths going up to several hundreds meters. Connection lengths are significantly larger than in the former case, and also quickly increase as the last surface intercepted by the limiter is approached. When the mobile limiters are removed, the connection length roughly varies as d^{-1} , the radial distance to the LCMS, with values about 2 - 3.5m for $d=0.5\text{cm}$., depending on the configuration, and less than 1m for $d=1.5\text{cm}$.

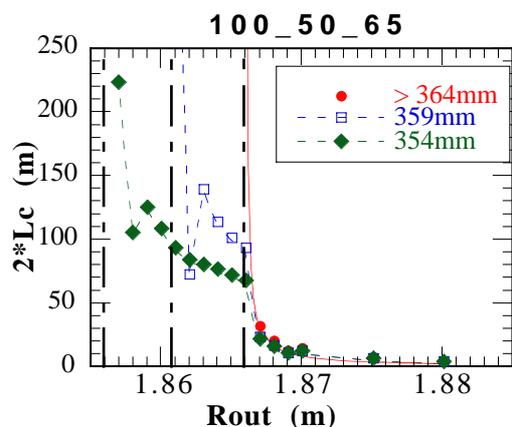


Fig.1. Radial evolution of the connection length for three positions of the poloidal limiters

When the poloidal limiters are inserted in the plasma, connection lengths become greater than 10m. and its average value varies with the radial position as shown in Fig.1. The calculations have been made for the magnetic configuration explored in the studies described below. The case of toroidal limiter ($z_{\text{pol.lim}} > 346\text{mm}$) and two inner positions of the poloidal limiters are depicted.

From this behaviour two different SOL density profiles are expected, corresponding to the action of the toroidal or poloidal limiters, with a transition when the poloidal limiters are near tangent to the LCMS. In

addition, poloidal and toroidal asymmetries are expected in the SOL profiles because of this complex interaction of magnetic surfaces with the vacuum chamber and mobile limiters.

III. Edge characterisation: Following the model predictions, an experimental campaign aimed to study the effect of the poloidal limiters insertion into the plasma has been carried out. Modifications in the density decay length of the SOL and global plasma parameters have been followed during the gradual insertion (in 5 mm steps) of the limiters towards the plasma center, in repetitive discharges at a constant line average density of 7.10^{18}m^{-3} . The largest reduction achieved in the plasma effective radius was about 27%, corresponding to about 45% in volume. A fast reciprocating Langmuir probe was used for the monitoring of the ion saturation current profile along the plasma periphery at each the limiter position. Two examples are shown in figure 2, where the horizontal axis has been corrected for the corresponding flux compression factor (≈ 2) between the limiter and probe poloidal locations. First, the sharp change in slope at $R_{\text{eff}} \approx 195\text{ mm}$ in the profile of the top figure, corresponding to the case of completely withdrawn poloidal limiter, is in good agreement (within 5mm) with the theoretical calculation of the LCMS according to the method above described. This location also corresponds, within the experimental errors, to that of floating potential inversion.

This criterion has been systematically used to define the location of the LCMS for other TJ-II magnetic configurations. Good agreement has been found if all the parts of the vacuum vessel that can intercept the flux surfaces are properly taken into account ⁴. As seen in the figure, an almost flat profile is found at radial locations beyond ≈ 205 mm, probably reflecting the complexity of the outer region of TJ-II plasmas. A SOL decay length, λ , of 0.9 cm is obtained in the region between these two limits. Insertion of the limiter 15mm inside the LCMS above defined leads to the kind of SOL profile displayed in the bottom of Fig.2. A decay length of 1.9 cm characterises the region between the poloidal and toroidal limiters, while a very similar value of that parameter at $\text{Reff} > 190$ mm describes the behaviour of the ion saturation current for the limiter configurations.

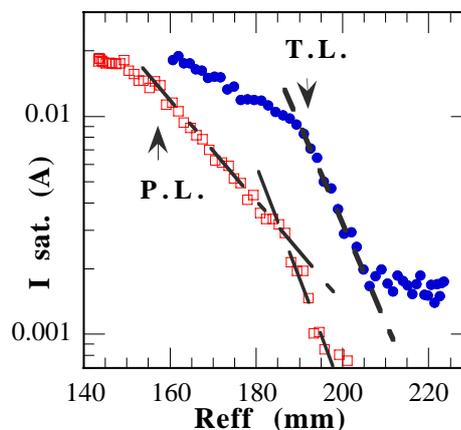


Figure 2. Radial profile of ion saturation current
 TL: Toroidal limiter location, P.L: same for poloidal

Significant changes in plasma edge parameters were also observed during the scan, as recorded by the set of Langmuir probes embedded in the mobile limiters and by a set of H α monitors used to follow the changes of the wall recycling characteristics as the limiters were inserted.

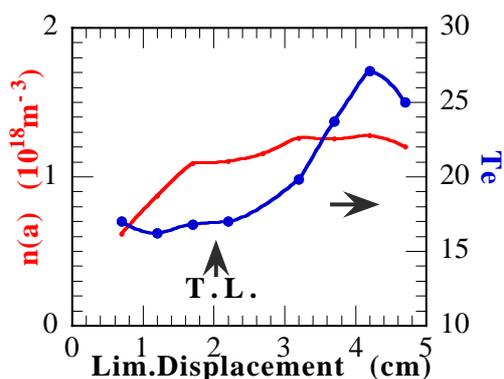


Fig.3. Plasma edge parameter evolution during the scan of pol. limiter position.

Figure 3 shows the summary of the plasma parameters at the limiter surface during their insertion into the plasma.

As it can be seen, a gradual increase of the electron temperature and saturation current takes place for the outer positions, followed by saturation of the latter at radial positions where the poloidal limiters are expected to define the location of the LCMS, as displayed above. A further increase in the electron temperature is obtained as the plasma volume is reduced, as it might be expected from corresponding increase

in the power density at constant heating power and the associated convective losses to the plasma periphery.

IV. Particle control: The changes taking place in the edge parameters have a direct impact in the global particle behaviour. Fig. 4 shows the evolution of the ratio of two H α signals, each of them corresponding to the recycling of plasma particles at two different locations, the poloidal

limiter and the area of the vessel wall acting as toroidal limiter. The trend of the data is identical to that of the limiter saturation current shown above, thus confirming the change that the TJ-II vessel walls undergo respect to their role in particle control during the discharges. This fact is directly reflected in the global particle control. As displayed in fig.4, the total particle content of the plasmas produced during the limiter scan with no external puffing evolves in the opposite way as the wall recycling does, the lowest value corresponding to the full insertion of the poloidal limiter. As a residual constant inventory of He in the vessel walls exists, due to wall conditioning by glow discharge in that gas at the beginning of the operation day¹, and due to the full recycling of that impurity in the metal walls, a constant total particle content is expected for wall fuelled discharges in these, low density ECRH plasmas.

The results here shown indicate that particle control by external puffing would be alleviated under full poloidal limiter action. Furthermore, the decay of electron density after the gas injection pulse was found to closely follow that of the limiter H α monitor only at the innermost positions of the poloidal limiters, while a systematically slower decay for the density trace was observed otherwise.

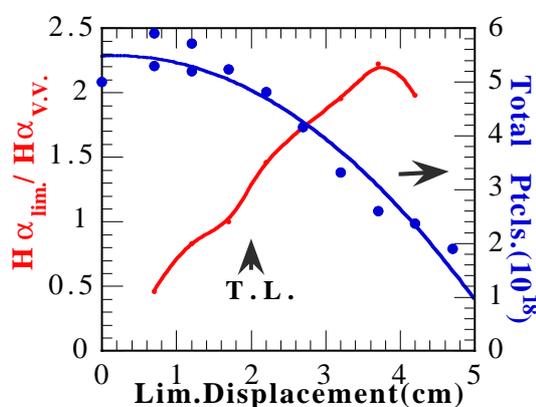


Fig.4. Plasma particle content and ratio of limiter/wall recycling during limiter scan

Combination of the data displayed in figures 2 and 3 allows us to make some estimate of the particle transport parameters of the TJ-II. Thus for example, a simple slab model calculation of the density decay length⁵ in the SOL, λ_n , gives for the diffusion coefficient $D = \lambda_n^2 \cdot c_s / 2Lc$, with c_s being the ion sound speed. For the case of the toroidal limiter, a value of $D \approx 1 \text{ m}^2/\text{s}$ is obtained if an average value of $2Lc = 4 \text{ m}$ is used and the value obtained for λ is assumed as an average of λ_n over the total LCMS of TJ-II. On the other hand, an estimate of the particle confinement time can also be made assuming such a diffusion coefficient: $\tau_p = \langle n_e \rangle V_p / (D \cdot n_a \cdot S_p / \lambda)$, with V_p and S_p being the plasma volume and outer surface area, respectively. A value of $\tau_p \approx 7 \text{ ms}$ is obtained under these assumptions, in agreement with the experimental value of 5-8 ms from perturbative experiments¹.

V. References

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