Study of impurity transport injected by laser ablation in the TJ-II

B. Zurro, M.A. Ochando, K.J. McCarthy, F. Medina, A. Baciero, R. Dux*, E. Ascasibar, A. López-Fraguas, A. López-Sánchez, T. Estrada, E. de la Luna, J. Vega and TJ-II Team. Laboratorio Nacional de Fusión por Confinamiento Magnético. Asociación EURATOM / Ciemat para Fusión

(*) IPP Garching

Introduction. Plasma experiments employing impurity injection by laser ablation have been carried out in several stellarators [1-3] as it is the most powerful method to probe particle confinement times in fusion devices. In particular, simpler methods to measure this confinement parameter in the TJ-II device cannot cope with the difficulties associated with its complicated geometry and intrinsic poloidal and toroidal asymmetries. In addition, such methods cannot resolve the radial confinement, information on which would appear to be most relevant for this device where good confinement is restricted to the central regions. Furthermore, in the TJ-II, advantage can be made of the wide range of broadband detectors, *e.g.* bolometers, x-ray detectors and VUV-sensitised phosphor detectors, where each detector type is sensitive to a specific spectral range and is located at different toroidal positions, thereby providing complementary information. Finally, the injected impurities are also being used to seed the plasma and to probe heavy ion particle temperatures using a high-resolution VUV normal spectrometer with millisecond time resolution.

Experimental. Preliminary results and a summary report of the TJ-II impurity injection system were reported elsewhere [4]. Therein we illustrated how tomographically reconstructed signals can be fitted by stretched exponentials, *i.e.* by $A_1 exp(-(t-t_0)/\tau)^{\beta}$. The behaviour of the terms τ and β with effective radius suggested that both of these parameters could have a radial dependence that requires empirically study as a function of the TJ-II operational space. Our starting hypothesis for this work is that such information might reveal particle trapping and de-trapping effects due to chains of islands, and that these may be more marked in certain TJ-II magnetic configurations. Hence the main purpose of this work to study and construct a database that will serve to shed some light on this hypothesis. However, in order to achieve a satisfactory fit of the relaxation with these two parameters the provoked perturbation should be strong enough so that the error bars are not too large. This requirement, together with the low electron density range of TJ-II ECRH plasmas (0.4 - 1.5 x 10^{19} m^{-3}), means that even moderate injections will influence the electron density. At first sight this might seem to be an inconvenience for using this technique in low-density plasmas. However it provides the additional advantage of simultaneously following the electron relaxation.

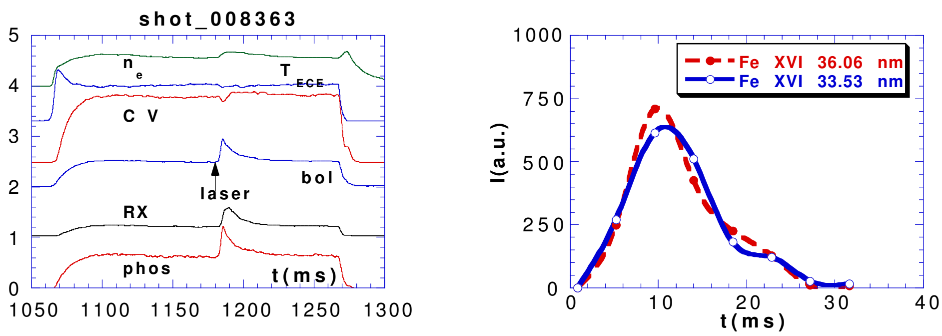

Fig. 1. a) A plot of a typical TJ-II discharge where Fe has been injected by laser ablation; the most relevant traces are included; b) the temporal evolution of two Fe lines recorded with a high temporal resolution CCD detector mounted at the focal plane of a normal VUV spectrometer.

Figs. 1 show typical raw data of impurity injection in TJ-II. In the left-hand side, (lhs) of Fig. 1 the most relevant discharge traces for the injection experiment show the line average density, where some enhancement is observed, the ECE central electron temperature, an impurity monitor signal (C V) and three radiation signals from broadband detectors whose time response to the perturbation is used when analysing the impurity confinement. In the case of the bolometer and soft x-ray detectors the reconstruction of the perturbation allow one to follow the temporal and spatial evolution. On the right-hand-side (*rhs*), we have plotted the temporal evolution of two Fe XVI lines recorded by a CCD attached to the normal VUV spectrometer. Such information is essential when simulating this data with the STRAHL code, a task that will be performed in the near future.

Results. We have determined the impurity confinement time for a series of discharges corresponding to different TJ-II magnetic configurations and electron densities. In all cases, the nominal ECRH power was kept constant at 300 kW. As the data set is still sparse we can represent almost the entire series in a single plot while being aware that the magnetic configuration, as well as the plasma density, may be playing a role. The plot in Fig. 2 suggests a systematic behaviour as a function of the line-averaged density before Fe injection, without taking into consideration the magnetic configuration. In particular, a decrease in impurity confinement time can be observed in the low-density range, *i.e.*, from 0.35 to about 0.7×10^{19} m^{-3} for this series of discharges. However, beyond this upper density point, confinement increases sharply to very high values.

Note here that these high confinement times were measured in discharges with iota bar >2, which is the only configuration range in the TJ-II where impurity injection can be performed into high density plasmas without causing the plasma to reach its density cut-off. In general, and according to the scaling law for Al confinement as deduced in the Wendelstein 7-AS stellarator [3], an increase in confinement with density is the expected behaviour. However, the latter scaling law does not cover the low-density range achieved in TJ-II ECRH plasmas. Nonetheless, the role of the radial electric field on injected particle confinement in magnetic fusion devices is known to be crucial, although at present this parameter is unknown for the core of TJ-II. Fig. 2 highlights the need to search for changes in the plasma potential or plasma rotation in order to understand these data. Indeed, this will be the goal of a more detailed analysis to be carried out in the next future.

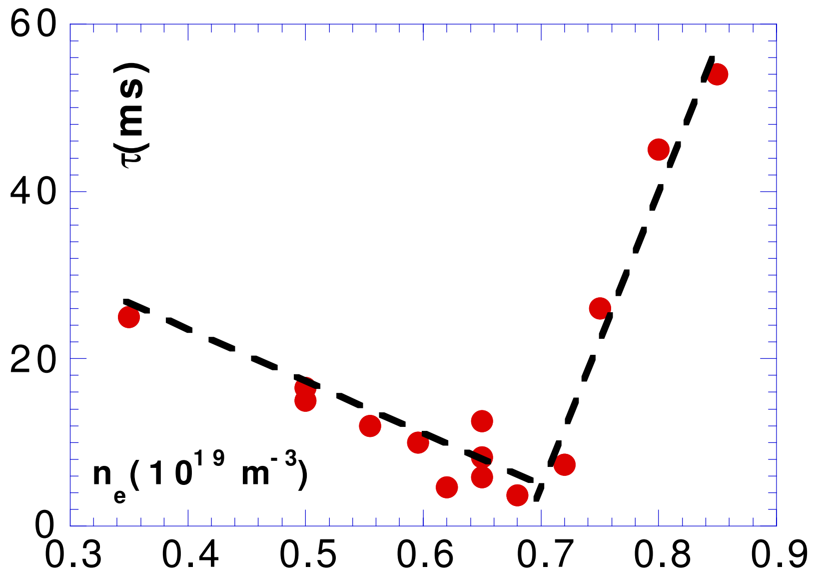

Fig. 2. Plots of the decay parameter τ versus line-averaged electron density for a series of TJ-II discharges with different magnetic configurations.

Although it is not shown here, the behaviour of the energy confinement time for this set of discharges exhibits a trend that is comparable with that seen in impurity confinement time. However, the uncertainties in the latter due to the unknown contribution of the ions to the energy balance, in the actual adsorbed power and in the direct losses [6] mean that the impurity confinement time is a more robust parameter than energy confinement time in TJ-II.

Next, in order to check that the results obtained are not a scattered outcome of mixing several magnetic configurations, we have performed a more controlled experiment, although yet incomplete, where we have measured the impurity confinement time in a sequence of discharges belonging to the same magnetic configuration (ι_{bar} (0) = 1.375, ι_{bar}(a) = 1.458) for a range of densities less complete than those of Fig. 2. The limited data points already obtained, which are plotted on the left-hand-side (*lhs*) of Fig. 3, suggest a trend that is similar to that of Fig. 2. On the *lhs* of Fig. 3, the τ and β terms for ρ = 0 are plotted. These were determined from tomographically reconstructed bolometer data. On the *rhs* of Fig. 3, a more complete analysis of τ and β versus effective radius is plotted for a single discharge of the same series.

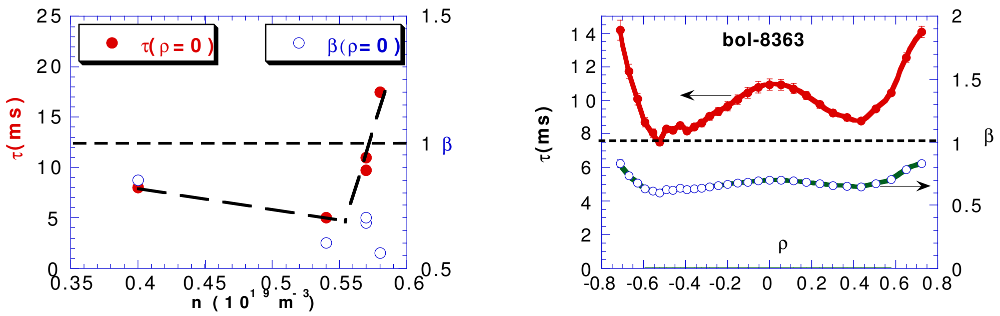

Fig. 3. Plots of the tau and beta parameter versus line-averaged density for plasmas with the same configuration (left), and versus effective radius, for the same discharge depicted in Fig. 1 (right).

In conclusion, a systematic study of impurity confinement is being carried out on the TJ-II. The results can contribute both to understand how TJ-II behaves to injected impurities and to determine whether non-exponential relaxation is important, and particularly under what circumstances, *i.e.*, namely magnetic configurations and density range, significant digression from pure exponential behaviour is observed.

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