Impurity transport and confinement in the TJ-II Stellarator

B. Zurro, M. A. Ochando, A. Baciero, A. Fernández, A. Cappa, V. Tribaldos, K. J. McCarthy, F. Medina, A. López-Sánchez, D. Jiménez Rey, D. Rapisarda, I. Pastor, J. Herranz, and TJ-II Team.

Laboratorio Nacional de Fusión, Asociación Euratom-CIEMAT, Madrid, Spain.

Abstract. In this study, performed by injecting impurities using the laser ablation method, we address impurity transport in the TJ-II stellarator for a broad range of experimental situations in electron cyclotron heated plasmas (ECRH): *i.e.* for a density scan, a magnetic configuration scan, a power scan and its dependence with power deposition profile. An analysis of impurity relaxation, defined by means of a stretched exponential, is presented in order to search for systematic behaviour in the tau and beta parameters of this function.

1. Introduction

Impurity confinement studies have been performed in several stellarator devices either by injecting impurities using laser ablation or by means of pellets, as these are the most powerful methods to probe particle confinement times in fusion devices. In particular, simpler methods to measure this confinement parameter cannot cope with the difficulties associated with the complicated geometry, as well as with the intrinsic poloidal and toroidal asymmetries, of the TJ-II device. When perturbation relaxation is considered only, it is possible to deduce the impurity confinement time from its decay constant. Indeed such studies have been performed in several stellarators, in particular in the W-7 AS where they have been carried out in some detail, [1] and [2], and where an impurity confinement scaling law was determined as a function of density, injected power, *etc.*.

The purpose of this paper is, in addition to the above goal, to look for non-exponential relaxation, as fitted by stretched exponentials of the type $A_1\exp[-((t-t_0)/\tau)^{\beta}]$, in selected impurity-injection discharges of TJ-II, and to figure out the global impurity confinement behavior of these plasmas. 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 regimes.

The paper is organized as follows. First, we describe the experimental system used to perform these experiments. Second, we present an analysis of the results of impurity injection experiments for: a magnetic configuration scan at different densities in order to elucidate the distinct influence of these two parameters, an ECRH power scan at a fixed density, and finally a power deposition scan at fixed power.

2. Experimental setup

The TJ-II is a four-period, low magnetic shear, stellarator with major and averaged minor radii of 1.5 m and $\langle a \rangle \leq 0.22$ m, respectively. At present, central electron densities and temperatures up to 1.7×10^{19} m^{-3} and 2 keV respectively are achieved for plasmas created and maintained by ECRH at second harmonics (f = 53.2 GHz, $P_{ECRH} \leq 400$ kW). In the experiments, silicon tracer ions were injected into almost stationary phases of ECRH plasmas using the laser ablation technique. For this, a thin film of material (2 μm Si), deposited onto the surface of a glass substrate, was ablated by the short pulse of a focused Q-switched Nd-YAG laser beam (800 mJ, 10 ns). The laser ablation system is described in Ref. [3].

To monitor the impurity injection we took advantage of the wide selection of broadband detectors available on TJ-II (bolometer and x-ray detector arrays, and phosphor detectors sensitized to the VUV). Each detector type is sensitized to a different spectral range and located at a different toroidal position about the device so that all contribute to provide complementary information.

3. Influence of magnetic configuration on impurity confinement

In the present experiment we have studied impurity confinement for three different magnetic configurations, *i.e.* for $i/2\pi$ =1.6, 1.8 and 2.2, by taking advantage of the magnetic configuration flexibility of the TJ-II (it can cover the iota range between 0.9 and 2.2). Due to the entangled dependence of confinement with density and iota we have performed a coarse density scan for these three magnetic configurations in order to separate these two experimental dependencies. In order to clearly show up the dependence which seems to emerge from this carefully performed experiment, we determined the tau and beta parameters obtained from an analysis of the impurity relaxation as tracked by the global radiation detectors.

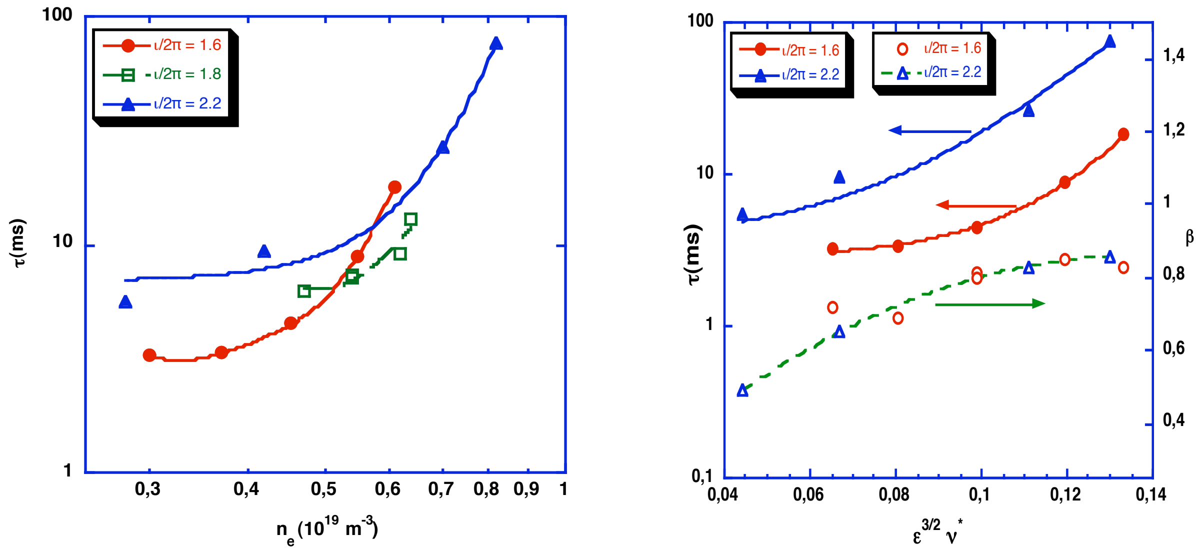

Fig. 1. *a) Density dependence of impurity confinement for three different magnetic configurations and at several densities, displayed in double logarithmic scales; b) Plot for the tau and beta parameters of the stretched exponential for two of the configurations as a function of the effective collision frequency.*

As seen in the left-hand-side of Figure 1, the confinement time, quantified by tau, increases slowly with density up to a certain point before it suddenly increases more rapidly. Moreover this turning density is found to be higher for higher rotational transform values; a double log plot was chosen to highlight the range of lower values of tau. On the right-hand-side of Figure

1, a plot of tau and beta as a function of the effective collision frequency, for two of these sequences, highlights the separate role of density and magnetic configuration on the impurity confinement time. We have chosen effective collision frequency here, because in neoclassical transport theory, the radial impurity flux is governed by the collisionality ν^*, which is defined as $\nu R_{ax} q / v_{th} \varepsilon^{3/2}$, where these parameters are: the collision frequency, the plasma major radius the safety factor ($2\pi/\iota$), the thermal velocity, and the helical ripple, respectively.

In Figure 1, the beta rises smoothly with density and tends to approach 1 -pure exponential relaxation- at the highest effective collision frequencies. However, we must remark that beyond the highest densities represented here the confinement times cannot be evaluated even with the stretched exponential function employed. The impurity injection does not relax, rather the signal increases monotonically with time and the discharge collapses within a few milliseconds. This is generally known as impurity accumulation. The hypothesis that long impurity confinement times and disruptions are connected was suggested several years ago in order to explain the operational limits in a tokamak [4]. A similar effect might account for collapses in stellarators.

4. ECRH power scan

In order to study the dependence of impurity confinement time on injected ECRH power we have selected discharges performed with densities about 0.45 x 10^{19} m^{-3} for three different microwave power levels. This scan was chosen since the degradation of confinement with power in different magnetic schemes is far from being well understood, and it is also relevant in Heliac configurations such as that of the TJ-II device.

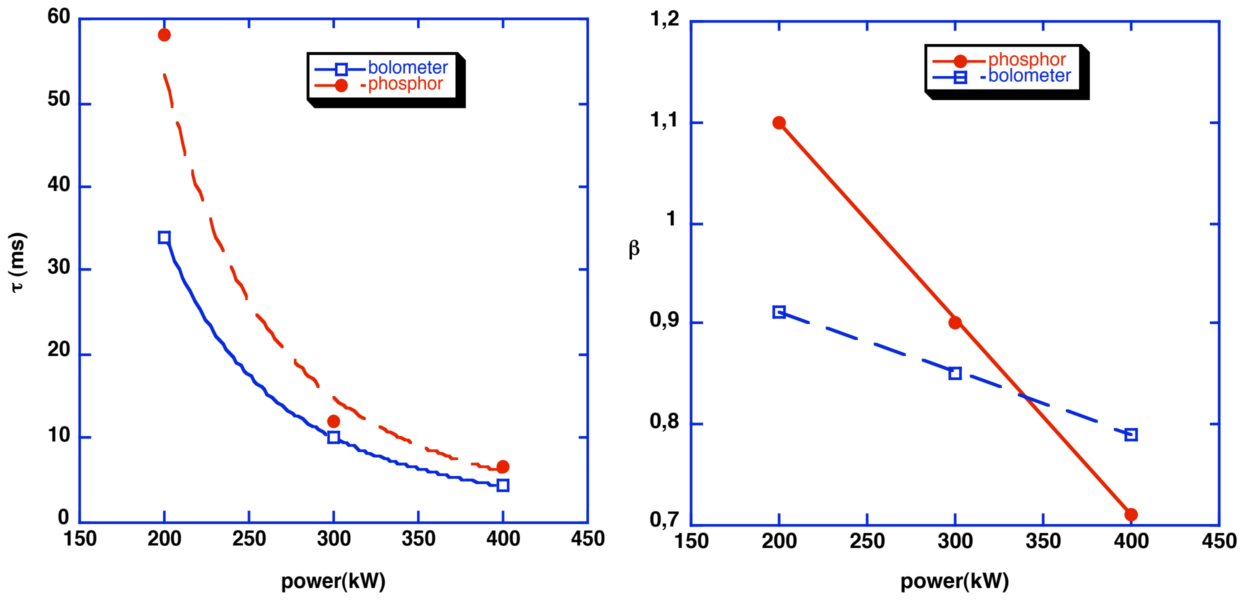

Fig. 2. *a) Plot of confinement time versus ECR power for TJ-II discharges with a fixed line-averaged density of ~$0.45 x 10^{19}$ m^{-3}; b) Similar plot for the beta parameter of the stretched exponential used to fit the relaxation. Results are plotted for a global bolometer and a VUV detector.*

The results of this power scan experiment are depicted in Figure 2. Here tau and beta are plotted as a function of ECRH power in order to extract their trends. Since the range of densities that can be covered, during routine machine operation, depends somewhat on the heating level, we have chosen a line-averaged electron density of ~ $0.45 x 10^{19}$ m^{-3} for this study, since this density can be easily attained with all power levels. The observed trend with power for the confinement time deduced in TJ-II (P^{-3}) is more dramatic than that previously reported in the W7-AS ($P^{-0.8}$), but is very similar to that reported in the LHD [5]. The differences with respect to W7-AS may be accounted for by the several differences between these devices: for instance, the TJ-II covers lower density and power ranges than W7-AS, the trend here represents the result of a power scan at a fixed density rather than being deduced from a data bank using regression analysis, and the power plotted along the horizontal axis is nominal power with the assumption that absorption does not change with power level. The behaviour of the beta parameter with power highlights the finding that the separation from a pure exponential relaxation increases with power. We should add that the electron temperature was not constant in this scan and therefore there exists the possibility that it might be the parameter capable of explaining the behaviour observed, but we have no means of controlling the heating power and electron temperature independently.

5. Probing the Influence of the Power Deposition Profile on Impurity Transport

However, to the best knowledge of the authors, the dependence of impurity transport when changing from on-axis to off-axis electron cyclotron resonance heating (ECRH) has not been studied in stellarator devices. In contrast, such studies have been performed in tokamaks for a full battery of heating schemes [6].

The present experiment was performed by creating almost constant electron density discharges in hydrogen for a standard TJ-II magnetic configuration, and by modifying, on a shot-to-shot basis, the position and width of the ECRH power deposition profile. The location of power deposition in TJ-II can be controlled by adjustment of the toroidal field or by poloidal and/or toroidal steering of the launched beam at a fixed magnetic field. The latter was the method employed here. For this, approximately 400 kW of power were launched at plasma radii from the

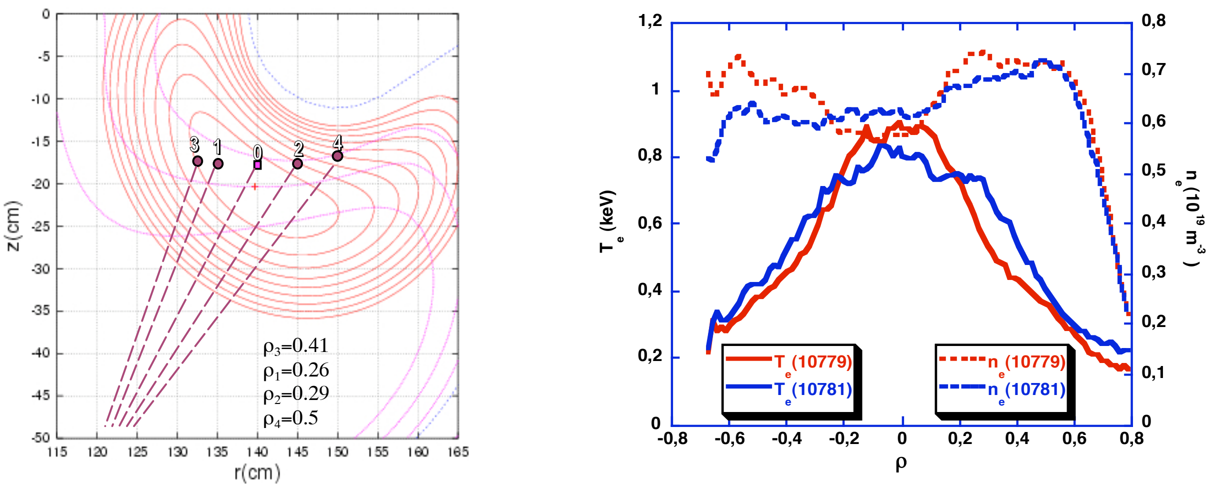

Fig. 3. ***Left***, *the contours of constant |B| and magnetic surfaces of the TJ-II standard configuration (100_44_64) showing the positions where the power deposition scan was performed.* ***Right***, *a comparison of Thomson scattering profiles for two discharges with on-axis heating (10779) and off-axis heating (10781).*

centre out to around $r \approx 0.5$, the beam waist in vacuum being 1 cm. On the right-hand-side of Figure 3, electron temperature (continuous lines) and density (dashed lines) profiles are compared for two discharges, one with on–axis ECR heating (red) the other with off-axis heating (blue).

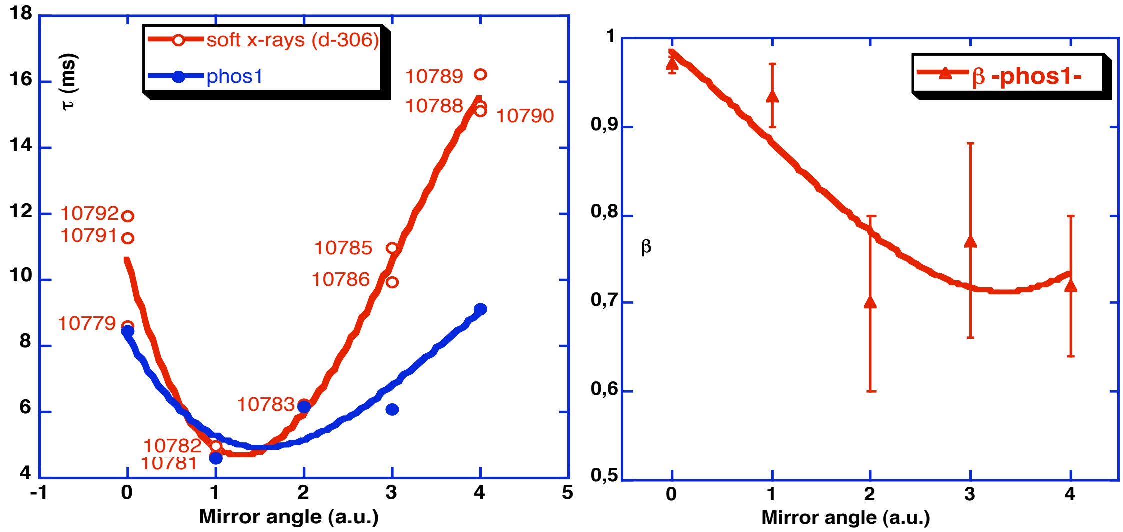

Fig. 4. ***Left***. *Impurity confinement time behaviour deduced from the soft x-ray central channel (E_{ph} > 1-2 keV) and a central chord channel of a global VUV monitor.* ***Right***, *β parameter of the stretched exponential deduced from the phosphor detector signature.*

In conclusion, we have illustrated how impurity relaxation, characterized by a stretched exponential, behaves during different operational scans in TJ-II plasmas heated by ECRH only. A deeper transport analysis will be addressed in the next future and a more detailed look at the role played by the asymmetries observed in TJ-II [7] with regard to impurity transport.

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References

[1] R. BURHENN ET AL., "Investigation of impurity tracer transport in high density plasmas at the stellarator W7-AS", Proc. 24th EPS Conf. **IV**, 1609 (1997).

[2] R. BURHENN *ET AL.*, "Derivation of local impurity transport quantities from soft-x-ray radiation evolution during tracer injection at W7-AS", Rev. Sci. Instrum. **70**, 603 (1999).

[3] B. ZURRO, M. A. OCHANDO, A. BACIERO ET AL., "A method to deduce local impurity transport quantities from the evolution of tomographically reconstructed bolometer signals during tracer injection at TJ-II", Rev. Sci. Instrum. (to be published) (2004).

[4] R. C. ISLER ET AL., "Long-time impurity confinement as a precursor to disruptions in ohmically heated tokamaks", Phys. Rev. Lett. **55,** 2413 (1985).

[5] Y. NAKAMURA ET AL., "Plasma performance and impurity behaviour in long pulse discharges on LHD" Nucl. Fusion **43**, 219 (2003).

[6] R. DUX, R. NEU, A. G. PEETERS ET AL., "Influence of the heating profile on impurity transport in ASDEX Upgrade" Plasma Phys. Control. Fusion **45**, 1815 (2004).

[7] M. A. OCHANDO, F MEDINA AND TJ-II TEAM, **"**Emissivity toroidal asymmetries induced by ECRH driven convective fluxes in the TJ-II stellarator" Plasma Phys. Control. Fusion **45**, 221 (2003).