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Confinement of impurities injected by laser blow-off in the ECRH and NBI regimes of the TJ-II stellarator

B. Zurro, A. Baciero, E. Hollmann*, M. Tillack*, M. Liniers, A. Fernández, A. Cappa, F. Medina, A. López-Sánchez, I. Pastor, J. Herranz, and TJ-II Team.

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

**University of California, San Diego, La Jolla, U.S.A.*

INTRODUCTION. Simultaneous achievement of high energy and low impurity confinement times are crucial for obtaining relevant nuclear fusion plasmas. One of the critical issues in stellarators is the avoidance of impurity accumulation whose details have been reviewed and discussed in a recent paper [1].

Previous results of impurity confinement in TJ-II ECRH plasmas [2] exhibited moderate confinement time at low densities, when the core plasma had positive radial electric fields. But close to or beyond the density value where the transition to negative fields occurs, a significant rise in impurity confinement time was observed. In the present paper, the emphasis has been on studying the impurity confinement time in the NBI phase of TJ-II plasmas, although recent ECRH data obtained with lithium coated walls were included for reference. Impurity confinement time measurements in TJ-II in the NBI phase are challenging due to the lack of a true plasma plateau. This lack of plateau is partly due to the shortness of the NBI pulse (100 ms) and partly due to a lack of density control in TJ-II NBI discharges, possibly due to beam-wall interactions. In spite of this limitation, studies of laser blow-off impurity injection (LBI) of iron and boron have been performed in NBI phase plasmas. An attempt is made to correct for the background plasma evolution of the NBI plasmas by comparing baseline (non LBI) data with LBI data.

The paper is organized as follows: first, an overview of the experiment is given; and second, the confinement time of impurities in NBI discharges, when measurable, has been compared with data obtained in the ECRH phase, plotted as a function of density. Finally, cases of impurity accumulation or long confinement times are illustrated showing the time evolution of relevant traces of the discharges.

EXPERIMENTAL. TJ-II is a four-period, low magnetic shear stellarator with major and averaged minor radii of 1.5 m and ≤ 0.22 m, respectively. Central electron densities and temperatures up to $1.7x10^{19}$ m^{-3} and 1 keV respectively are achieved for plasmas created and maintained by ECRH at the second harmonic (*f* = 53.2 GHz, $P_{ECRH} \leq 400$ kW). Additional heating is provided by two neutral beam injectors: NBI_1 and NBI_2 parallel and anti-parallel to the toroidal field (up to 400 kW from each NBI). LBI was performed with two different types of tracers: boron and iron. Both materials were deposited in glass samples as a thin film of thickness 2 and 1 micron, respectively. The first sample has been deposited at the UC San Diego using a magnetron and the second one has been obtained from a company (LeBow). The thin film was blown off by the pulse of a Q-switched Nd-YAG laser beam (800 mJ, 10 ns), which was focused to a spot of diameter 1 mm. The blow-off system was described in more detail in Ref. [2].

RESULTS AND DISCUSSION. We have studied impurity confinement in the ECRH and NBI phase of TJ-II plasmas. In the ECRH phase, we can compare with two old campaigns where more detailed studies were performed in ECRH plasmas [2-3]. The novelty of these results, although not as systematic as before, lie in that they have been carried out in a lithium coated wall [4], and we have used iron and boron as tracer elements. The main goal of the present study has been to study the impurity confinement in NBI scenarios of TJ-II, with co and counter beam injection.

Typical results of confinement time, measured either in pure ECRH discharges or in the NBI_1 phase, are depicted in Fig. 1, for iron and boron injection within the ECRH phase, but only for Fe injection when working with the co-beam NBI_1. The scarce data is a manifestation of two facts: first, only in some discharges heated with the co-injected beam (NBI_1) it was possible to estimate the confinement time from the decay of the perturbation measured by global VUV radiation detectors. Second, the moderate temperatures of these discharges ($T_{e0} \leq 300$ eV) preclude, in general, the use of soft X-ray detector signals to follow the perturbation. The confinement time of boron in ECRH discharges exhibits a more systematic trend than iron data, because they were measured the same day, and in exactly the same conditions regarding ECRH power and deposition position. On the other hand, the iron data correspond to a wider range of plasma conditions taken in different discharges of the last experimental campaign.

In the case of TJ-II discharges heated only by the counter injection beam (NBI_2), we believe we are observing the so-called impurity accumulation: the impurity confinement time is much longer than the discharge duration and it is not possible to deduce any value for the confinement time, since no decay of the perturbation is observed. This effect is illustrated in a discharge with iron injection, Figs. 2a and 2b, as well as in a discharge with boron injection, Figs. 2c and 2d. Both discharges were chosen because they correspond to two cases of weak impurity injection, where long impurity confinement can be observed

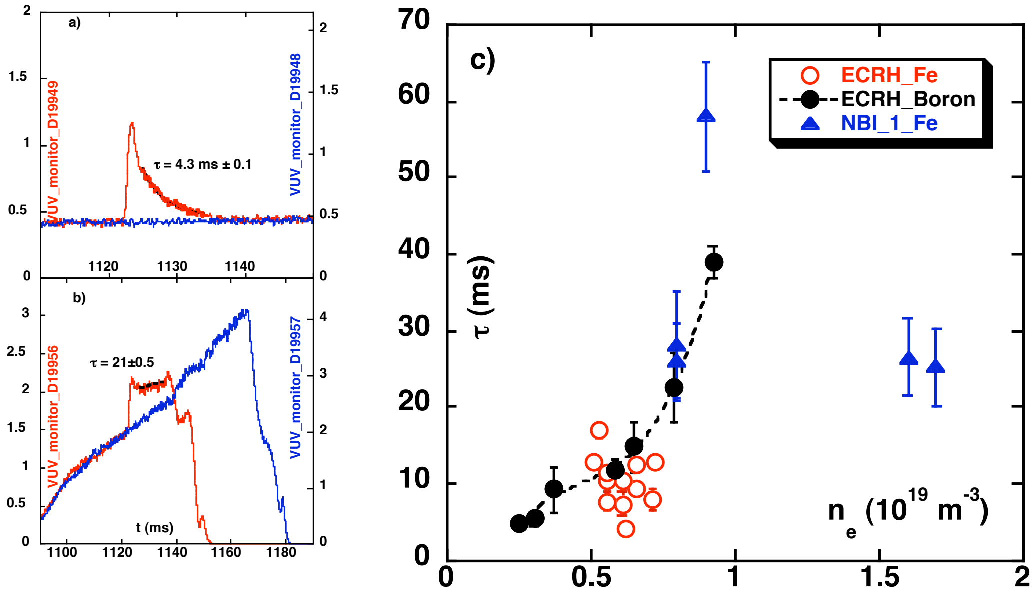

Figure 1. Typical raw data for iron injection (red) and reference discharge (blue): a) ECRH discharge and b) NBI_1 discharge; c) Impurity confinement time, plotted versus density, for a set of TJ-II discharges. Tracers of iron (open red circles for ECRH and triangles for NBI_1) or boron (full black points –ECRH-) were injected by laser blow-off.

more readily than in strong injection cases. Most relevant traces of the injected and reference discharge are plotted superimposed to highlight the behaviour of the injected discharge. The selected traces of the injected discharge tend to separate or run almost parallel to those of the reference discharge, until the discharge terminates. The injected discharge tends to be shorter than the reference one, and although the shortening of the discharge is almost negligible in the case of boron injection, the behaviour, from the point of view of impurity confinement, is very similar for both ions in spite of their different charge and mass.

The NBI phase is established after a short phase of pure ECRH discharge. In some particular cases, we have applied at least one off-axis tuned gyrotron during the NBI phase in order to figure out if it could change the impurity accumulation effect. This operational mode was effective to reduce the level of the perturbation caused in the discharge for a similar level of impurity injection, but does not change the confinement behaviour significantly.

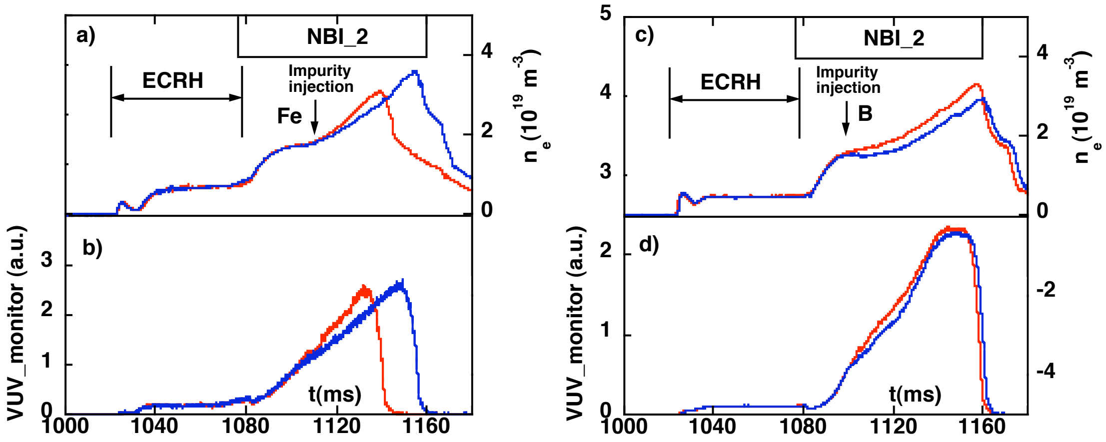

Figure 2. Comparison of different traces of an impurity injected discharge (red) versus a reference one (blue): a) electron density and b) VUV emission vs time for iron LBI; c) electron density and d) VUV emission vs time for boron LBI.

Overall, the measurements shown here indicate that core impurity confinement in TJ-II does not have a strong mass dependence, suggesting that impurity confinement is limited by ExB-type transport, not, for example, parallel loss on open field lines. A trend in increasing confinement is observed with increasing electron density; possibly due to the concomitant change in radial electric field – the TJ-II plasma core changes from positive radial electric fields at low densities to negative radial electric fields in the high density regime [5]. In contrast with tokamaks, all thermodynamic forces in stellarators are predicted to support accumulation in the standard case with negative E_r, the so-called ion-root regime [1]. The observation of extremely long impurity confinement (impurity accumulation) seen in discharges heated by the counter injected beam is not understood at present.

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