Studying the mass dependence of impurity ion confinement in ECR-heated TJ-II stellarator plasmas

B. Zurro[1], E.M. Hollmann[2], A. Baciero[1], M.A. Ochando[1], K.J. McCarthy[1], F. Medina[1], I. Pastor[1], J. Herranz[1], D. Baião[3], I. O. Nekhaieva[4] and TJ-II team[1]

[1]*Laboratorio Nacional de Fusión, Asociación Euratom-CIEMAT, Madrid, Spain*

[2]*University of California-San Diego, La Jolla, CA, USA*

[3]*Associação EURATOM/IST, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, 1049-001 Lisboa, Portugal*

[4]*Univ. Ghent, Ghent, Belgium*

INTRODUCTION. The simultaneous achievement of high energy and low impurity confinement times is crucial for obtaining relevant nuclear fusion plasmas. One of the critical issues for stellarators is the avoidance of impurity accumulation [1].

Laser blow-off injection (LBI) of boron carbide, iron and lithium fluoride films has been used to perform trace seeding of different impurities into the core of ECR-heated plasmas in the TJ-II stellarator. The purpose of this work is to: a) search for differences in impurity confinement for different species, in particular between light (B, Li, F) and heavy (Fe) impurities and between different charge states; b) investigate the possibility of controlling the laser blow-off impurity deposition profiles and explore whether the deposition profiles affect the subsequent impurity transport; and c) investigate whether the isotope effect on impurity confinement exists in TJ-II plasmas.

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 1.7×10^{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 that are (NBI_1) and anti-parallel (NBI_2) to the toroidal field (≤400 kW from each NBI). LBI was performed with different types of tracers: boron-carbide (B_4C), lithium fluoride and iron. These materials were deposited in glass samples as a thin film of thickness 2 and 1 μm (two last samples), respectively. The first sample has been deposited at the UC San Diego using a magnetron and the other two have been obtained from a company (LeBow). The thin films were blown off using pulses from a

Q-switched Nd-YAG laser beam (800 mJ, 10 ns), which was focused to a 1 mm diameter spot. The system is described in more detail in Ref. [2].

RESULTS. We have selected experimental results obtained in three particular areas of interest of these studies: a) light versus heavy impurity confinement and the influence of injection speed on confinement, the latter being achieved by varying the laser power density; b) the search for a Z dependence of confinement for Fe injection, and c) the exploration of an isotope effect, if it exists, on impurity confinement, which is still an open question in stellarators.

In Fig. 1(a), we plot a global impurity confinement time deduced from the exponential decay of central chord-integrated radiation in standard monitors (X-rays and bolometers), as a function of the injection velocity where the blown material entrance velocity is estimated by a time-of-flight technique. Although a small effect can be seen in these data, a more significant effect is observed for the case of LiF injection. See also Fig. 1. Note, for this plot ECRH discharges with similar densities were selected. Also, it should be noted that whilst the B_4C and Fe samples are deposited directly onto the glass, the LiF film is deposited onto a thin intermediate layer of Cr (10 nm). It is assumed that the laser energy is absorbed in this intermediate layer to create a small plasma capable of projecting more compactly the LiF sample towards the TJ-II plasma.

A slight increase in confinement time for higher charge states monitored by the VUV spectrometer is seen, see Fig. 2(a), as would be expected for charge states created deep in the plasma core. This is also seen in Fig. 2(b) where a detailed analysis of Fe confinement is

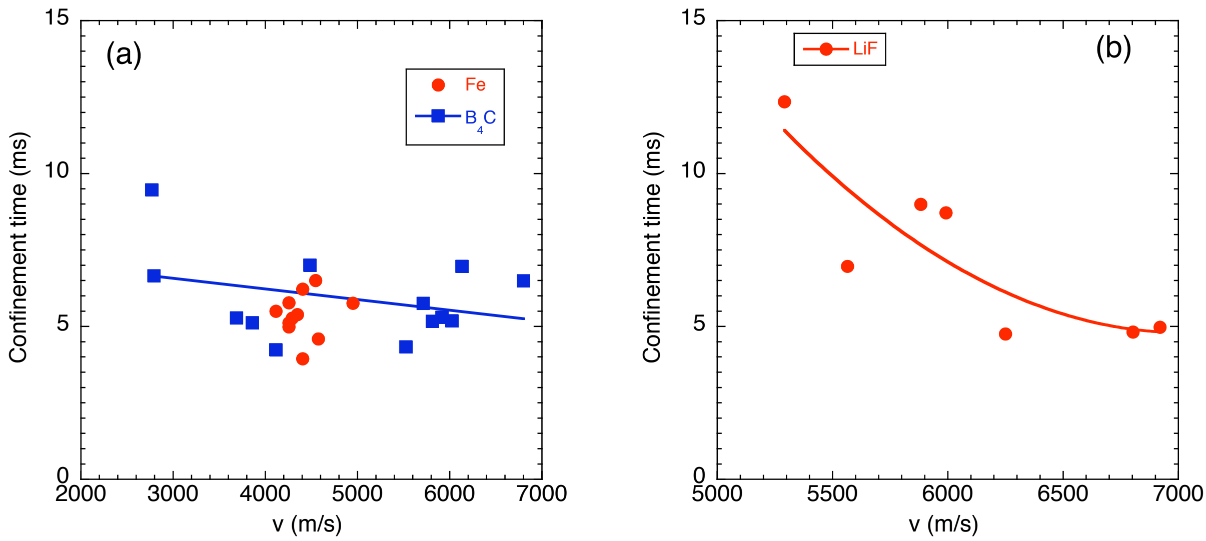

Fig. 1. The influence of LBI injection velocity on the impurity confinement time: (a) A minor dependence of impurity species confinement with velocity is seen for Fe and B_4C; (b) A significant dependence of the impurity confinement time with LBI speed is observed for LiF.

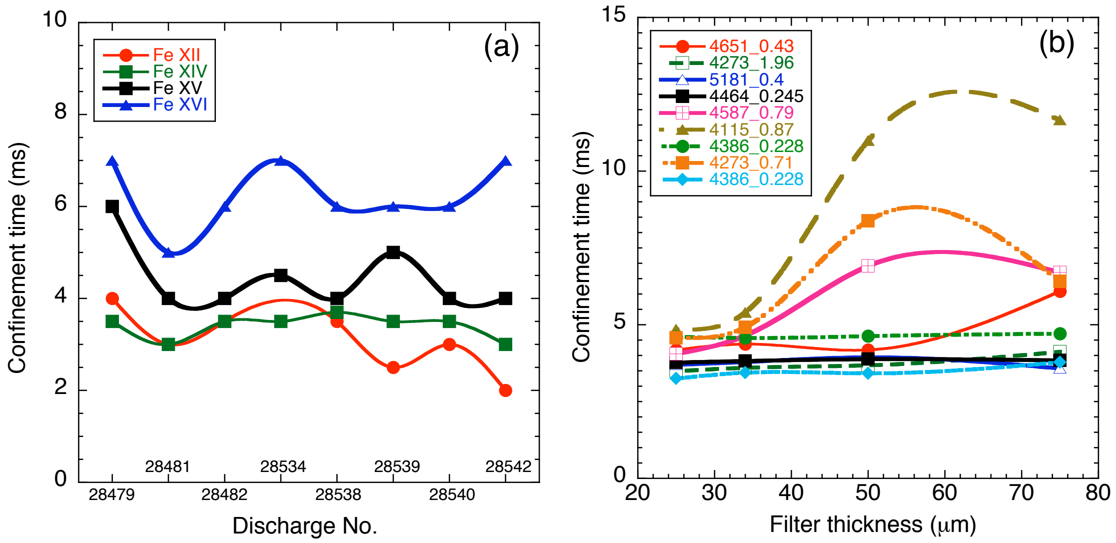

Fig. 2. Z-dependence study of Fe confinement using different diagnostics: (a) Confinement time for several Fe ionization stages deduced from VUV spectrometer data; (b) Confinement time for several discharges (inset: injection velocity in m/s and strength) deduced from X-ray traces with different filter thickness.

plotted. These times are determined from trace analysis of the four X-ray detector signals of the T_e(RX) diagnostic of TJ-II [3]. X-ray detectors look at the plasma core through 25, 34, 50 and 75 μm Be filters. Decay times for Fe LBI are seen to depend on filter thickness in some particular injections, while no significant differences have been observed in the case of LiF injection. This could be a clear signature, first reported in a stellarator, of transport dependence on Z based on injection of a single species, although a Z dependence has been already reported in other stellarator [4] and tokamaks [5, 6] by studying the transport of impurities with different charge.

Isotope effect. Although the TJ-II is normally operated with H_2 as the base gas, this was changed to D_2 for a few weeks of operation thereby enabling an exploration of the isotope effect. Impurity confinement of LiF was studied the third and sixth day of D_2 operation with the purpose of determining whether this effect, i.e., an improvement in confinement with ion mass ($\propto \sqrt{A_i}$), exists in this stellarator plasma (to date no effect has been observed in stellarators). The effect has been observed in many tokamaks and linear machines [7, 8], although in some tokamak experiment it has been elusive. In TJ-II there is an added difficulty, the device is operated with a lithium–coated wall, thereby making it difficult to quantify the efficiency of the isotope exchange. However, the isotope exchange was followed by analyzing emission spectra about the H_α and D_α lines, separating the cold (edge) from the thermal (core) contribution. It was found that the line ratios were significantly different. If the isotope effect exists, then it should be small in TJ-II, thus only discharges with well-documented D_2/H_2

ratios and similar electron densities are considered. These data are plotted in Fig. 3 for discharges corresponding to two days during which LiF was injection was employed to probe particle transport. The observations depicted in Fig. 3 exhibit an isotopic effect, which although small, is in the direction suggested by gyro-Bohm scaling. All Bohm-like scaling of transport parameters for main ion species indicate $D_\perp, \chi_\perp \approx A_i^0$, and gyro-Bohm-like scaling implies $\approx\sqrt{A_i}$ [8].

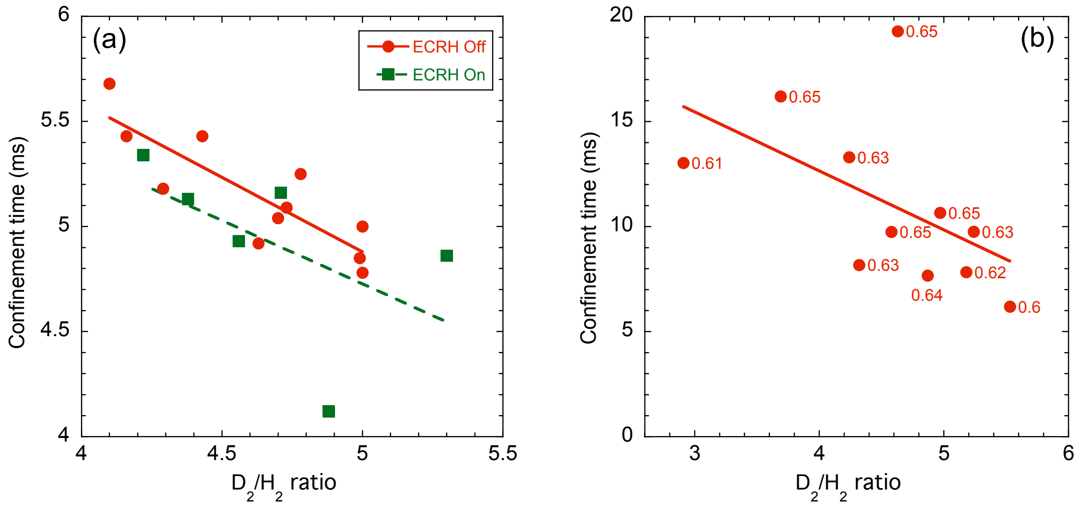

Fig. 3. Plots of impurity confinement for an isotope experiment in TJ-II: (a) The dependence of the central impurity confinement times for a selected set of data [$n_e = (0.5 \pm 0.1)\times10^{19}$ m^{-3}] as function of the D_2/H_2 ratio; (b) Similar plot for a sequence with densities closer to the transition of radial electric field (n_e are given in 10^{19} m^{-3}).

Overall, these results do not indicate an impurity confinement time which depends on mass. However, an improved impurity confinement with higher ion charge is observed. Also, when changing the main species ion (H_2 isotope), impurity confinement is worse for higher main ion mass.

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