Impact of lithium-coated walls on plasma performance in the TJ-II stellarator

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The TJ-II stellarator has been operated under several first wall conditions until now: full metallic scenario, full boronized walls and, in the last campaign, lithium coating. Particularly conspicuous has been the change in recycling associated to the different wall conditions, but also in impurity content. Lithium coating, tested for the first time in a stellarator, has proven a very effective method for particle control in TJ-II. Changes in the shot by shot fuelling characteristics as well as in the total particle inventory compatible with good density control have been recorded after the Li deposition. Thus, a factor of 4 increase in the fuelling rate at constant density compared with the B-coated walls was recorded, and even a higher value was estimated for the allowed H inventory in the puffing-controlled ECRH discharges. These changes were also mirrored in the radiation and edge radial profiles, with increased electron temperatures. This led to enhanced interaction with the poloidal graphite limiters, which had a deleterious effect on plasma performance. The lower instantaneous recycling also worked for the density control under NBI heating scenarios. Record values of plasma energy content were measured at densities up to $4.5.10^{13}$ cm^{-3} under Li-coated wall conditions.

Keywords: plasma-wall interaction, density control, low Z components, wall coatings, low recycling, lithiumization, TJ-II stellarator.

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1. Introduction

Plasma wall interaction issues are paramount in achieving fusion plasmas with high purity, controlled density and high confinement. Even when the selection of plasma facing components, such as limiter and divertor target materials, is made based on their ability to withstand the very high particle and power fluxes characteristics of present fusion plasmas, the interaction with the first wall, reached by charge exchange neutrals, photons and some more or less tenuous plasma, is considered to contribute to the plasma impurity content as much as the PFCs do. Therefore, a growing concern about proper conditioning of the total inner wall of the fusion device has been taking place in the last decades. Compared to tokamaks, stellarator plasmas show distinct features in their interaction with the surrounding materials. On the good side, the lack of disruptions and type I ELMs make them more reliable for reactor operation. So it is the lack of MHD-driven density limit. However, due to their significantly higher aspect ratio, they offer a less favorable area to volume ratio and also, a worse screening of recycled neutrals. This last parameter has obvious implications in divertor design and, in general, in density control by external sources. Although some specific divertor concepts have been developed for stellarator with reasonable success for impurity and particle control, no specific coating strategies for the first wall exist. However, the application of those concepts with good performance in tokamaks, such as boronization or Ti gettering, has also improved machine operation in the stellarator community. It must be said here that, due to the systematically higher complexity in the vacuum vessel topography of stellarators, homogeneous coatings are harder to produce, in particular if line of sight deposition (i.e. Ti gettering) is sought. In the present work, the implementation of a system for the full coating of the inner walls of a stellarator with lithium (the TJ-II Heliac) is described for the first time. Compared to other low Z coating elements such as Be, C and B, lithium is a very attractive element due to its very low radiation power, strong H retention (leading to the formation of the very stable hydride, LiH) and strong O getter activity and excellent results have been achieved recently in tokamaks [1]

The structure of the paper is as follows: first, the inner wall conditioning history of the device is summarized. Then, results achieved in terms of particle control by the use of Li walls are presented. The performance of plasma parameters associated to the change in wall conditions is then addressed. Finally, the prospects for improvement and possible extension to other stellarators are described.

2. Wall conditioning of the TJ-II stellarator

The TJ-II stellarator has been operated under diverse first wall conditions since its beginning [2]. Under ECR plasma generation and heating, density control is hampered by the combination of low cut-off density and the large surface/volume ratio of the vacuum vessel respect to the plasma. However, different origins of the problem were identified depending on wall conditioning and plasma facing materials. For the initial scenario, a full metal machine, desorption of high recycling He from the walls, which was implanted during overnight GD conditioning, either by the plasma or by direct interaction with the microwave beams was the main responsible. The systematic use of a short Ar GD period led to a significant improvement of the control. Under boronized walls and graphite limiters (low Z scenario), the improvement in plasma purity and the low recycling conditions at the beginning of the operation (shortly after the depletion of H from the film by He GD) provided a higher tolerance of the plasma to the external fuelling. Two complications, however, were found under boronized walls. First, the gradual loading of the C/B film by hydrogen deteriorates the good recycling characteristics in a relatively short period. After a total implantation dose corresponding to the maximum uptake of the film of~1.10^{17}cm^{-2}, was achieved, spontaneous density rise drove the discharge to cut-off density, even in the absence of external puffing. The application of a few dry discharges was required for recovery, but this was only transiently obtained. A second factor in play was the presence of the Enhanced Particle Confinement (EPC) mode, characterized by a sudden increase of particle confinement at a critical density in the order of $0.6.10^{13}$ cm^{-3} [3] This mode, whose presence seems correlated with edge collisionality and the development of a velocity shear layer at the edge [4], was found to strongly depend on fuelling pulse shape and amplitude [5] and, its development can be eventually suppressed by proper tailoring of the gas puffing.

In the 2007 campaign, a low recycling, low Z wall has been tested. For that purpose, an *in situ* lithium coating technique was developed. It is based on evaporation under vacuum from four ovens, symmetrically spaced and oriented tangentially to the plane of the corresponding flanges in the equatorial plane of the vacuum vessel, filled with 1g of metallic Li each. A set of metallic resistances (Thermocoax) and thermocouples (K type, two per oven) are operated at pre-programmed temperatures of 500-600 ºC by a central, PID-based power supply. Effusion from

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the ovens creates an atomic beam aiming at the remote region opposed to the corresponding flange. Under HV operation, the mean free path of the Li atoms is long enough to produce a thin layer at the vessel walls located midway between adjacent ovens. The deposition pattern, directly visible in the groove protecting the central coils, matches the line of-sight flight of the Li atoms. .Alternatively, effusion under a He atmosphere was tried to enhance lateral diffusion of the beam, hence providing a more homogeneous coating of the walls in areas closer to the ovens. A pressure of 10^{-5} mbar was chosen, based on the experimentally determined mean free path for the He-Li system at this pressure, $\lambda \sim 70$ cm and the characteristic length of the vacuum vessel, $V/S \sim 20$ cm (assuming pure cylindrical geometry). In order to extend the lifetime of the Li coating, and due to the very high reactivity of this species with background gases (water, O_2, N_2, CO…) a ~50 nm boron layer was deposited prior to the evaporation by conventional GD of an o-carborane/He mixture. The B coating was depleted of H by a pure He GD after its deposition. Also, He GD was applied every day on the Li layer in order to remove hydrogen from the areas not fully covered by the coating. A total of 12 g of Li were evaporated for the ~650 discharges performed in this period.

3. Particle control on Li walls

Compared to former operation on boronized walls, the control of plasma density by external puffing was very much upgraded upon lithiumization of TJ-II. Not only the required puffing levels were significantly higher for the same density, but also no sign of saturation was observed after a full day of ECRH operation. Of particular relevance on machine performance is the recovery of pumping walls characteristics after shots with densities above cut-off. Typically, one or two purges (dry discharges) were required in B scenarios. However, no such a need was found upon lithiumization, the wall memory effect being basically washed out. In order to quantitatively understand this effect, the particle balance in a shot to shot basis was evaluated from the injected hydrogen, and the desorbed one after the plasmas, the latter being measured by an absolutely calibrated mass spectrometer. In figure 1 the results for a typical operation day under both types of wall conditions are displayed. Two main differences between B and Li walls are clearly seen from the figure. First, the required particle injection for a give density is systematically higher in the Li case. Second, while the B wall shows saturation at total retained inventory of H< 5.10^{20} (which, for the nominal saturation level of B films, implies an effective interaction area of less than 1 m^2) no sign of such saturation is seen for values up to 4 times higher in the Li case.

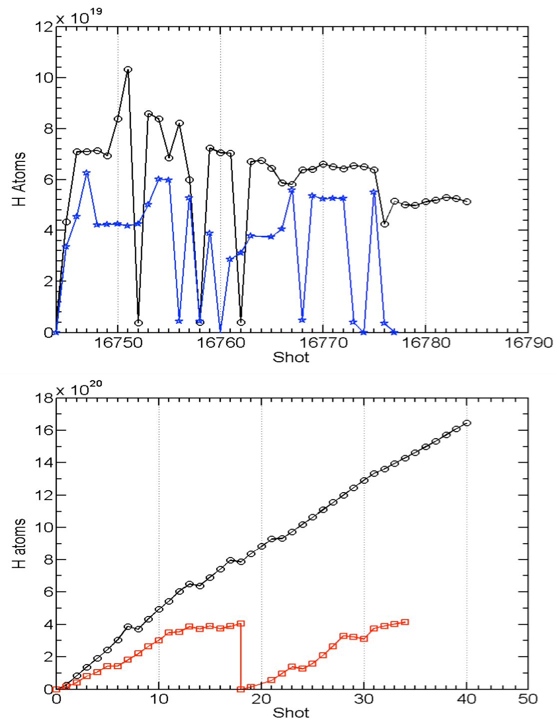

Fig.1. Particle balance under B and Li wall conditions. Top: integrated particle injected per pulse. Bottom. Cumulative retention of H in the walls. Black, Li. Blue and red, B.

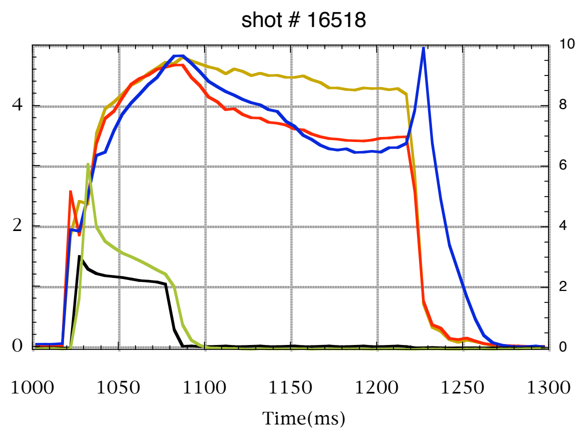

Fig.2. Time response of electron density (blue) and Ha fluxes to the wall (red and brown) to a short gas puff (green Ha and black manometer)

The dynamic behavior of plasma particles during the discharge is shown in figure 2 for a characteristic shot. First, gas puffing is injected for density built up. Then it is abruptly interrupted and the evolution of cord density and Hα emission are recorded. For pure H plasmas, a simple equation of the form

$$dN/dt= f. Qin-N/(\tau p/1-R) \qquad (1)$$

can be applied. Here, Qin stands for the puffing rate (e^{-}/s), τp is the particle confinement time, f is the fueling efficiency and R the recycling coefficient. Application of eq.1 to the data of fig. 2 yields a f value near unity and an effective confinement time, τp/1-R, of ~30 ms. Assuming no major changes in particle confinement respect to the boron and metal cases (see below), a value of ~0.65 is obtained for R. This value, although lower than that deduced under boronized walls, is significantly higher than expected for a fully absorbing wall and may reflect the limited extension of the wall coverage by the Li coating achieved.

Another important factor contributing to density control by external puffing in the absence of discontinuities in the confinement characteristics, as that introduced by the transition to the EPC mode. In figure 3, the dependence of line average density with particle flows to the wall (Hα signal) is shown for Li wall operation. The location of the EPC transition for the B and metal cases is also shown. For constant recycling conditions and negligible contribution of impurities to Ne, the linearity displayed in the figure obviously implies that no change in the particle confinement characteristics of the plasma is taking place during the scan. This is also confirmed through the ion energy confinement analysis shown in section 5.

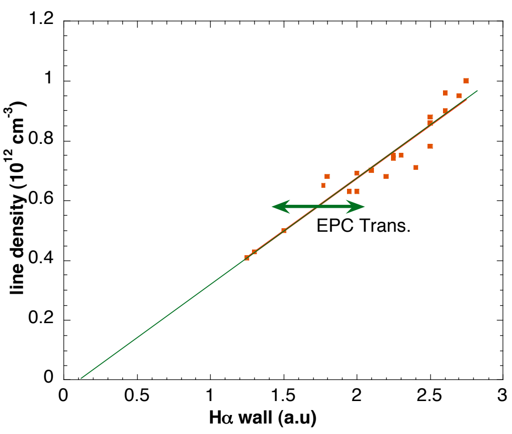

Fig.3. Line average density vs. flux to the walls for Li wall conditions. Line is a linear regression to the data

4. Impurity behavior and plasma parameters

Clean plasmas are routinely obtained in TJ-II ECR heated plasmas under low Z scenarios, largely due to the strong oxygen gettering effect of the B coatings and the use of graphite limiters [6] Although the Li coatings were not aimed at improving this situation, a significant effect has been observed in that last campaign. So, carbon emission was seen to decrease during the operation day. Figure 3 shows the shot by shot evolution of some relevant signals, normalized to the line average density. As seen, after an initial spike in all impurity monitors, associated to the very first shots after Li deposition, a systematic decrease takes place upon plasma operation. Of special relevance is the strong decay of the bolometer signal, closely related to the suppression of carbon impurities from the plasma. The strong reduction of carbon source in the presence of Li is a well documented effect which has been associated to the decrease of physical and chemical sputtering of carbon by its coating with Li [7]. The second day of operation is preceded by 30 min of He GD. The impurity levels are seen to rise again, but they soon recover to their low levels, the Li signal reaching levels

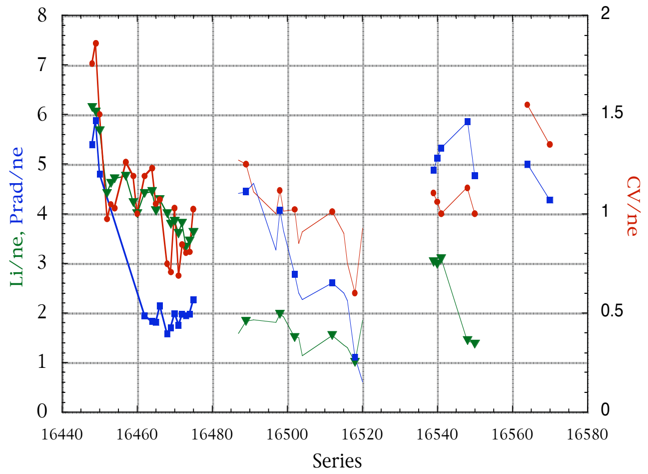

Fig. 4. Shot to shot evolution of some impurity signals normalized to the line density. Circles (left) CV, triangles LiI, squares, Bolometer

even lower than before. Since its measurement is local, the erosion of the initial layer at the observation window, with subsequent spreading over other areas of the vessel, could account for this effect. This will also account for the concomitant decrease of impurity radiation, not to be expected if simple removal of the beneficial effect was taking place. After discharge 16540, systematic higher contamination of the plasma is seen. This is associated to the insertion of the graphite limiters one cm into the separatrix during several shots. The interaction of the limiters with the plasmas was seen to be stronger under Li walls than in the B case, as monitored trough the increase in total radiation and CV signal upon their insertion up to 2 cm. This is apparent contradiction with the effect just described, and it was ascribed to the higher edge temperature in Li-wall plasmas. A profile of edge parameters, as deduced from the supersonic He beam diagnostic, is displayed in figure 4. Although electron densities are similar to those found under boronized walls, electron temperatures are higher by a factor between 1.5 and 2, tentatively ascribed to changes in dominant impurity and edge power balance rather than to changes in confinement. Since physical sputtering of carbon has been proposed as the main contamination mechanism in TJ-II ECRH plasmas [8], these changes are in line with the observed increase.

Impurity radiation profiles are also seen to evolve upon changing the wall material. Even when total radiation levels are somehow lower in the Li case (clean discharges), the analysis of SXR emission profiles suggests central values of Zeff higher for the Li case. The important issue of impurity accumulation in central heated plasmas, however, deserves a more rigorous analysis of the observed changes and it is out of the scope of this work.

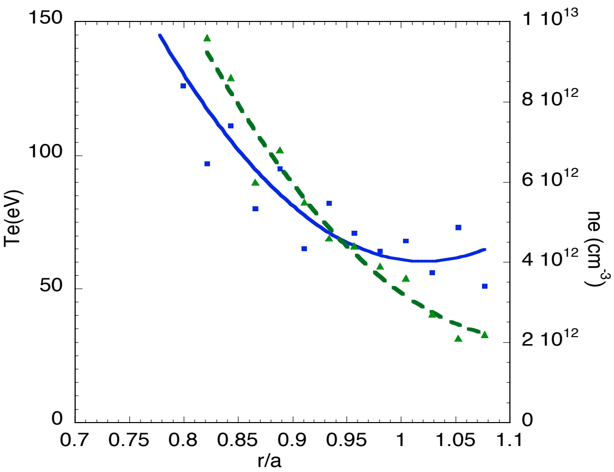

Fig. 5. Edge parameters under Li-wall conditions

Although no major changes in density profiles is seen by the Thompson Scattering diagnostic, it is worth mentioning that cut-off line densities are a 10% higher than in the B counterpart, and a more detailed characterization of the profiles is presently underway. Ion energy balance and confinement has been analyzed through a simple 0-dimensional model for the metal and boron cases in previous campaigns [9]. In its volume average notation, for an ECRH plasma it can express in the form

$$\nu_{i\text{-}e}.\Delta T_{i\text{-}e}.ne\text{-}\ (Ti/\tau_i+K_{cx}n_0Ti).ni=0 \qquad (2)$$

where electron-ion collision frequency, ion energy confinement time and CX losses are integrated in the steady-state balance. Volume averaged electron temperatures are used for Te. Previous estimate of CX losses allow for neglecting this channel in eq. 2 under ECRH conditions in TJ-II, which allows for the evaluation of the characteristic τ_i value by simple plotting the terms of the equation, as displayed in figure 6. Two important remarks must be made from the behavior displayed in the figure. First, a very similar slope, directly giving a first-order estimate of the τ_i value of ~5 ms, in agreement with particle confinement times above mentioned, is found in the three cases. Secondly, the discontinuity observed at collisional frequencies of 10 s^{-1}, corresponding to the transition to the EPC mode is missing in the Li case, thus

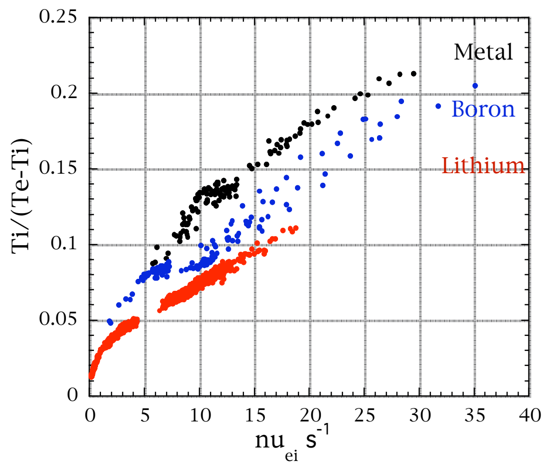

Fig. 6. Ion energy balance analysis for three wall scenarios.

confirming the results found through the fueling analysis of figure 3. Thus, although central electron temperatures were found to be higher under Li walls, which can be initially ascribed to the higher performance of the ECRH system in the last campaign, no changes in the ion channel are observed as the wall material is changed, at least at electron-ion collisionalities high enough to disregard CX losses.

5. NBI plasmas

High beta operation is one of the major goals of the TJ-II program. Therefore, extensive NBI heating must be coupled to the plasma and efforts in this direction have been made in the last years. It was early found, however, that proper density control was extremely challenging under additional heating, partly due to the extra fuelling term introduced by the beams and their interaction with the vessel walls. In the absence of divertor configurations, a low recycling wall can be of great help in preventing plasma collapse by excess density under finite heating power. Although at present, the discharge duration under NBI heating is still dominated by this problem, important changes have been detected in the evolution of the NBI plasma parameters. In figure 7, a comparison of these parameters under boron and lithium walls is shown. Central electron temperature, edge and central radiations and line average densities are shown in both cases. The

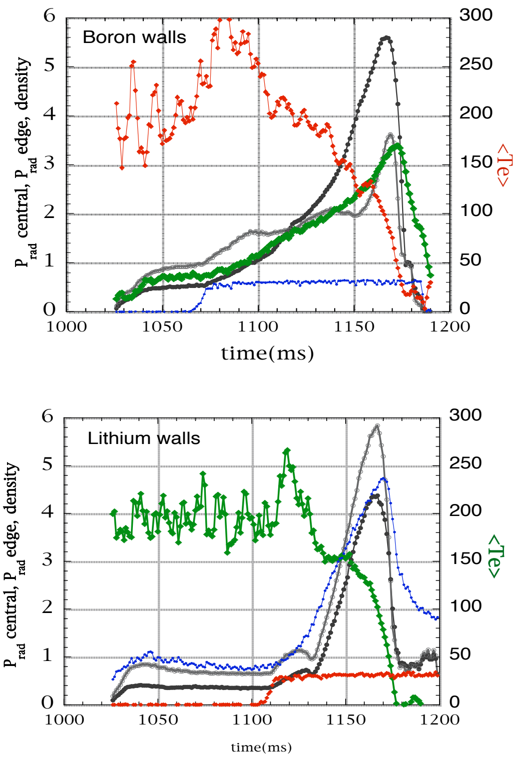

Fig.7. Plasma emissivity (W.cm^{-3}, central and edge lines), line density (10^{13} cm^{-3}) and central electron temperature during the injection of a 500kW neutral beam during the time indicated by the squared pulse.

time of injection is shown by a squared pulse. Although central emissivites are similar at the collapse, a higher line density (4.6 vs. 3.4) is reached in the Li case. Interestingly, edge emissivities are significantly lower in the Li case. Furthermore, the ratio of central to edge radiation behaves in a significantly different way in both cases. According to the running models for radiation collapse in stellarators [10] and the different shape of the cooling rates for the dominant impurities at the edge, the results here presented suggest the presence of radiative instability as candidate for the B case, while a pure thermal collapse would be limiting the plasma density in the lithium wall scenario, with obvious implications in the future upgrading of the NBI power in TJ-II.

6. Conclusions

The TJ-II has been operated under lithiated wall conditions, the first time that this technique has ever been applied to a stellarator. Very encouraging results in terms of density control and impurity level have been obtained; even when only partial coverage was achieved. The strong improvement in density control is not only due to lower recycling of the walls but also to the inhibition of the transition to the EPC mode by the higher puffing levels required. NBI heating has been possible for record densities of 4.5 10^{13} cm^{-3}, its limit possibly due to a pure thermal collapse under the limited NBI power available at present. New techniques for improvement of film homogeneity and careful control of limiter conditions are foreseen in order to improve the results.

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