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The Lithium Wall Stellarator Experiment in TJ-II

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In the last years, lithium wall conditioning has been carried out in several fusion devices by different techniques, providing in many instances record values of plasma parameters and enhanced plasma reproducibility and opening the possibility of developing high radiative, low recycling liquid divertor concepts of high potential for future reactors. This concept has been termed the Li Tokamak Reactor. Compared to tokamaks, stellarator plasmas show distinct features in their interaction with the surrounding materials. 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. On the other side, the intrinsic radiative character of the density limit of stellarators and the tendency to central impurity accumulation makes wall-material selection paramount. In the present work, the plasma performance of the TJ-II Heliac under Li-coated wall conditions is described. Compared to previous coatings, lithium has produced the best plasma performance to date, leading to the achievement of record values in plasma density and energy confinement. Plasma profiles free from impurity accumulation have been obtained under specific fuelling schemes. The development of L-H transitions has been characterized in terms of steep gradients in edge parameters and broadband fluctuation suppression.

Keywords: lithium, stellarator, fusion reactor, first wall materials, recycling, impurity accumulation, TJ-II, H-mode

1.Introduction

Plasma wall interaction issues are paramount in achieving fusion plasmas with high purity, controlled density and high confinement. 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 the choice of plasma facing components less demanding. In addition, the lack of MHD-driven density limit [1] has allowed their operation at densities well above the corresponding Greenwald limit for tokamaks [2]. Since plasma collapse in stellarators seems to be mainly governed by local power balance considerations [3], changes in wall materials are ideally suited for the validation of the running models for the density limit in these devices. As a potential drawback, neoclassical transport characteristics of the core plasma in stellarators make them prone to impurity accumulation [4], thus stressing the use of low Z elements as PFC. A closed coupling between the divertor efficiency and the recycling characteristics of the wall has been recently evidenced in LHD, as shown by the achievement of the IDB-SDC mode in the absence of the LID operation, only under low recycling wall conditions [5]. Therefore, low Z, low recycling first wall scenarios look highly promising if a stellarator reactor concept is to be developed. Among the available low Z coating options (Be, C and B) lithium is a very attractive element due to its very low radiation power, strong H retention and strong O getter activity and excellent results have been achieved recently in tokamaks [6]. Also, and in direct connection to the lower recycling scenario leading to decreased CX losses and higher temperatures, important changes in energy confinement have been predicted and observed [7]. In the present work, the operation of a stellarator, the TJ-II Heliac [8], with lithium-coated walls is described. The most relevant changes on the plasma performance and confinement characteristics associated to the new wall scenario are described and analysed in terms of enhanced impurity and particle control.

2. Coating technique

The TJ-II stellarator has been operated under different first wall conditions since its beginning and details about the applied techniques and resulting plasma performance can be found in [9]. Basically, under ECR plasma generation and heating, the density control is hampered by the combination of low cut-off density (ne (0) <$1.7 .10^{19}$ m^{-3}) and the fast saturation of the small (~0.5 m^2 vs. ~40 m^2) plasma-interacting

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surface located at the grooved wall area which surrounds the two characteristic central coils.

For the results here reported (2007-08 campaign), a low recycling, low Z wall has been produced by *in situ* lithium coating. It is generated by evaporation under vacuum from four ovens, symmetrically spaced and oriented tangentially to the vacuum vessel in the equatorial plane of the machine. A total of 4g of metallic Li are evaporated during each conditioning cycle, at temperatures of 500-600 ºC over the chamber (at room temperature). Effusion from 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 initial deposition pattern, directly visible in the groove protecting the central coils, matches the line of sight flight of the Li atoms. However, plasma operation was found to redistribute the initial coating very efficiently and the beneficial effect of the coating extended far beyond that expected from the localized deposition. Nevertheless, 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 by glow discharge in a He/o- carborane mixture prior to the evaporation (see [9] for more details). A He GD depleted the H from the B coating 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 ~1000 discharges performed in a four month period.

3. Density control

The most remarkable change upon lithiation of TJ-II was a conspicuous improvement of particle control by external puffing compared to the former, B-coated scenario. Not only the required puffing levels were significantly higher, by a factor of 2-3, to obtain the same density (feed-forward operation mode), but also no sign of wall saturation was observed after a full day of ECRH operation. Particle balance measurements under the Li coated walls yields a total retention $\sim 4.10^{21}$ H/m^2 after one day of operation (~45, 200 ms discharges), a factor 5 higher than the B wall saturation limit at room temperature, which takes place at total retained inventory of ~ 8.10^{20} H/m^2 (RT values). 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 lithiation, the wall memory effect being basically washed out. All these observations concerning wall inventory under Li walls point to strong diffusion of the implanted H into the wall coating, which may be different from the initially deposited one after plasma operation.

The dynamic behaviour of plasma particles for H and He plasmas was investigated by perturbative experiments. A value of the effective confinement time, $t_p/(1-R)$, of ~8 ms were deduced for H plasmas in freshly deposited Li. Assuming no major changes in particle confinement respect to the boron and metal cases [10], a value of R<0.20 is obtained. This value was slowly evolving after some hundreds of shots up to values of R~0.5. Perturbative experiments in He fuelled discharges yields an R value of ~0.93. This, less than one, recycling coefficient value is in line with previous observations of He pumping in low temperature Li walls [6] and opens the possibility to selective removal of reactor fuel particles and resulting ashes. Of special challenge in TJ-II, density control in NBI plasmas was dramatically improved by the lithium coating. Both, plasma reproducibility and density control were significantly better than in previous campaigns [10]. As an example of density control in NBI heated plasmas, a high challenging issue under previous wall conditions, figure 1 shows the plasma density and fuelling waveform of three consecutive discharges. As seen, an almost flat density plateau is achieved by external puffing control. It is also worth noting that particle fluxes to the wall during the NBI phase, as monitored by the different Ha monitors located all over the machine, remain basically at the ECRH plasma level thus indicating a strong enhancement (up to a factor of 4) of global particle confinement. For high particle confinement and NBI pulse length of ~100 ms, the density rise should be ultimately limited by the beam fuelling rate which, for a 31keV, 0.5 MW power can be evaluated in $\sim 10^{20}$ e^-/s.

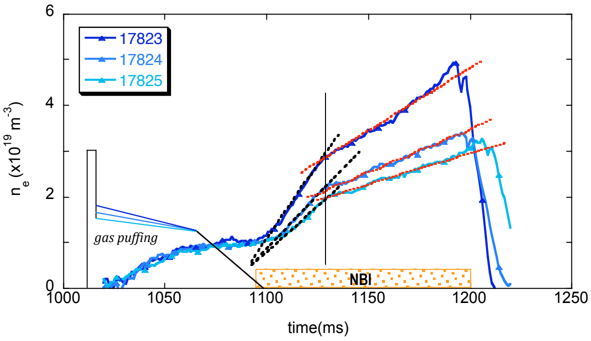

Fig.1. Density evolution for three consecutive NBI discharges under different fuelling waveforms.

This value was indeed experimentally observed. Furthermore, no sign of collapse was seen up to central density values of 8.10^{19} m^{-3}, depending on the shape of the resulting plasma profile (see below).

4. Impurity behaviour and plasma profiles

Significant effects concerning impurity concentration have been observed upon Li wall conditioning: the electron density-normalized signals from carbon emission, radiated power, neutral lithium and other impurity-related signals were seen to systematically decrease during the operation. A concomitant evolution of particle recycling towards lower levels was eventually observed. A spectroscopic estimate of the erosion yield of Li by the plasma was made from the calibrated intensities of the Ha and LiI (671 nm) lines. A yield of (0.5-1). 10^{-3} Li/H was deduced at several locations of the vessel. These figure is at least a factor 30 lower than expected from TRIM code [11] for the calculation of the corresponding sputtering yield at the measured edge temperature of 50-60 eV and the reason of this mismatch is still under investigation. Plasma spectroscopy and soft X ray measurements, together with the IONEQ impurity transport code [12] indicate that carbon still represents the main contaminant in Li-wall scenarios. Radial profiles of radiation losses were determined from absolutely calibrated bolometer arrays located at several toroidal and poloidal locations. Two different profiles developed depending on fuelling strategy and local plasma parameters. Examples of these profiles are shown in figure 2. For the broad, dome-type profile (on the left), central radiation levels are almost half than those observed in the peaked, bell-type counterpart (on the right). From the analysis of SXR emission profile, it is concluded that central values of Zeff differ, indicating an impurity accumulation in the bell-type scenario with central Zeff values up to 2.8. The radial shapes of plasma emissivity of figure 5 are mirrored by the Thomson Scattering data of plasma density, with central values up to 8.10^{19} m^{-3} in the bell-type profile and almost constant electron temperatures of 200-300 eV across the plasma minor radius.

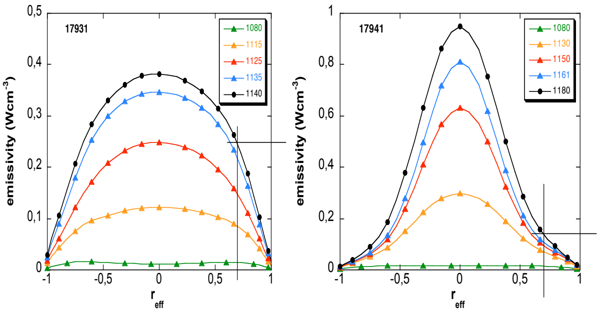

Fig.2. Radial profiles of plasma emissivity (bolometer) for two different type of profiles obtained under Li-wall operation: left: dome type, right: bell type. Note the different central and peripheral radiation levels.

In spite of their lower, total radiated power, development of the dome-type profile was systematically associated to a prompt plasma collapse. One of the possible causes of this fact can be found in the local power balance established at the plasma edge under central heating conditions. Indeed, the data shown in fig.3 indicate a significantly lower radiated power at the edge for the peaked, non-collapsing profiles. This balance has been called into play in defining the density limit in stellarators through the so-called *"low-radiative collapse"*[4*]*. Interestingly, transition from the bell to the dome type profile can be readily achieved by gas puffing during the NBI phase of the discharge.

5. Energy Confinement and L- H mode transition

Figure 3 shows the evolution of plasma energy content as a function of the average electron density for B and Li wall scenarios. The energy content is evaluated by integration of the plasma Te, Ti and ne profiles.

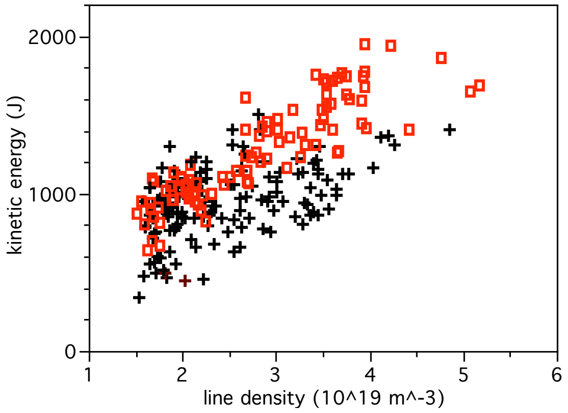

Fig.3. Plasma energy content versus line density for B (black pluses) and Li (red squares) coated-wall discharges in plasmas heated with only one NBI.

For the density span shown in the figure, a clear improvement of energy confinement from the B to the Li wall scenario takes place. Confinement times were evaluated at the maximum of diamagnetic energy content, Total injected power by the NBI system was measured by calorimetry and corrected by shine-through an ion losses effects. Total radiation was also taken into account for the available power coupled to the plasma. A strong dependence of t_E with <ne> was deduced at least from the Li-wall scenarios, with t_E up to 20 ms [13]. This enhancement of energy confinement with density is beyond that expected from usual scaling laws for stellarators [14]. Some evidence on the presence of transport bifurcations leading to enhanced confinement modes was provided through the conspicuous ELMy behaviour in the Hα signals observed under NBI operation. A periodic oscillation in the edge parameters, with sharp bursts of less than 300μs duration and a repetition rate of a few kHz, between two defined levels takes place at given line average density values and magnetic configuration. This plasma edge activity is correlated with important changes in the broadband density and electrostatic fluctuation levels at the edge, as detected by the reflectometer (in the density gradient region) and Langmuir probes (region around the LCFS), and it shows the characteristics of the L-H transition reported elsewhere [8,15]

6.Conclusions

In the last year, the TJ-II has been operated under lithium-coated wall conditions, the first time that this technique has ever been applied to a stellarator. Very encouraging results in terms of density control, plasma reproducibility and confinement characteristics have been obtained, dramatically enlarging the operational window of the machine even when only partial wall coverage with Li was achieved. NBI heated plasmas under stationary conditions have been produced up to record central densities of 8.10^{19} m^{-3}, with no sign of local thermal collapse under the limited NBI power available during the campaign. Two different types of plasma profiles were recorded, with different behaviour respect to impurity accumulation. Strong ELM-type activity has been detected, in close correlation to fluctuation suppression at the edge and enhanced confinement.

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