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Effect of lithium PFC coatings on NSTX density control

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Abstract

Lithium coatings on the graphite plasma facing components (PFCs) in NSTX are being investigated as a tool for density profile control and reducing the recycling of hydrogen isotopes. Repeated lithium pellet injection into Center Stack Limited and Lower Single Null ohmic helium discharges were used to coat graphite surfaces that had been pre-conditioned with ohmic helium discharges of the same shape to reduce their contribution to hydrogen isotope recycling. The following deuterium NBI reference discharges exhibited a reduction in density by a factor of about 3 for limited and 2 for diverted plasmas, respectively, and peaked density profiles. Recently, a lithium evaporator has been used to apply thin coatings on conditioned and unconditioned PFCs. Effects on the plasma density and the impurities were obtained by pre-conditioning the PFCs with ohmic helium discharges, and performing the first deuterium NBI discharge as soon as possible after applying the lithium coating.

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1. Introduction

To achieve the National Spherical Torus Experiment (NSTX) goal of sustaining for several current–relaxation times its presently transient high-performance plasma regimes, we are investigating lithium plasma-facing components (PFCs) for particle and power handling. We have embarked on a phased, three-step approach to studying and developing the potential of lithium in NSTX: first by coating the present PFCs using lithium pellet injection, then using lithium evaporators, and finally, possibly,

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installing a liquid lithium divertor target. Taking the last step will depend on results to be obtained from the lithium tokamak experiment (LTX), formerly known as the current drive experiment-Upgrade (CDX-U), which recently succeeded in reducing the global recycling coefficient to less than 50% by using a toroidal tray of molten lithium as a limiter [1]. The techniques under development in NSTX and LTX may also be applicable to the International tokamak experimental reactor (ITER) and other future burning plasma fusion reactors.

Previously, achieving particle and impurity control in NSTX has involved a combination of high-temperature backout, boronization, and between-discharge helium glow discharge conditioning (HeGDC) [2]. In light of NSTX needs for controlling the density rise and profile during long-duration H-modes, and in anticipation of similar ITER requirements, we have evaluated variations in the frequency and extent of boronization, and the effectiveness of boronization with the PFCs hot (250–300 °C) and cold (20 °C) for facilitating access to H-modes. It was found that boronization on hot surfaces facilitated H-mode access, but reverted slowly (over ~200–300 discharges) to the behavior of boronization on cold surfaces. Short boronizations, lasting ~15 min and introducing about 2 g of deuterated trimethyl boron followed by a comparable duration of HeGDC, applied in the morning before the start of daily experiments, could restore reduced impurity levels and ready access to the H-mode [2]. In the past year, we have also evaluated different techniques for helium plasma cleaning to reduce deuterium recycling, e.g. varying the duration of HeGDC between tokamak discharges, using fixed, wall-mounted vs. retractable, centrally located anodes for HeGDC, and testing the efficacy of using ohmic helium tokamak discharges between deuterium discharges. These comparisons were used to develop procedures which were successful in controlling impurities and the density rise during short-duration discharges of up to about 1 s. To achieve better density control in longer-pulse discharges and more efficient current-drive for non-inductive current sustainment, more effective control of edge recycling is required, and this has motivated the lithium research that is now underway on NTSX.

The first step of the NSTX lithium program used lithium pellet injection (LPI) into standard NSTX discharges to produce lithium coatings on the plasma contact areas of the PFCs. This technique was pioneered on the Tokamak Fusion Test Reactor (TFTR) where reduced recycling and significantly enhanced fusion performance were obtained by starting with a limiter thoroughly depleted of hydrogen isotopes and applying lithium with three deposition methods: (i) LPI, (ii) evaporation of lithium from an oven, and (iii) deposition of lithium by laser outside the plasma directly into low density plasmas [3]. During and since the TFTR experiments, the LPI technique was investigated in other devices with divertors, notably ALCATOR C-Modification (C-MOD), Doublet III-D (DIII-D), and Tokamak de Varennes (TdeV). However, without the thorough wall degassing applied in TFTR, none of these experiments yielded similar performance improvement other than a small decrease in impurities [4]. The goal of these NSTX LPI experiments was to build on the TFTR lithium experience, i.e., to investigate the effect of the wall conditions on the success of LPI, and to reproduce the recycling reduction and improved density control. These LPI investigations in NSTX have been followed by recent experiments using a lithium evaporator to deposit lithium films on the lower divertor and the center stack regions of the PFCs.

2. Lithium pellet injection into discharges not preceded by helium discharge conditioning

In the initial NSTX LPI experiment, lithium pellets were injected during the plasma current ramp-up in ohmic discharges, and into NBI discharges, both before and during the NBI heating pulse. Pellets were also injected late into discharges which preceded the NBI discharges of interest. In this experiment, first about 34 mg of lithium was injected using 2 mg pellets into 16 discharges in lower single null (LSN) and double-null (DN) divertor configurations. Each of these discharges was preceded by 7–11 min of HeGDC to remove adsorbed fuel gas from PFC surfaces but no helium conditioning discharges were used. During the LPI sequence, the C III (977 nm) luminosity was approximately constant, but the O V (629 nm) luminosity fell steadily to about 50% of its original level. Long after these LPI experiments, residual Li I (671 nm) luminosity was observed from the center stack region. During NBI heating of the LSN discharges, the pellets ablated near the plasma edge and much lithium appeared to be transported not only to the lower divertor, but also to the upper divertor along open field lines, as indicated by a

TV image of the Li I (671 nm) emission. During NBI in DN discharges, the pellets also ablated near the edge but the lithium exhibited transport more uniformly to both divertors along open field lines. In both LSN and DN plasmas, the rise in the line-average density during NBI was not obviously changed by the lithium deposition. When pellets were injected into the ohmic phase of discharges pre-heated with NBI, the pellet penetration depth was sensitive to a 10 ms change in NBI turn-off time relative to pellet arrival. After LPI, some discharges continued for their programmed duration, but others collapsed slowly; locked modes seemed more prevalent as the lithium deposition increased.

3. Lithium pellet injection experiments in center stack limited discharges preceded by helium discharge conditioning

In the next NSTX lithium experiments, Center-Stack Limited (CSL), ohmic helium conditioning discharges (0.5 MA, 0.45 T) were used to degas the PFCs on the NSTX Center Stack. Each of these discharges was preceded by 7–11 min of HeGDC to augment the degassing process. Fig. 1 shows how the D_α emission from the Center Stack region decreased with discharge number until after about 8 discharges a baseline level was reached beyond which only a relatively small change per discharge occurred. This behavior, which has been observed in repeated, widely spaced, experiments, may be understood as due to the deuterium depletion of the primary contact region combined with a continuing residual outgassing from the main chamber outer wall components within range of recycling from fast change–exchange neutrals. After the first 8 helium discharges shown in Fig. 1, 3 deuterium, CSL, NBI-heated reference discharges (0.9 MA, 0.45 T) were run to evaluate the wall conditions. The D_α signal exhibited a monotonic increase in this sequence as the conditioned surfaces were 're-gassed' by these discharges. Four ohmic helium conditioning discharges were then applied to degass the PFC surfaces once more. Lithium pellets, with masses 1.7, 3.4, or 5.0 mg, were then injected into 9 of the next 12 similar ohmic, helium discharges. During this sequence of discharges with LPI, the D_α luminosity (Fig. 1) continued to decrease slightly (~25%). Fig. 2 shows how the Li I (671 nm) luminosity from the Center Stack region increased as the lithium injection accumulated to about 30 mg. After this lithium coating sequence, three reference NBI-heated CSL discharges (Fig. 3) were performed. Following the initial gas puff, the first of these discharges exhibited a reduction in the volume-average density of about a 33% compared to the reference shot prior to the lithium coating.

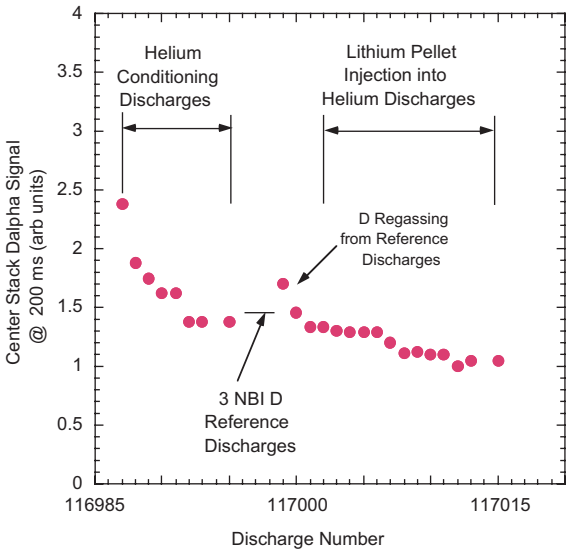

Fig. 1. Evolution of the representative level of D_α luminosity from a sequence of 8 ohmic conditioning discharges (0.5 MA, 0.45 T), followed by 3 deuterium reference discharges, four additional ohmic clean-up discharges, and then 12 ohmic helium discharges, 9 of which with LPI of either 1.7, 3.4, or 5.0 mg. A small decrease in D_α luminosity was evident in the discharges with LPI prior to the arrival of the LPI.

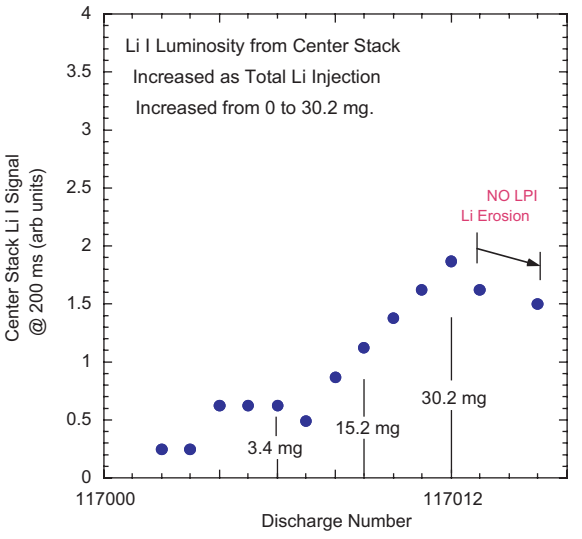

Fig. 2. The Li I (671 nm) luminosity from the center stack increased as the total lithium injection increased to 30 mg.

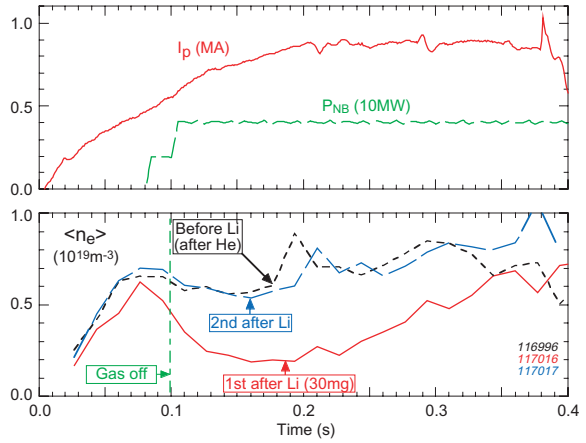

Fig. 3. Initial CSL NBI deuterium reference discharge (0.9 MA, 0.45 T) following 30 mg of lithium deposition exhibited a decrease in density of about 33% after termination of the initial gas puff. On the second discharge, the effect was less while on the third, the density was higher than before. Approximately 3.5 mg of D_2 gas fueling was injected into each discharge.

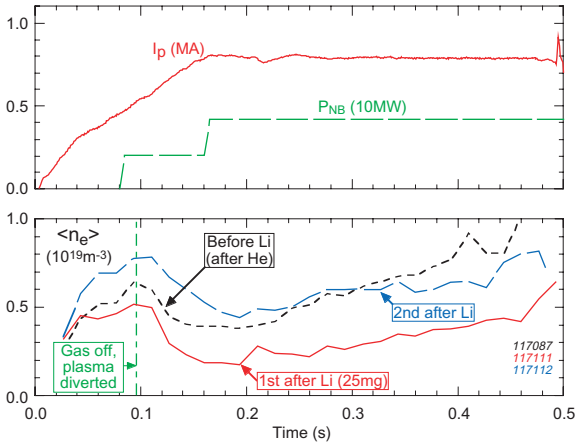

Fig. 4. Initial L-mode, LSN, NBI deuterium reference discharge (0.8 MA, 0.45 T) following 25 mg of lithium deposition on lower divertor exhibited a decrease in density by about 50%. Approximately 3.5 mg of D_2 gas fueling is injected into each discharge.

After reaching the minimum in density, the rate of density rise in this first discharge was approximately equal to the rate of fuelling from the NBI. The second reference discharge reverted to almost the density level before lithium application, and by the third discharge there was sufficient recycling from the walls to exceed the pre-lithium density. After this sequence, another 24 mg of lithium was deposited using the same ohmic helium discharges, and almost identical density behavior was observed in the subsequent CSL NBI reference discharges. These results are similar to the experience in TFTR in which the benefit of lithium coating by LPI was observed only if the discharges were preceded by adequate degassing of the graphite PFC surfaces using helium discharges.

4. Lithium pellet injection experiments in lower single null discharges preceded by helium discharge conditioning

In a subsequent NSTX experiment, LSN divertor, ohmic helium discharges were used to condition the lower divertor target. This was followed by a reference LSN, deuterium plasmas (0.9 MA, 0.45 T) with NBI. LPI into a sequence of similar helium discharges was then used to introduce a total of about 25 mg of Li. As this deposition progressed, the Li I (671 nm) line emission from the lower divertor region increased. Finally, a series of three reference plasmas with NBI was performed (Fig. 4). In the first of these, the density was reduced about 50% from the reference discharge prior to the lithium coating. The reduction in density was less on the second and absent on the third shot, again consistent with exhausting the capacity of the deposited lithium to absorb deuterium. In this experiment the rise in density increased with the introduction of NBI core fueling but in a more complex manner than as in the CSL experiments described above.

5. Initial experiments on evaporated lithium surfaces

A lithium evaporation oven was mounted on an upper divertor port and aimed downward at an angle of 22° from the vertical to provide coverage over the lower divertor and Center Stack regions. Five evaporations were performed in amounts ranging from 14 to 640 mg, for evaporation times ranging from 68 to 387 min. The amount of lithium evaporated from the oven was calculated from the temperature vs. time of the oven. The graphite PFCs were at room temperature throughout the evaporation. The time between end of evaporation and the next discharge ranged from 23 to 140 min. During this delay, some fraction of the deposited lithium may have reacted with the vacuum residual gas components or have intercalated into the graphite PFC surface [5–7]. These 5 evaporations were preceded by different wall conditioning procedures, either none, or with HeGDC, or with ohmic helium discharges.

The initial, relatively small evaporations (2–200 mg), applied slowly over long times on essentially unconditioned surfaces, and with relatively long times between end of evaporation and next L-mode LSN NBI discharge produced no change in the density evolution of a reference discharge, even though the total lithium deposition exceeded that of the LPI experiments discussed above. However, improved plasma effects were obtained by running 6–8 ohmic helium discharges first, then evaporating a relatively large amount of lithium (~400 mg) onto the conditioned surfaces as fast as possible (68 min), and then performing the first reference discharge as soon as possible thereafter (23 min). The first of a sequence of 4 l-mode, LSN, NBI reference discharges following this evaporation exhibited approximately a 29% decrease in density relative to the comparison discharge, peaked density profiles, electron temperatures of 2 keV for 1 MW NBI, and an energy confinement time of ~90 ms. Fig. 5 shows profiles from this and the next discharge in the sequence. Through this sequence the emission from hydrogen-like oxygen time-integrated through each discharge was being measured by an extreme ultra-violet spectrometer. The near-core O VIII (1.9 nm) level was essentially the same for the first post-lithium discharge (120474) as before the evaporation. However, over the following three NBI shots the signal fell to the noise background indicating a significant reduction in near-core oxygen impurities.

An experiment was also conducted to assess whether the apparent effects of the lithium coating

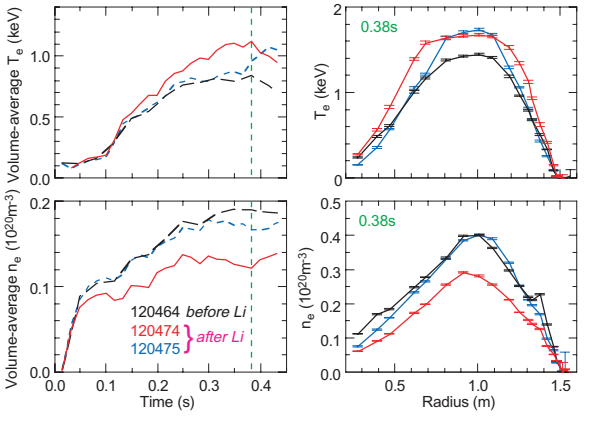

Fig. 5. Comparison of Thomson scattering profiles for L-mode, LSN, NBI D reference discharges before (shot 120464) and after (120474, 5) lithium deposition following ohmic helium conditioning discharges. Pumping by the lithium coating on the conditioned graphite PFCs exhibited almost a 29% decrease in density relative to the comparison discharge.

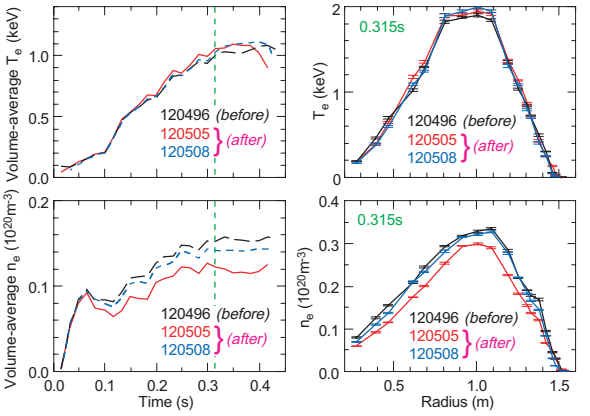

Fig. 6. Comparison of Thomson scattering profiles for L-mode, LSN, NBI D reference discharges before (120496) and after (120505, 8) ohmic helium conditioning discharges applied to the graphite plasma facing surfaces. Pumping by the degassed graphite exhibited about an 18% decrease in density relative to the comparison discharge.

on the density could be attributable solely to the helium pre-conditioning of the PFCs. Fig. 6 compares the profiles of discharges before and after a sequence of helium conditioning shots, showing that these discharges alone were responsible for an approximately 18% decrease in density relative to the comparison discharge. Thus, under the present experimental conditions, helium conditioning appears to produce a similar pumping rate for the graphite surfaces to lithium deposited on the conditioned graphite surfaces.

6. Discussion

During NSTX diverted, NBI heated discharges of up to 6 MW, the incident power densities range up to 10 MW/m^2 and peak front-face temperatures of the graphite tiles reach 300–400 °C. During these conditions the divertor graphite tiles are able to absorb large amounts of deuterium fuel gas. Subsequent deposition of lithium on these graphite tiles reacts with this absorbed fuel gas, and renders it unavailable for pumping incident deuterium during the following discharges. In the experiments described in this work, the densities of the NBI reference discharges were found to be unchanged by lithium deposition on surfaces which had not been depleted of fuel gas by helium conditioning discharges. However, in both the CSL and LSN experiments involving lithium deposition after helium discharge conditioning, a significant reduction in

density was observed in the first reference discharge, a small reduction on the second and essentially no effect on the third shot. This is consistent with reaction of the deposited lithium with the deuterium gas puffed into the plasma, typically about 1.0×10^{21} D per shot, to form LiD. Our initial experiments applying L-mode LSN NBI D discharges to evaporated lithium surfaces demonstrate the effectiveness of the thin lithium coating pumping on deuterium-depleted graphite surfaces and the need for prompt application of the reference discharge. The lithium coatings used in these experiments appear sensitive not only to interactions with residual fuel gases in the graphite substrate but also to time after the deposition since interactions with vacuum vessel residual gas components (H_2, D_2 H_2O, D_2O, N_2, CO, and CO_2) and intercalation of the lithium into the graphite [5–7] can occur. These results are consistent with TFTR results [3] and laboratory experiments [5–7]. This sensitivity to substrate conditions may change as a lithium coating thickness is increased further. The effect on density control of increasing the lithium deposition amount, the rate of deposition, the duration before the reference discharge, and the discharge start-up conditions are under investigation. The installation of a liquid divertor in NSTX will depend on results to be obtained from the LTX experiment, formerly known as CDX-U, where a substantial reduction in recycling and a complete suppression of oxygen contamination of the plasma was produced by using a toroidal tray of molten lithium as a limiter [1].

Acknowledgements

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