Plasma Performance Improvement with Lithium-Coated Plasma-Facing Components in NSTX*

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Abstract. Lithium as a plasma-facing material has many attractive features, including a reduction in the recycling of hydrogenic species and the potential for withstanding high heat and neutron fluxes in fusion reactors. Recent NSTX experiments have shown, for the first time, significant and recurring benefits of lithium coatings on plasma-facing components (PFC's) to the performance of divertor plasmas in both L- and H- mode confinement regimes heated by high-power neutral beams. They included decreases in the plasma density and inductive flux consumption, and increases in the electron temperature, ion temperature, energy confinement time, and DD neutron rate. Extended periods of MHD quiescence were also achieved, and measurements of the visible emission from the lower divertor showed a reduction in the deuterium, carbon, and oxygen line emission. Other salient results with lithium evaporation included a broadening of the electron temperature profile, and changes in edge density gradients that benefited electron Bernstein wave coupling. There was also a reduction in ELM frequency and amplitude, followed by a period of complete ELM suppression. In general, it was observed that both the best and the average confinement occurred after lithium deposition and that the increase in W_{MHD} occurs mostly through an increase in W_e. In addition, a liquid lithium divertor (LLD) is being installed on NSTX this year. As the first fully-toroidal liquid metal divertor target, experiments with the LLD can provide insight into the behavior of metallic ITER PFC's should they liquefy during high-power divertor tokamak operations. The NSTX lithium coating and LLD experiments are important near-term steps in demonstrating the potential of liquid lithium as a solution to the first-wall problem for both magnetic and inertial fusion reactors.

I. Introduction

Lithium as a plasma-facing component (PFC) can reduce the recycling of hydrogenic species, and may offer a solution to the problem of high heat and neutron fluxes in fusion reactors. This has motivated its investigation on many fusion devices, including TFTR,[1] T-11M,[2] and FT-U.[3] Using a liquid-lithium-filled tray as a limiter, the CDX-U device achieved very significant enhancement in the confinement time of ohmically heated plasmas.[4] The recent NSTX experiments reported here have demonstrated, for the first time, improvements in plasma performance when lithium PFC coatings are present in high-power divertor discharges. This paper summarizes the results with lithium-coated PFC's during neutral beam heating of L- and H- mode discharges.

II. Description of NSTX and Lithium Evaporation System

The NSTX[5] device is a large spherical tokamak with plasma major and minor radii of 0.85 m and up to 0.67 m, respectively. Auxiliary heating capabilities include 7 MW of deuterium neutral beam injection (NBI) and 6 MW of RF power for high-harmonic fast-wave (HHFW) heating and current drive. Discharges in excess of 1 MA can be sustained for more than 1 s. The present PFC's are primarily ATJ graphite and carbon fiber composite tiles.

During NSTX experiments in 2008, lithium coatings of the PFC's were applied with two ovens mounted on the upper dome of the vacuum vessel (Fig. 1a).[6] Each LIThium EvaporatoR (or LITER) consisted of a lithium reservoir, with a 90 gm capacity, inside a heated stainless steel oven. They were used to direct a collimated stream of lithium vapor downwards toward the tiles on the lower center stack and divertor.

The two LITERs were separated by 150° toroidally to coat the entire divertor area. The larger arrows indicate the "centroids" and the smaller arrows approximate the "e-folding" distance of the lithium deposition pattern. The trajectories bend away from the axis of the LITERs, since they had exit ducts that were oriented to maximize evaporation into the divertor region. Figure 1b depicts the areas covered by the LITERs, and the radial extent of the inner and outer divertors. Since the lithium deposition was "line-of-sight," the center stack partially blocked the area either LITER covers. The lithium from each LITER, however, could reach the "shadow" region of the other (Fig. 1b).

A typical sequence prior to a plasma shot would be to conduct helium glow discharge cleaning (HeGDC) for up to 9.5 min, followed by lithium evaporation onto the PFC's for up to 10 min. It typically takes over an hour for the oven temperature to drop sufficiently for lithium evaporation to cease. Since the goal was to minimize the passivation of the lithium after deposition onto the PFC's, each LITER was withdrawn behind a movable shutter prior to HeGDC and plasma shots. This minimized the time from the end of the application of the lithium to the PFC's, while still preventing lithium from entering the vacuum vessel. Depending on the LITER temperature settings, the total rates from the two evaporators varied between 5 and almost 85 mg/min. This was monitored with a quartz deposition monitor, whose position is indicated by "QDM" on Fig. 1b.[7]

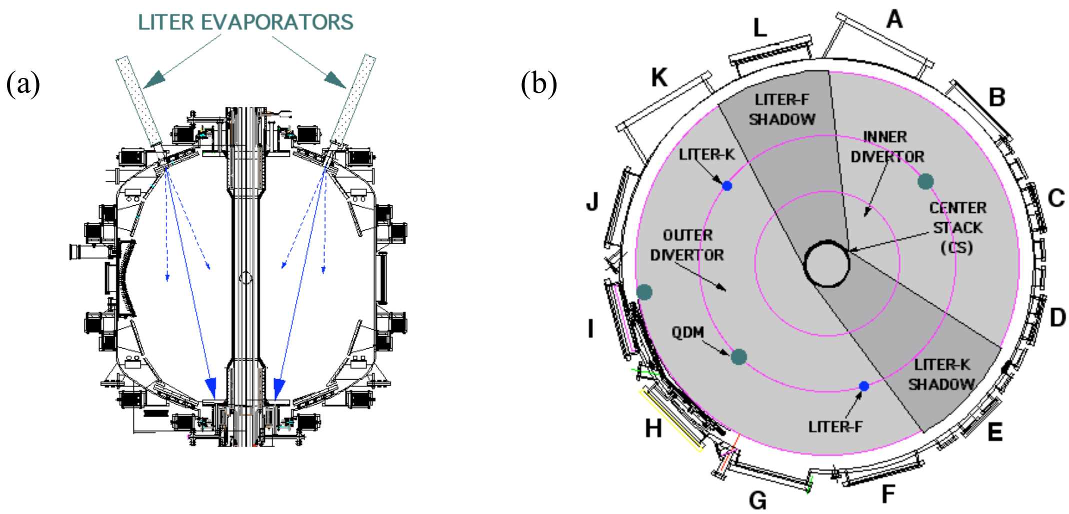

FIG. 1. (a) Elevation of NSTX showing position of LITERs. (b) NSTX plan viewing indicating toroidal location of LITERs and coating regions blocked by center stack.

III. Effects of Lithium Coatings on Plasma-Facing Components

Experiments before 2008, which were conducted with a single LITER, indicated that lithium deposition prior to a NBI-heated plasma shot decreased the plasma density, inductive flux consumption, and ELM frequency and increased the average electron temperature, ion temperature, energy confinement time, and DD neutron rate. In addition, extended periods of MHD quiescence were observed.[8]

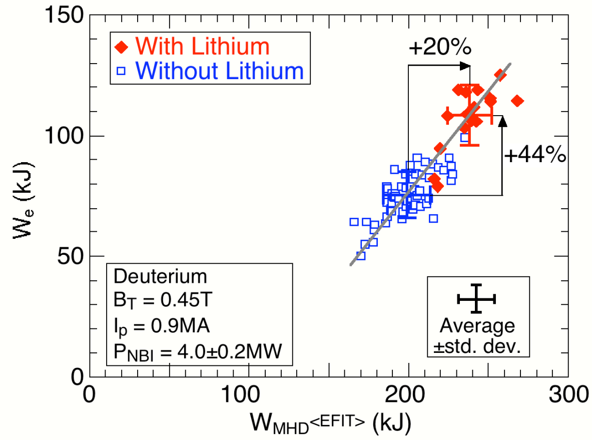

FIG. 2 Demonstration of stored energy (W_{MHD}) increase after lithium deposition

These features were again observed with two LITER evaporators, but were more pronounced and reproducible. An example of this is the increase in stored energy after lithium deposition (Fig. 2), which is greatest for the electrons. Plasma parameters as a function of time are compared for discharges before and after lithium evaporation in Fig. 3. Prior to 2008, the maximum evaporation rate from the one available LITER evaporator was about 40 mg/min. With two LITER operation in 2008, a maximum evaporation rate of over 80 mg/min was achieved.

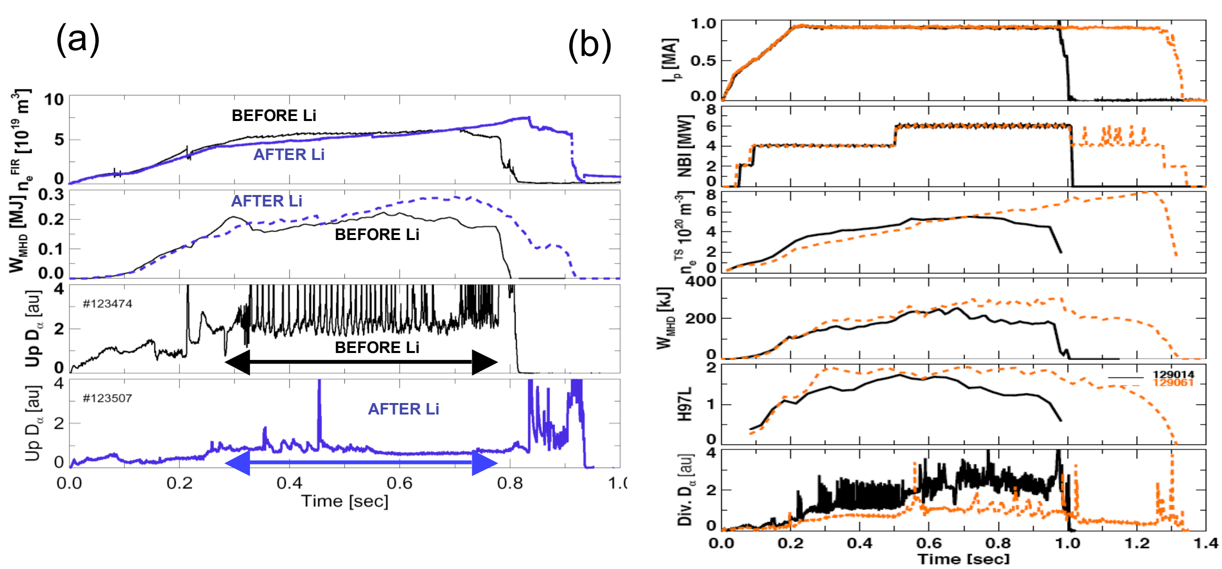

FIG. 3 Time evolution of plasma parameters before and after lithium evaporation at (a) lower rate with one LITER prior to 2008 and (b) higher rate with two LITERs in 2008

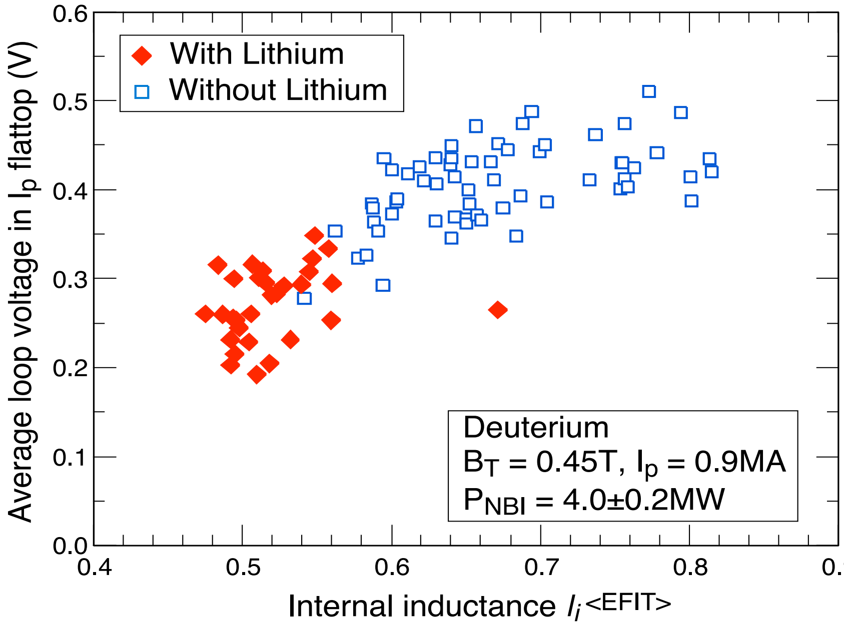

FIG. 4. Average loop voltage during current flattop as function of internal inductance.

The most conspicuous difference between the lower and higher lithium deposition rates is the extended plasmas obtained under the latter conditions (Fig. 3b). When combined with improved error-field correction at high beta, the longest discharges ever observed on NSTX were achieved. Plasmas with lithium-coated PFC's exhibited reduced flux consumption, as summarized in Fig. 4. The squares correspond to plasmas before the application of lithium, and the diamonds are for shots taken right after LITER evaporation. In the discharges shown, the average of the loop voltage was calculated from 0.2 s after the start of the plasma until the time of maximum stored electron energy. The distinct grouping of the plasmas after lithium evaporation around lower average loop voltages at lower internal inductances suggests more efficient flux consumption, and one potential mechanism is the change in conductivity as the temperature profile broadens in the presence of lithium-coated PFC's.

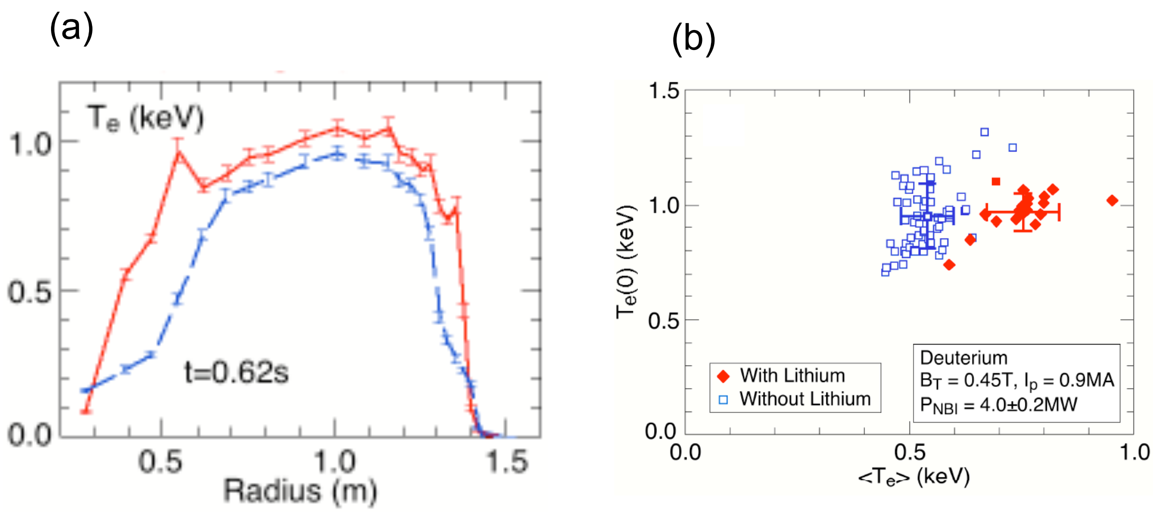

FIG. 5. (a) Electron temperature profiles and (b) peak electron temperature as function of average value for discharges with and without lithium-coated PFC's

The profiles for discharges with and without lithium evaporation are compared in Fig. 5. Electron temperature profiles are typically broader with lithium-coated PFC's (upper curve in Fig. 5a). The consistency of this tendency is evident in Fig. 5b, where the peak electron temperatures are plotted as a function of their average values. In this figure, the same symbol convention used in Fig. 4 is followed. Broader electron temperature profiles mean higher gradients in the edge pedestal region, which should lead to higher edge bootstrap currents. Current density profiles were calculated with the TRANSP transport code, based on parameters measured for plasmas with and without lithium-coated PFC's. These are shown in Fig. 6, and they illustrate the increase in the edge bootstrap current for discharges after the application of lithium. Such behavior is consistent with the absence of ELM's in these plasmas, if their stability against ballooning modes is a requirement for ELM suppression. Edge stability calculations using the ELITE and DCON codes have been performed for NSTX plasmas with Type V ELM's. These discharges did not have lithium PFC's, and similar analysis is planned for plasmas after lithium was introduced.[9]

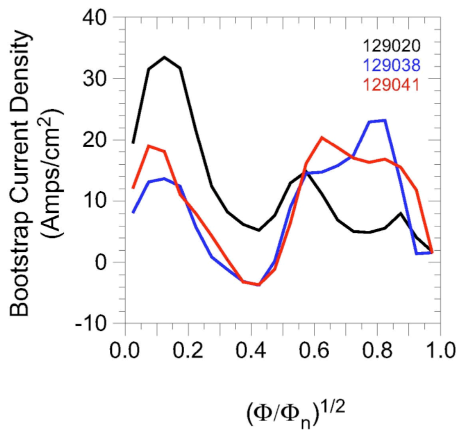

FIG. 6. Bootstrap current profiles for discharges with and without lithium-coated PFC's

Lithium-coated PFC's are expected to reduce edge recycling. To look for evidence consistent with this in the density profile in the scrapeoff layer (SOL), measurements were performed using a broadband swept X-mode reflectometer, covering a frequency range of 6 to 27 GHz. By sweeping the frequency, average density profiles were obtained at 1.8 ms intervals.[10] Fig. 7 compares the SOL density profiles from shots at about 0.36 s into discharges with two LITERs operating. The evaporation rate was 18.2 mg/s prior to shot 129024, when the profile labeled with that discharge was obtained and ELM's were still present.

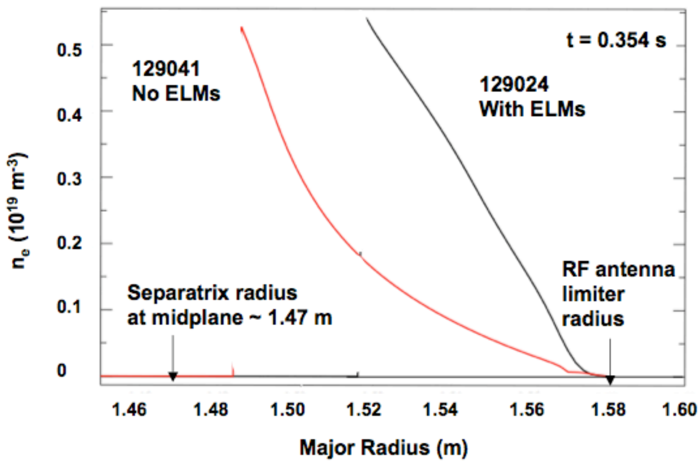

FIG. 7. Scrapeoff layer density profiles for discharges with and without lithium-coated PFC's

The evaporation rate was 81.7 mg/s prior to shot 129041, when the profile corresponding to that shot in Fig. 7 was measured and the ELM's were suppressed. At the lower lithium evaporation rate, the density rise is almost linear with decreasing radius. The density reaches the same value at a significantly smaller major radius at the higher evaporation rate, and the shape of the profile has markedly changed.

In addition to lowered recycling, there is evidence for deuterium pumping with lithium coatings. Figure 8 shows the fueling required from gas puffing and NBI to achieve a given plasma electron inventory. Prior to the application of lithium, there is a clustering in the range of 2 to 3×10^{21} total electrons. After lithium evaporation, the data show that consistently higher fueling rates are needed to achieve the same electron content in the plasma.

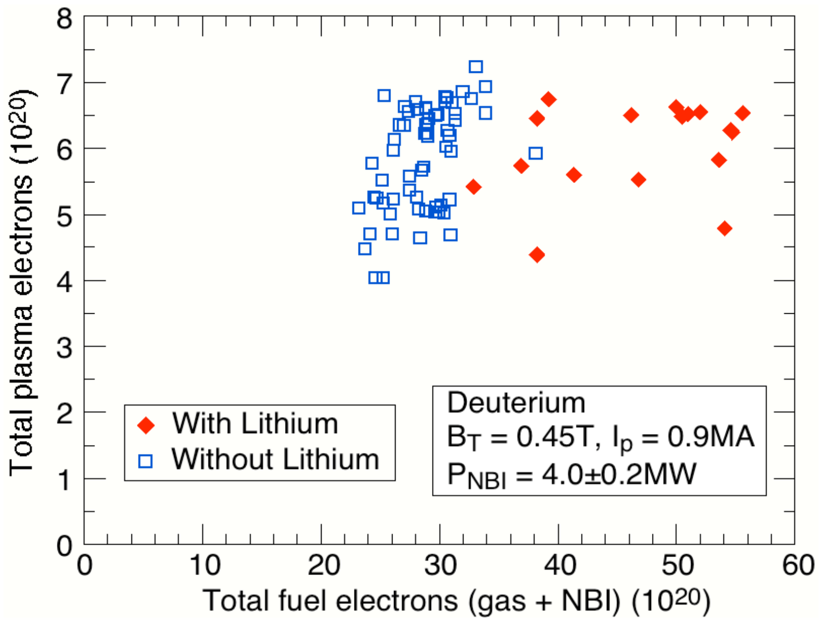

FIG. 8. Dependence of electron inventory on fuel electrons in plasmas with and without lithium-coated PFC's

IV. Liquid Lithium Divertor

A liquid lithium divertor (LLD) is being installed on NSTX, to enable experiments with the first complete liquid metal divertor target in a high-power device in 2009. The location in the vacuum vessel is shown schematically in Fig. 9. The LLD is a conic section with four 90-degree segments, each consisting of a 1.9 cm-thick copper plate with a 0.02 cm-thick stainless steel liner that is isolated toroidally with carbon tiles. Molybdenum will be plasma sprayed onto the liner in vacuum, to form a 0.01 cm-thick layer with 50% porosity. This will become the plasma-facing surface when filled with lithium, which will be kept liquid by resistive heaters in the plates.[11]

The present outer divertor (Fig. 1) consists of concentric rows of ATJ graphite tiles on copper baseplates. Lithium evaporated onto the tiles prior to a shot would solidify, and pump only while the hydrogenic atoms can react with the surface layer of the lithium coating. The LLD will replace part of these tiles with lithium that will be kept molten. Because the lithium will continue reacting with hydrogen or deuterium until it is volumetrically converted to hydrides,[12] the LLD is expected to provide better pumping than lithium coatings on carbon PFC's.

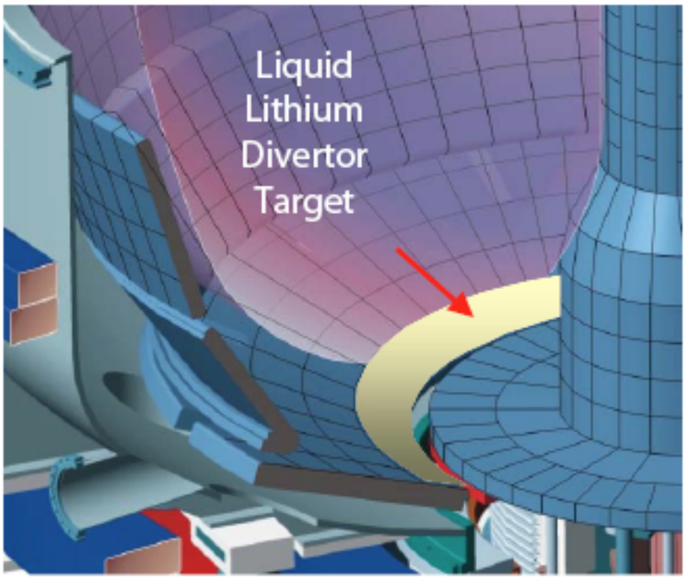

FIG. 9. Schematic of NSTX showing location of Liquid Lithium Divertor inside vacuum vessel

Detailed edge plasma modeling has begun with the UEDGE transport code to simulate the effects of reduced recycling expected from the LLD.[13] The simulations start with adjusting the transport coefficients until the edge temperatures and densities match the data from the multipoint Thomson scattering diagnostic for existing NSTX plasmas. New profiles are then generated for a variety of recycling coefficients (Fig. 10).

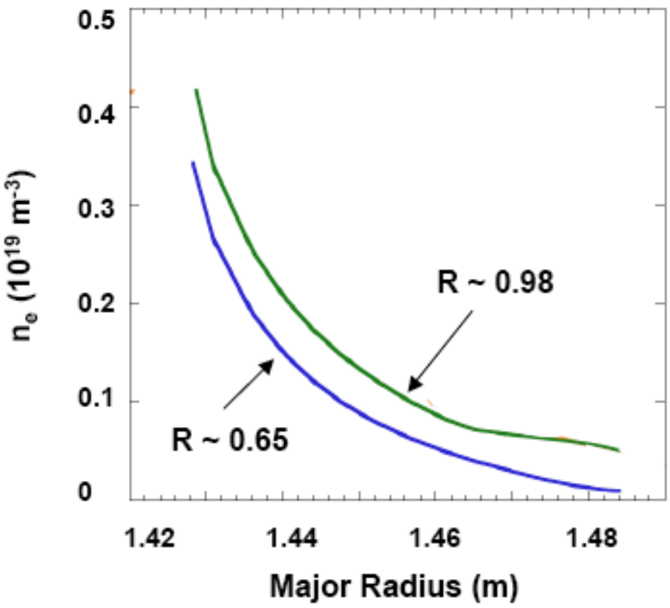

FIG. 10. Edge density profiles calculating with UEDGE for NSTX Liquid Lithium Divertor assuming different recycling coefficients

The results of the simulations have the same nonlinear radial dependence as the SOL measurements during high lithium evaporation. The simulations, however, do not show the linear density rise observed at the low lithium evaporation rate during NSTX experiments. This suggests that more work needs to be done on the transport modeling before further conclusions can be drawn from the UEDGE calculations.

V. Conclusions

Two lithium evaporators have been used successfully to increase lithium coating rates for NSTX PFC's. As in earlier experiments with one evaporator,[8] plasma performance improved. Significantly reduced inductive flux consumption was achieved with two-LITER operation, reminiscent of the decrease in loop voltage that was observed with large-area liquid lithium limiter experiments on CDX-U.[14] While further analysis is required to understand the relationship between the effects of lithium-coated PFC's on impurities and recycling and plasma performance, higher lithium evaporation rates appear to be advantageous.

In addition to further improving the performance of NSTX plasmas, experiments with the LLD can help explore the behavior of metallic ITER PFC's should they liquefy during high-power operation. The NSTX lithium coating and LLD experiments are important near-term steps in demonstrating the potential of liquid lithium as a solution to the first-wall problem for both magnetic and inertial fusion reactors.

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