Active Recycling Control Through Lithium Injection in EAST

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***Abstract*— The coating of tokamak walls with thin layers of lithium has been demonstrated to reduce plasma recycling from the plasma-facing surfaces and to improve overall plasma performance. These effects, including reduced divertor D_α emission, the elimination of edge-localized modes, and increased energy confinement have been observed in multiple experiments when lithium coatings are applied before plasma discharges. However, this coating technology does not extrapolate to future long-pulse devices, since the lithium coatings will be passivated by the continual plasma flux onto the surface. In order to provide active conditioning capability, a new technology has been developed that is capable of injecting lithium powder into the scrape-off layer plasma during plasma discharges, where it quickly liquefies and turns into an aerosol. The use of this "lithium dropper" is under study at the Experimental Advanced Superconducting Tokamak (EAST), where the potential benefits of real-time wall conditioning via lithium injection are being tested. Here, we present an analysis of the recycling characteristics during EAST experiments testing active lithium injection in order to assess recycling reduction and control. Lithium aerosol was injected from the top of the machine, with one system dropping lithium near the X-point and another into the low-field side divertor leg. The injection of lithium into the SOL reduced divertor recycling, as evidenced by reduced D_α emission with ion flux measured by probes relatively unchanged. This effect is strongest in the active divertor, confirming the lithium is transported to strongly plasma-wetted areas. Quantitative analysis of the recycling changes using the SOLPS edge plasma and neutral transport code indicated a ∼20% reduction in recycling coefficient with lithium injection.**

***Index Terms*— Divertor, Experimental Advanced Superconducting Tokamak (EAST), lithium wall coatings.**

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I. Introduction

The coating of plasma-facing components (PFCs) with thin layers of lithium has been shown to improve plasma performance, for example, by eliminating edge-localized modes (ELMs) and increasing energy confinement [1]–[6]. This is thought to be in part related to the reduction in particle recycling of plasma ions from the PFCs as neutrals, an effect both expected and observed when deuterium plasma is incident on a reactive lithium surface [7]. However, many of these effects have been observed in experiments where evaporative coatings were applied prior to plasma discharge initiation, with no replenishment of the coatings while the plasma was present [8]. This method does not clearly extrapolate to long-pulse devices, where the plasma will eventually passivate the lithium surface and negate its impact on recycling and confinement.

Recently, a new lithium injection technology has been developed that is capable of dropping a lithium powder directly into the plasma during operations [9]. Lithium droppers of this type have been tested in the Experimental Advanced Superconducting Tokamak (EAST) [5], DIII-D [6], and carbon-walled NSTX [10], with NSTX and EAST showing the potential to control divertor recycling similar to that achieved with predischarge lithium coatings. This provides the potential for active recycling control during long-pulse plasmas, as well as more efficient application of lithium coatings as the plasma transport naturally deposits lithium where the plasma flux is high. Here, we present the results of recent tests of this active wall conditioning technique on the EAST tokamak, using tungsten as the plasma-facing material in the active divertor.

II. Setup of Experiments

Experiments were carried out on EAST [11] testing the ability of real-time lithium injection via the powder dropper technology to provide active wall conditioning. The dropper relies on a piezoelectric crystal driven at resonant frequencies to cause lithium power particles to random walk to an opening through which they fall directly into the EAST plasma [9]. By varying the applied voltage on the crystal, the mass flow rate of lithium into the plasma can be controlled. Lithium injection was tested in upper single-null plasmas, which put the primary plasma flux into the upper tungsten divertor; the plasma boundary shape and lithium injection locations are shown in Fig. 1. This configuration allows tests of lithium

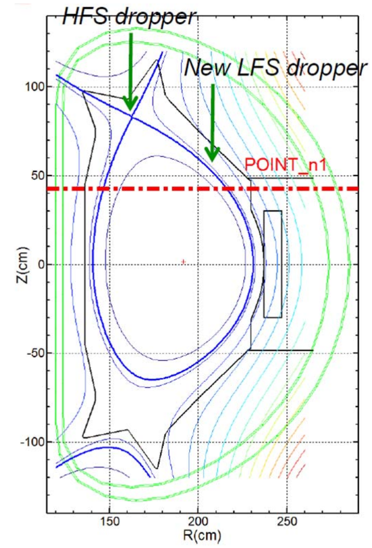

Fig. 1. Setup of lithium droppers using upper single-null plasma shape.

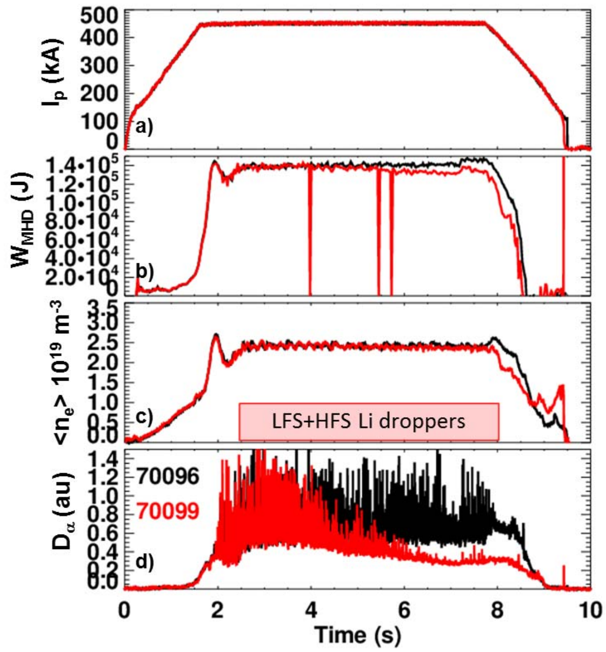

Fig. 2. Time traces of (a) plasma current, (b) stored energy, (c) line-averaged density, and (c) upper divertor D_α emission without (black) and with (red) intrashot lithium injection.

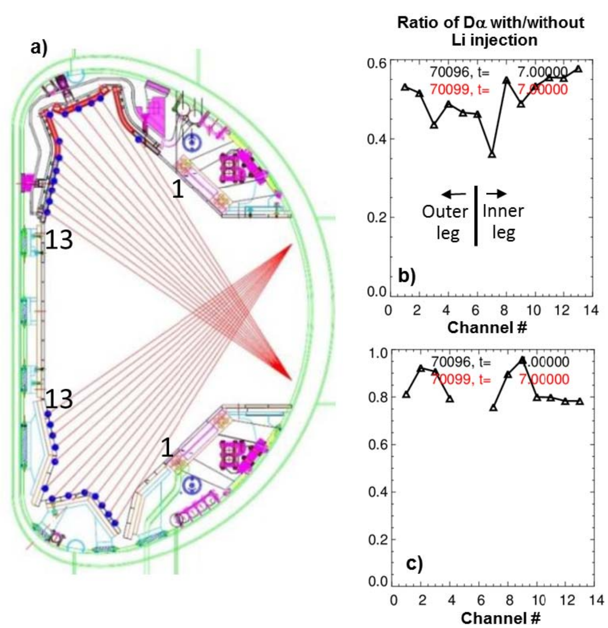

Fig. 3. D_α (a) lines of sight and brightness profile at $t = 7$ s with lithium injection (70 099) normalized to that without lithium injection (70 096) in the (b) upper and (c) lower divertors.

coatings of tungsten, for which few lithium studies have been performed. Most lithium results have so far been obtained with carbon walls (which could result in a different chemistry [12] than tungsten). Two injectors were used in these experiments, one dropping lithium on the low-field side of the plasma, and the other injecting near the X-point; both injectors were used simultaneously in the experiments described here. Since the lithium is then transported by the plasma to the walls, it expected that high-flux regions of the PFCs will be preferentially coated. Hence, wall conditioning will be naturally applied to locations where it is most effective.

Real-time lithium injection was tested in high-performance noninductive plasmas. These had a plasma current I_p of 0.45 MA, toroidal magnetic field of $B_t = 2.5$ T, and were sustained using a total auxiliary heating power of $P_{\text{aux}} =$ 3.5 MW (making use of a combination of lower hybrid, ion cyclotron, and electron cyclotron heating systems). Time traces from discharges without and with active lithium injection are shown in Fig. 2. Although lithium coatings were applied to the walls at the beginning of the run day via evaporative ovens, these experiments were performed after several hours of plasma operation which passivated the original lithium layer. Thus, the discharge without lithium injection showed relatively high recycling and the presence of robust ELMs. Lithium injection begins at 2.5 s, as illustrated in Fig. 2. Over several seconds during the discharge, this results in a strong reduction in D_α emission due to deuterium recycling in the upper divertor, as well as some modification in the ELM behavior.

III. Particle Recycling Response to Lithium Injection

The recycling characteristics and their response to lithium injection have been analyzed in more depth to assess the viability of lithium injection to actively control the PFC recycling coefficient. D_α emission is used as a measure of the rate at which the neutrals originating from recycling of deuterium ions off the PFC surface are ionized, since the ratio of photons emitted to the ionization rate is fairly constant over a broad range of plasma conditions [13]. Fig. 3 shows the ratio of D_α brightness measured with lithium injection to that measured without, for $t = 7$ s where the lithium injection effect is strong. The effect is strongest in the upper divertor, with lithium injection reducing D_α brightness by approximately 50% across both the outer and inner divertors.

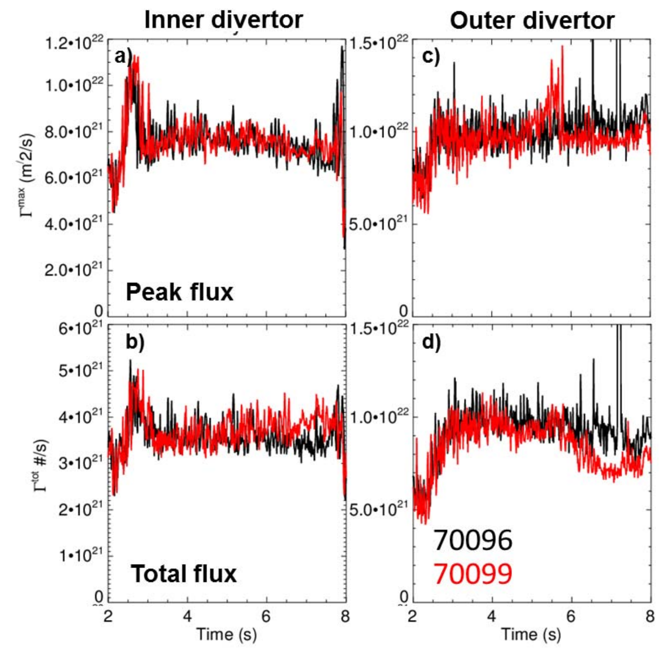

Fig. 4. Time traces of (a) and (c) peak and (b) and (d) total ion flux in (a) and (b) inner and (c) and (d) outer divertors without (black) and with (red) lithium.

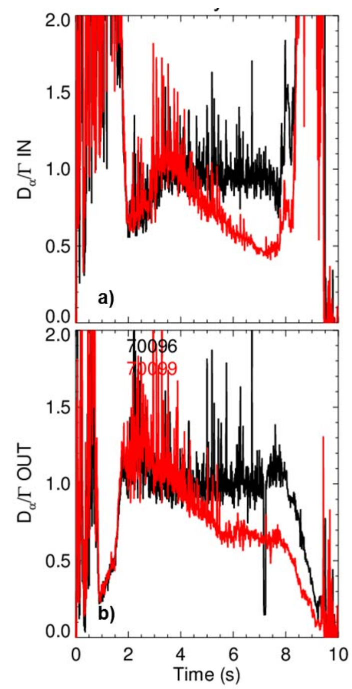

Fig. 5. Time traces of D_α normalized to ion flux ($D_\alpha/\Gamma_{\text{ion}}$) in the (a) upper and (b) lower divertor without (black) and with (red) lithium injection.

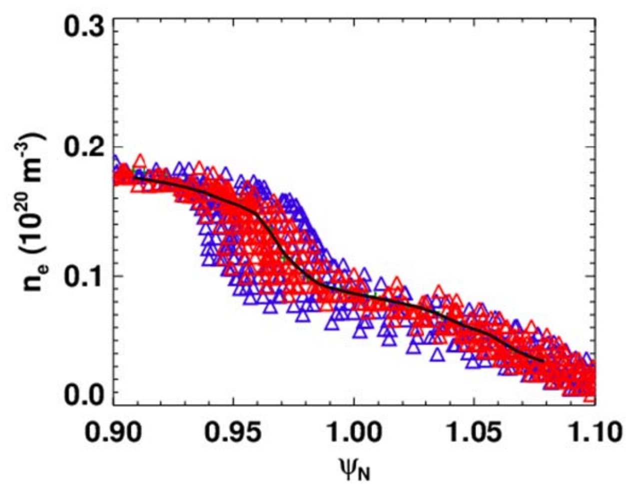

Fig. 6. Measured edge density profile without (blue) and with lithium injection (red). SOLPS profile shown as black solid curve.

The outer upper divertor shows slightly stronger reduction than the inner divertor (55% compared to 45%). The effect is much weaker in the lower divertor, where emission is reduced by less than 20% across the divertor, with reduction of only 5%–10% observed near the plasma strike points. That emission is reduced preferentially on the upper divertor supports the expectation that lithium injected into the plasma will flow primarily to the active divertor, providing conditioning directly in locations where plasma fluxes are highest.

The behavior of the particle flux measured by divertor Langmuir probes [14] without and with lithium injection is shown in Fig. 4. The impact of lithium injection is much weaker on the ion flux in the upper divertor than it is on the D_α emission. On the inner divertor, both the peak and total ion flux are essentially unchanged between the control and lithium injection cases. The outer divertor measurements show a stronger effect of lithium. The peak ion flux shows only a slight decrease later in the discharge with lithium injection, but the total ion flux integrated across the outer divertor shows a decrease of $\sim$20% with lithium during the same time in the discharge when the D_α emission is reduced. Overall, the weaker change in the divertor ion fluxes indicates that the reduction in neutral light emission is not simply due to lower ion fluxes but instead indicates a change in the recycling coefficient R relating the neutral flux off of the divertor to the incident ion flux as $\Gamma_{\text{neutral}} = R\Gamma_{\text{ion}}$. The ratio of the D_α emission to total ion flux in the inner and outer divertors is shown in Fig. 5, in order to assess the degree to which the divertor recycling coefficient R is affected by the lithium injection. Since the D_α emission is proportional to the neutral flux, the strong reduction in $D_\alpha/\Gamma_{\text{ion}}$ of 50% on the inner and 30% on the outer divertor indicates that R is indeed being reduced by lithium.

IV. Modeling of Changes to Recycling Coefficient

Modeling of the recycling behavior has been performed using the SOLPS suite of codes [15], which couple a 2-D fluid plasma model B2.5 [16] to the EIRENE [17] Monte Carlo neutral transport code. Plasma transport is modeled as classical parallel to the magnetic field, with *ad hoc* transport coefficients specified for cross-field transport. Here, an iterative method is used to adjust the cross-field diffusivity to match the experimental data following the procedure outlined in [7]. Density profile data are obtained via profile reflectometry and show similar densities in the SOL with and without lithium injection as shown in Fig. 6. Due to this similarity, a constant density profile is used in the SOLPS modeling described

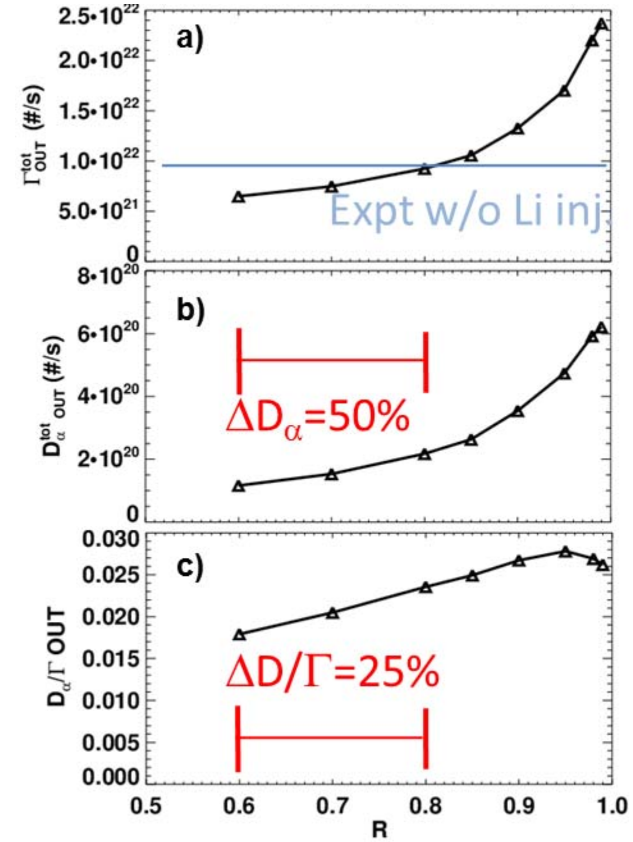

Fig. 7. Variation in (a) total particle flux, (b) $D\alpha$ emission, and (c) ratio of $D\alpha$ to ion flux in the outer divertor as recycling coefficient is varied in SOLPS simulations with constant upstream density.

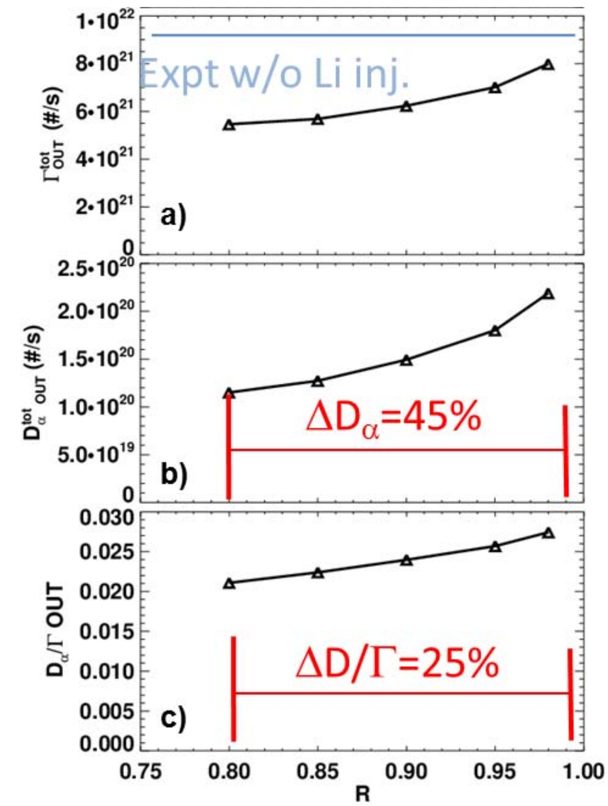

Fig. 8. Variation in (a) total particle flux, (b) D_α emission, and (c) ratio of D_α to ion flux in the outer divertor as recycling coefficient is varied in SOLPS simulations with upstream density reduced 35%.

here, as indicated in the SOLPS curve in Fig. 6. For the electron and ion heat diffusivities, a constant value of 2 m^2/s is assumed; in principle, these can also be constrained by measured temperature and divertor heat flux profiles, but this is left to future work as the particle behavior is of primary interest here.

Results of scans of the divertor recycling coefficient are shown in Fig. 7, using fixed measured density profiles as described above. As the recycling coefficient approaches $R = 1$, the outer divertor enters the high-recycling regime [18] with rapidly increasing total ion flux to the outer divertor. In this case, the ion flux is much higher (by a factor of more than two) than is measured. As R is reduced from unity, the ion flux is rapidly reduced initially, with a more gradual decrease at the lower values of R; the modeled D_α emission shows a qualitatively similar reduction with R. The total ion flux to the outer divertor from SOLPS matches the experimental value for the case without lithium at $R \sim 0.8$. A reduction in R from 0.8 to 0.6 results in a reduction in ion flux by 25%, D_α emission by ~50%, and $D_\alpha/\Gamma_{\text{ion}}$ ratio by 25%. All of these reductions are reasonably consistent with the experimentally measured reductions, indicating that lithium injection reduces R by ~20%.

Since the absolute density has some uncertainty due to, e.g., uncertainty in the exact spatial location with respect to the separatrix, sensitivity of the calculated change in R has been checked by performing a second set of SOLPS runs with the midplane profiles reduced by 35%. This gives a set of runs that avoid the high-recycling regime for all values of R, and yield a cross-check of the relative reduction in R that is consistent with the changes in ion flux and divertor emission. As shown in Fig. 8, for these runs the modeled ion flux agrees with experiment near $R = 1$. Reducing the recycling coefficient to $R \sim 0.8$ results in a decrease in D_α by ~45% and in $D_\alpha/\Gamma_{\text{ion}}$ ratio by 25%, again consistent with experiment. Thus, although the absolute value of R is not sufficiently constrained by data at this point, a reduction in R by ~20% from the value that matches the measured particle flux is consistent with the experimental changes in ion flux and recycling emission. In order to more conclusively determine the absolute value of R, further measurements would be needed to constraint the modeling, such as including upstream temperature and divertor heat flux measurements; this will be the focus of the future research.

V. Conclusion

The real-time injection of lithium power into EAST plasmas has demonstrated the potential for this technique to provide active control over divertor recycling. Following injection, strong decreases to the D_α emission and relatively weak changes to the divertor ion flux indicate that the real-time replenishment of the lithium coating is effective in maintaining a reduced recycling coefficient in the active divertor. Modeling of the D_α and ion flux behavior using the SOLPS code indicates a relative change to the recycling coefficient of $\Delta R \sim 20\%$. Although these results indicate the relative change in R due to lithium injection, further data constraints are needed to establish the absolute value of R. Quantitative determination of R will be an important part of the future research, since this is critical to establishing the total particle removal and the degree to which it is increased with lithium injection. While these results indicate that lithium may provide particle control for long pulse operations, these results have been obtained with fairly low flux levels into the divertor. Future research should include tests at higher absolute fluxes to test the technique under higher particle loading conditions.

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