Characterization of lithium and carbon divertor sources in the mixed material NSTX divertor with lithium-coated plasma facing components*

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In the National Spherical Torus Experiment (NSTX) divertor with lithium coatings evaporated on graphite and molybdenum plasma facing components (PFCs), a reduction in the carbon sputtering yield to $Y_C \leq 1\%$ was observed on lithium-coated graphite tiles, up to a 4x reduction in yield compared to non-conditioned graphite (see Figure 1). The lithium sputtering yield (Y_{Li}) from lithiated graphite (see Figure 2) and porous molybdenum [1] was found to be consistent with physical and surface-temperature-enhanced sputtering [2] from deuterium-saturated lithium ($Y_{Li} \leq$ 10-20%). The larger core impurity penetration factors (>100x) for carbon divertor influxes with respect to lithium, indicated a difference in the source distribution and/or scrape-off layer (SOL) transport of the two impurities in NSTX. The difference in parallel SOL transport between carbon and lithium was confirmed by 2D multi-fluid edge transport simulations with the UEDGE code. The NSTX Upgrade (NSTX-U) will use evaporative lithium coatings on graphite PFCs as the baseline wall conditioning technique. These results will help the extrapolation of the lifetime and erosion characteristics of lithium coatings in NSTX-U discharges with higher divertor heat and particle fluxes and longer pulse length. Furthermore, understanding the behavior of different impurities, in terms of sputtering, material migration and potential for core contamination, will be critical to control impurity accumulation in future devices such as ITER, which will employ mixed materials (beryllium and tungsten) as PFCs.

The total (physical + chemical) carbon sputtering yield (as derived from C II spectroscopic line emission) was reduced with the application of lithium coatings on the divertor graphite tiles in lower single null, NBI heated (4-6 MW), H-mode discharges in NSTX. These discharges had divertor ion fluxes between 10^{22} and 10^{23} ions/m^2/s and electron temperatures between 5 and 40 eV, as determined by flush-mounted Langmuir probes. A relative decrease in the total carbon sputtering yield was observed after the first application of lithium on boronized graphite in 2008. Absolute values of the total carbon sputtering yield from lithiated graphite during the 2010 run campaign indicated carbon sputtering yield $Y_C \leq 1\%$, which is up to 4x less than the combined yield for physical and chemical sputtering, as shown in Figure 1. These measurements also indicated an important contribution from chemical sputtering to the total carbon sputtering yield. Total divertor carbon influxes from the outer strike point were estimated to be on the order of several 10^{20} carbon ions/s. Toroidal asymmetries in carbon sputtering, due to the toroidally asymmetric lithium deposition, were not observed from singly ionized carbon emission but a potentially important role of leading edges of the divertor tiles was identified.

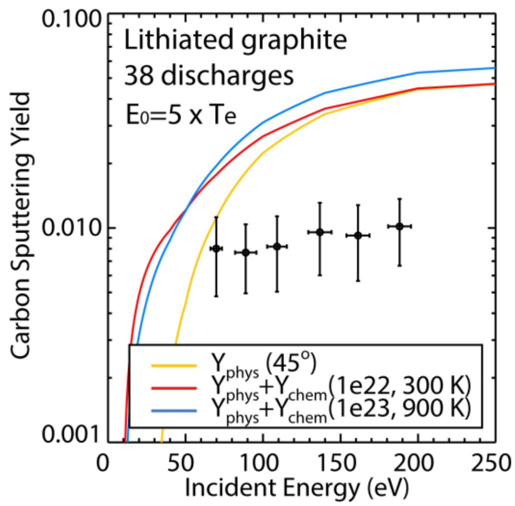

Figure 1 Carbon sputtering yield: experimental from lithiated graphite in NSTX (black) and estimates from physical (yellow) and physical + chemical sputtering (red and blue) from Eckstein and Roth scaling.

Neutral lithium sputtering yields from solid lithium coatings (areal densities > 10^{21} atoms/m^2) on graphite and porous molybdenum substrates [1], derived from Li I spectroscopic line emission, were found to be consistent with physical sputtering from deuterium-saturated lithium. Lithium sputtering yields on the order of a few % (3-7%) were typically observed. As a result of the heating of the PFCs due to the plasma heat flux and due to internal resistive heaters embedded in the PFCs, the temperature dependence of the lithium sputtering yield was observed on both graphite (Figure 2) and molybdenum substrates. This was found to be qualitatively consistent with the temperature-enhanced sputtering behavior observed on test stands (IIAX [2] and PISCES [3]), with yield values on the order of 10-20% and the enhancement of the sputtering yield between 250º and 500º C. For these temperatures and typical NSTX incident ion fluxes, the contribution of evaporative fluxes to the total lithium divertor influxes is negligible. The measured gross divertor lithium influxes were on the order of a few 10^{21} atoms/s as inferred from neutral lithium emission. The lower lithium influxes (10-100x), inferred from singly ionized lithium emission, possibly indicate the importance of prompt re-deposition effects. Toroidal asymmetries in lithium sputtering yields were transiently observed in the NSTX divertor, with the toroidal profile of neutral lithium influxes at the strike point closely matching the deposition profile of the lithium evaporators.

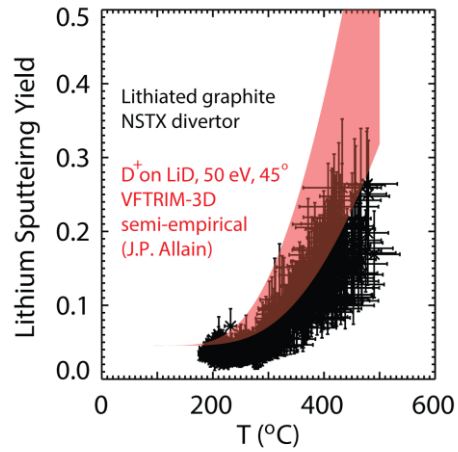

Figure 2 Lithium sputtering yield: experimental from lithiated graphite in NSTX (black), semi-empirical VFTRIM-3D model (red, J.P. Allain [6])

A large difference (>100x) in the impurity penetration factors was found between lithium and carbon divertor influxes. Impurity penetration factors were inferred in ELM-free discharges, based on the divertor impurity influxes determined spectroscopically and the measured core impurity inventories [4], following the method developed in Ref. [5]. This difference is only partially (~10x) explained by the different core particle transport between carbon and lithium [6]. The larger carbon penetration factors indicate the importance of carbon sources from the main wall (in addition to divertor sources) and/or the weaker divertor retention for carbon impurities. The latter was confirmed by 2D multi-fluid edge transport simulations with the UEDGE code [7] performed in slab and NSTX geometries with the inclusion of charge state resolved impurity fluids for both carbon and lithium. UEDGE simulations indicated better divertor retention for lithium with respect to carbon as a result of the narrower source profile at the target and the weaker classical parallel forces. Prompt re-deposition effects are also expected to be more important for lithium than carbon, due to the short ionization mean free path [8].

In addition to NSTX, lithium wall conditioning has been successfully applied on an increasing number of tokamaks worldwide, including EAST [9], FTU [10], and T11-M [11]. The very low lithium core contamination [4], combined with the low atomic number, offers a great opportunity for the use of lithium as a PFC in current and future fusion devices. Large influxes of lithium at the target may be exploited to control divertor heat flux, while allowing for a minimal core contamination. The behavior of lithium coatings in ITER-relevant divertor heat and particle fluxes in NSTX-U will help understand the potential for the application of solid/liquid lithium PFCs in future fusion reactors.

This work was supported by U.S. DOE Contracts: DE-AC02- 09CH11466, DE-AC52-07NA27344, DE-AC05-00OR22725.

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