**Topic: EX-D**

# 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 ($Y_C \leq 1\%$, see Figure 1) was observed on lithium-coated ATJ graphite tiles with respect to virgin graphite tiles. The lithium sputtering yield ($Y_{Li}$) from lithiated graphite (see Figure 2) and molybdenum was found to be consistent with physical and surface-temperature-enhanced sputtering from deuterium-saturated lithium ($Y_{Li} \leq$ 10-20%). The larger core impurity penetration factors (>100x), determined 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 behavior of lithium coatings, in terms of lifetime and erosion characteristics, in NSTX-U discharges with higher divertor heat and particle fluxes and longer pulse length.

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 ATJ 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 ATJ 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 below the estimates for the combination of 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 but a potentially important role of leading edges of the divertor tiles was identified.

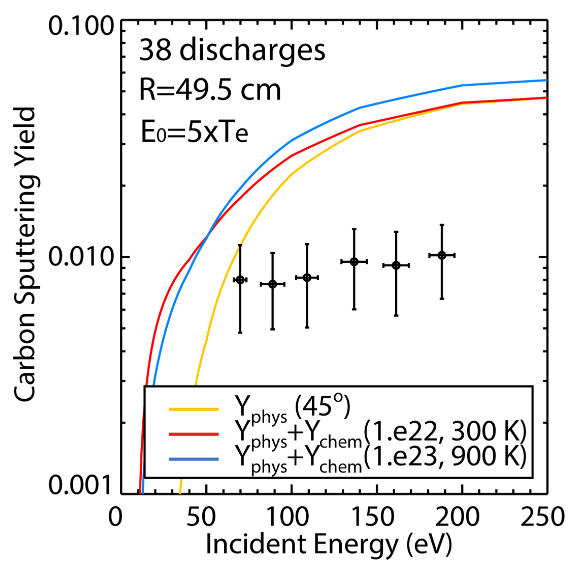


*Figure 1 Carbon sputtering yield from lithiated graphite: experimental (black) and expectations from physical (yellow) and physical + chemical carbon sputtering (red and blue) from Eckstein and Roth scaling.*

Neutral lithium sputtering yields from solid lithium coatings (areal densities > $10^{21}$ atoms/m$^2$) on graphite and molybdenum substrates, derived from Li I spectroscopic line emission, were found to be consistent with expectations from 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 [1] and PISCES [2]), 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 can be neglected. Toroidal asymmetries in lithium sputtering yields were transiently observed with the toroidal profile of lithium influxes at the strike point closely matching the toroidal profile of lithium deposition from the evaporators. The measured gross lithium influxes are 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.

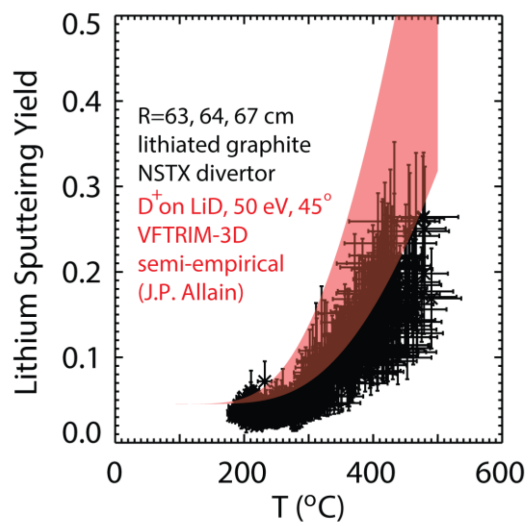


*Figure 2 Experimental lithium sputtering yield (black), semi-empirical lithium sputtering yield model from VFTRIM-3D (J.P. Allain)*

A large difference (>100x) in the impurity penetration factors was found for 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 [3], following the method developed in Ref. [4]. The larger carbon penetration factors indicate the possible 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 [5] 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 [6].

Recently, lithium wall conditioning has been successfully applied on an increasing number of tokamaks worldwide, including EAST [7], FTU [8], and T11-M [9], among others. The very low lithium core contamination [3], despite the large divertor influxes, offers a great opportunity for the use of lithium as a PFC in current and future fusion devices. The large influxes at the target can be exploited to control the divertor heat flux, dissipating power via lithium radiation, while allowing for a minimal core contamination. The core carbon accumulation observed in NSTX [10], resulting from the disappearance of ELMs and the incomplete suppression of carbon sputtering, however, requires the development of impurity control techniques.

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