Study of Carbon and Lithium Neoclassical Impurity Transport in ELM-Free H-Mode Discharges in NSTX

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Neoclassical transport and mechanisms of accumulation of intrinsic impurities (carbon and lithium) are analyzed for H-mode discharges in the National Spherical Torus eXperiment (NSTX). Impurity control is one of the major concerns for the applicability of high performance ELM(edge localized mode)-free regimes in NSTX and in future devices, such as ITER, where the number/size of ELMs will be limited due to constraints on the lifetime of divertor materials. In NSTX, the triggering of ELMs via 3D fields was successful in the reduction of core radiated power but did not change the central carbon accumulation that usually affects ELM-free discharges [1]. In NSTX, changes in neoclassical transport due to modifications in main ion temperature (T_D) and density (n_D) profiles with the application of lithium coatings, together with the disappearance of ELMs, can explain the core carbon accumulation. High lithium particle diffusivities, caused by the high density background carbon ions, can instead account for the low level of lithium core contamination.

The application of lithium evaporative coatings on the graphite plasma facing components (PFCs) led to longer NSTX H-mode discharges with increased stored energy (up to 20%) and suppression of ELMs [2]. Lithium-conditioned discharges are affected by a concomitant core impurity accumulation with Z_{eff} increasing up to 4 and 50-60% of the total electron inventory due to carbon. An early hollow carbon density (n_C) profile (with edge concentrations up to 10-15%) develops at the L-H transition with a slower accumulation in the core, as shown in Fig.1. Lithium ions, instead, do not accumulate and have densities (n_{Li}) only up to 1% of n_C [2]. Here, high performance, ELMy (Type I, 200Hz), NBI-heated (4-6MW) H-mode discharges with boronized PFCs are compared to ELM-free discharges with lithium coatings (up to 600mg). While the application of lithium coatings did not increase carbon influxes from main wall and divertor outer strike point [3], the core carbon inventory increased by a factor of 3-4. While a more comprehensive analysis should also take into consideration possible changes in the SOL parallel and radial impurity transport, this work will focus on the changes in core radial impurity transport due to lithium conditioning.

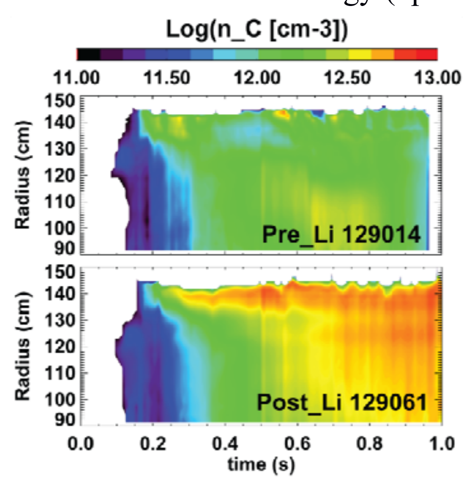

Figure 1: Core carbon density measurements for a discharge without (top) and with lithium coatings (bottom).

Core transport codes TRANSP[4], NCLASS[5] and MIST[6] are used to assess the impact of lithium conditioning on impurity transport. In NSTX H-mode discharges, anomalous ion transport is generally suppressed and ion particle transport is close to neoclassical [7]. TRANSP/NCLASS are used to generate multi-impurity neoclassical transport coefficients, which are used by MIST to predict the evolution of n_C and n_{Li} and check consistency with measurements.

In a typical NSTX H-mode discharge, deuterons are in the banana-plateau regime while both carbon and lithium ions are in the Pfirsch-Schlüter (PS) regime for $\rho>0.4$ and $\rho>0.6$ respectively, where ρ is the normalized low field side radius. Carbon is a strong impurity (impurity strength $\alpha_C=n_C Z_C^2/n_D>5$ at $\rho\sim0.8$) mostly collisional on deuterium ions ($\nu_{C\_D}\sim10^4 s^{-1}$, $\nu_{C\_Li}\sim5\times10^2 s^{-1}$) while lithium is a weak impurity ($\alpha_{Li}\sim0.02$ at $\rho\sim0.8$), mostly collisional on background carbon ions ($\nu_{Li\_D}\sim5\times10^3 s^{-1}$, $\nu_{Li\_C}>\sim5\times10^4 s^{-1}$), thus the importance of including multi-ion effects for lithium transport. A sensitivity study on n_{Li} confirms the negligible effect of lithium ions on carbon transport while transport driven by carbon ions represents the dominant transport channel for lithium. The enhancement (up to 4×) in lithium particle diffusivities (D_{Li}) due to the presence of a strong impurity (carbon) makes lithium transport dominated by diffusive fluxes. Modeling with MIST code shows how the high core D_{Li} ($\sim5m^2/s$ at $\rho\sim0.8$) results in core n_{Li} of the order of 1-10% of n_C (assuming the same edge source for the two impurities).

Carbon neoclassical transport can be approximated as being mostly driven by collision on deuterium ions and T_D and n_D gradient effects. Pumping of deuterium atoms by lithium coatings results in a lower core n_D and a steeper edge ∇n_D, compared to discharges with boronized PFCs while the weaker edge ∇T_D results in a higher edge T_D (by as much as 100-200 eV). The consequent reduction in edge carbon collisionality leads to reduced carbon diffusivities ($D_C<1m^2/s$) for $\rho > 0.8$. The increase in ∇n_D results in an increase in both edge and core inward convective velocity ($v_C\sim$-10m/s at $\rho\sim0.8$) while the reduction in ∇T_D at the edge ($0.7<\rho<0.9$) reduces the temperature screening component in the PS flux. These effects are shown in Fig.2 where D_C and v_C profiles from NCLASS are shown for discharges with (red) and without lithium (black). The overall neoclassical v_C profile, together with a flat D_C, is consistent with the early formation of a hollow profile and a slower accumulation in the core as an effect of both the core pinch term and of diffusion from the edge. Forward modeling with the MIST code indicates that these changes between discharges with and without lithium coatings are sufficient to explain the observed increase in core n_C.

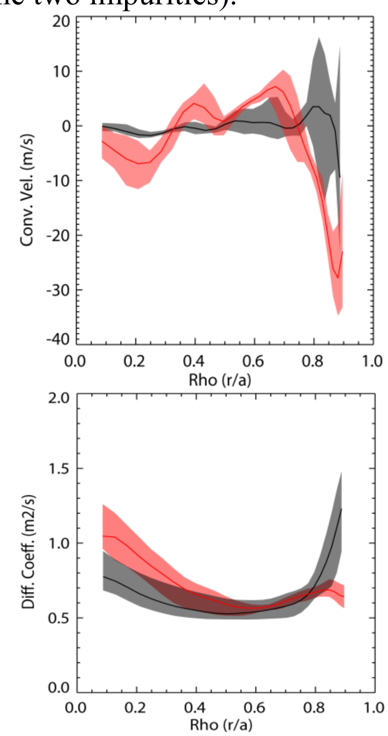

Figure 2: Neoclassical carbon convective velocity (top) and diffusion coefficient (bottom) for a discharge without (black) and with (red) lithium coatings.

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