Study of lithium and carbon sputtering from lithium-coated graphite plasma facing components in the NSTX divertor

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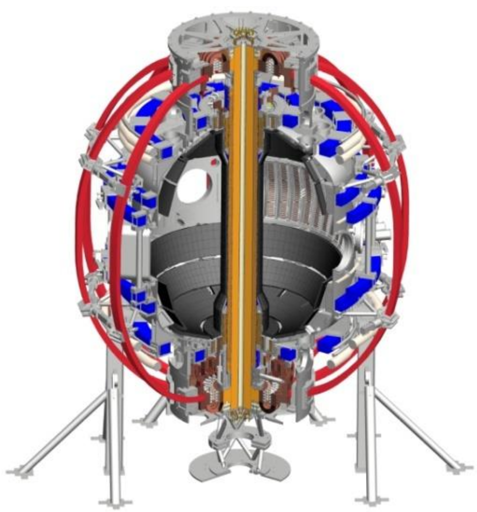
Filippo Scotti[1]

V.A. Soukhanovskii[2], E.M. Meier[2], A.L. Roquemore[1], J-W. Ahn[3], J.P. Allain[4], R.E. Bell[1], A. Diallo[1], S.P. Gerhardt[1], M.A. Jaworski[1], R. Kaita[1], B.P. LeBlanc[1], A.G. McLean[2], M. Podestà[1]

[1]PPPL, [2]LLNL, [3]ORNL, [4]U.Illinois U.C.

55th APS-DPP Meeting
Denver, CO - November 11th-15th, 2013



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Abstract

In this work, the behavior of lithium conditioned graphite PFCs in the NSTX divertor is characterized in terms of lithium and carbon sputtering yields and gross impurity influxes during H-mode ELM-free NBI-heated discharges. Impurity influxes and sputtering yield measurements in the NSTX divertor are derived from photometrically calibrated filtered cameras and divertor Langmuir probes via the S/XB method.

Neutral lithium sputtering yield Y_{Li} from solid lithium coatings in NSTX is found to be consistent with values reported from test stand experiments (with Y_{Li}~0.03−0.07). Temperature-enhanced sputtering yield is generally observed for surface temperatures above the lithium melting point (with Y_{Li}~0.1−0.2) in the proximity of the divertor strike point, leading to divertor gross lithium influxes of a few 10^{21} atoms/s. A moderate reduction of the carbon sputtering yield is observed with the application of lithium coatings with gross divertor carbon influxes of several 10^{20} atoms/s.

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

Outline: lithium conditioning affects divertor impurity influxes, SOL transport, and core transport

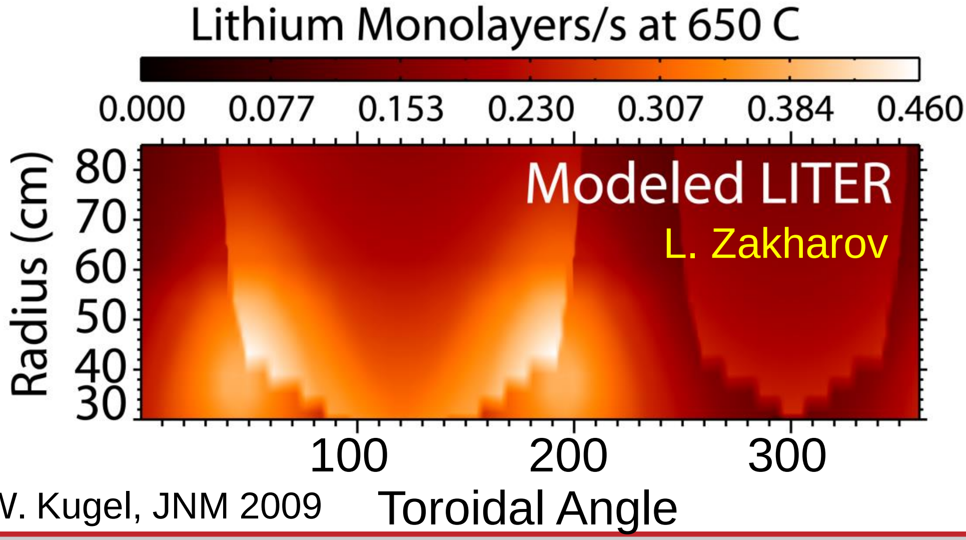
- Divertor impurity influxes in NSTX:
  - Lithium sputtering consistent with physical and thermal sputtering
  - Reduction in carbon sputtering yield observed on lithiated graphite
  - Toroidal asymmetries in divertor lithium influxes follow LITER deposition
  - Penetration factors indicate divertor lithium retention stronger than carbon

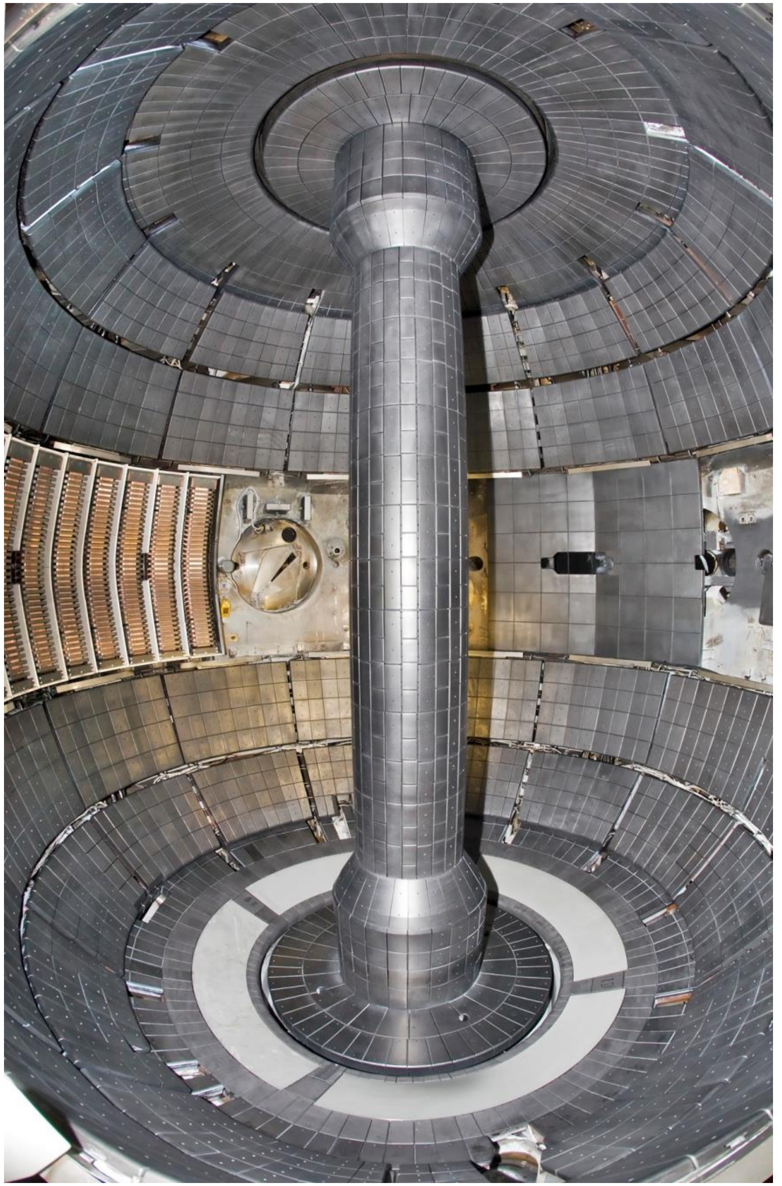
- SOL/edge parallel and radial transport (via UEDGE modeling):
  - Stronger divertor retention for lithium than carbon
  - High classical/neoclassical diffusivity further helps prevent lithium accumulation (F. Scotti , NF 2013)
  - No effect of lithium radiation on divertor power balance
  - Divertor impurity retention weakens with reduced divertor recycling

- NSTX-U baseline scenario still includes lithium coatings on graphite PFCs:
  - Benefits observed with lithium conditioning
  - Lithium effectively retained in divertor
  - ELMs suppression results in carbon accumulation
  - Techniques developed in NSTX to limit impurity accumulation will be considered in NSTX-U

Evaporative lithium coatings routinely applied on NSTX plasma facing components for wall conditioning

- Graphite is the main PFC material in NSTX:
  - ATJ tiles on divertor and outer wall
  - ATJ and CFC tiles on center stack
  - Porous moly in outer divertor (LLD)
- Lithium coatings evaporated on PFCs [1]:
  - 100–300 mg of lithium applied between discharges using LITERs
  - nominal “coating” thickness ~20-40 nm ($\sim 10^{21}$ atoms/m^2)
- Highly toroidally asymmetric deposition

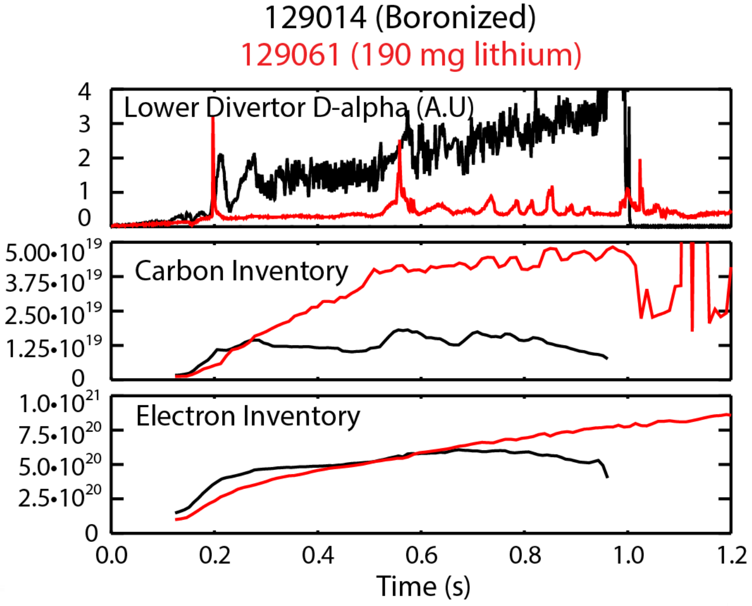


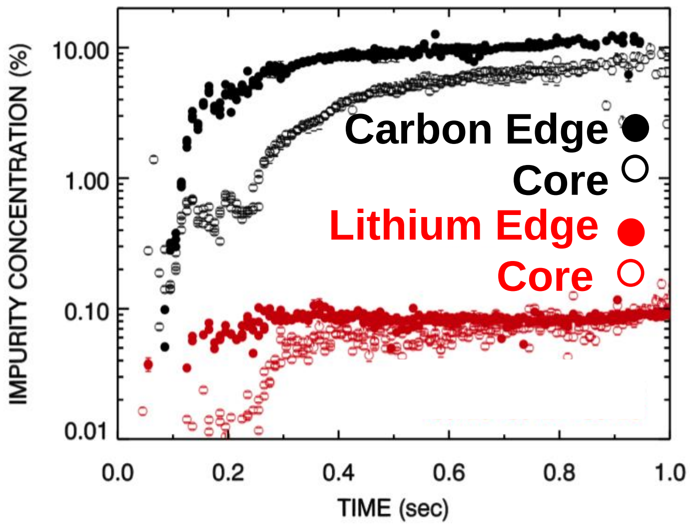


[1] H.W. Kugel, JNM 2009

Wall conditioning via lithium evaporative coatings on graphite PFCs results in carbon accumulation

- Benefits observed with lithium conditioning:
  - reduction in deuterium wall recycling
    - re-attachment of inner divertor, disappearance of MARFE [1]
  - deuterium inventory control
    - via reduced recycling [2]
  - increase in energy confinement time
    - reduced transport at lower ν^*_e [3]
  - suppression of ELMs
    - due to changes in n_e profiles [4]
- However:
  - carbon inventory increased by 3-4X [5]
  - low core lithium density (n_{Li}/n_e<0.1%) [6]
  - high-Z impurity accumulation leads to core P_{rad} up to 50% of P_{inj} [7]

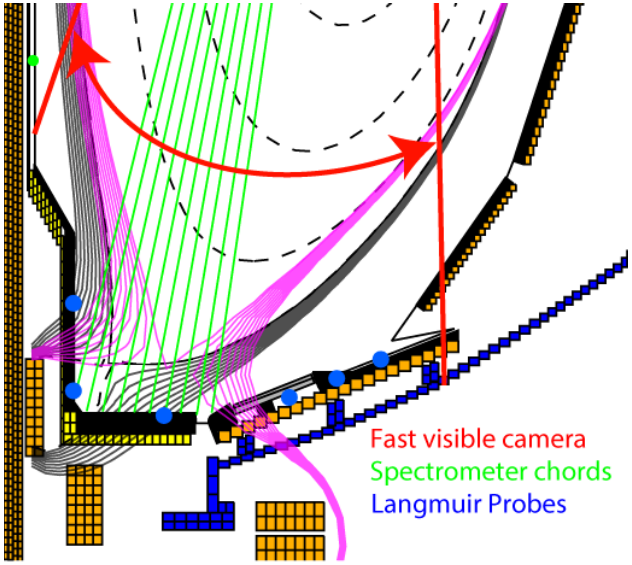




[1] F. Scotti, JNM 2011.
[2] V.A. Soukhanovskii, IAEA 2010.
[3] S.M. Kaye, NF 2013.
[4] R. Maingi, NF 2013.
[5] F. Scotti, NF 2013.
[6] M. Podesta, NF 2012.
[7] S.F. Paul, JNM 2009.

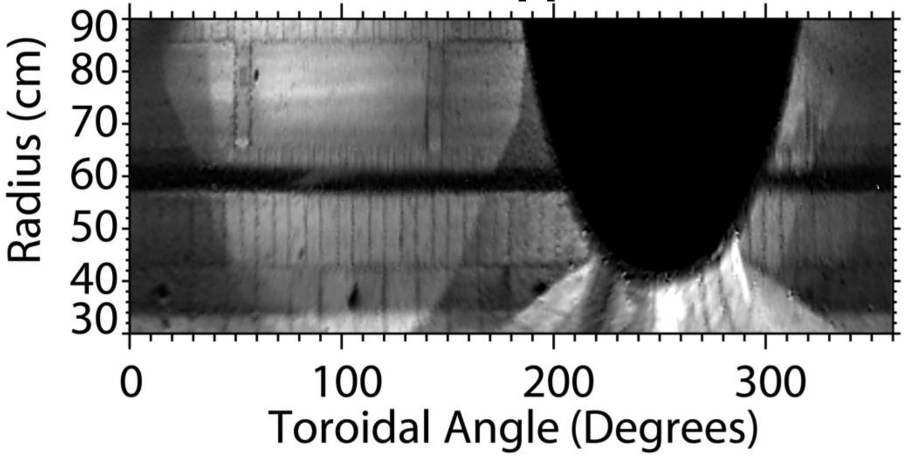
NSTX divertor diagnostics well suited for analysis of impurity influxes and sputtering yield

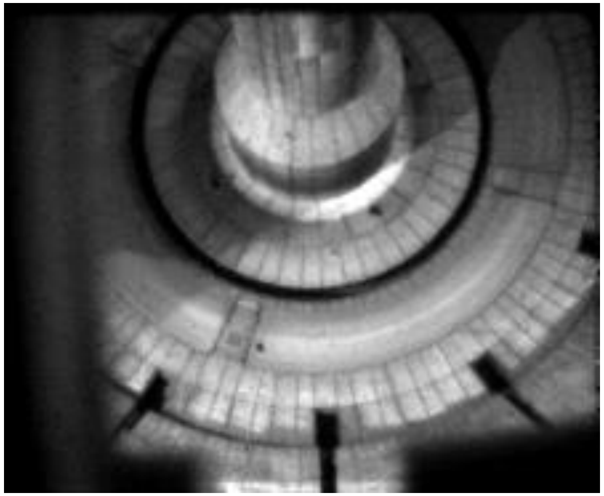
- Diagnostics for divertor impurity influxes :
  - 1D/2D cameras (Li I, Li II, C II, C III, C IV) [1]
  - divertor spectrometer VIPS2 (C II, CD) [2]
  - Langmuir probes for T_e, n_e, Γ_{D+} [3]
  - two color IR thermography for T_{surf} [4]
  - inverse photon efficiencies (S/XB) from ADAS
  - sputtering yield derived from impurity influxes



$$\Gamma_i = \frac{S}{X\ B}\,\Gamma_{ph} \qquad Y = \frac{\Gamma_{imp}}{\Gamma_{D+}} = \frac{\Gamma_{ph-imp} S / XB_{imp}}{J_{SAT}}$$

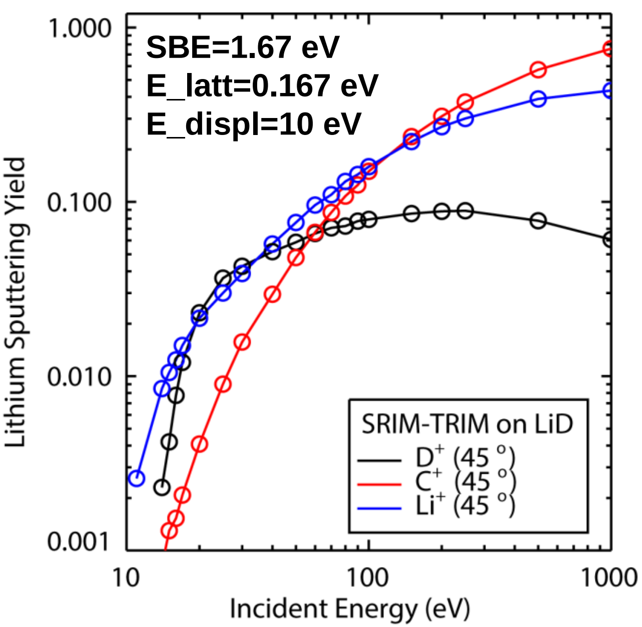
[1] Scotti, RSI 2012.
[2] Soukhanovskii, RSI 2010.
[3] Kallman, RSI 2010.
[4] McLean, RSI 2012.

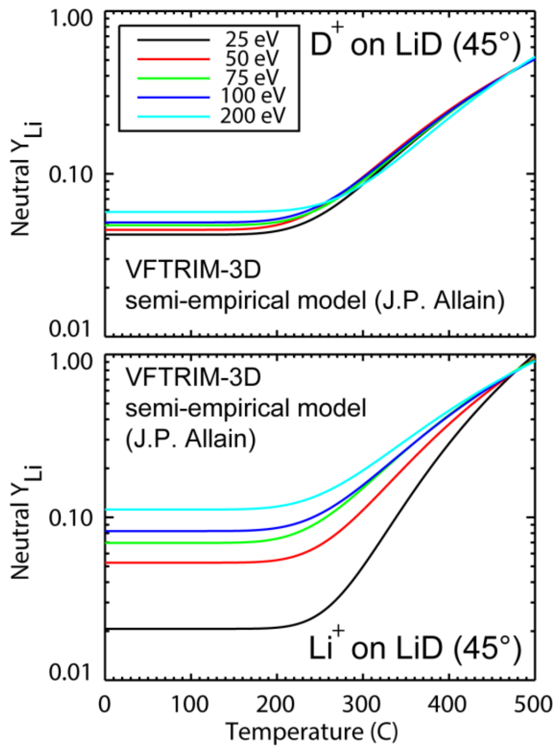




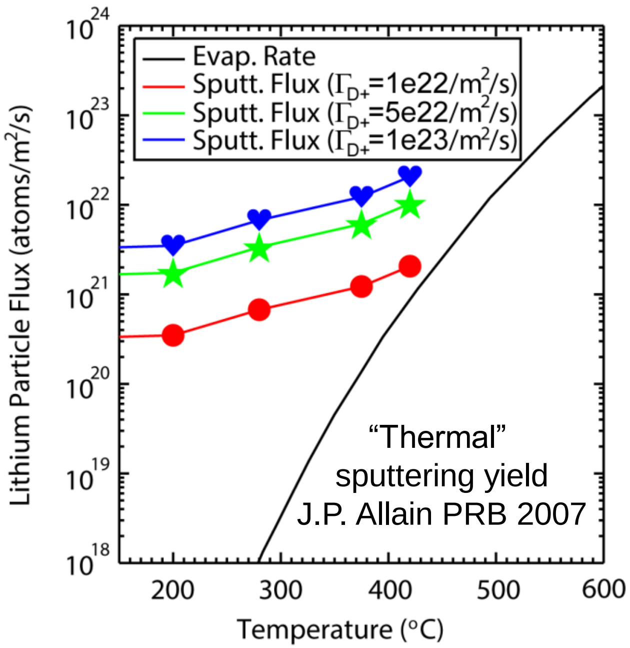
"Thermal" lithium sputtering yield is expected to be the dominant sputtering mechanism in the NSTX divertor

- Physical sputtering is the main lithium sputtering process
  - threshold energy E_{th} ~10 eV, 2/3 sputtered as ions → "invisible" to plasma
  - sputtering yield (Y_{Li}) ~ constant for typical incident energies in NSTX
- "Thermal" enhancement observed in test stands (PISCES [1] and IIAX [2])
  - expected to dominate lithium influxes for T_{surf} < 550ºC for typical NSTX divertor incident ion fluxes (Γ_{D+}<~10^{23} ions/m^2/s)



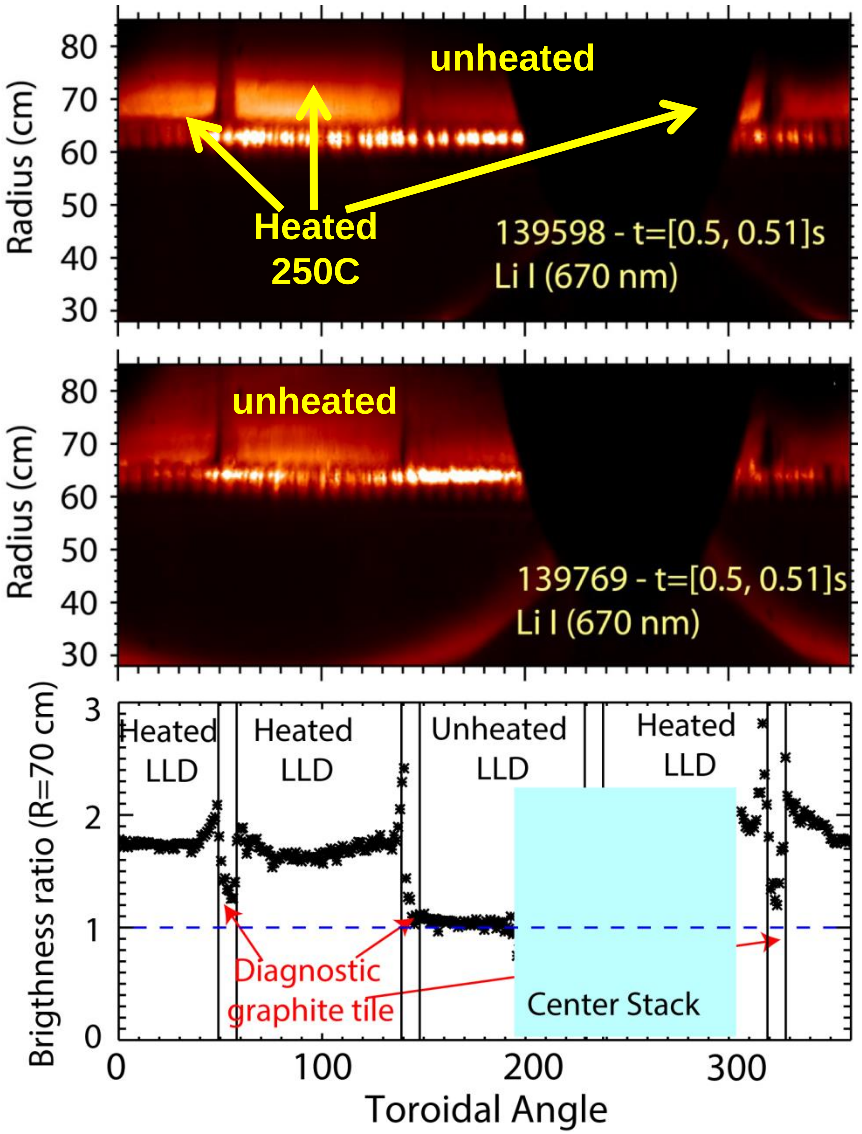


[1] R. Doerner, JNM 2003.
[2] J.P. Allain, PRB 2007.



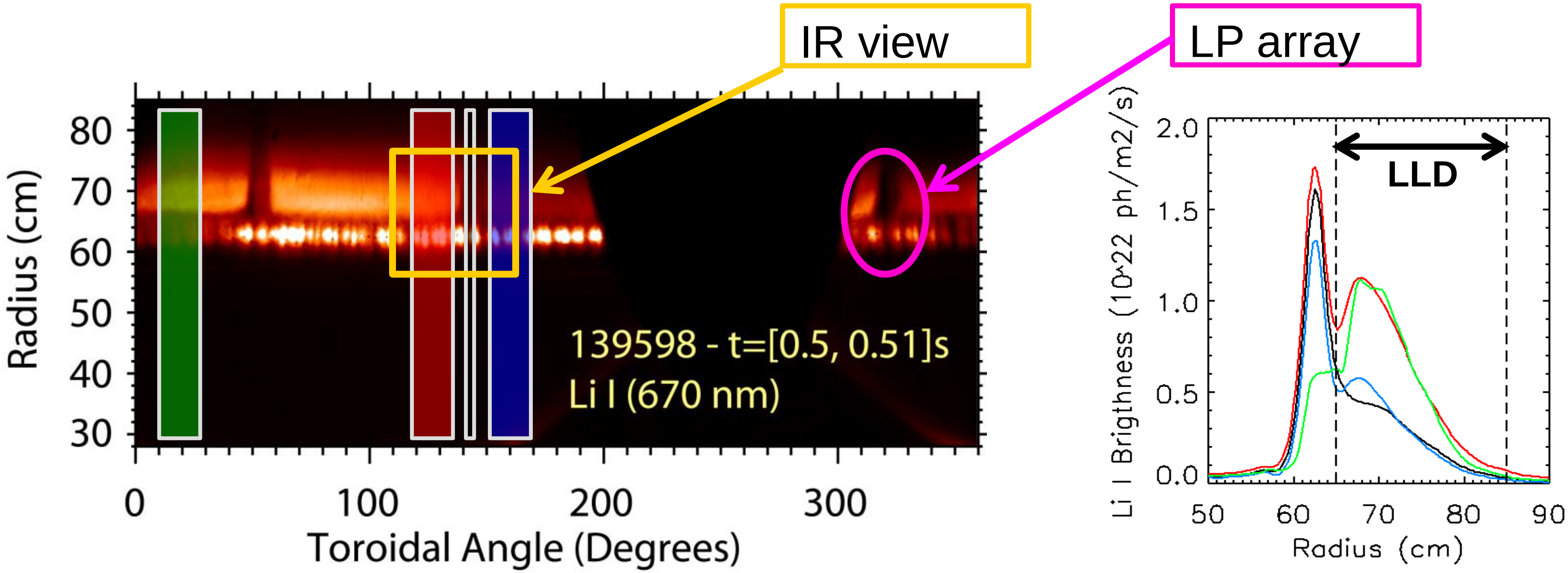
External and plasma heating of divertor PFCs allow study of thermal response of Y_{Li} in NSTX

- Discharges with unheated and externally heated PFCs (LLD):
  - after large evaporation (~200 g) nominal "coating" thickness ~10s μm
  - outer strike point at R ~ 62 cm
- Differential heating of LLD leads to non-axisymmetric lithium influxes:
  - 3 LLD plates externally heated to 250ºC only in one discharge
  - enhancement consistent with expectations from T_{surf} enhanced Y_{Li}
- Asymmetries observed also at strike point as a result of plasma heating
  - follow LITER deposition profile



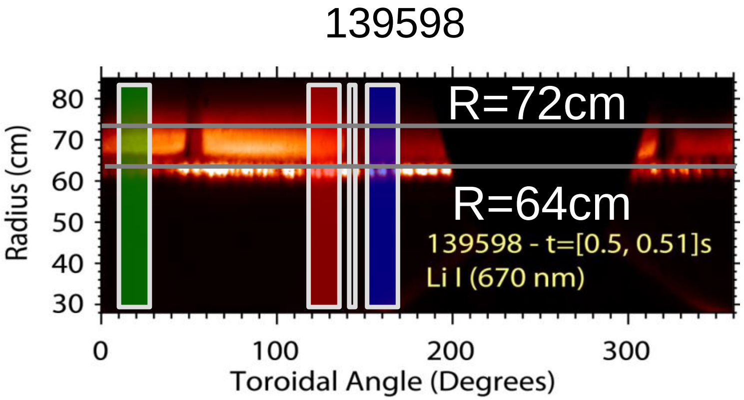
Sputtering yields derived at different toroidal and radial locations via 2D visible and IR cameras and LP array

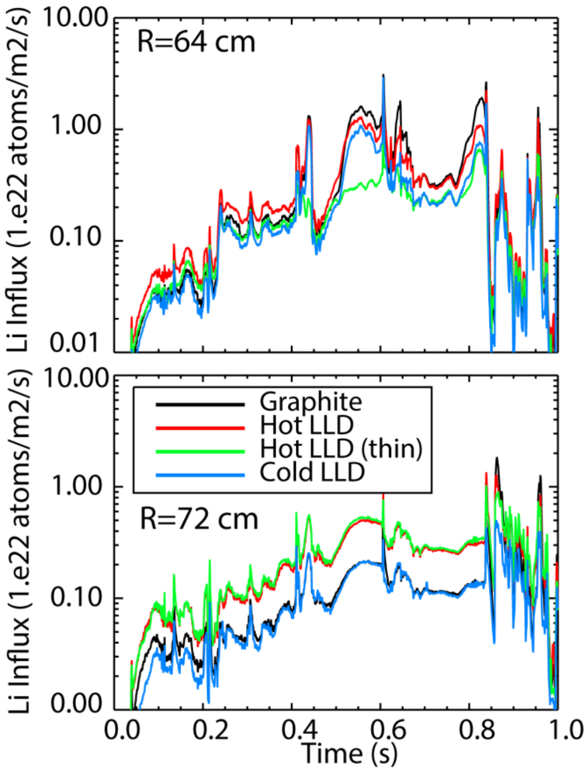
- Four different toroidal locations analyzed:
  - Diagnostic graphite tile Φ = [142°-148°]
  - Cold LLD segment Φ = [150°-160°]
  - Hot LLD segment + thick coating location Φ = [120°-135°]
  - Hot LLD segment + thin coating location Φ = [10°-30°]
- Six different radial locations analyzed:
  - R = [63, 64, 67, 70, 71, 72] cm from outer strike point to far SOL

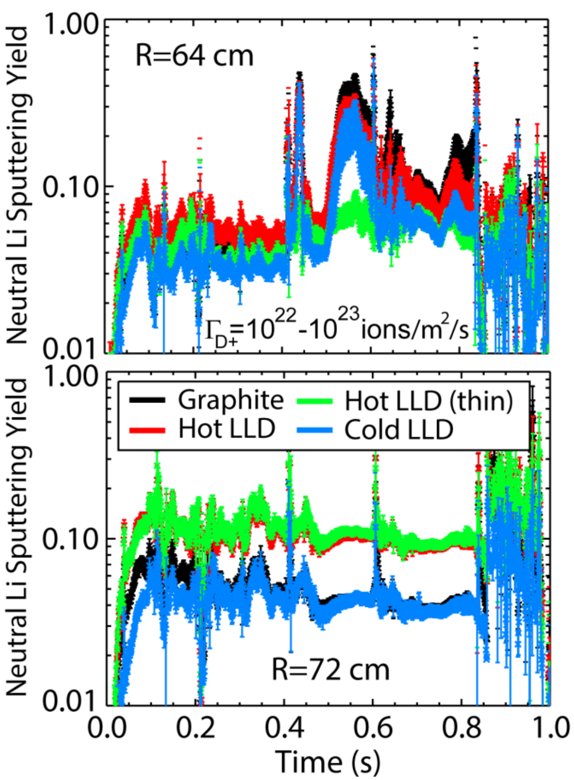


Temperature enhanced sputtering observed as a result of external and plasma heating of divertor target

- T_{surf} dependence of Y_{Li} observed as a result of external heating (up to 2X)
  - consistent with expected T_{surf}-dependence of Y_{Li}
  - comparable response from moly and graphite with thick lithium coatings
- Enhancement in sputtering yield at strike point only with thick coatings



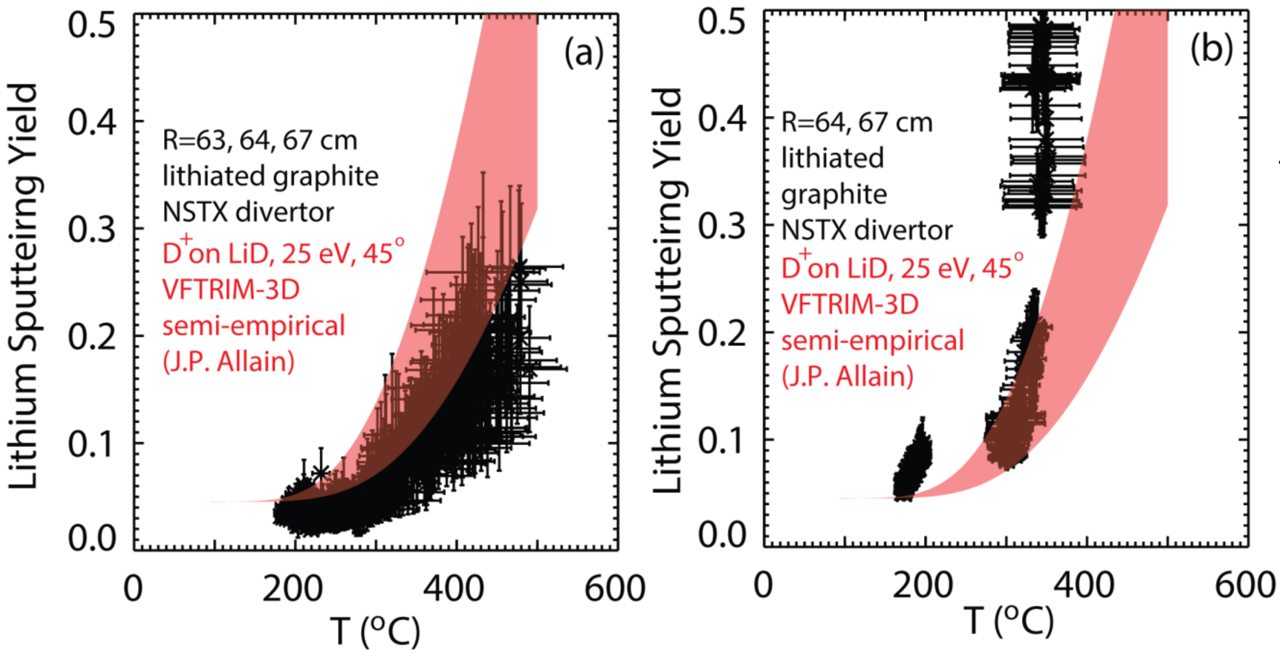




Experimental Y_{Li} consistent with physical sputtering with signature of T_{surf} dependent sputtering yield

- Y_{Li} from solid coatings consistent with SRIM-TRIM from LiD/Li (Y_{Li}~3-7%)
- Y_{Li} from liquid coatings consistent with "thermal" sputtering (Y_{Li}~10-20%)
  - consistent results obtained over large set of discharges (Figure a)
  - data averaged over 1 ms and 2-4º toroidally
  - leading edge effects lead to variation of T_{surf} over graphite tile
- Transient anomalous enhancement of Y_{Li} at the OSP observed with fresh thick coatings (Figure b)
  - enhancement follows toroidal asymmetry in lithium deposition profile

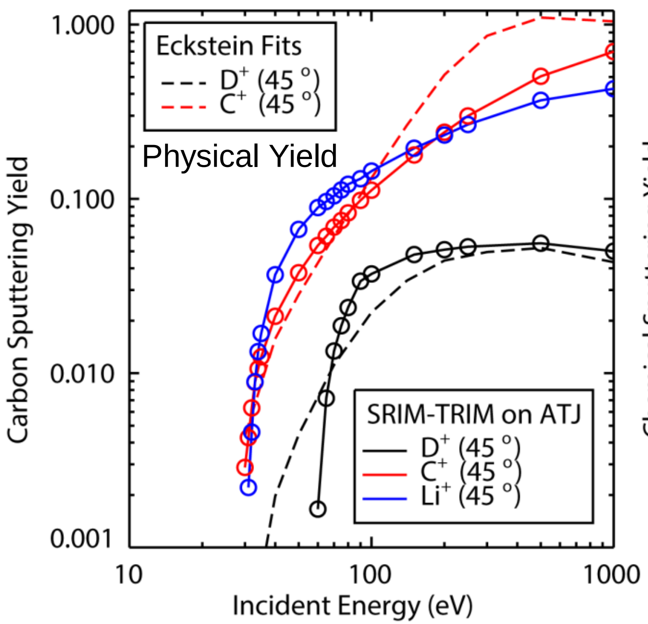
139769
several discharges
after 200g evap

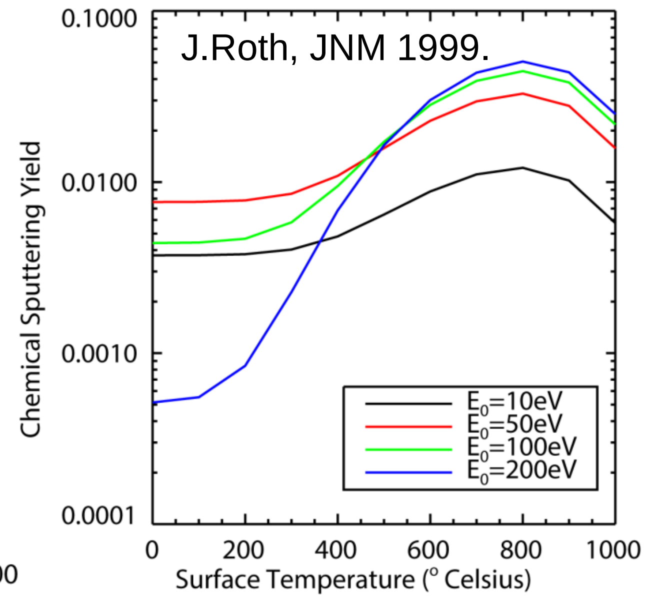


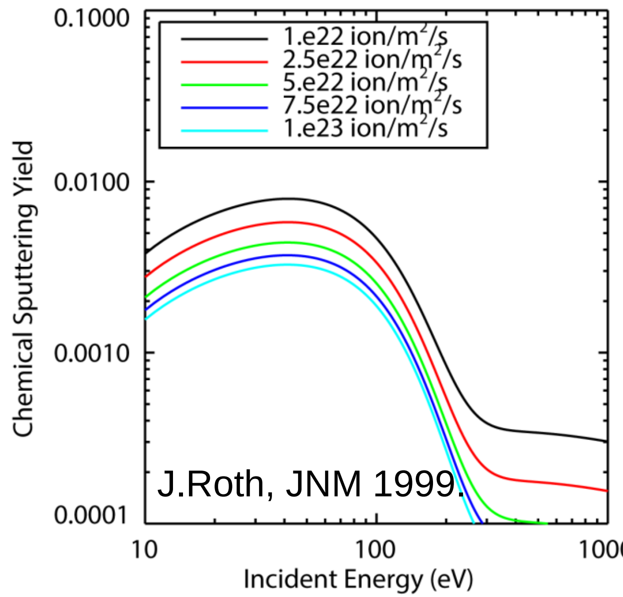
139598 – fresh thick coatings

Carbon sputtering yield has contributions from physical and chemical sputtering processes

- Carbon: physical (Y_{phys}, E_{th}~30 eV) and chemical (Y_{chem}) sputtering processes
  - Y_{chem} dominates in low T_e plasmas
  - depends on incident flux and T_{surf}
- Reduction in Y_C on lithium-coated graphite observed in test stands (e.g. IIAX)
  - Associated to formation of ionic bonds between C - Li [Racic, JNM 2009]
  - Observed in MD simulations due to Li-C-O chemistry [Krstic, PRL 2013]
- In NSTX graphite surface roughness>> lithium "thickness" [Taylor, APS 2013]

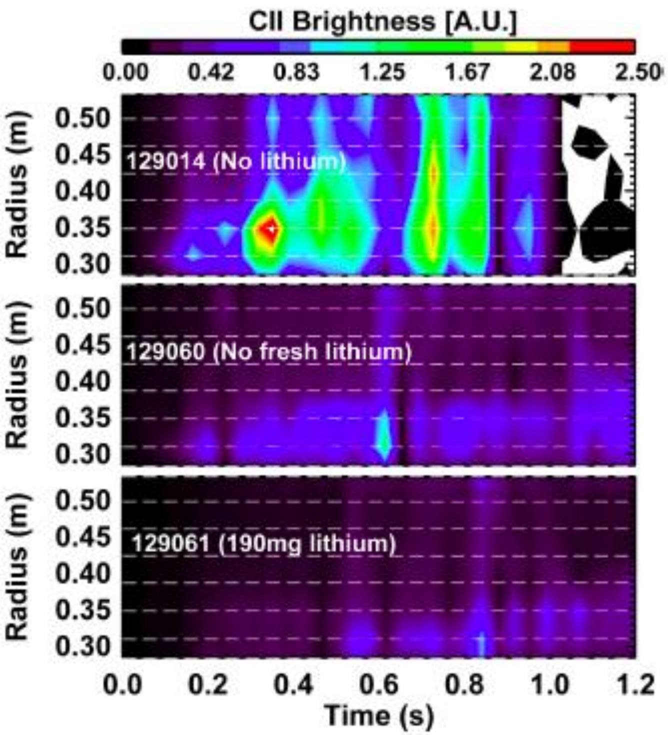


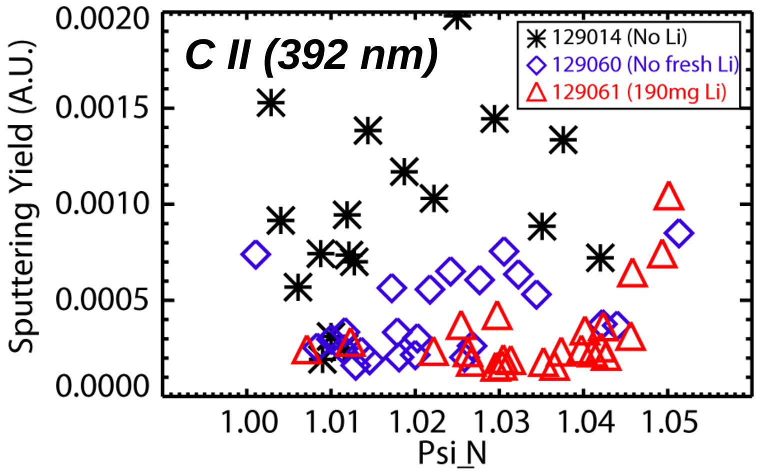




Moderate reduction in carbon sputtering yield in near/far SOL observed with lithium conditioning

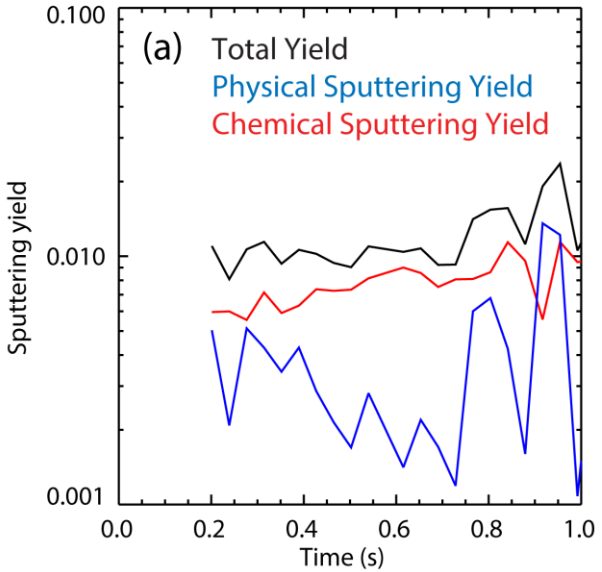
- Y_C measured in near/far SOL during first lithium evaporation on boronized graphite in 2008 (190 mg fresh Li evaporation)
- Moderate reduction in sputtering yield (Y_C) with application of lithium:
  - Y_C from C II (VIPS2 at 392 nm): physical + chemical component
  - Complicated by T_e sensitivity of S/XB
  - Uncorrelated with increase in core C inventory (due to ELM suppression)

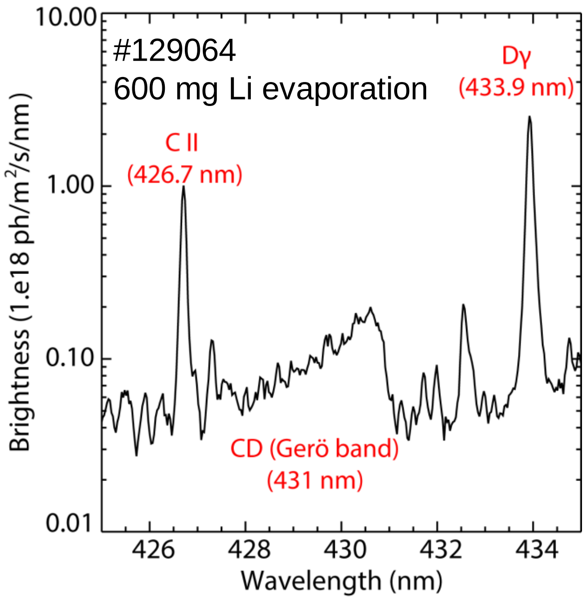


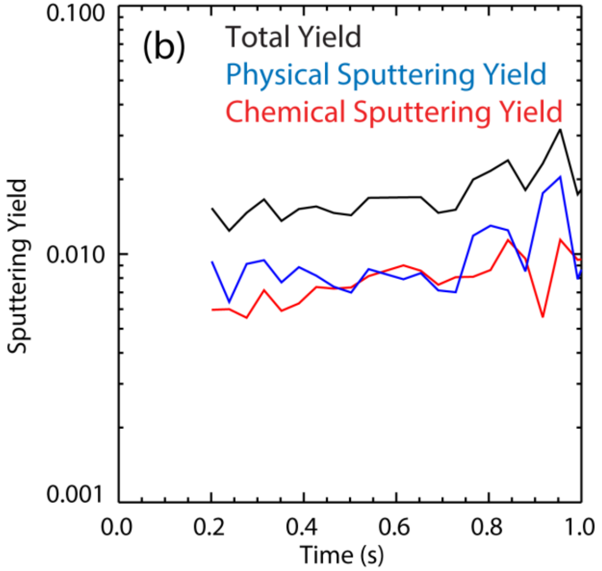


Significant contribution from chemical sputtering is still observed in discharges with lithium conditioning

- Significant contribution from chemical sputtering:
  - incident fluxes from D-γ (using S/XB from ADAS)
    - chemical yield from CD(430 nm)/D-γ
  - uncertainty in D/XB_{430} coeff. (20-40) [McLean]
  - total sputtering yield from C II(426 nm)/D-γ
    - (a) S/XB for both chem. and phys. contrib
    - (b) D/XB_{426} for chem. [McLean, PhD thesis] and S/XB for phys. contribution







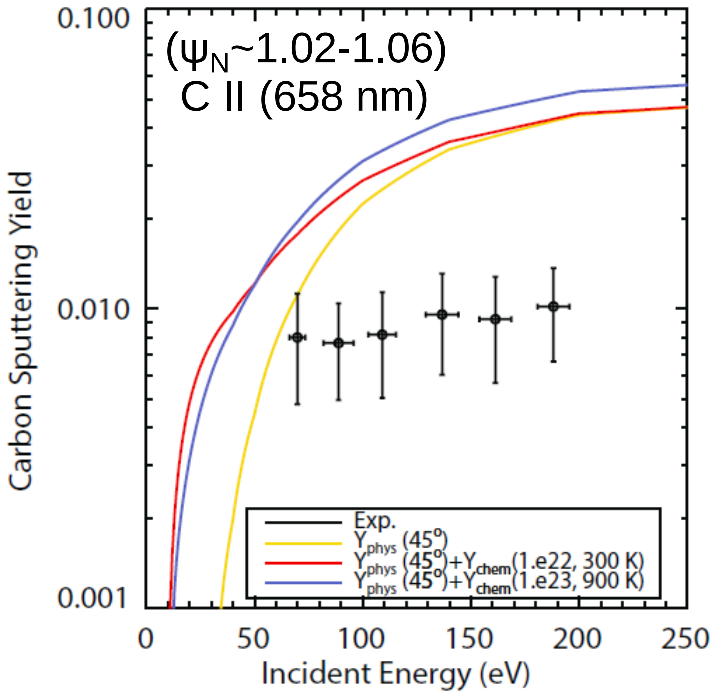
Measured Y_C on lithium conditioned graphite below estimates for physical and chemical sputtering

- In 2010, only lithium-coated divertor conditions (typical dose 0-400 mg Li):
  - large set of 2D camera data: C II (658 nm), C III (465 nm), C IV (580 nm)

- Y_C near SOL reduced with respect to $Y_{phys}+Y_{chem}$ estimates [Eckstein+Roth]
  - Statistical analysis of 40 ELM-free H-modes (thin "coatings" only)
  - Y_{Chem} data from VIPS2 still need to be included in analysis

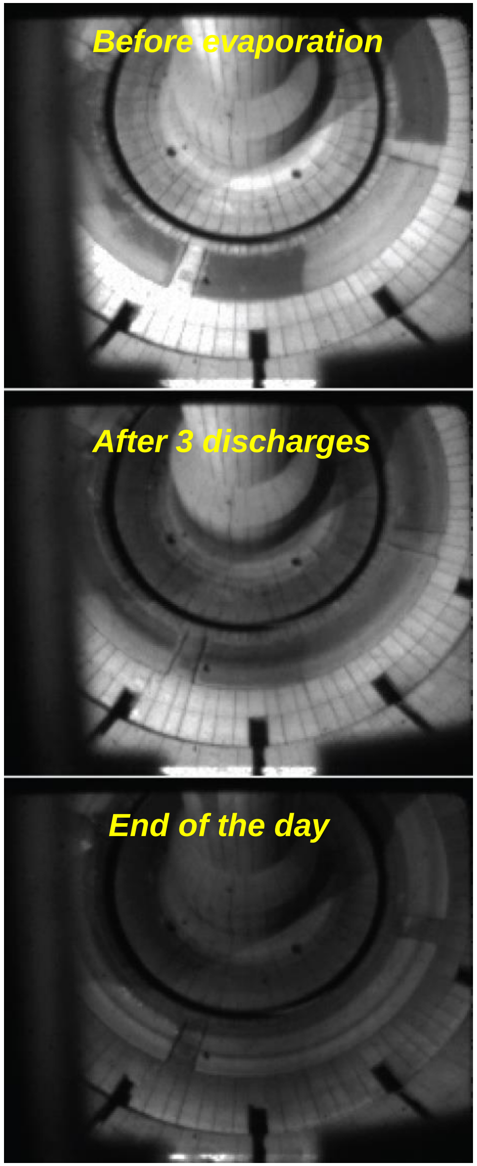
- However:
  - No clear dependence on amount of lithium
  - No increase in Y_C during discharge

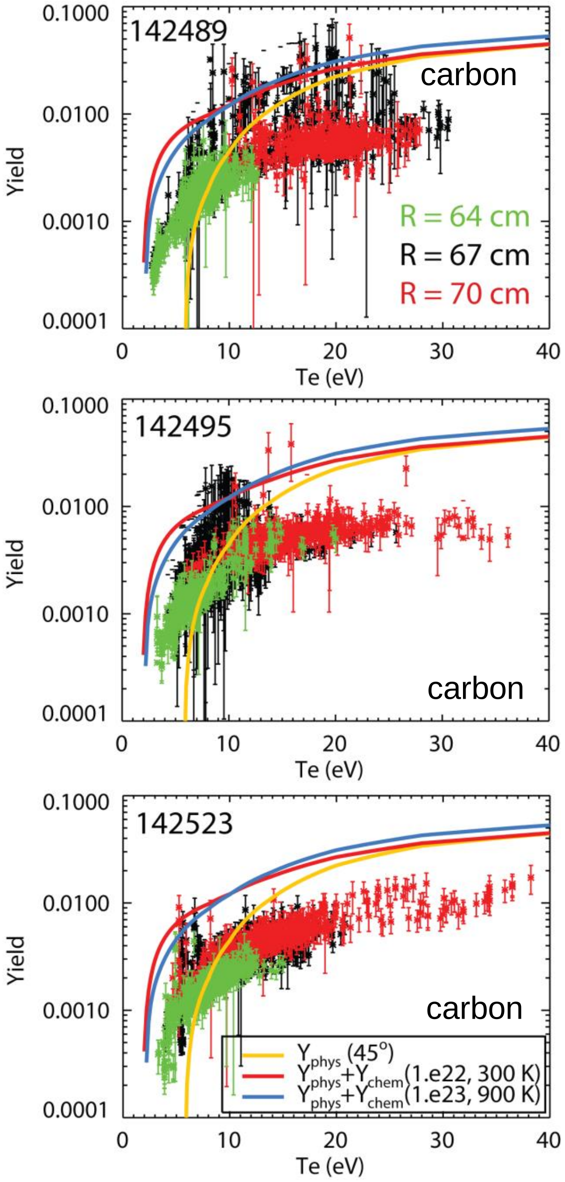
- Y_C reduction from lithium coverage limited by:
  - Lifetime of coatings (intercalation, erosion)
  - Higher OSP T_e
  - Surface roughness >> "coating" thickness
  - Effect of tile leading edges
  - Migration/redeposition of carbon from other sources



Modifications of lithium coatings in the divertor evident from visible imaging after one single discharge

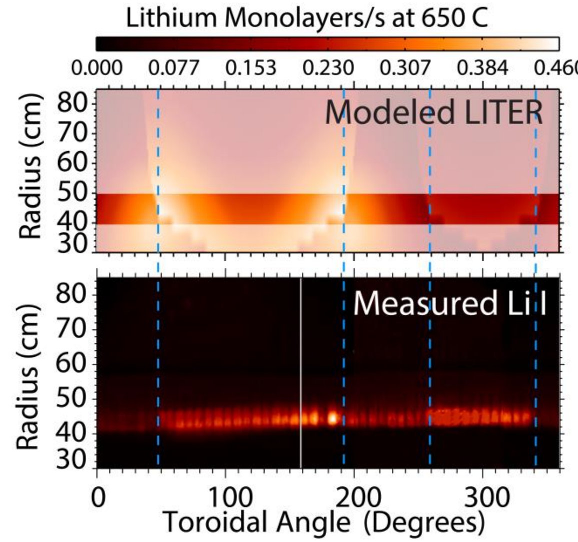
- Visible imaging indicates clear change in surface conditions after repetitive discharges without lithium evaporation:
  - 6 g of Li before #142485
  - changes in surface reflectivity after one single discharge
  - suggest changes on thickness ~100s nm (λ_{vis})
- No clear change in Y_C:
  - First useful discharge, 4 discharges after evap.
  - No increase during day
  - But in-vessel cumulated lithium ~ 900 g
  - Energy dependence consistent with $Y_{phys}+Y_{chem}$
  - Absolute value reduced

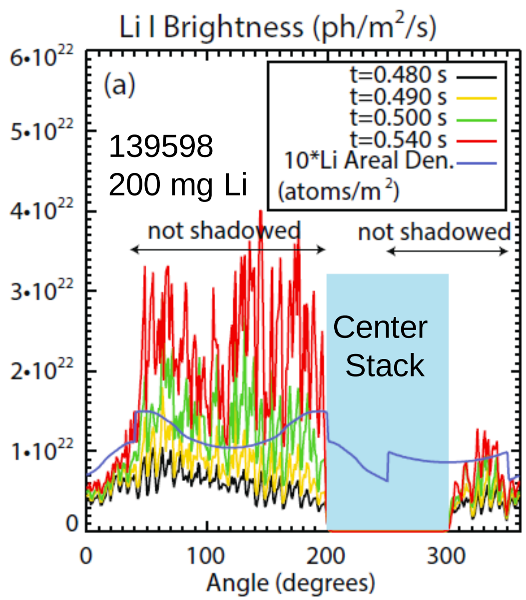


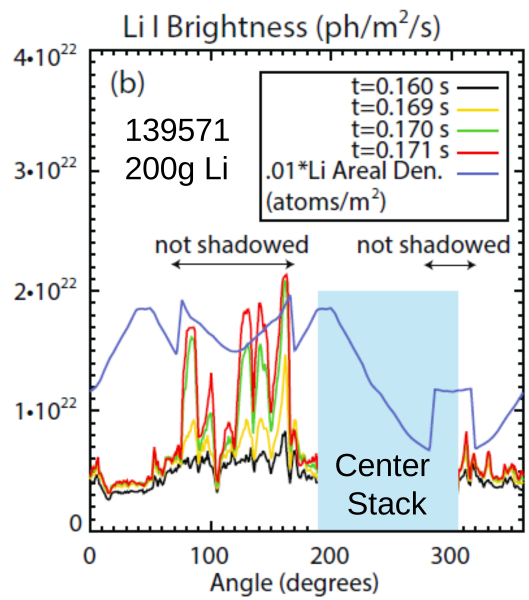


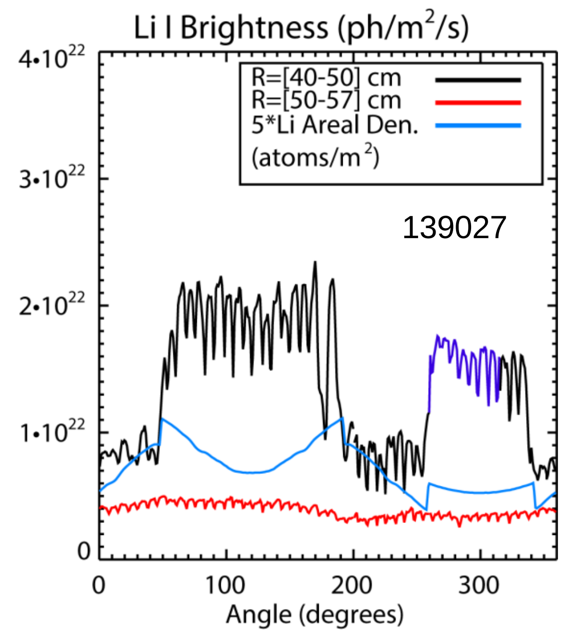
Toroidal asymmetries in lithium influxes/sputtering yield observed closely following LITER deposition profile

- Anomalous transient Y_{Li} associated with toroidal asymmetries in lithium influxes
- Asymmetries occurring only close to the strike point
  - Closely follow LITER deposition profile
- Possibly associated with different thermal response, degradation of lithium coatings or generation /ejection of lithium droplets
  - Not expected if lithium thickness > ion range



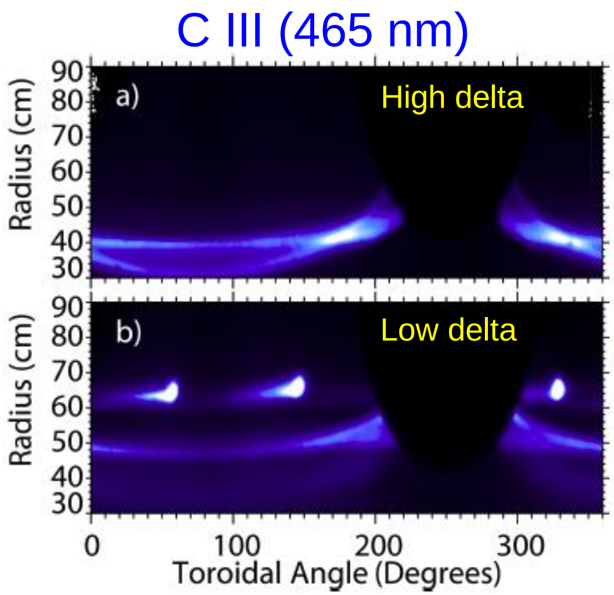


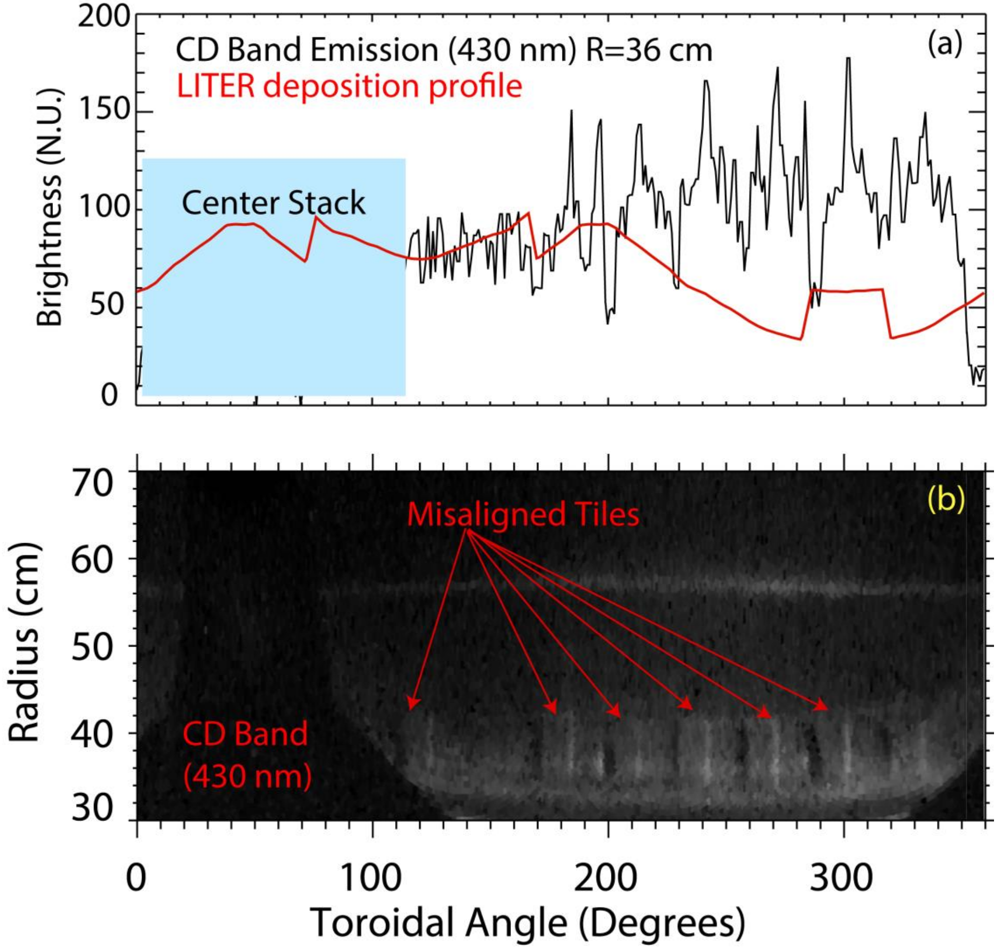




Toroidal asymmetries in carbon influxes are typically observed due to leading edges of divertor tiles

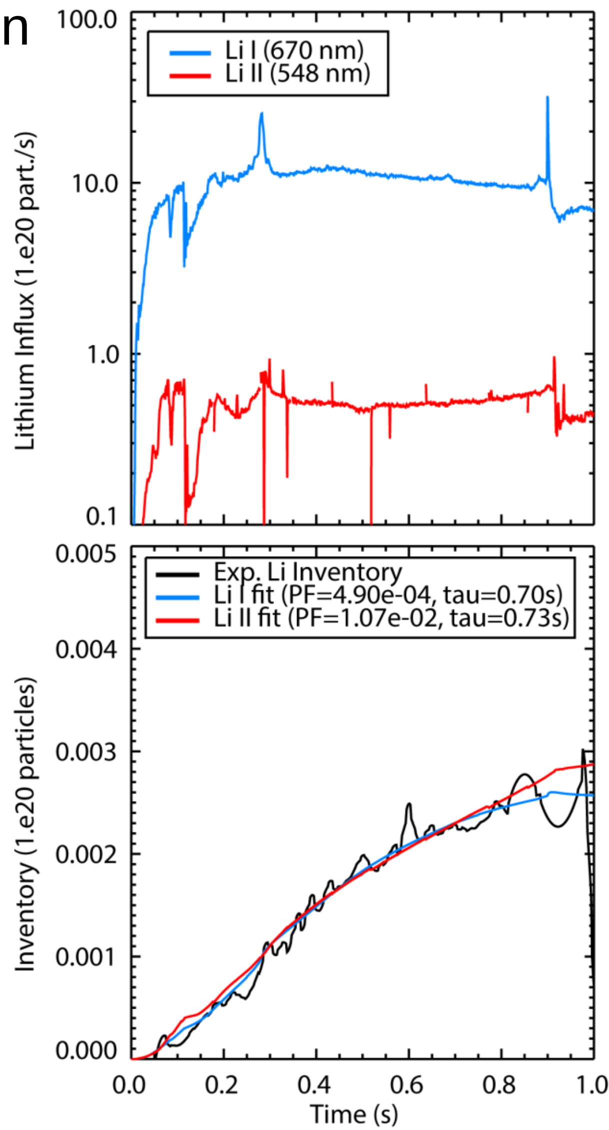
- Unlike for lithium, no toroidal asymmetries in carbon influxes are observed as a result of toroidally asymmetric lithium deposition
  - More spectroscopic coverage of neutral carbon emission needed
- Toroidal asymmetries clearly observed as a result of leading edges due to tile-to-tile misalignments and shallow field lines





Upper estimate for penetration factor of divertor lithium sources suggest strong lithium divertor retention

- Lower divertor largest source due to LITER deposition pattern [Soukhanovskii, IAEA 2010]
- OSP influxes from database using constant S/XBs:
  - Large neutral lithium divertor influxes
    - 1-6x10^{21} atoms/s (Li I)
  - Largely reduced (>x10) lithium ionized influxes
  - Suggest large re-deposition fraction ($\lambda_{mfpLi}<\rho_{Li}$)*
- Core penetration factors for OSP sources fitting core particle inventories
  - F ~10^{-4}-10^{-3} from Li I ; F~10^{-3}-10^{-2} from Li II



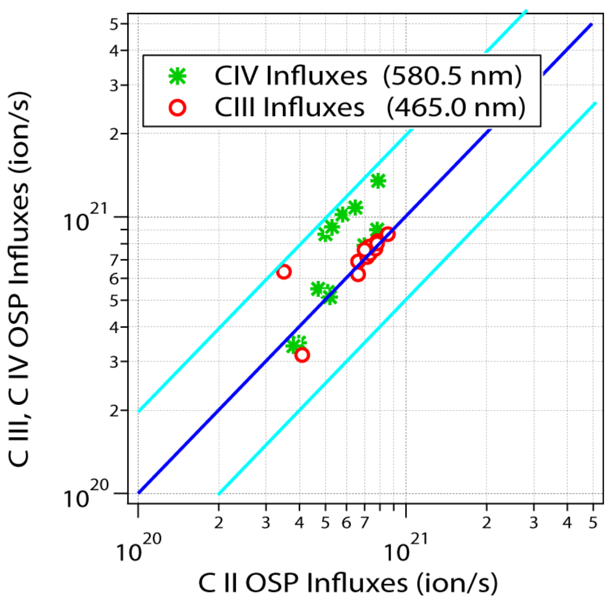
$$\frac{dN_Z(t)}{dt} = -\frac{N_Z(t)}{\tau_Z} + \sum_i F_i \Gamma_i,$$

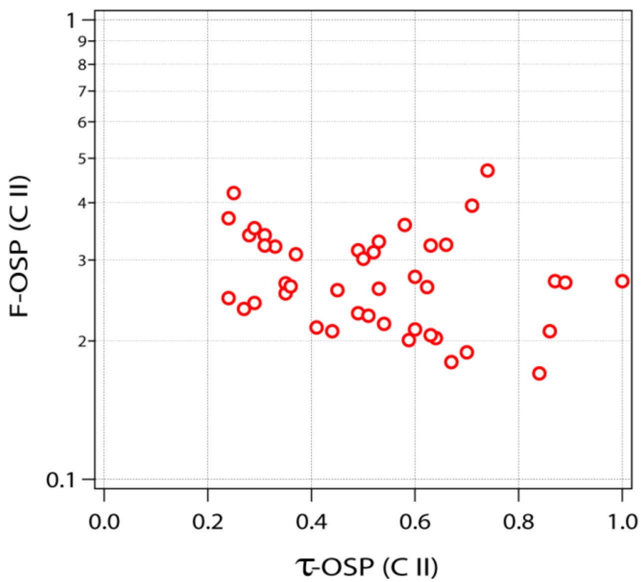
$$N_Z(t) = F_i \exp\left(-\frac{t}{\tau_Z}\right) \int_0^t \Gamma_i(t) \exp\left(\frac{t}{\tau_Z}\right) dt.$$

* Consistent with Allain NF 2011

Upper estimate for penetration factor of divertor carbon sources suggest divertor retention worse than lithium

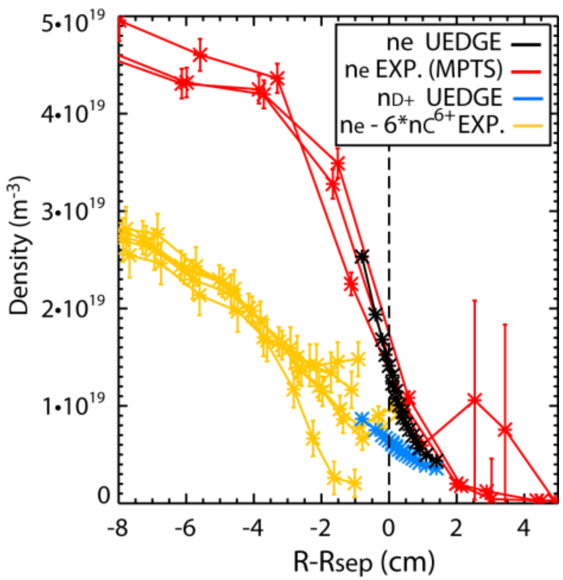
- OSP influxes from database using constant S/XBs:
  - Consistent divertor carbon influxes derived from C II, C III, C IV
    - 3-10x10^{20} ions/s (C II)
- Core penetration factors for OSP sources fitting core particle inventories
  - F~0.1-0.5 from C II
- Suggest worse divertor retention for carbon
- Poloidal distribution of carbon sources not understood
  - Upper divertor, wall sources not diagnosed
  - Study divertor influxes is one part of the problem

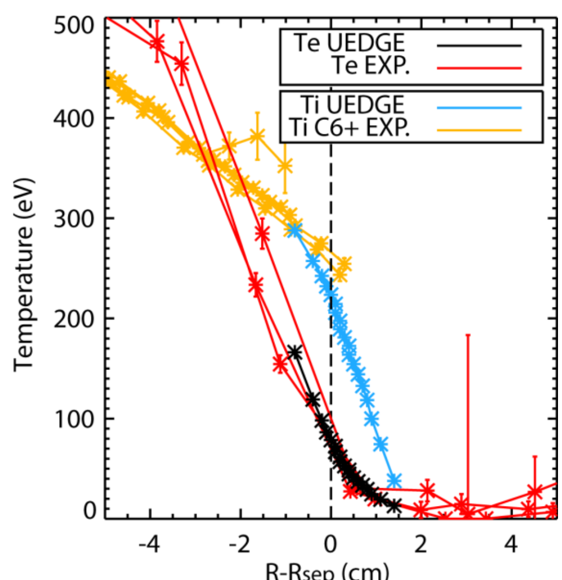


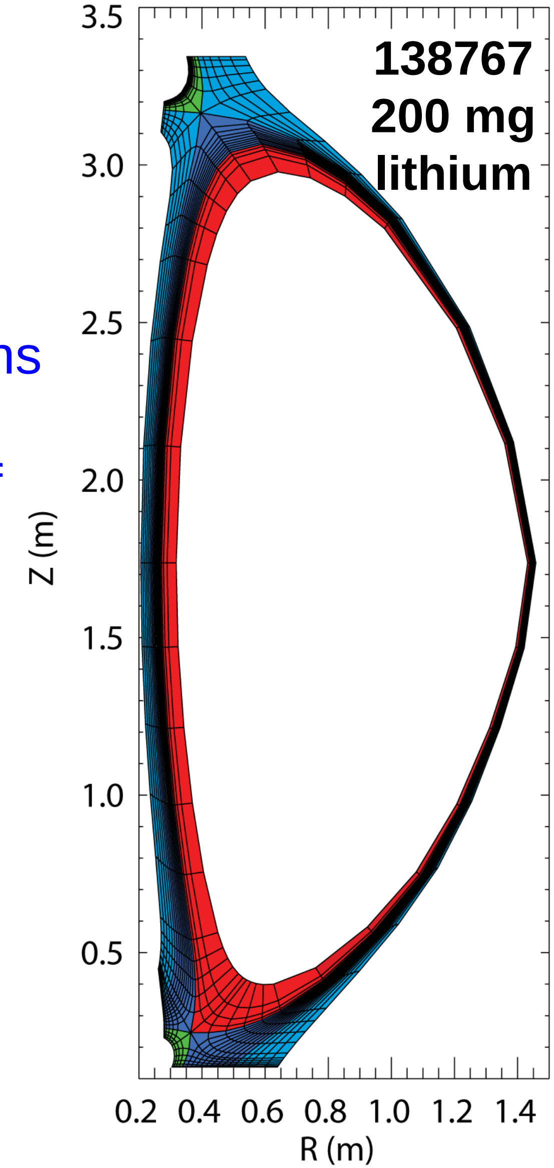


2D multi-fluid UEDGE simulations performed to investigate reasons for difference in penetration factors

- UEDGE, 2D multi-fluid edge transport code:
  - Fluid (Braginskii) model for D^0, D^+, e^-, $C^{0\text{-}6+}$, $Li^{0\text{-}3+}$
  - 20 radial, 60 poloidal cells
- Drifts not included in simulations:
  - in NSTX no SOL flows measurements
  - classical parallel transport in exp. relevant conditions
- Radially varying main ion D_{perp}, χ_e, χ_i
  - Flux B.C. at core (64 A from NBI) + 500 A HFS puff
  - Core power B.C. (1.5+1.5 MW e,i)



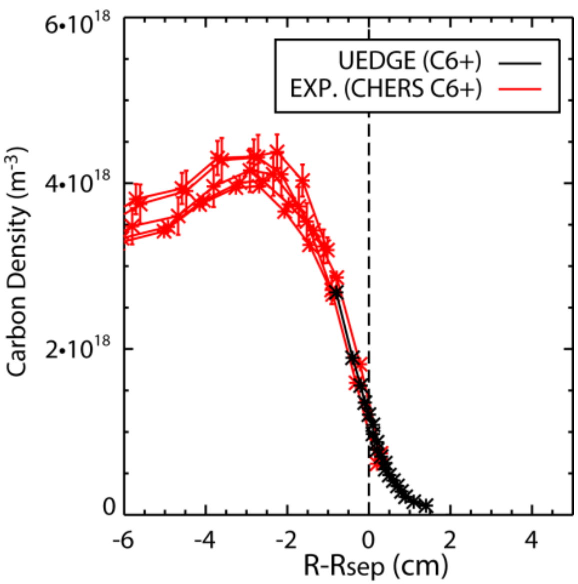


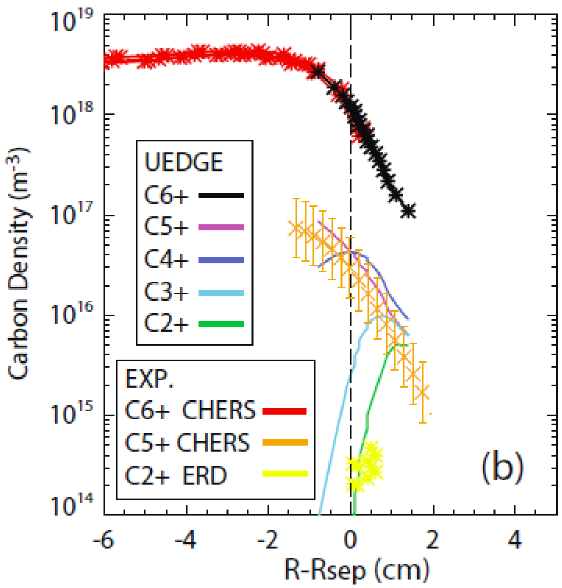


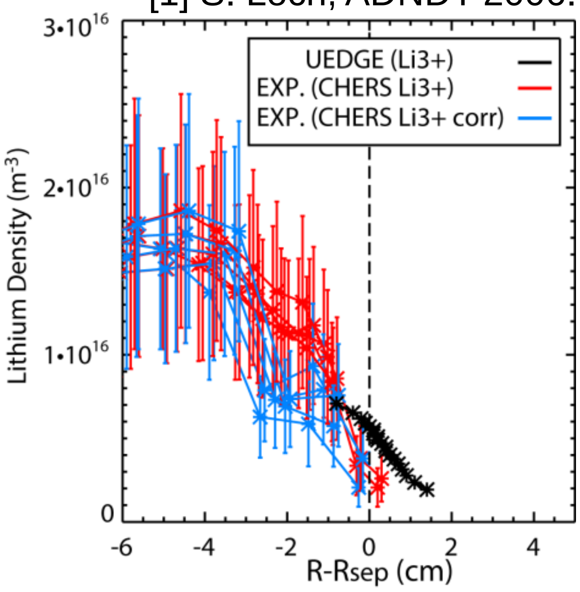
Charge state resolved model employed including lithium and carbon impurities

- Charge state resolved model for both carbon and lithium
  - Analytic solution of impurity parallel momentum equation
- Atomic rates from ADAS
  - Latest lithium rates from Auburn group [1]
- Carbon and lithium radial transport
  - Radially uniform diffusivity for all charge states
  - Radially varying velocity for C^{6+}, Li^{3+} to match CHERS data
  - Core C^{1+}-C^{5+} (Li^{1+}-Li^{2+}) influx balanced by C^{6+} (Li^{3+}) outflux → zero net flux

[1] S. Loch, ADNDT 2006.

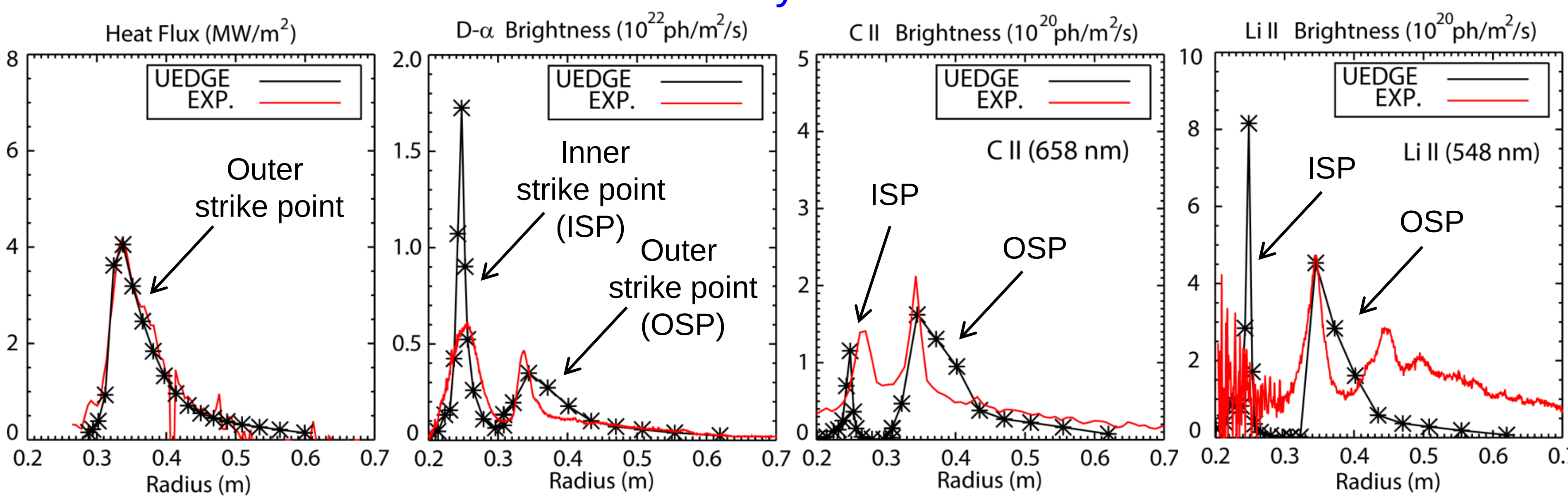






Recycling and impurity sputtering adjusted to match divertor heat flux, D-α, C II, Li II and particle balance

- Synthetic diagnostics used to reproduce experimental spectroscopic views
- Target recycling adjusted (R=0.95) to match strike point heat flux and D-α
- Carbon sputtering adjusted to match peak divertor C II
  - Haasz-Davis yield scaled by 0.4 at divertor → Y_C ~ 1%
  - consistent with moderate reduction in Y_C with application of lithium
- Uniform lithium sputtering at target to match Li II
  - difficult to match Li I and Li II brightness for same Y_{Li}
- No effect on heat flux due to lithium radiation (even for 10X higher Y_{Li})
  - divertor radiation still dominated by C and D



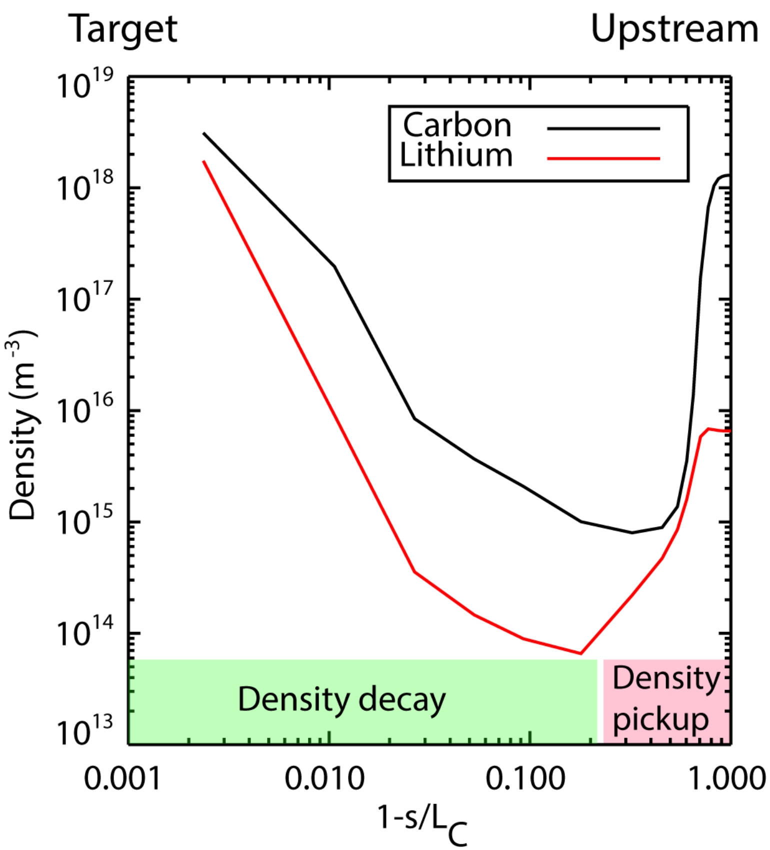
Difference in parallel impurity profiles observed between carbon and lithium in near target region and upstream

- Better divertor trapping of lithium ions with respect to carbon, weaker upstream pickup

- However, to match exp. lithium profiles higher perp. diffusivity was used for lithium with respect to carbon
  - affects parallel impurity profiles, reducing upstream pickup
  - even with $D_{Li}=D_C$, lower upstream contamination for lithium wrt carbon

- To address causes for differences in parallel transport, higher resolution slab simulations with same transport coefficients

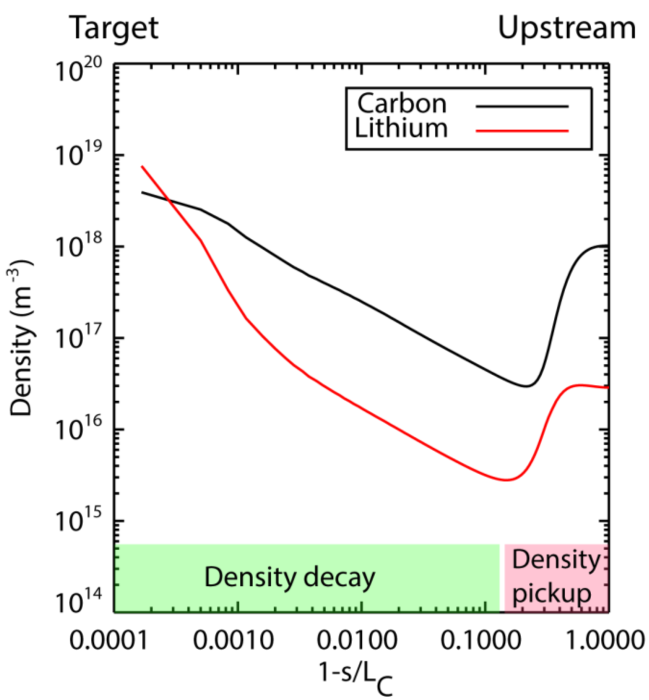
Parallel impurity density profile
First SOL cell

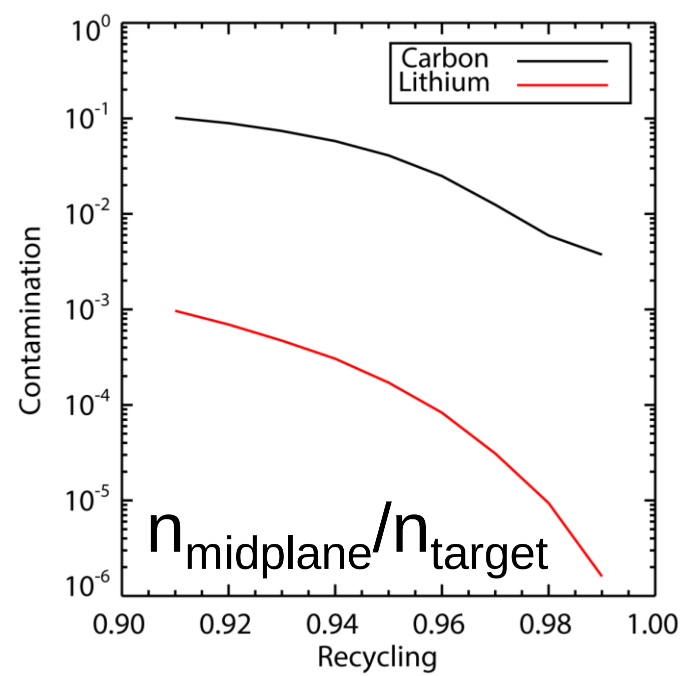


s distance from midplane
L_C midplane-target connection length

UEDGE simulations in simplified slab geometry to study SOL parallel impurity transport for carbon and lithium

- Simulations in slab geometry with NSTX-like plasma parameters:
  - Fixed pitch angle (B_p/B_T~0.1)
  - 12 m midplane-target connection length ~1mm flux surface in NSTX
  - 104 poloidal cells (80 cells from X-point to target), 16 radial cells
- Stronger divertor retention (n_{min}/n_{target}) for lithium than carbon
- Stronger midplane trapping ($n_{midplane}/n_{min}$) for carbon than for lithium
- Divertor retention improved for both carbon and lithium at increased recycling





Weaker upstream lithium contamination due to short ionization λ_{mfp} and weaker ∇(Ti) force in slab simulations

Impurity parallel force balance

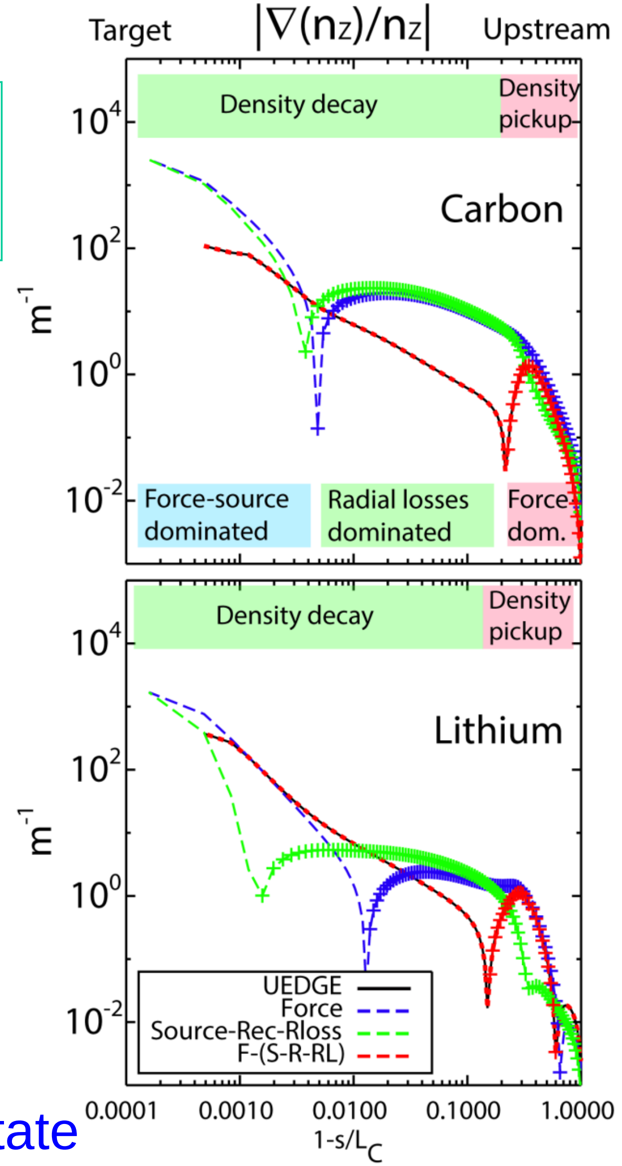
$$F_z = -\frac{1}{n_z}\frac{dp_z}{ds} + m_z\frac{(v_i - v_z)}{\tau_s} + ZeE + \alpha_e\frac{d(kT_e)}{ds} + \beta_i\frac{d(kT_i)}{ds}$$

∇p_Z Force	Friction Force (**FF**)	E-field Force (**FE**)	∇T_e Force (FeG)	∇T_i Force (FiG)

$$F_{eff-j} = m_Z\frac{\langle v_i\rangle}{\tau_j} + Z_j eE + \alpha_j\frac{\partial T_e}{\partial s} + (\beta_j - 1)\frac{\partial T_i}{\partial s}$$

$$\frac{1}{n_z}\frac{\partial n_z}{\partial s} = \frac{F_{eff}}{T_i} - \frac{1}{D_{eff} n_z}\int_0^s \left(S^0 n_e n_{Z0} - L_\perp\right) ds'$$

- In density decay region, n_{Li} has larger poloidal drop:
  - controlled by difference in source profile
- In impurity buildup region n_{Li} has weaker pick-up:
  - in source free region, poloidal density profile controlled by force balance
  - ∇T_i force weaker for lithium due to lower charge state



Summary

- Divertor impurity influxes from plasma material interaction:
  - Lithium sputtering consistent with expectations from physical sputtering and thermal sputtering
  - Reduction in carbon sputtering observed with lithium conditioning
  - Toroidal asymmetries in divertor lithium influxes follow LITER deposition
  - Penetration factors indicate divertor lithium retention stronger than carbon
- SOL/edge parallel and radial transport via UEDGE modeling:
  - Stronger divertor retention for lithium than carbon
  - High neoclassical diffusivity further helps preventing lithium accumulation
  - No effect of lithium radiation on divertor power balance
- NSTX-U baseline scenario still includes lithium coatings on graphite PFCs:
  - Significant benefits observed with lithium conditioning
  - Lithium effectively retained in divertor
  - ELMs suppression results in carbon accumulation
  - Several techniques developed in NSTX to suppress impurity accumulation will be considered in NSTX-U