Study of C and Li neoclassical transport in NSTX Li-conditioned ELM-free H-mode discharges

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APS-DPP 2011
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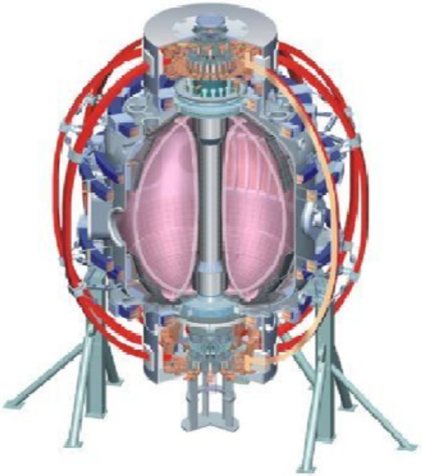

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Abstract

ELM-free H-mode discharges are routinely achieved with lithium wall conditioning in NSTX, with a concomitant core impurity accumulation. Z_{eff} generally increases up to 4-5 (due to C) and core P_{rad} ramps up to several MWs (due to metals). In contrast, Li is efficiently screened from the core, where it is present at about 1% of C densities. C and Li density profiles show similar time evolutions, with the early formation of a higher density ‘ear’ and a slower diffusion to the core.

In this work, the neoclassical transport code NCLASS is used to study neoclassical multi-ion transport in NSTX plasmas. In particular, possible effects leading to a change in C transport due to Li conditioning are analyzed in discharges with and without applied Li coatings; these include the presence of a low Z collisional background ion (Li) and changes in the D ion temperature and density profiles.

Neoclassical predictions are tested with the MIST impurity transport code to check consistency with experimentally measured core impurity density profiles.

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Outline - Summary

Core impurity accumulation observed with lithium conditioning in NSTX:

- Carbon accumulates, lithium screened from the core plasma

- No apparent increase in carbon sources from main wall or divertor

Impurity transport close to neoclassical in NSTX:

- TRANSP/NCLASS/MIST: used to analyze neoclassical transport, check consistency with experiment

Neoclassical multi ion effects analyzed using NCLASS:

- Negligible role of lithium ions on carbon transport

- Li transport driven by C ions, high particle diffusivity prevents core accumulation (similar conclusions with C.S. Chang XGC0 physics study)

C transport mostly driven by main ions:

- Change in main ion profiles due to Li-conditioning leads to changes in C transport

- Edge pinch, reduced edge diffusivity and ELM suppression sustain C 'ear'

- C buildup in the 'ear', diffusion and core pinch lead to core accumulation

MIST/NCLASS results qualitatively in agreement with experimental observations:

- Limits in time dependent analysis in MIST and radial extent of NCLASS analysis

- Possible role of ion turbulence and MHD

Plasma performance improvements are generally observed with solid lithium coatings in NSTX

High triangularity/elongation(δ~0.6,κ~2.3)

Lower biased double null (δ_{sep}~ -7mm)

Outer strike point on horizontal ATJ tiles

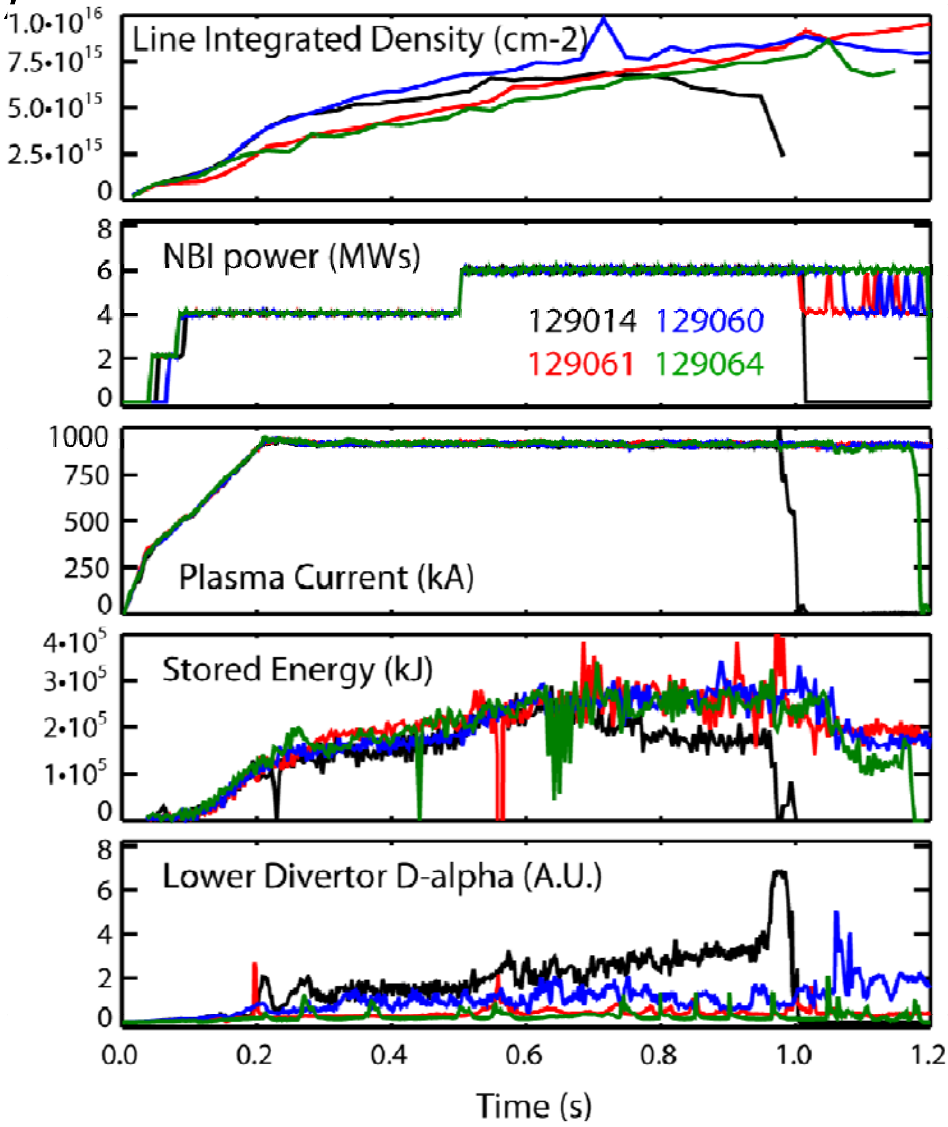
Inner strike point on center stack

- Boronized graphite PFCs
- 2.2 grams of Li but no fresh Li
- 190 mg of fresh Li / 400 mg of fresh Li

- Medium size, 200Hz ELMs
- Small 300 Hz ELMs

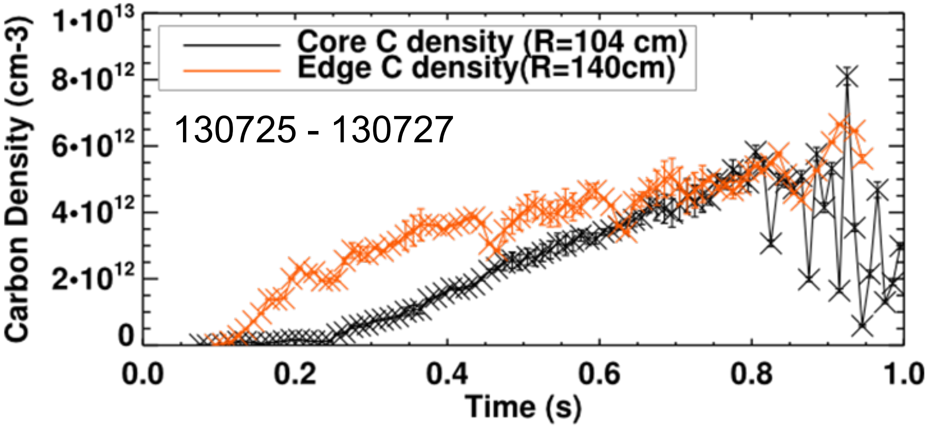
  ELM free / ELM free , few giant ELMs

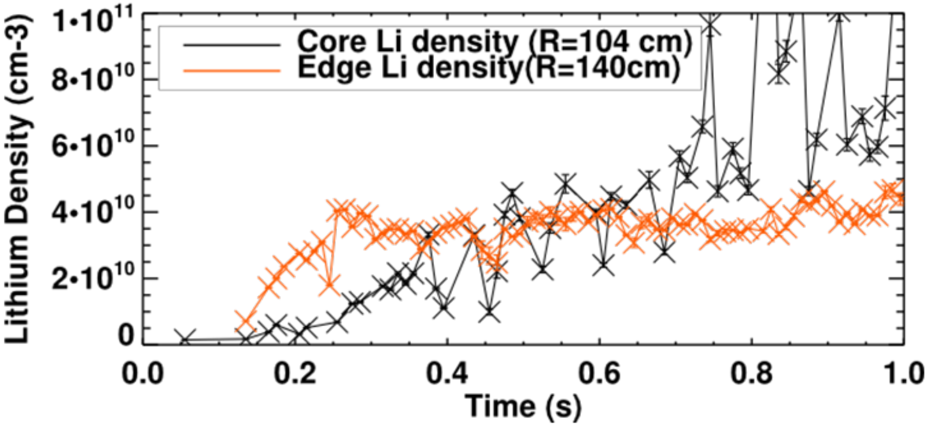
- MARFE / MARFE (see next slide)
- No MARFE / No MARFE

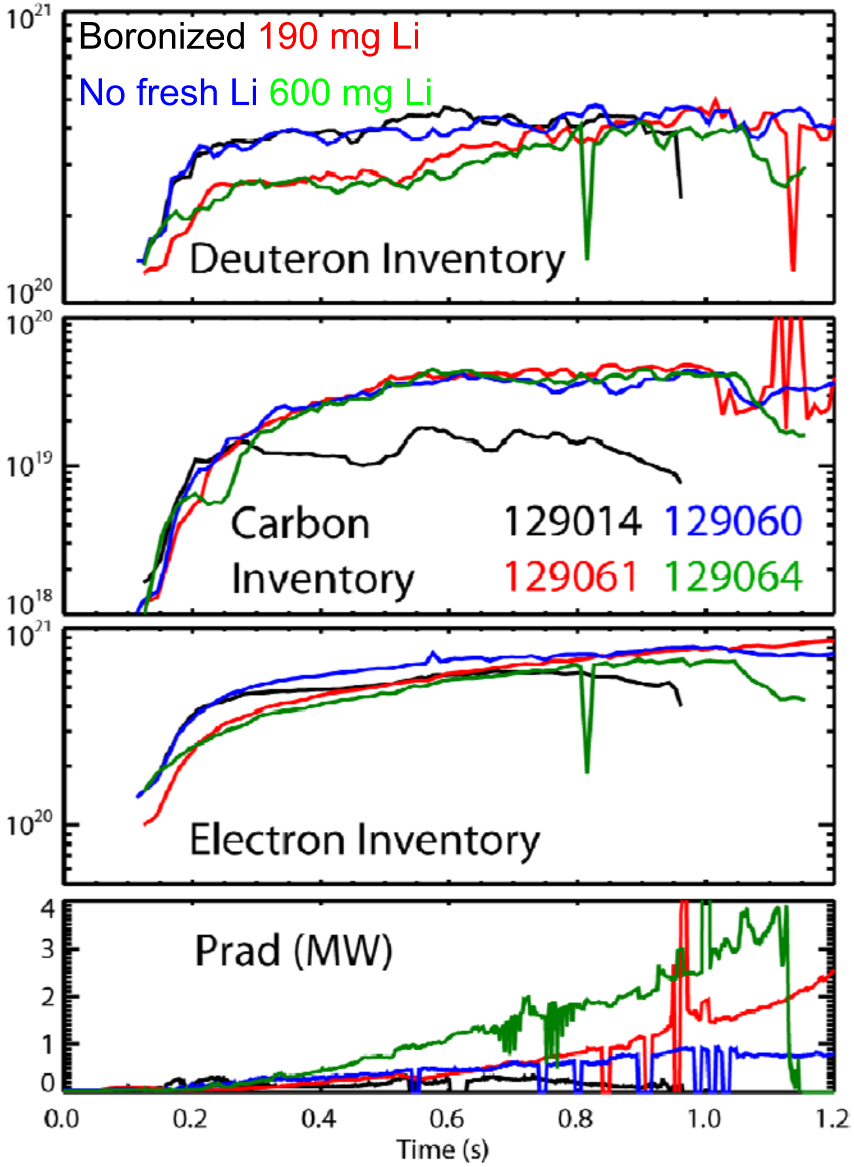


Core carbon accumulation observed in lithium conditioned discharges, lithium is screened from core

- Severe core carbon accumulation
- Li screened from core (1% of core C)
- Ramping radiated power (metals)

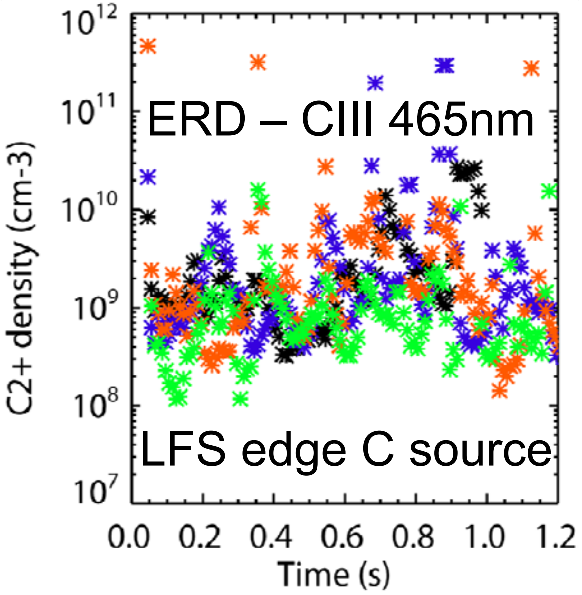


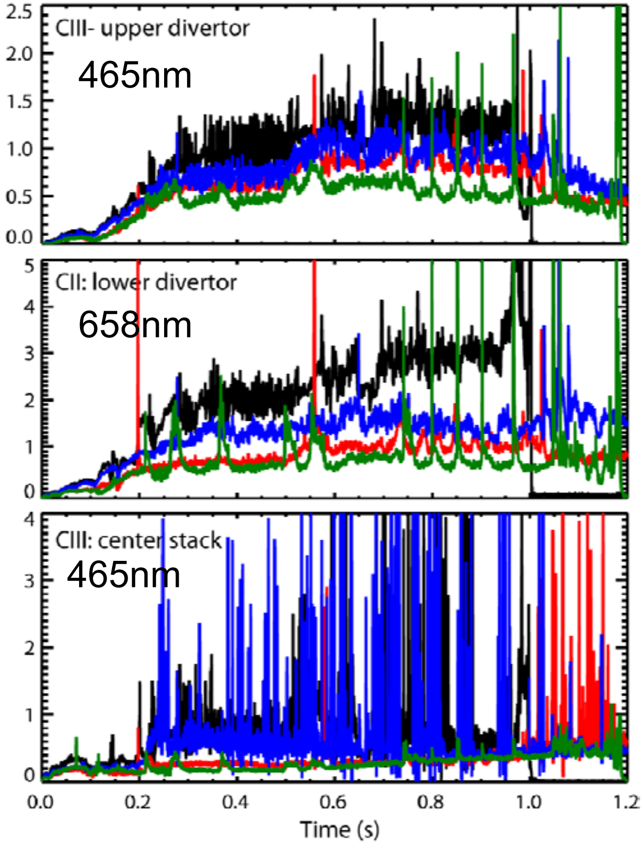




No apparent increase in carbon sources with increased thickness of lithium coatings

- **No evidence for increase of C source at LFS LCFS**
- Possible increase in divertor sputtering rate
- **However, overall divertor source NOT increased**
- High uncertainty on change in divertor parameters and S/XB coefficients





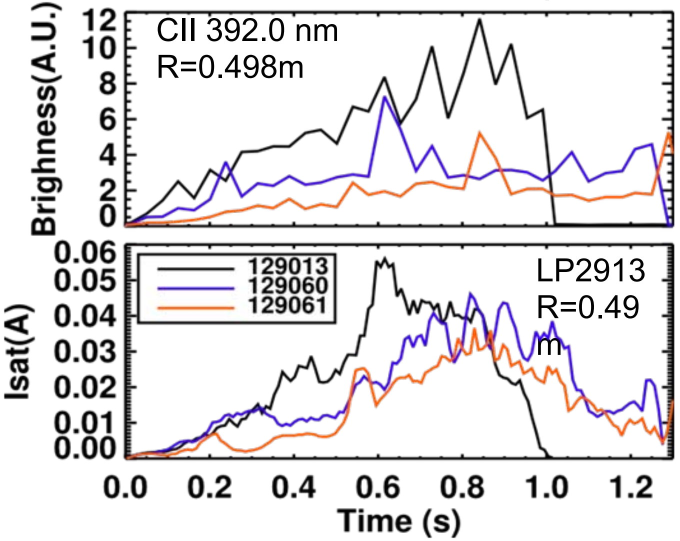
Boronized PFCs 129014

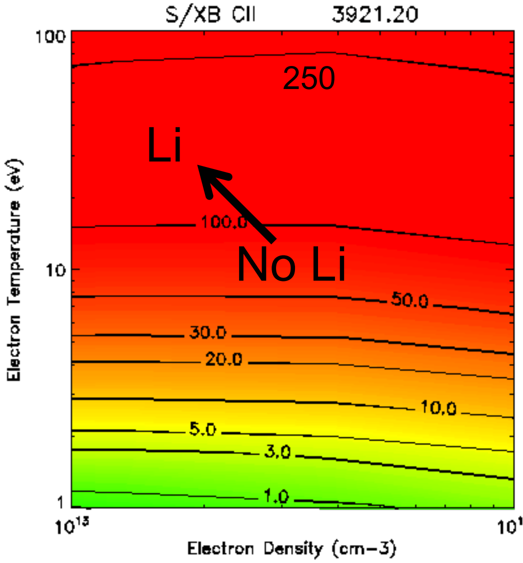
No fresh Li 129060

190 mg fresh Li 129061

600 mg fresh Li 129064

Divertor Outer strike point





Addressed in this poster

- Core & edge radial transport

☐ Core impurity confinement

- SOL transport

☐ Perpendicular anomalous transport

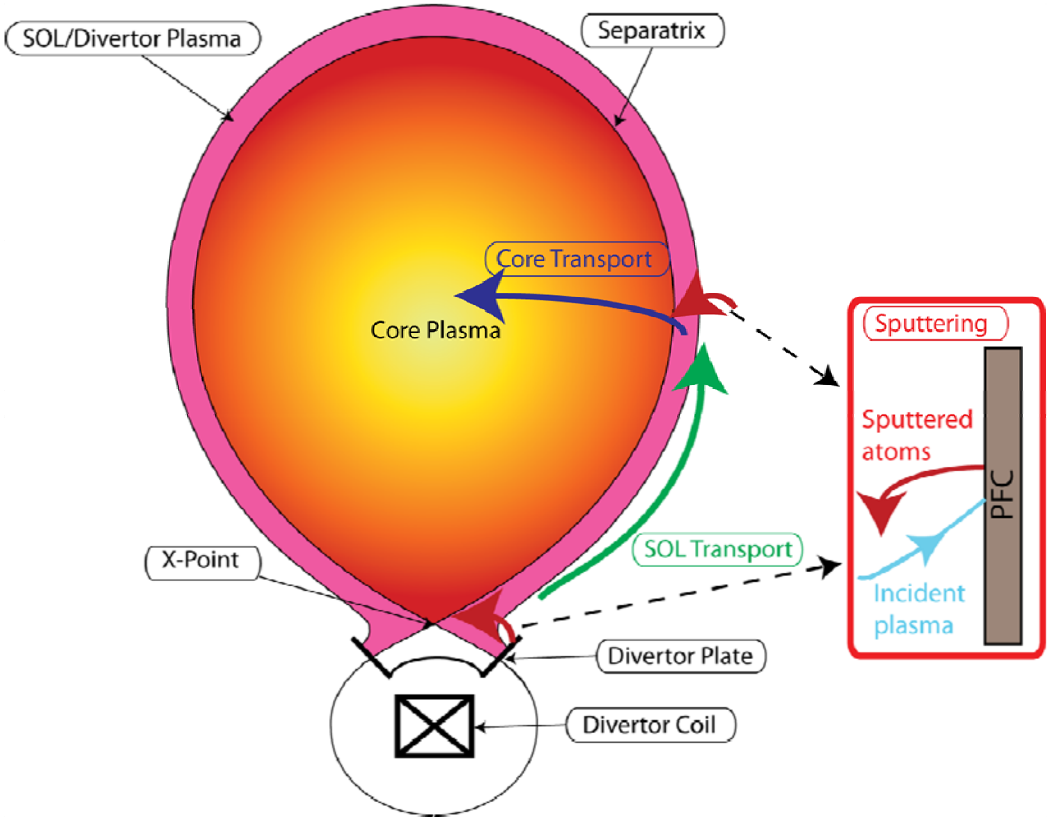
☐ Parallel classical transport

  - SOL force balance

- Sources from plasma material interaction:

☐ Sputtering from Divertor

☐ Sputtering from Main Wall



Work currently under progress for better assessment of carbon sources distribu

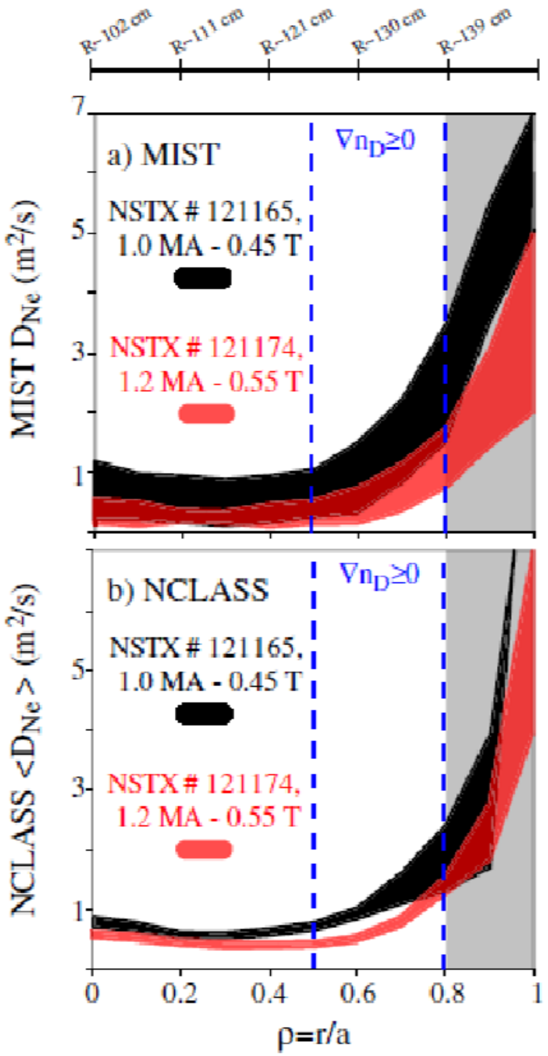
Core ion impurity transport close to neoclassical in spherical tokamak H-mode discharges

- Radial Core Impurity Transport
- Neoclassical transport
- Turbulent transport

- Core impurity transport in spherical tori close to neoclassical:
- CDX-U – [V.A. Soukhanovksii, PPCF 2003]
- NSTX – [L. Delgado-Aparicio, NF 2009]

- Diffusive and convective transport

$$\Gamma_r = -D_r \nabla n_Z + v_r n_Z ,$$



1. Soukhanovskii V.A. et al 2003 Plasma Phys. Control. Fusion 44 2239

2. L. Delgado-Aparicio, Nucl. Fusion 49 (2009) 085028

Core transport modeling used to assess core/edge carbon and lithium transport

- How does the presence of background lithium ions affect C transport?
- How does the modification of deuterium ion profiles due to Li conditioning affect C transport?
- Why is lithium screened out from the core plasma?

MAIN TOOLS USED

- TRANSP: run with multiple impurities (C + Li profiles from CHERS)
- NCLASS: run on TRANSP outputs to simulate multi-ion neoclassical transport
- MIST: to simulate impurity density profiles based on NCLASS predictions

NCLASS used to estimate multi-ion mixed regime neoclassical transport coefficients

- NCLASS calculates neoclassical transport properties of a multi-species axisymmetric plasma of arbitrary aspect ratio, geometry and collisionality
- NCLASS input from TRANSP (T_e, n_e, T_i, n_C, n_{Li}, T_i, V_{tor}, EFIT02 geometry)
- NCLASS solves:
- Parallel and radial force balance equations in axisymmetric geometry
- Multiple impurity species can be included
- Non-local physics (finite orbit width effects) are not included

$$\rho = a_0 \left(\frac{\Phi_{tor}}{\Phi_{tor_tot}} \right)^{\frac{1}{2}} \quad a_0 = \left(\frac{V_p}{2\pi^2 R_0} \right)^{\frac{1}{2}} \quad \langle \Gamma_j \cdot \nabla \rho \rangle = \Gamma_j = \sum_m \Gamma_j^m$$

$$\frac{\partial n_j}{\partial t} = \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left(\frac{\partial V}{\partial \rho} \Gamma_j \right) + S_{pj}$$

$$D_{MIST} = D_{NCLASS} / \left(\nabla \rho \right)^2$$

$$v_{MIST} = v_{NCLASS} / \left(\nabla \rho \right)$$

$$\Gamma_j = -n_j D_j \frac{\partial n_j}{\partial \rho} + n_j \left(v_{nj}^{nT} + v_{nj}^{EB} + v_{nj}^{ex} \right)$$

MIST code was used to verify consistency of NCLASS estimates with respect to experimental data

- MIST computes the evolution of impurity charge states given experimental n_e and T_e
- External profiles of particle diffusivity (D) and convective velocity (v)
- Source (S) adjusted to match measured impurity density
- MIST solves continuity equation for every impurity ionization stage

$$\frac{\partial n_q}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_q) + I_{q-1}n_{q-1} - (I_q + R_q)\,n_q + R_{q+1}n_{q+1} - \frac{n_q}{\tau_q} + S_q$$

$$\Gamma_q = -D\frac{\partial n_q(r)}{\partial r} + v(r)n_q(r)$$

- MIST will be used to check consistency of NCLASS predictions with experimentally measured impurity profiles

Mixed-regimes, multi-ion neoclassical effects need to be taken into consideration in NSTX lithium-conditioned discharges

Collision frequencies analytically calculated for test particle of the three species
Shot 130725/130727, t=0.4s
TRANSP 130725A18

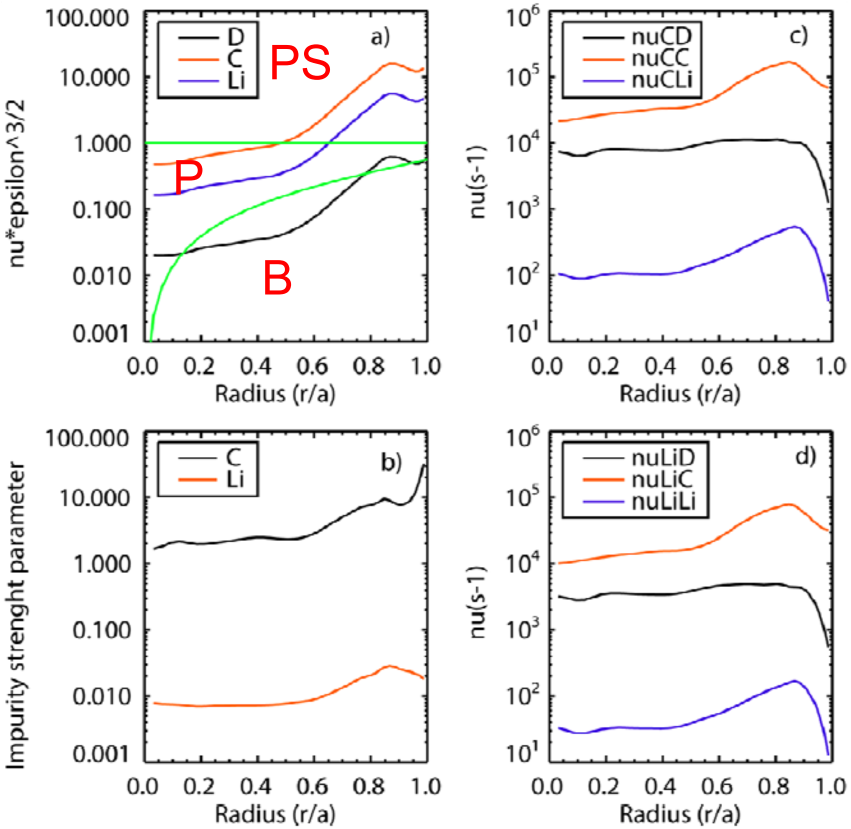
- Main ion well in the banana-plateau regime
- C and Li in Pfirsch-Schluter regime respectively for r/a>0.5 and r/a>0.6

Li 'weak' impurity, ambipolarity constraint must retain neoclassical electron flux to first order

$$\nu_C = \frac{16\sqrt{\pi}e^4 Z_C^2 \log(\Lambda)}{3m_C}\left[\frac{n_D}{m_D v_{thD}^3} + \frac{n_{Li} Z_{Li}^2}{m_{Li} v_{thLi}^3} + \frac{n_C Z_C^2}{\sqrt{2} m_C v_{thC}^3}\right]$$

$$\nu_{Li} = \frac{16\sqrt{\pi}e^4 Z_{Li}^2 \log(\Lambda)}{3m_{Li}}\left[\frac{n_D}{m_D v_{thD}^3} + \frac{n_{Li} Z_{Li}^2}{\sqrt{2} m_{Li} v_{thLi}^3} + \frac{n_C Z_C^2}{m_{Li} v_{thLi}^3}\right]$$

$$\nu_D = \frac{16\sqrt{\pi}e^4 \log(\Lambda)}{3m^2_D v^3_{thD}}\left[\frac{n_D}{\sqrt{2}} + n_C Z_C^2 + n_{Li} Z_{Li}^2\right]$$



ν (s-1)	D	Li	C	Total
D	796	7	1831	2634
Li	2940	24	8879	11843
C	6797	78	19091	25967

Background lithium ions have a negligible effect of on neoclassical carbon transport

- Simulations with TRANSP/ NCLASS/ MIST :

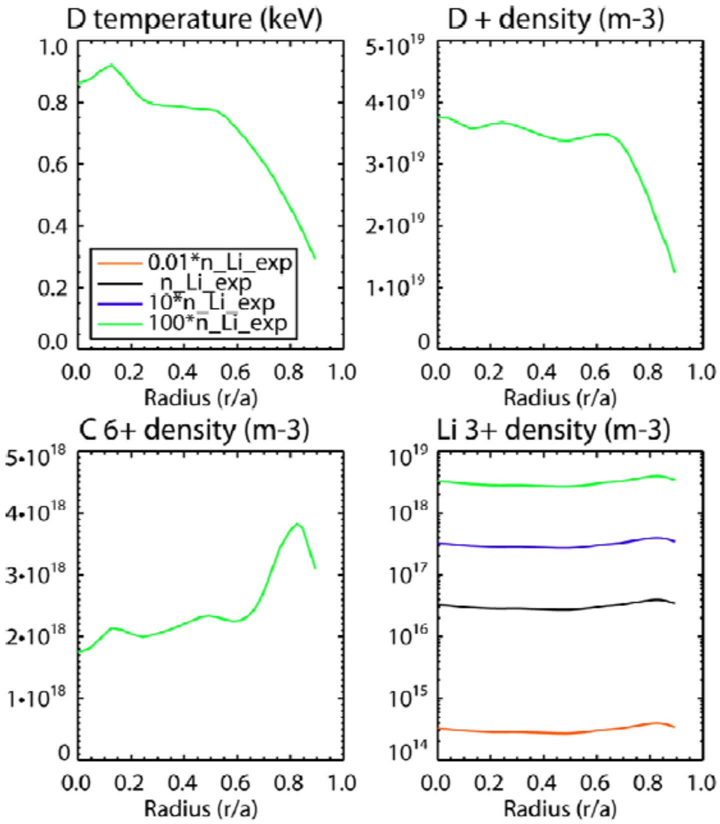
☐Li density varied between 0.01 and 100 times the experimentally measured one

☐**Effect of Li on C negligible at n_{Li} in NSTX**

☐Increase in $\mathbf{n_{Li}}$ would result in increased C diffusivity
–> reduced core C

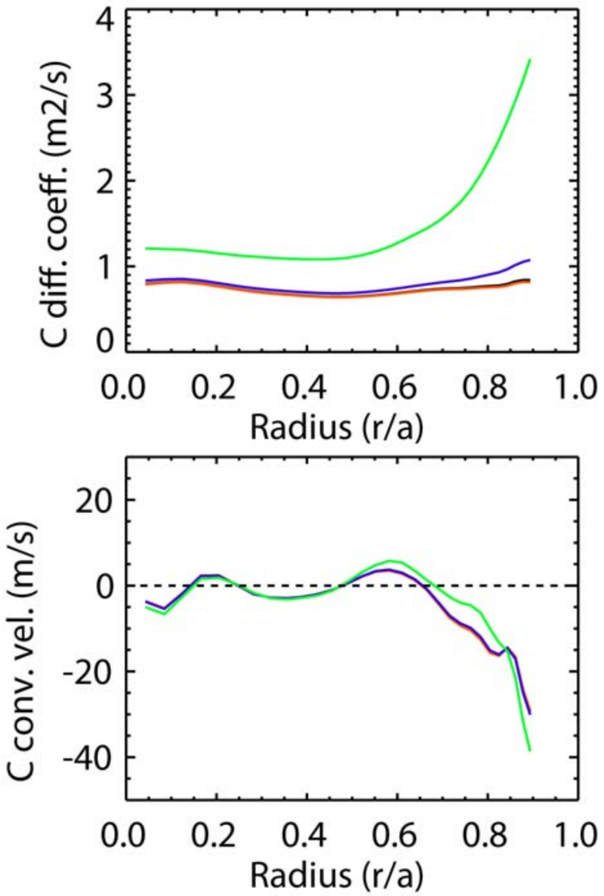
Li starts having an effect on C transport when C ions become collisional on Li ions

Radial coordinates are normalized to the low field side values



NCLASS

C transport coefficients



For lithium ions, neoclassical transport dominated by collision on carbon ions

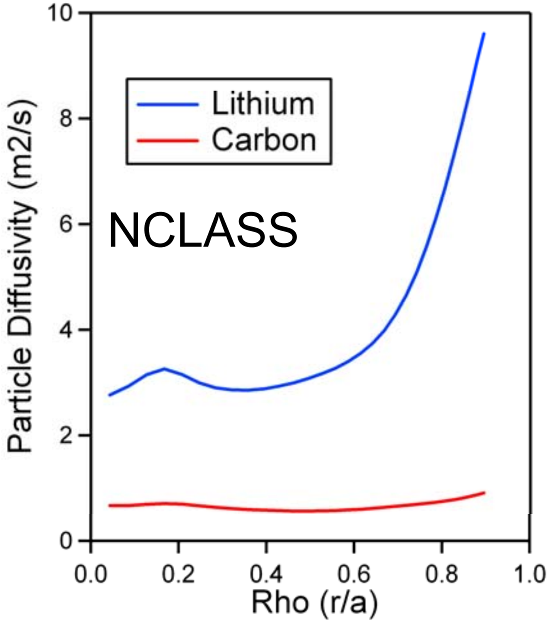
Hirshmann-Sigmar multi-ion PS formulation (trace impurity (T) =Li, main impurity (I) =C)
For Li ions in NSTX, C contribution to Li Pfirsch-Schluter transport becomes dominant

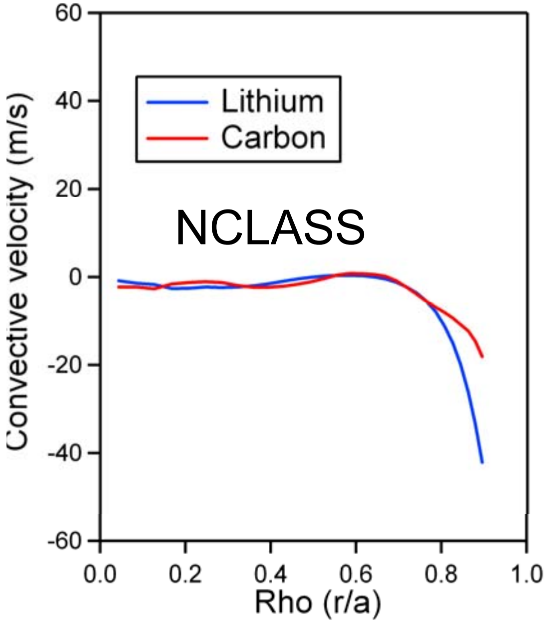
$$D_T^{PS} = D_{TD}^{PS} + D_{TI}^{PS} = \frac{4}{3\sqrt{\pi}} \frac{2\pi c}{\partial\psi/\partial r} \langle RB_\phi \rangle^2 \left(\langle B^{-2}\rangle - \langle B^2\rangle^{-1}\right) T^{-\frac{1}{2}} ln\Lambda \sqrt{m_D} \cdot \left[n_D + Y(m_T/m_D) n_I Z_I^2 \sqrt{\frac{m_T}{m_D}} \right]$$

$$\frac{D_{TI}^{PS}}{D_{TD}^{PS}} = \frac{Y(m_T/m_D) n_I Z_I^2 \sqrt{\frac{m_T}{m_D}}}{n_D} \approx 1.04 \cdot \frac{n_I Z_I^2}{n_D}$$

For trace Li impurity on background C ions

- At C concentrations of 3% contribution to diffusivity due to C ions and main ions is comparable
- Effect enhanced at the edge due to high n_C
- NCLASS result consistent with analytical derivation

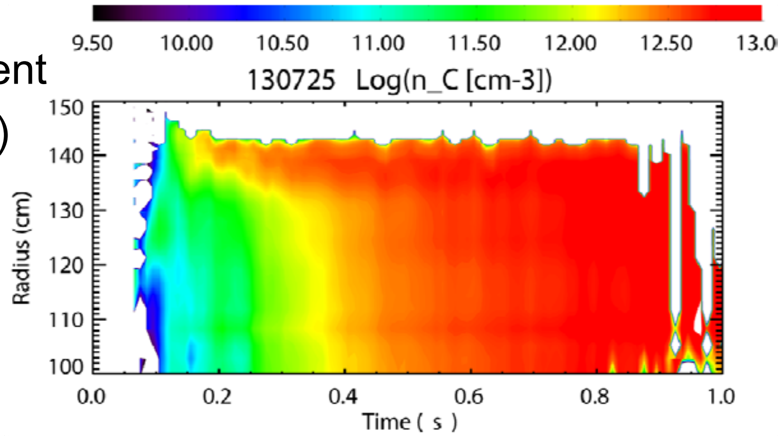




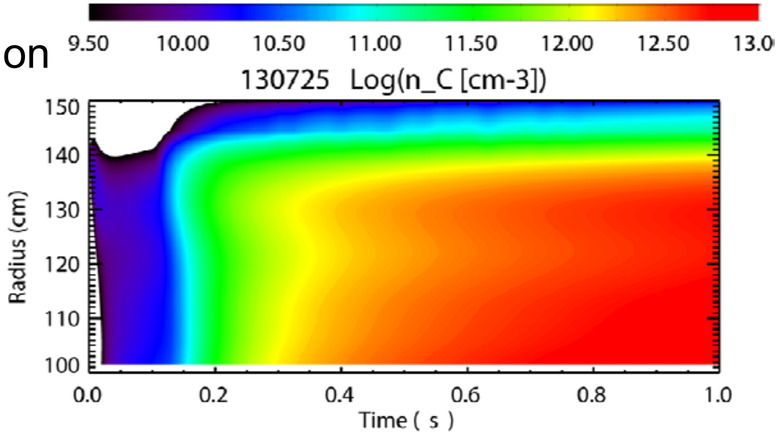
High particle diffusivity prevents lithium accumulation in NSTX core plasma

- Flattop averaged NCLASS *D* and *v* for C and Li (not trying to reproduce time evolution)
- C^{1+} source adjusted such that simulated $n_{C\text{-}MIST} \sim n_{C\text{-}EXP}$
- Same source used for Li^{1+} ions → results in flat Li densities ~ 1-10% of C densities
- Divertor/SOL contribution to Li screening could also play a significant role

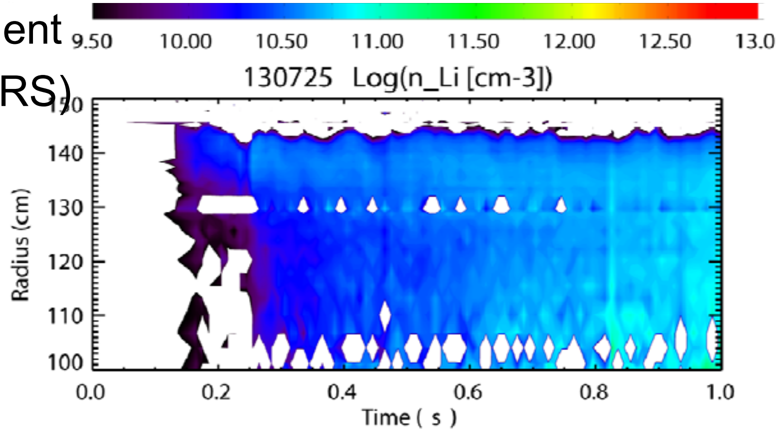
Experiment (CHERS)



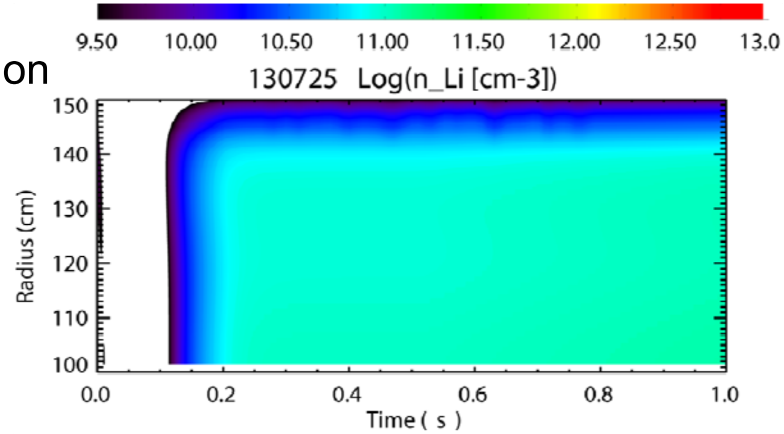
Simulation (MIST)



Experiment (Li-CHERS)



Simulation (MIST)



Neoclassical C transport dominated by collision on main ion and T_D and n_D gradient effects

- C transport is mainly driven by collisions with D ion and T_D and n_D gradient effects

- NCLASS shows C radial transport dominated by PS fluxes

$$\Gamma^{PS}{}_{C} = \frac{q^2 n_D \rho_D \nu_{DC}}{Z_C} \times \left[K\left(\frac{\partial \ln(n_D)}{\partial r} - \frac{Z_D}{Z_C}\frac{\partial \ln(n_C)}{\partial r} \right) + H\frac{\partial \ln(T_D)}{\partial r} \right]$$

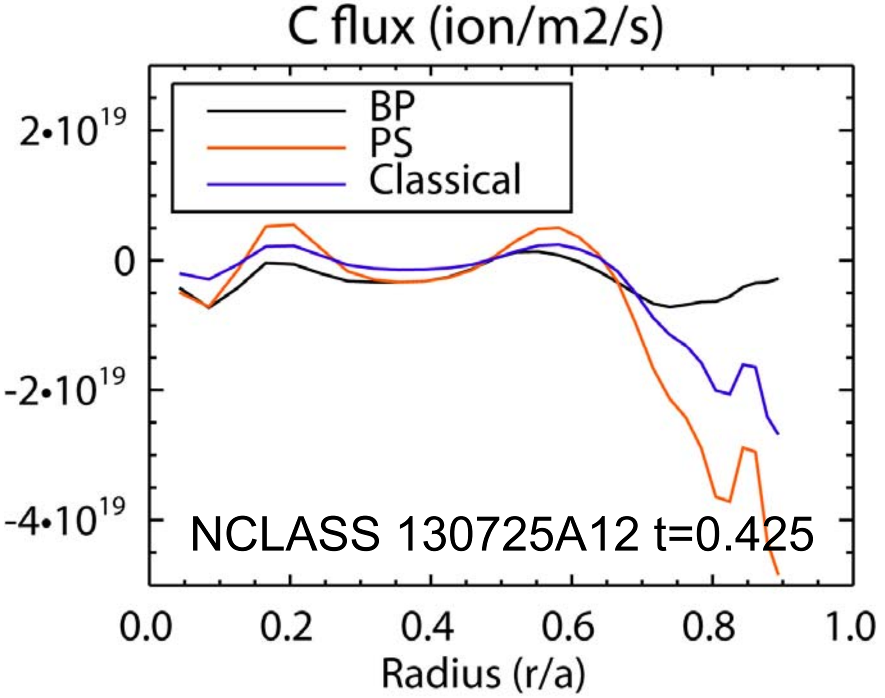
In typical NSTX main ion collisionality regimes:
K~1.0 and H~-0.5

- D temperature gradient component provides screening effect.

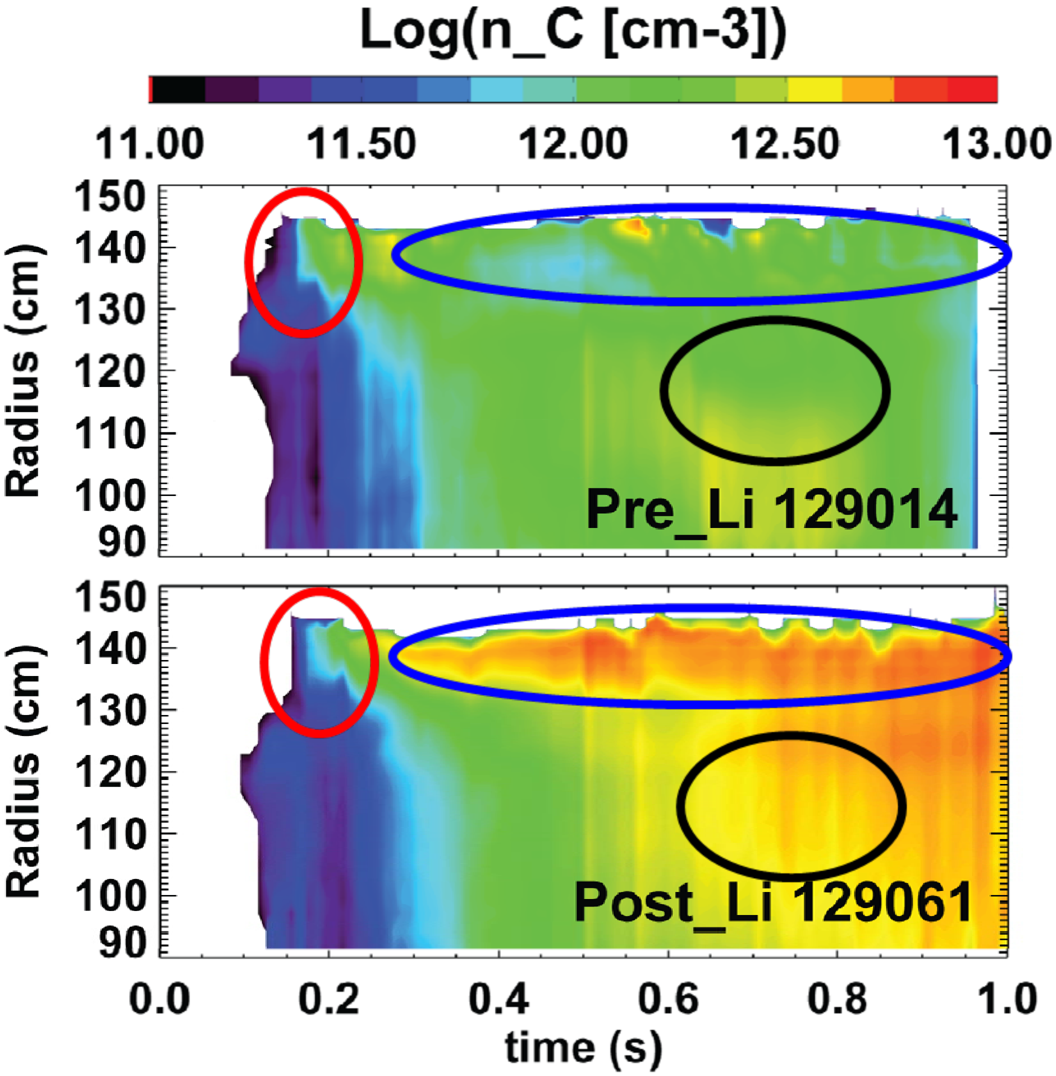
- Inward convective velocity (if present) due to D density gradient component.

- C 'strong' impurity, main ion-electron friction negligible --> 0th order ambipolarity

[redacted]



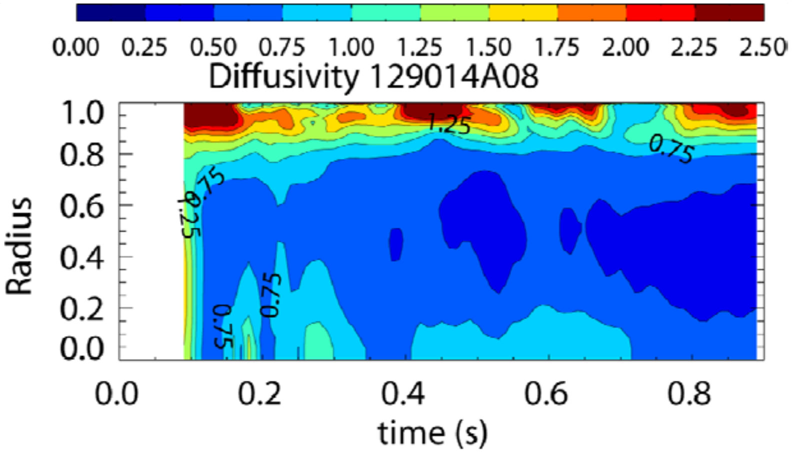
C ions show early hollow profile following L-H transition and slower but steady core accumulation

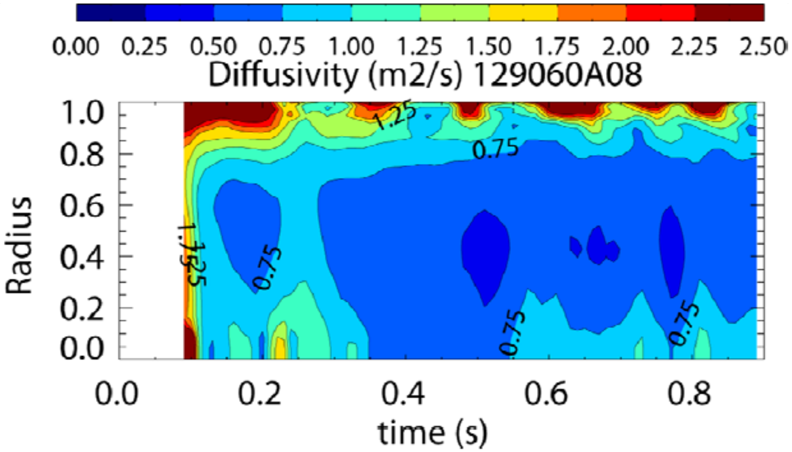


- Same early discharge behavior: hollow profile forming after L-H transition
- Pre-Li:
- ELMy – Weak edge C 'ear'
- Post-Li:
- ELM free – Strong C ear
- Pre-Li: no core accumulation
- Post-Li: core accumulation
- Regular ELMing in Li assisted discharge appears to influence only 'ear'
- Core accumulation cannot be simply due to diffusion from edge 'ear'

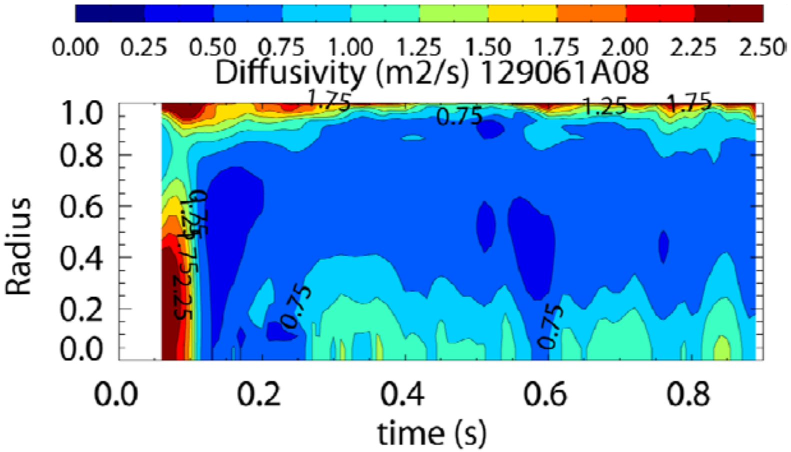
NCLASS indicates reduction in edge impurity particle diffusivity with increased lithium deposition

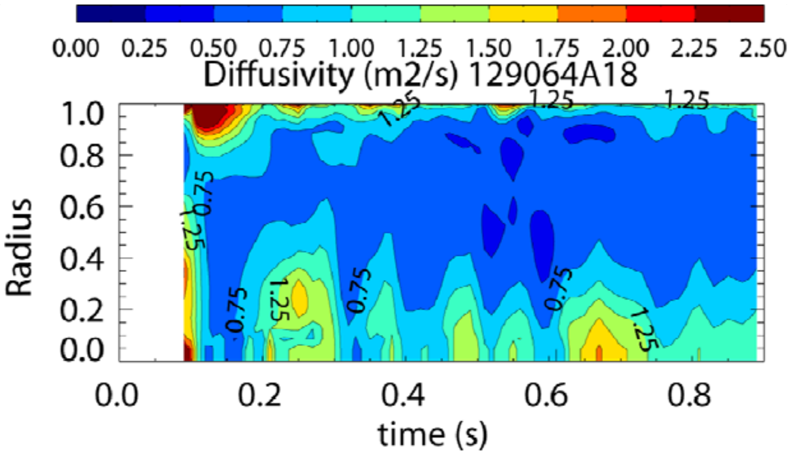
- NCLASS indicates flat impurity particle diffusivity
- With Li: reduction of edge n_D, increase in edge T_i --> reduction in edge D


Diffusivity 129014A08


Diffusivity (m2/s) 129060A08

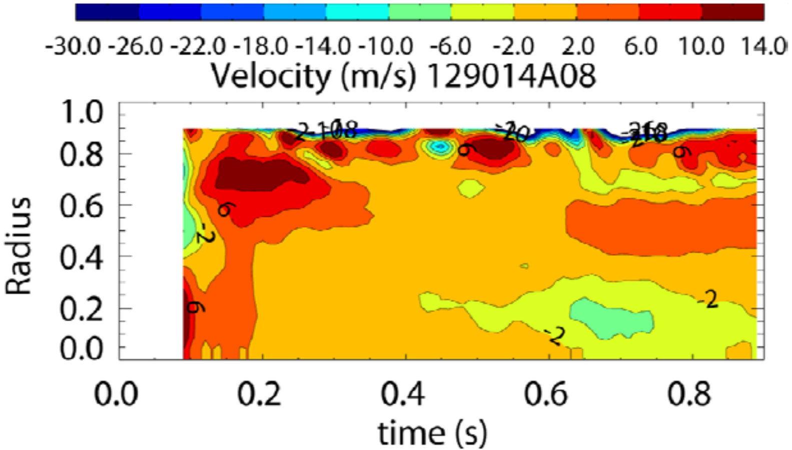
Boronized
129014
No fresh Li
129060
190 mg Li
129061
600 mg Li
129064

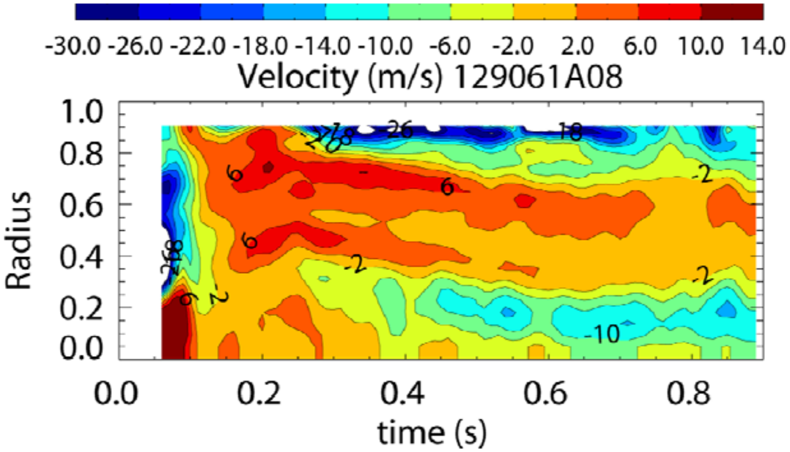

Diffusivity (m2/s) 129061A08


Diffusivity (m2/s) 129064A18

NCLASS indicates increase in edge and core inward pinch velocity for C ions with increased Li deposition

- NCLASS --> Li conditioning leads to inward pinch in edge and core
- Positive convective velocity at r/a~0.7 ~consistent with edge C 'ear'
- C convective velocity evolution at the L-H transition is consistent with transition from peaked to hollow impurity profile


Velocity (m/s) 129014A08


Velocity (m/s) 129061A08

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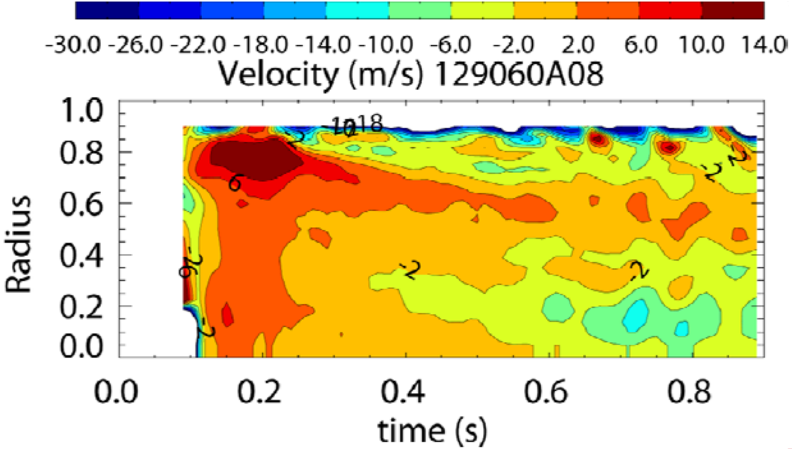
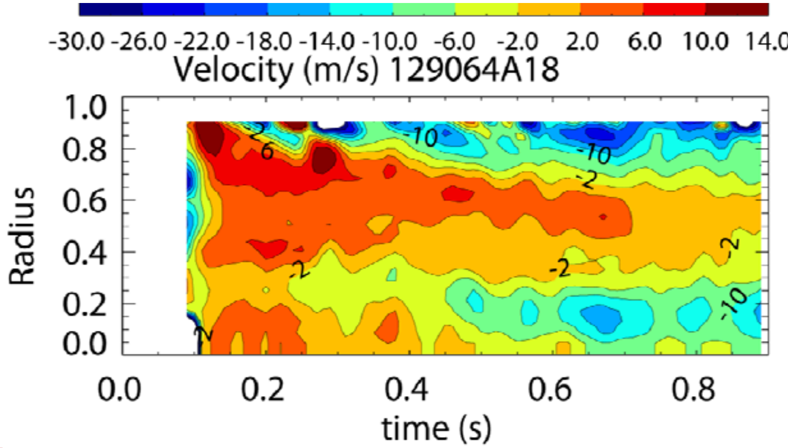
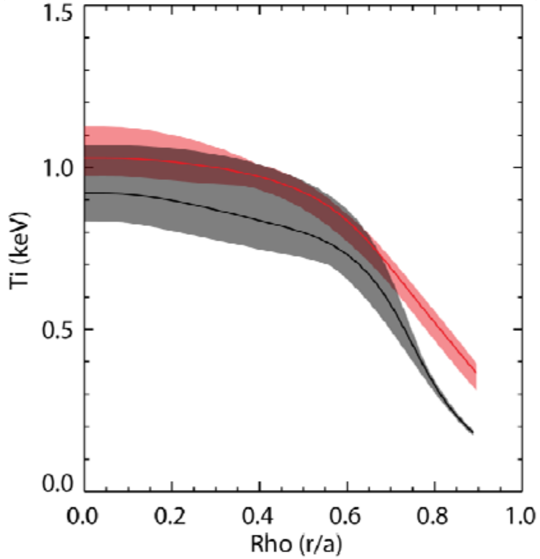

Velocity (m/s) 129060A08


Velocity (m/s) 129064A18

Lithium conditioning results in the decrease in edge n_D and increase in edge T_D

With Li conditioning:

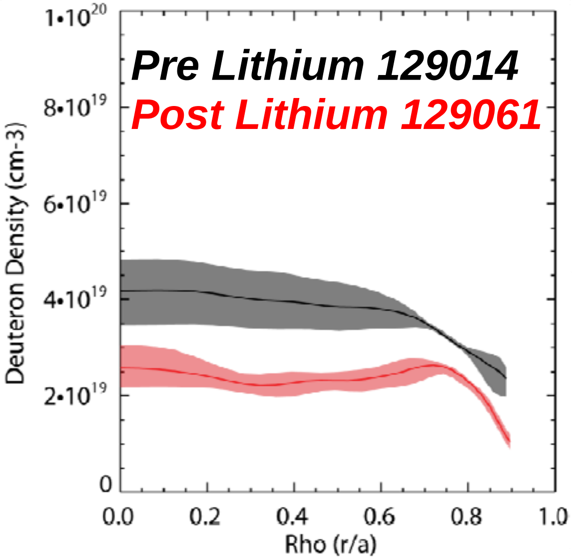
- Deuteron density reduced, increased edge density gradient due to Li pumping
- Higher edge Ti, weaker edge temperature gradient (due to ELMs? See later)

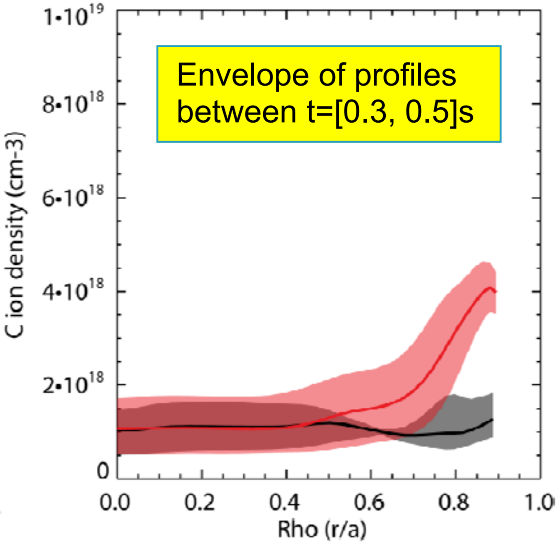


CAVEATS

- n_D inferred from n_e, assuming C as only impurity → larger uncertainty on profiles and gradients

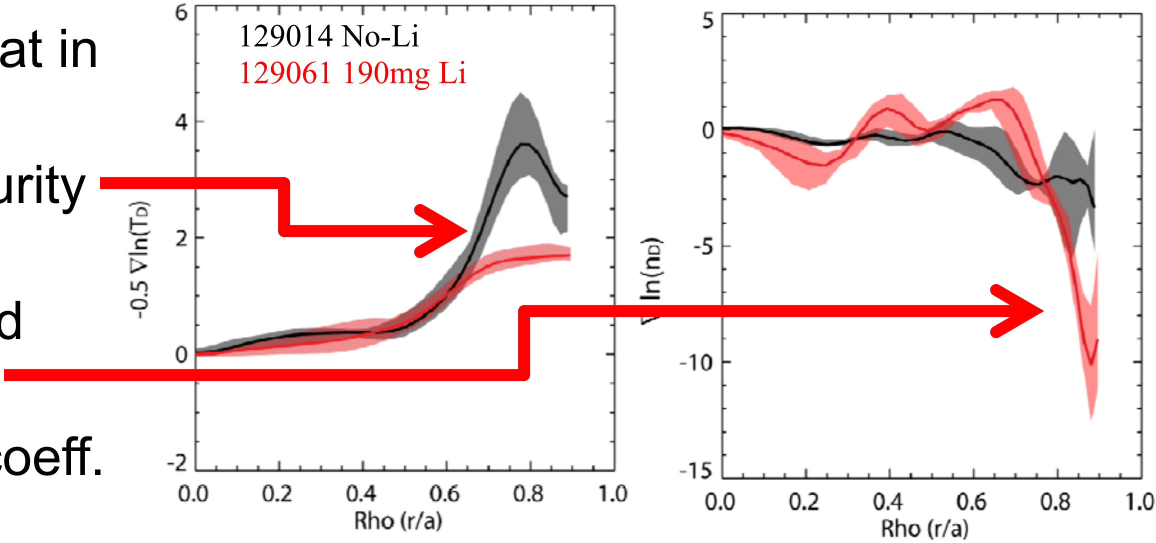
- r/a >0.9 not considered due to uncertainty in n_D gradient but likely to play an important role

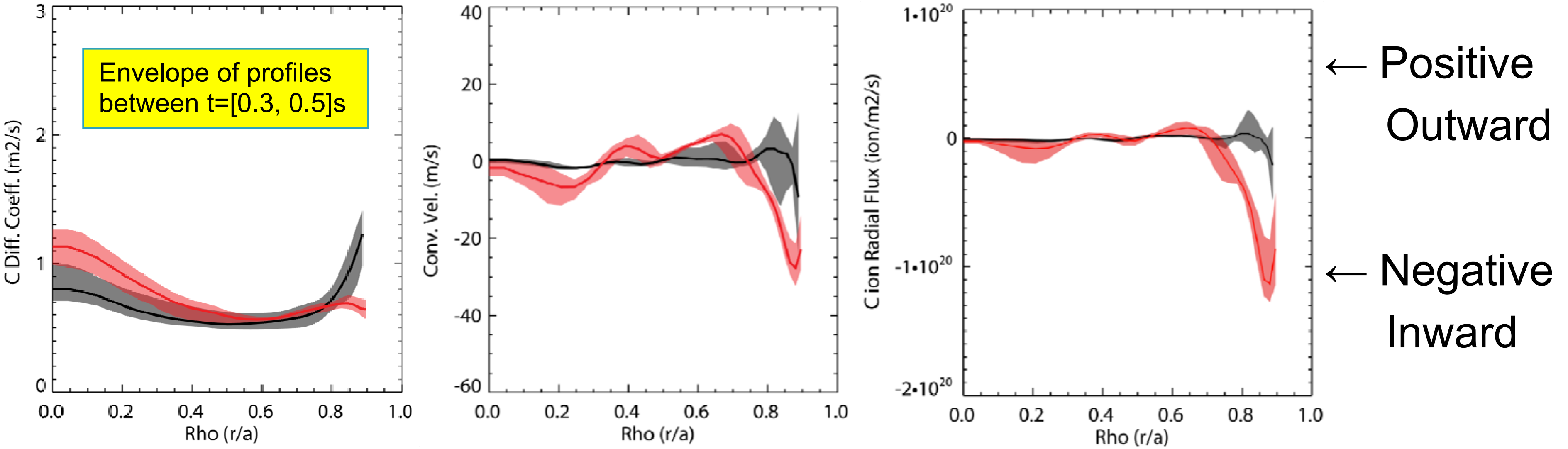




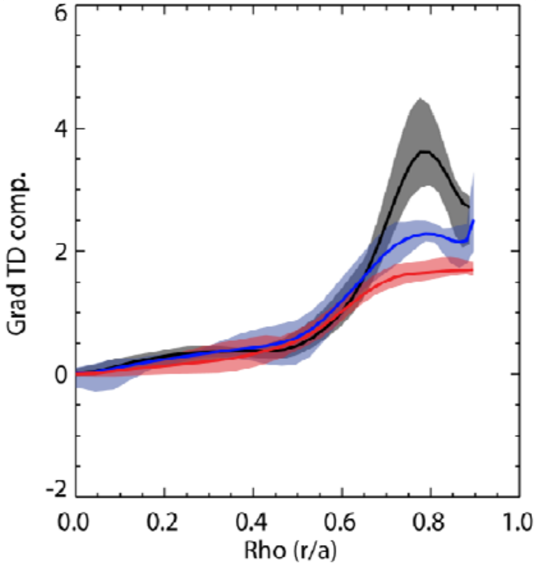
Neoclassical theory indicates change in carbon convective transport as T_D and n_D gradients change

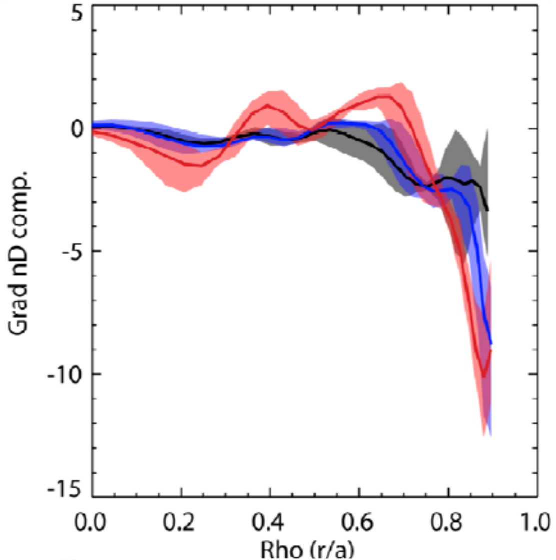
- NCLASS simulations show that in Li conditioned discharges :
  - Change in ∇T_D reduces impurity screening
  - Change in ∇n_D leads to inward pinch
  - Reduced v reduces diffusion coeff. at the edge

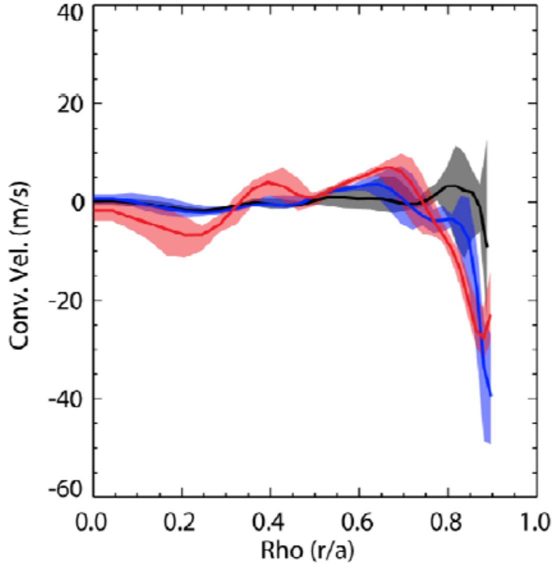


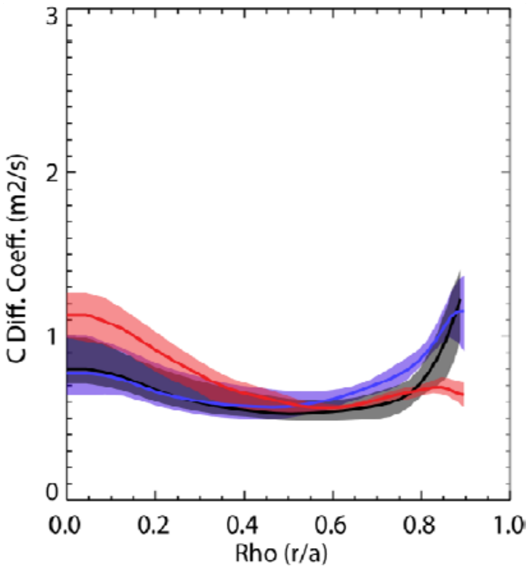


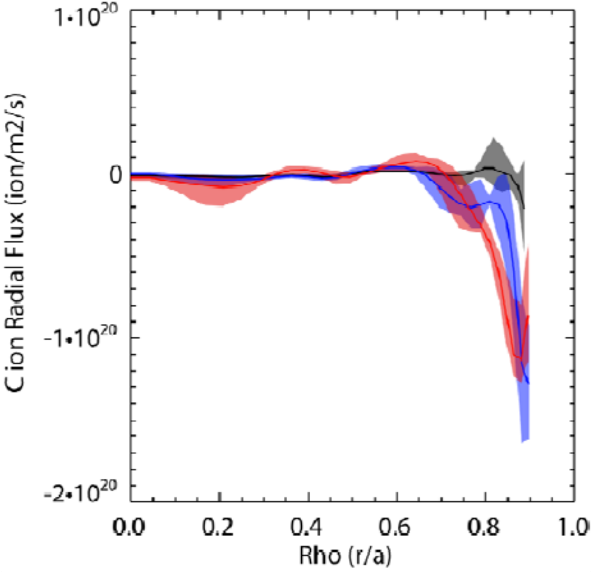
Effects on particle diffusivity and convective velocity progressive with increase in lithium deposition











Envelope of profiles between t=[0.3, 0.5]s

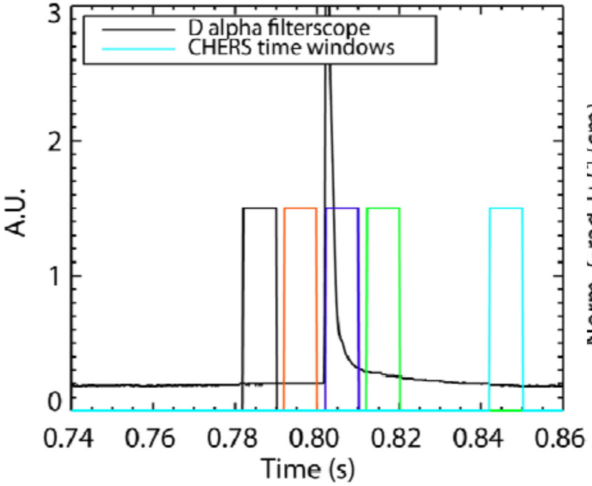
Boronized PFCs 129014

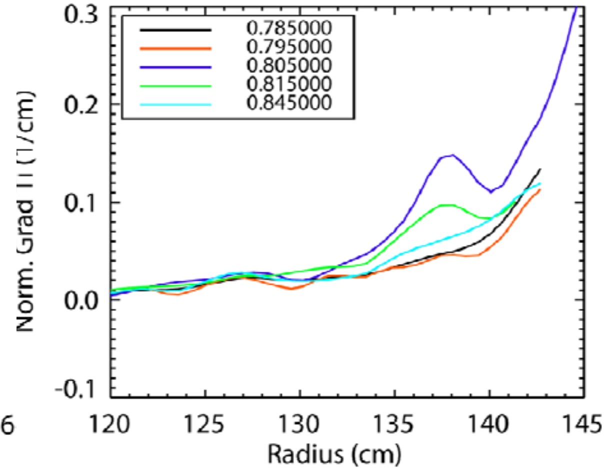
No fresh Li 129060

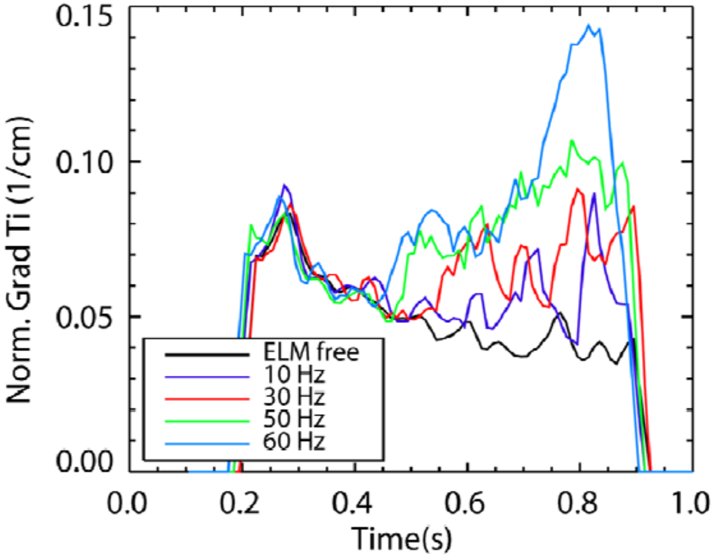
190 mg fresh Li 129061

ELMs contribute to impurity flushing in the edge region and installing edge ion temperature gradient

- Evidence for edge Ti gradient installed by large RMP induced type I ELMs from 10 to 60Hz → Can it be extrapolated to natural faster/smaller ELMs?
- Gradient relaxation through ELM cycle suggests it's not simply an artifact due to CHERS averaging over ELM event
- Hypothesis:
  - ELM contributes to flushing of impurity in the edge region
  - Increase in edge ion temperature gradient increases impurity screening
  - Increasing ELM frequency → stable impurity screening at the edge



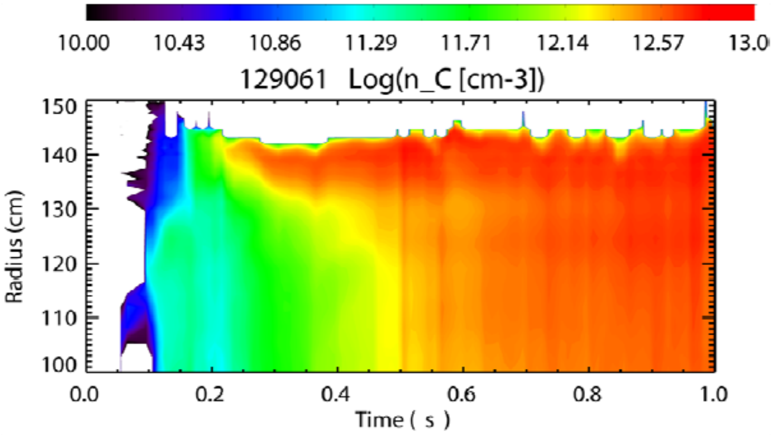


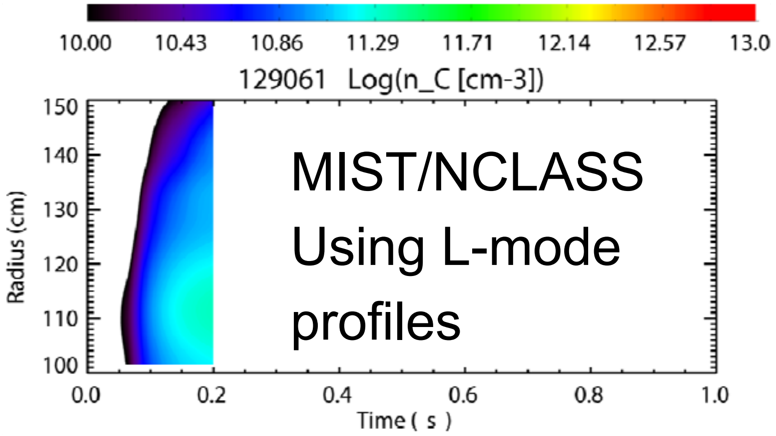


NCLASS/MIST qualitatively consistent with experimental observations of early formation of hollow profile

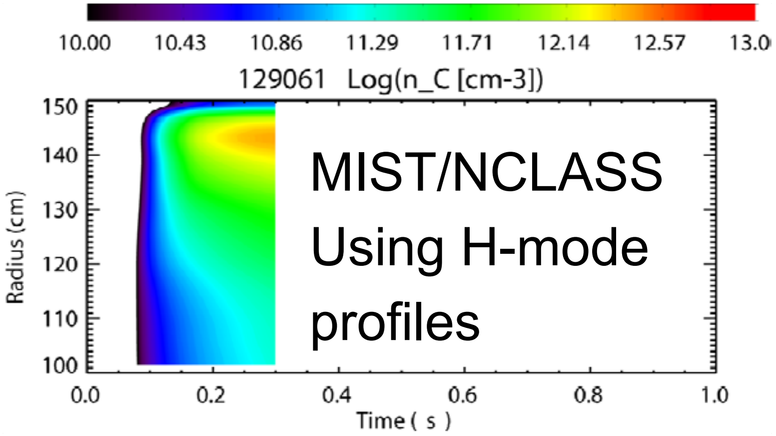
- At L-H transition carbon peaked profile evolves in hollow profile
- MIST/NCLASS consistently predict transition of C density profile
- Mostly due to change in main ion density profile
- Sources are matched to reproduce core concentrations

Experimental (CHERS)





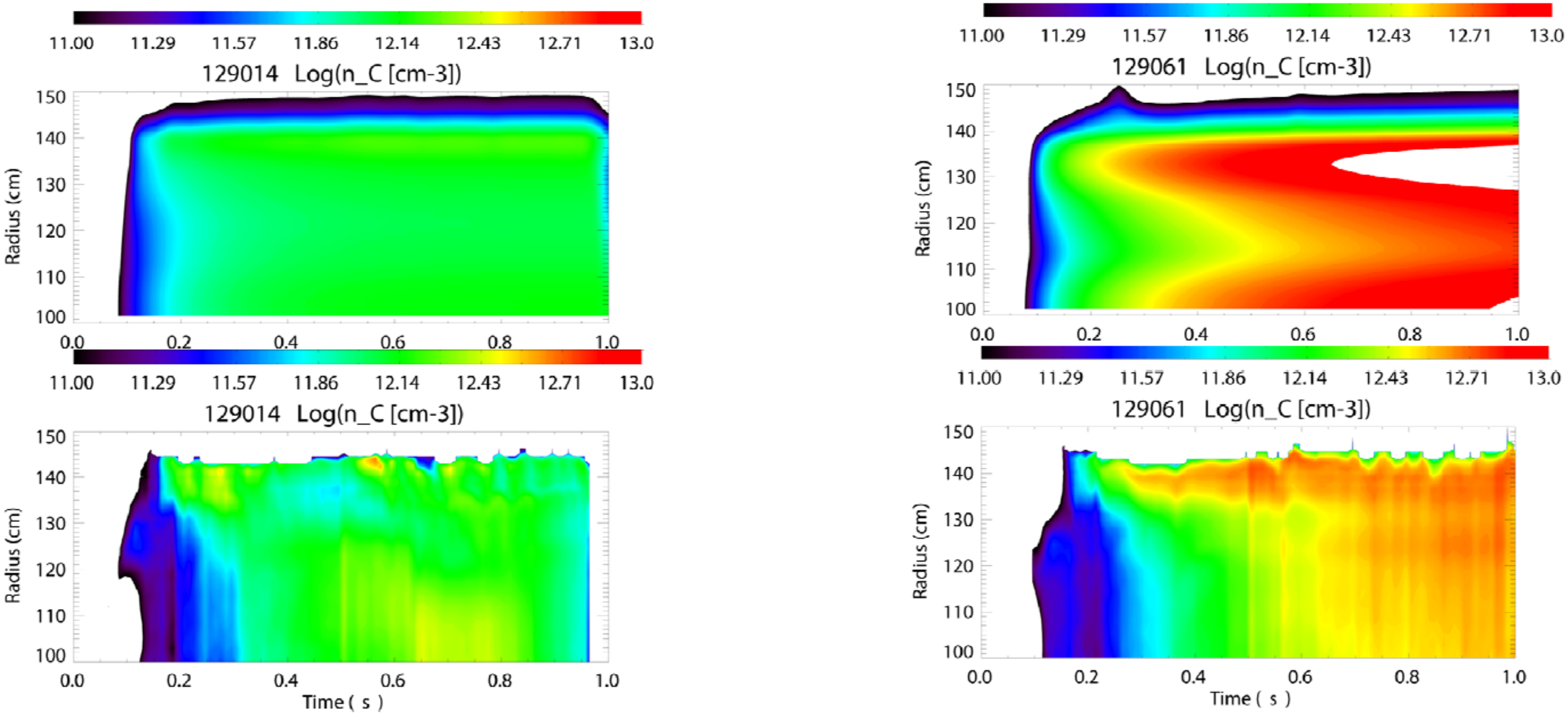
MIST/NCLASS
Using L-mode
profiles



MIST/NCLASS
Using H-mode
profiles

NCLASS/MIST indicates qualitative consistency with experimental observations of carbon accumulation

- NCLASS suggests C transport coefficients evolving in time - but - MIST only allows for input transport coefficients constant in time
- C density profiles don't usually reach steady state in Li-conditioned discharges
- MIST inability to predict C profiles time evolution for intrinsic impurity studies
- Overall: matching source for pre-Li profiles and updating NCLASS post-Li transport coeff → 'ear' and core accumulation but significant difference from exp.

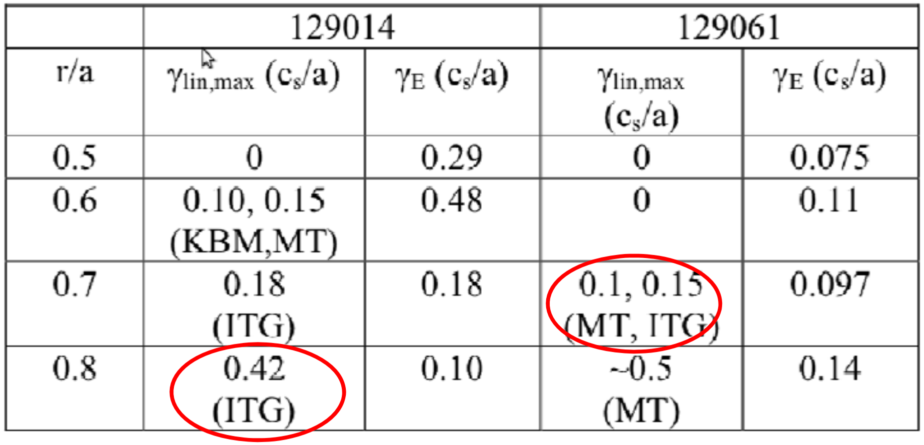


Linear gyrokinetic simulations indicate ion scale turbulence could remain in the edge region

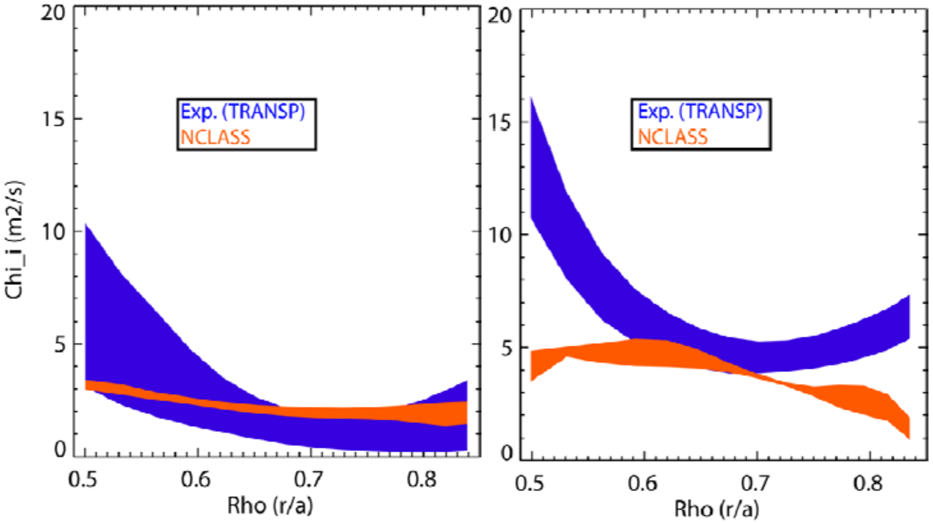
- Linear gyrokinetic simulations (GYRO*) carried out by W. Guttenfelder
- For both pre and post-Li discharges, a mix of Kinetic Ballooning Modes, MicroTearing, ITG and ETG are found to be unstable in the region r/a=0.5-0.8
- In pre-Li at r/a=0.8 and post-Li at r/a=0.7 local ITG modes have linear growth rates larger than local E×B shear rates
- Ion scale turbulence could remain, influencing particle/impurity transport
- However, thermal transport is experimentally (TRANSP) close to neoclassical.
- Non-linear simulations are required for a more accurate prediction

Pre-Li

Post-Li



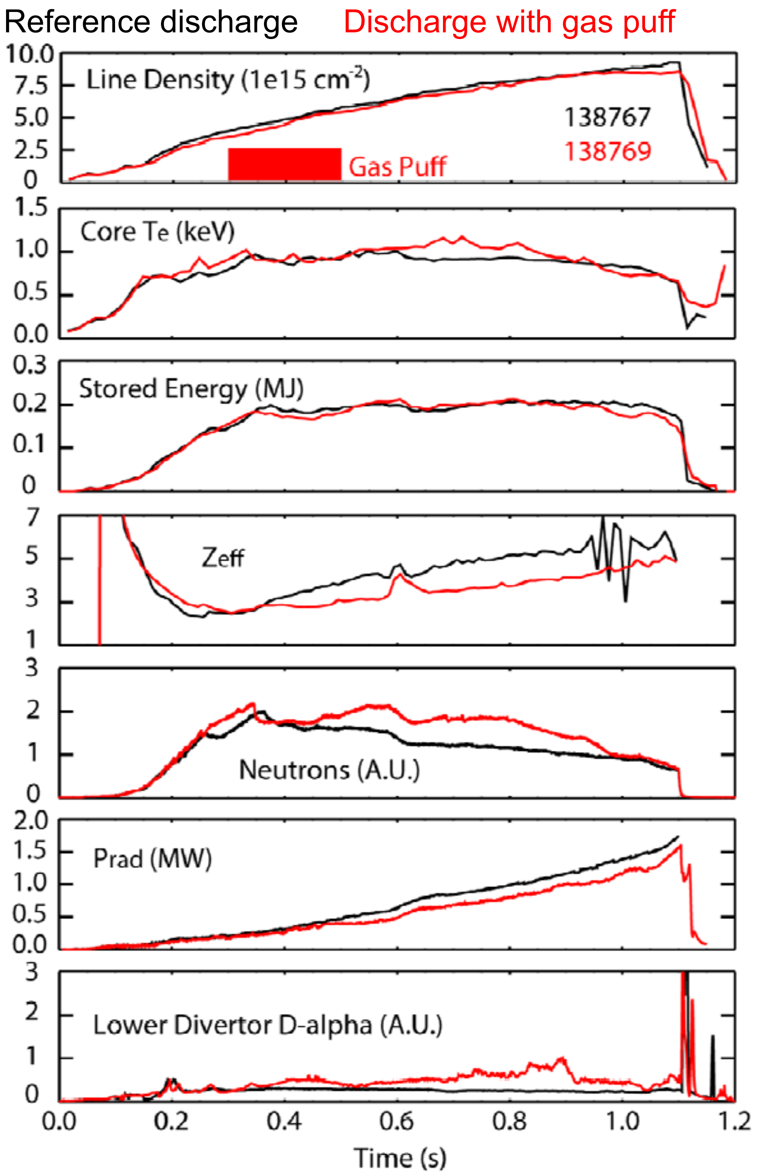
	129014		129061	
r/a	$\gamma_{lin,max}$ (c_s/a)	γ_E (c_s/a)	$\gamma_{lin,max}$ (c_s/a)	γ_E (c_s/a)
0.5	0	0.29	0	0.075
0.6	0.10, 0.15 (KBM,MT)	0.48	0	0.11
0.7	0.18 (ITG)	0.18	0.1, 0.15 (MT, ITG)	0.097
0.8	0.42 (ITG)	0.10	~0.5 (MT)	0.14



* J. Candy, R.E. Waltz, PRL (2003)

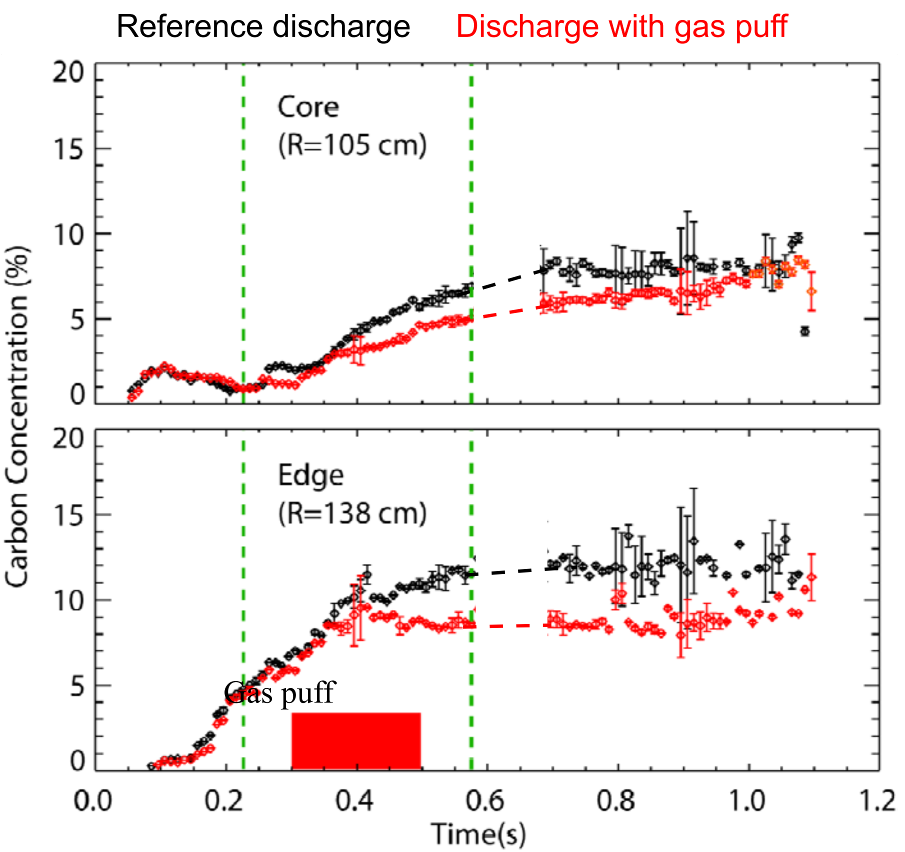
Increased impurity confinement with Li conditioning brings need to mitigate impurity sources

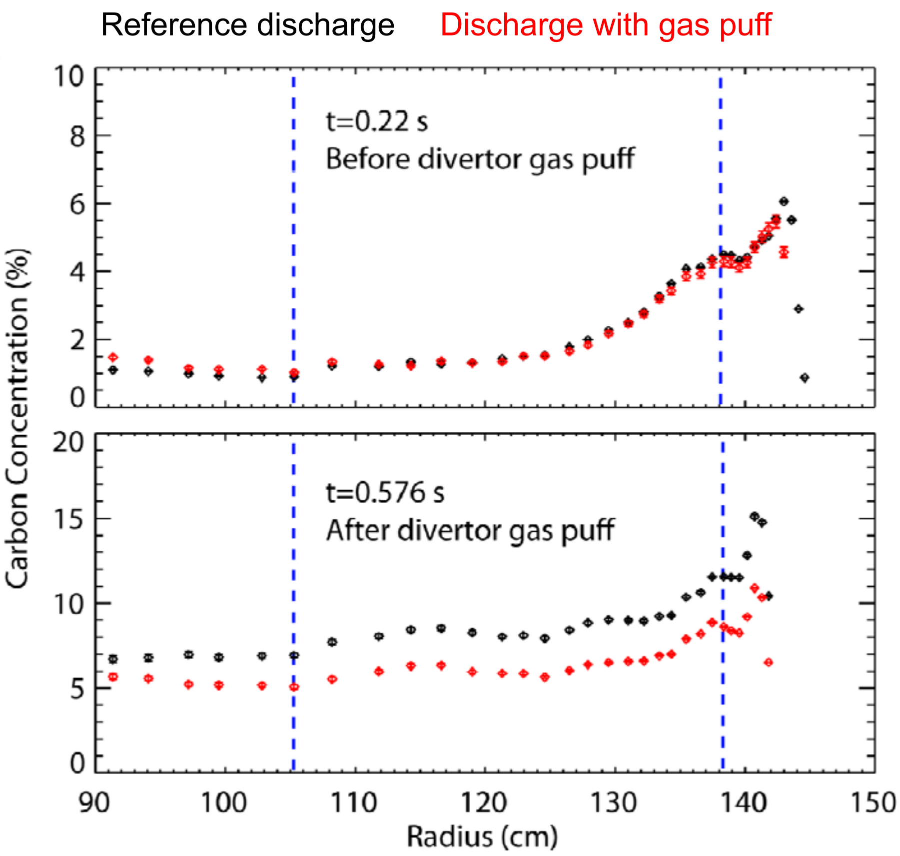
- In a dedicated XP in FY10, D_2 divertor puff in high flux expansion far SOL
- Core plasma parameters and confinement unaffected
- Z_{eff} reduced up to 30%, P_{rad} up to 20%
- Higher gas injection rates lead to stronger impurity reduction until OSP partial detachment is achieved
- Spectroscopic observations suggest reduced physical sputtering
- Impossible to discern reduced sputtering (decreased T_e) vs change in SOL transport (increased SOL flow) or divertor retention (increased n_e).



Carbon concentration reduced up to 30% in both core and edge plasma

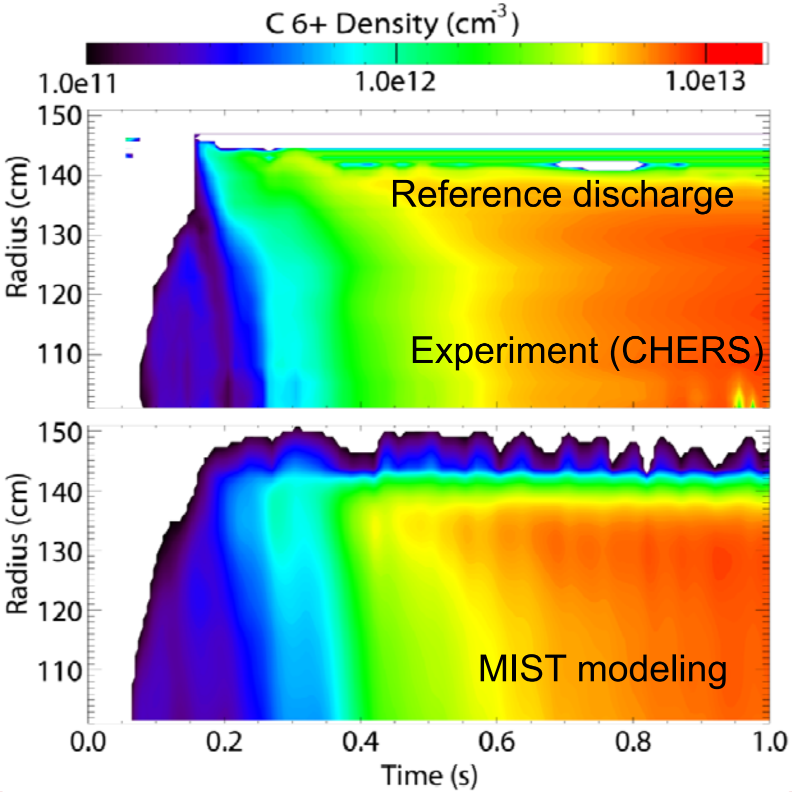
- Core carbon densities from CHERS (C VI, n=8-7, 529.1 nm)
- Carbon concentration reduced up to 30%, both in core and edge
- Carbon concentration radial profile shape unchanged
- Total carbon inventories reduced up to 30% (~1.5e19 ions)

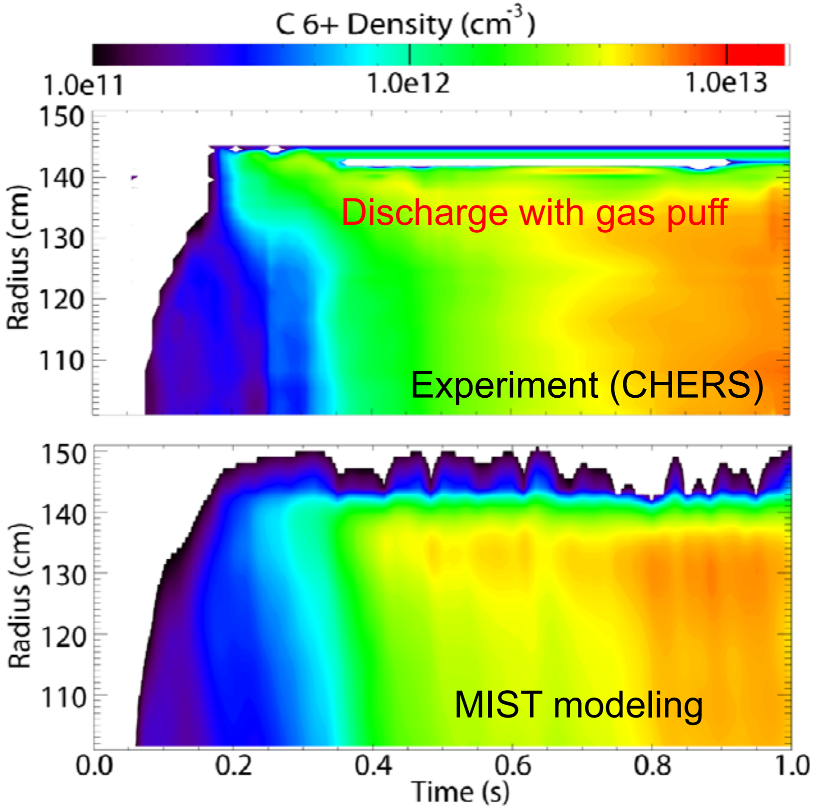




1-D radial transport modeling shows that reduced impurity source is needed to explain core carbon concentrations

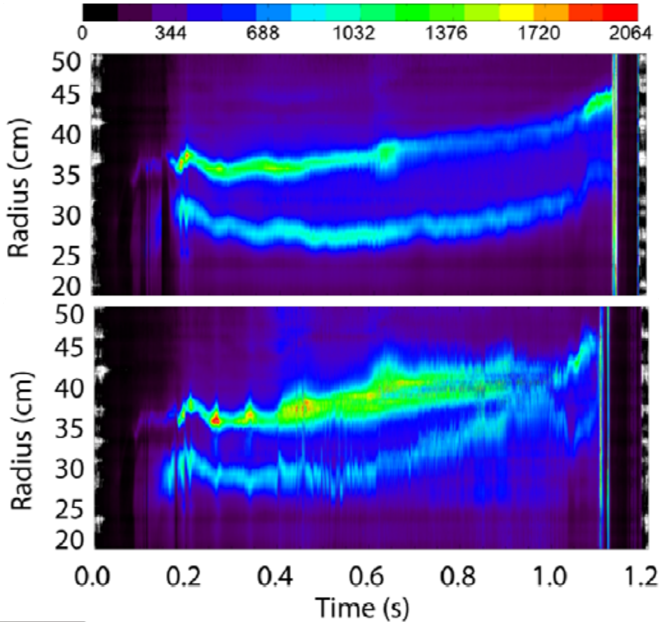
- MIST code simulations for reference discharge without gas puff:
  - neoclassical level diffusion (D = 1 m^2/s)
  - strong inward pinch velocity
- Core carbon concentration of gas puff discharge reproduced reducing LCFS impurity source by ~20-25%
- NCLASS doesn't indicate any significant change in neoclassical transport





Reduced divertor T_e with divertor gas puff suggests reduced physical sputtering rate

- C II emission: spatial extent increases, radiation front moves upstream
- 5 point SOL transport model* suggests gas puff is effective in increasing n_e and decreasing T_e
  - – Suggests reduction in OSP physical sputtering yield
- Lack of direct n_e and T_e measurements precludes use of S/XB method on gas puffing discharges

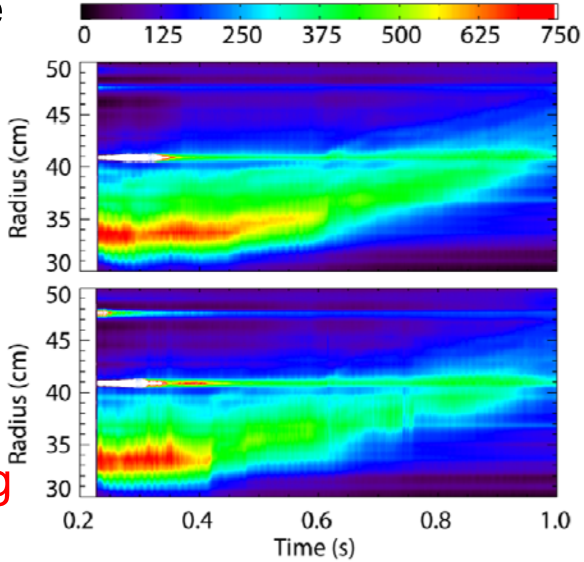


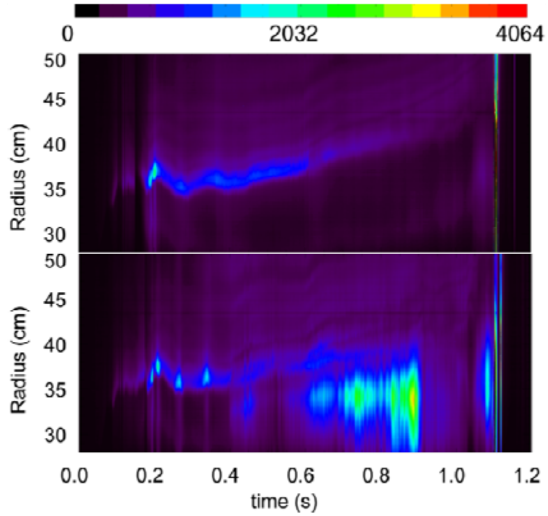
With gas puff, reduction in surface T up to 150°C observed w/o OSP detachment

– T decrease not enough to support conclusions about chemical sputtering yield

With gas puff inner strike point detaches

– Reduced ISP physical sputtering





Goswami, *Phys. Plasmas*, **8**,3 (2001)]

BACKUPS

NSTX routinely exploits lithium evaporation as wall conditioning technique

- Lithium conditioning routinely applied on graphite PFCs in NSTX

- Lithium conditioning led to

☐ Longer discharges
☐ Improvement of energy confinement
☐ ELMs suppression

Global Effects

☐ Reduced recycling
☐ Change in divertor/SOL heat transport regimes

Divertor/Edge Effects

☐ Deuterium ion inventory reduced by up to 50 %
☐ Lithium screened from core plasma
☐ Carbon and high-Z impurity accumulation
☐ Peaked P_{rad} profile, up to 50% of P_{inj}

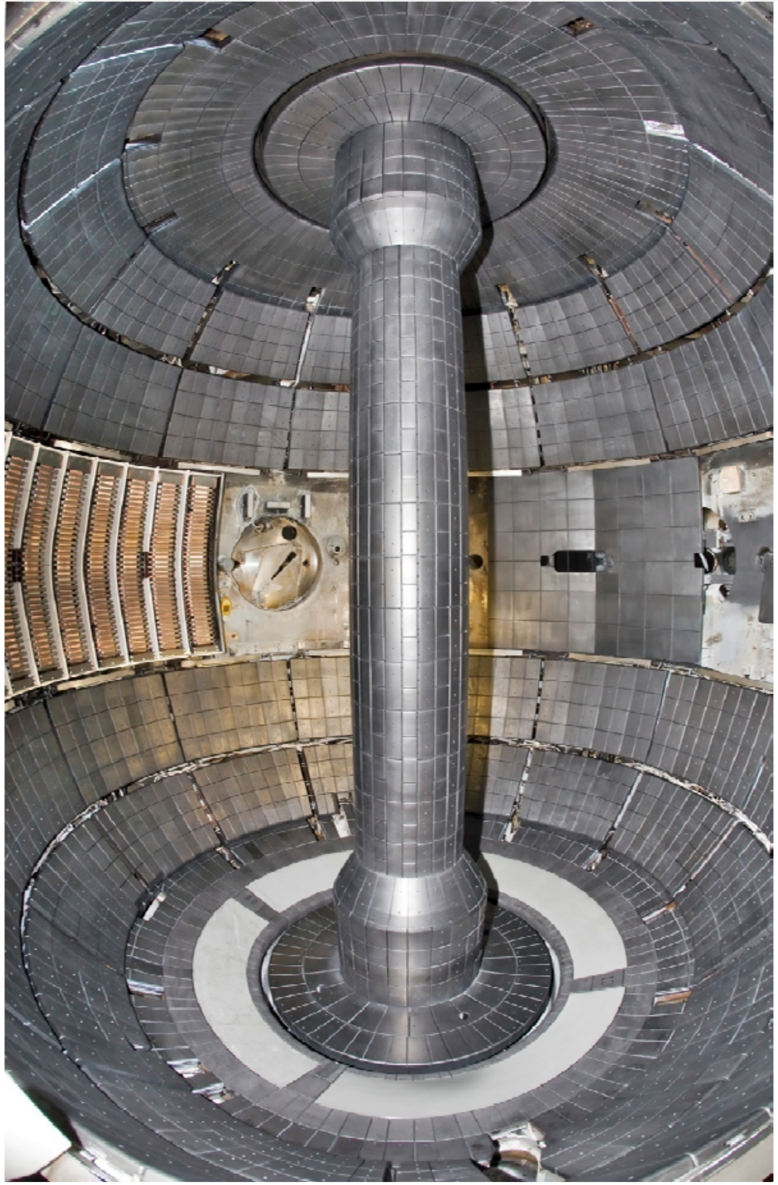
Particle and Power Balances

NSTX and PFCs Reference Data

Aspect ratio A	1.27 – 1.6
Elongation ⍰	1.8 – 3.0
Triangularity ⍰	0.2 – 0.8
Toroidal Field BT0	0.4 – 0.55 T
Plasma Current Ip	<1.3MA
NBI (100kV)	up to 7 MW

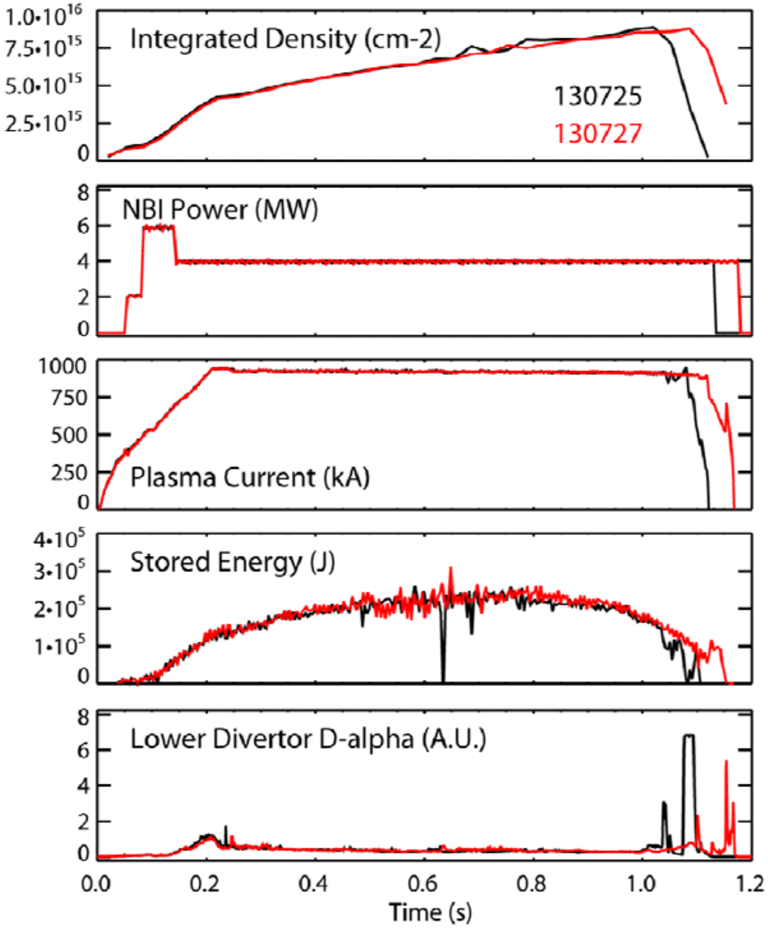
Plasma Facing Components

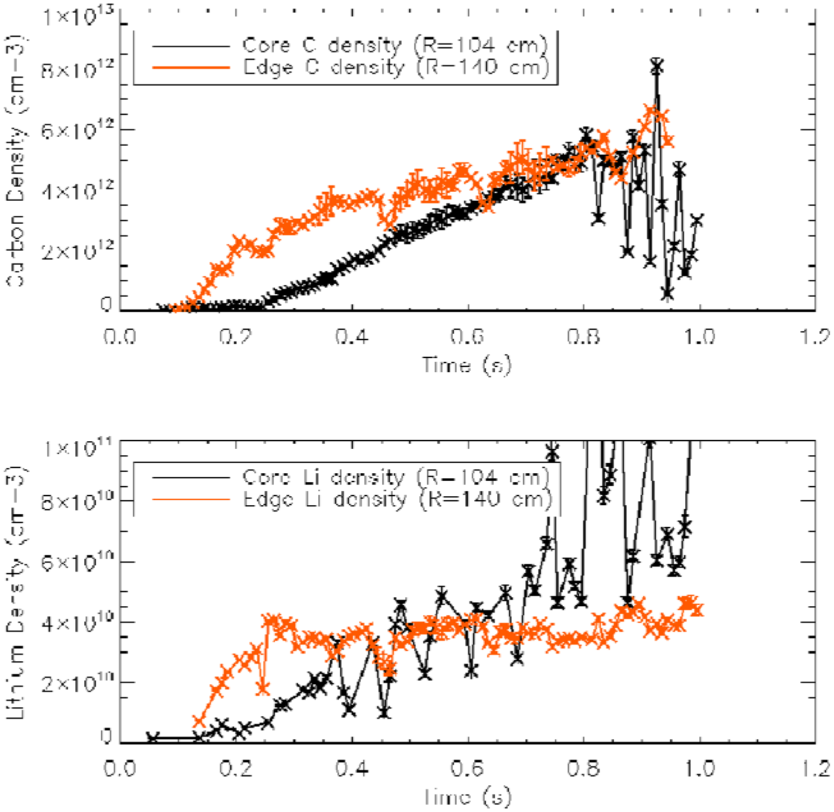
- ATJ graphite tiles on divertor and passive plates
- ATJ and CFC tiles on center stack
- Molybdenum porous mesh plasma sprayed on SS and 1” thick Cu plate at divertor major radius of R=65-84 cm since FY10
- Molybdenum tiles on outer row of inner divertor since FY11



Li and C ion profiles have similar time evolutions but Li ions do not accumulate in core plasma

- C and Li measured in two similar discharges by toroidal CHERS system
- Similar time evolution, with early 'ear' formation and slower core buildup
- Li screened out from core with densities less than 1% of C density

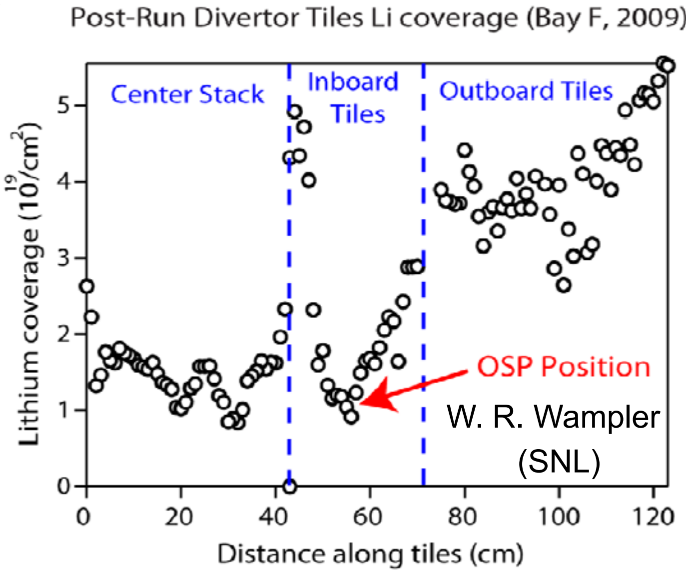


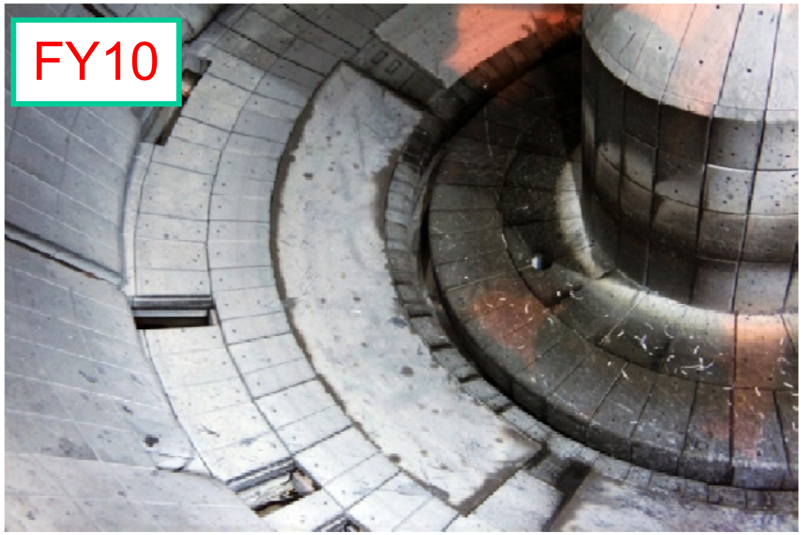


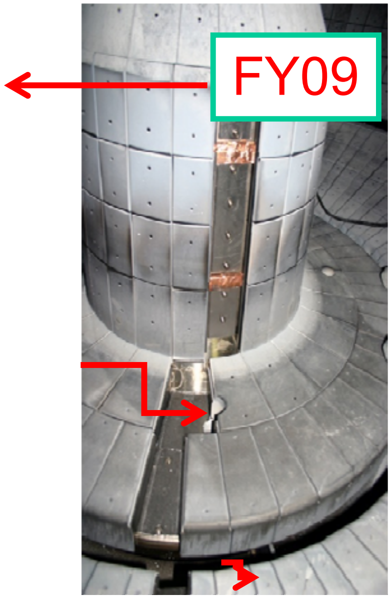
Impurity density profiles from CHERS
– C VI, n = 8-7, 529.1 nm
– Li III, n = 7-5, 516.7 nm

How can you have C accumulation if PFCs are coated with Li?

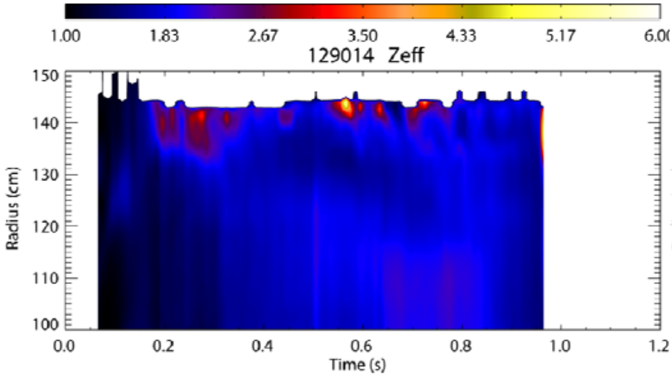
- Lithium layers at the OSP region degrade during discharges due to sputtering, evaporation
- C sputtering possible despite Li conditioning
- Sputtering yield experimentally consistent with graphite physical sputtering ~1%
- Currently no idea on C source repartition

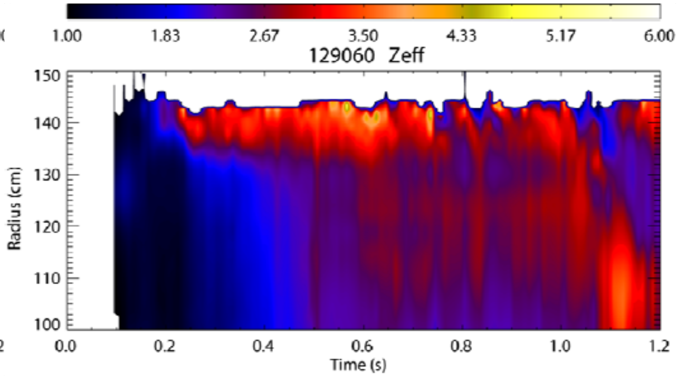




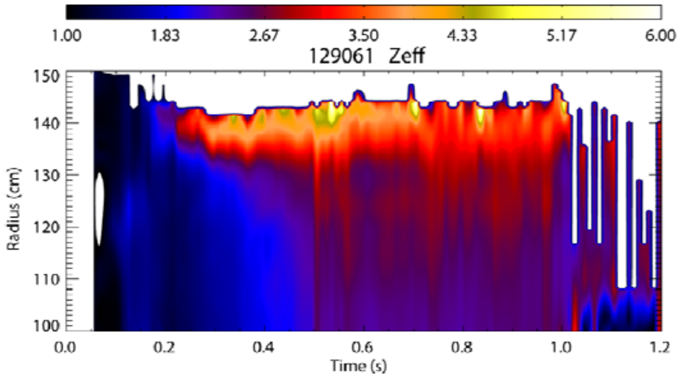


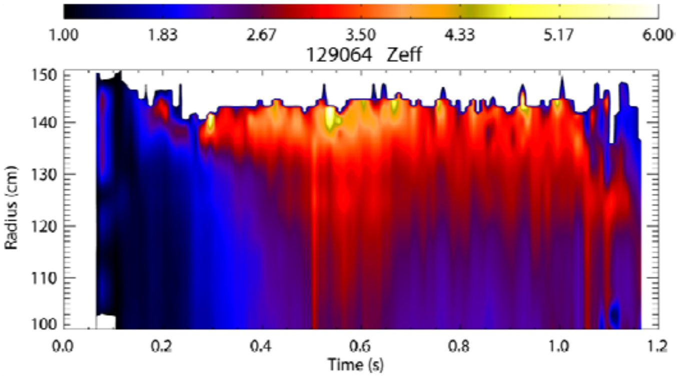
Carbon accumulation progressively worsens with lithium conditioning

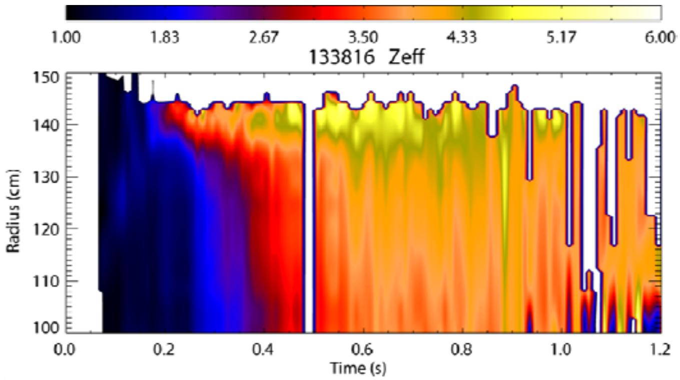




- Progressive effect on Z_{eff} with lithium conditioning







More 'extreme' examples exist in similar discharge configurations

S/XB method is commonly used to derive impurity influxes from spectroscopic measurements

$$\Gamma_{ph} = \int_{x_1}^{x_2} n_i \, n_e \, X \, B \, dx$$

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(v_i \, n_i) = S^{i-1} \, n_e \, n_{i-1} - S^i \, n_e \, n_i$$

$$\Gamma_{ph} = -\frac{X \, B}{S^i} \left(v_i \, n_i|_{x_1}^{x_2} - \int_{x_1}^{x_2} S^{i-1} n_{i-1} \, n_e \, dx + \int_{x_1}^{x_2} \frac{\partial n_i}{\partial t} \, dx \right)$$

$$\Gamma_i = -v_i \, n_i|_{x_1}^{x_2} + \int_{x_1}^{x_2} S^{i-1} n_{i-1} \, n_e \, dx$$

- 1D viewing geometry
- x1- recycling / erosion boundary, x2 - detector location
- Ionizing plasma, recombination neglected
- Excitation and ionization occur in the same volume
- Steady-state condition

$$\Gamma_i = \frac{S}{X \, B} \, \Gamma_{ph}$$