NSTX

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Modifications in divertor and scrape-off layer conditions with lithium coatings in NSTX

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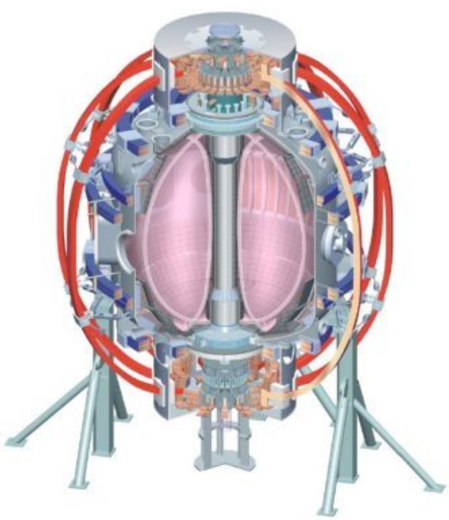

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Abstract & Acknowlegments

Two lithium evaporators were used in NSTX to deposit lithium coatings on graphite plasma-facing tiles in the lower divertor, enabling neutral deuterium pumping and resulting in reduced recycling. This was evident from the reduction by 50 % - 80 % in Dα poloidal and divertor brightnesses, as well as the ion outfluxes, edge neutral pressure, core and divertor n_e. The two point and multi-fluid UEDGE code modeling suggested a shift of the outer divertor operating space toward the sheath-limited transport regime with lithium. Particle balance calculation showed that the deuteron inventory was well controlled and remained nearly constant in the long 1.2-1.4 s ELM-free H-mode discharges with lithium coatings. However, n_e rose due to the increasing carbon inventory. The carbon source, estimated from C II and C III intensities and atomic S/XB factors, was reduced, suggesting that impurity accumulation was due to the improved particle confinement.

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Summary and Conclusions

- Evaporative lithium coatings on carbon PFCs modify divertor and SOL sources
  - Lower divertor, upper divertor and inner wall recycling was reduced by up to 50 %
  - Local recycling coefficients reduced on inner wall and far SOL, remained similar in the outer strike point region
  - Lower divertor carbon source from physical sputtering also reduced
  - Divertor lithium influx increased, however, lithium was retained in divertor

- SOL transport regime changes from high-recycling to low-recycling (sheath-limited)
  - Apparently small parallel T_e gradient
  - Detached inner divertor re-attaches, X-point MARFEs disappear

- Pedestal and core confinement improvement leads to
  - Surface pumping reduces ion inventory (density) by up to 50 %
  - Lithium is effectively screened from plasma
  - Carbon accumulation observed

Lithium research program on NSTX focuses on solid and liquid lithium plasma facing components

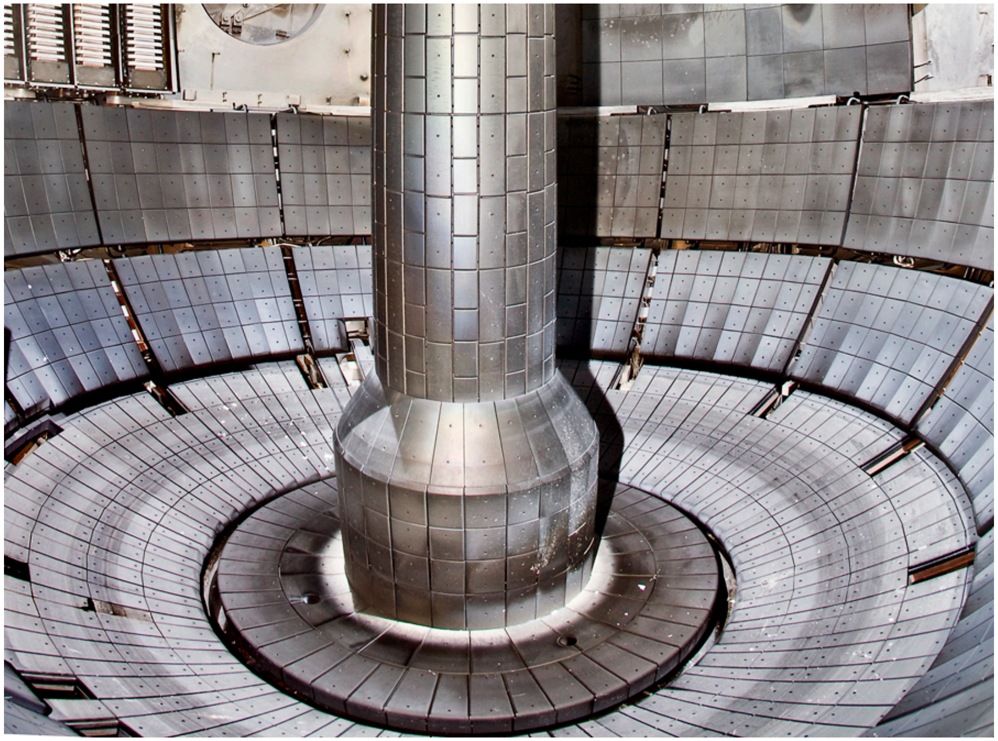
- Primary motivation for lithium coating studies – ion and impurity density control in H-mode plasmas

- Multi-phase lithium research plan on NSTX
  - Lithium pellet injection (2005-2009)
  - Lithium evaporation (2006-2009)
  - Liquid lithium divertor module (2009-2012)

- Recent NSTX experiments with lithium have shown
  - Reduced plasma density early in discharge
  - ELM suppression and longer pulse length
  - Improved energy confinement
  - Reduced flux consumption
  - Broader electron temperature profile

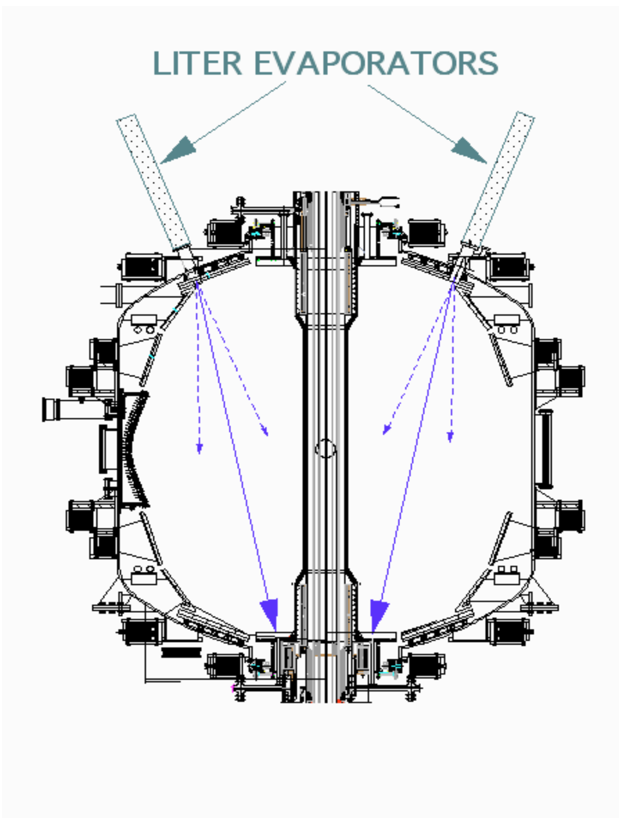
Plasma-surface interaction with lithium-coated graphite plasma-facing components

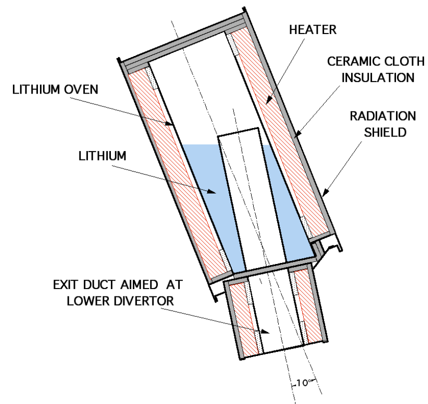
- **NSTX plasma facing components**
  - ATJ and CFC graphite tiles
  - Typical divertor tile temperature in 1 s pulses $T < 500$ C ($q_{peak} \leq 10$ MW/m^2)
- **Lithium pumping**
  - Through formation of LiD
  - Coating can bind D with a full 200-400 nm thickness
- **Impurity (Li, C) generation**
  - Sputtering by D ions
  - Self-sputtering
  - Evaporation

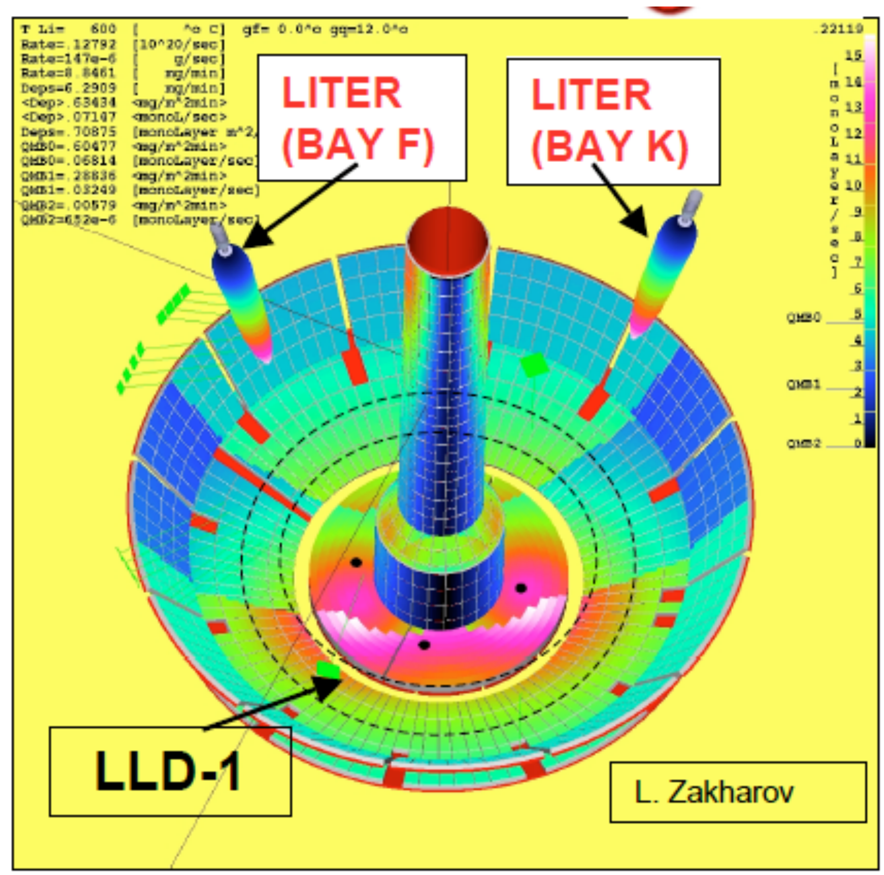


Two lithium evaporators (LITERs) were used in 2008 and 2009 experiments in NSTX

- Two LITERs
  - fuller coverage of lower divertor region
  - higher deposition rate



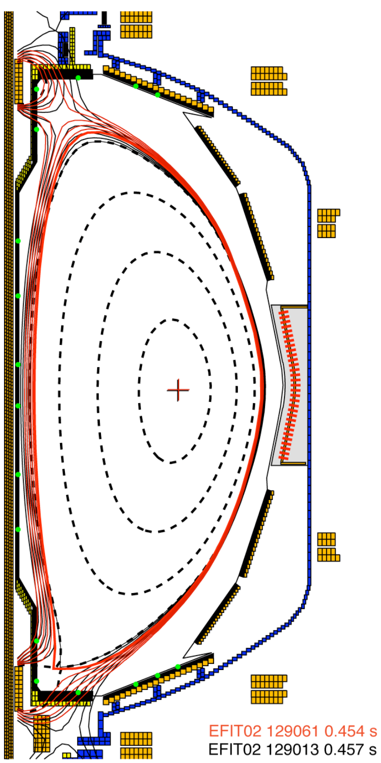




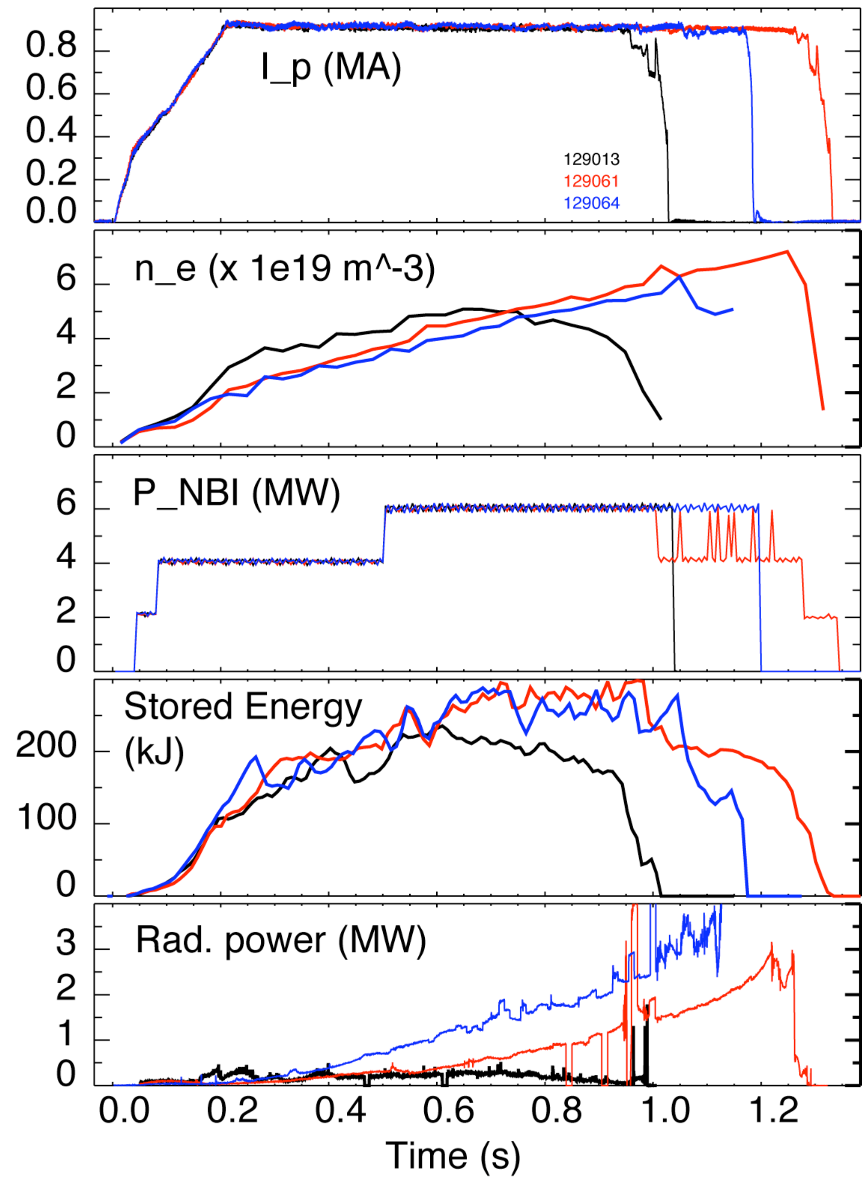
- Typical Operating Conditions
  - Capacity: 90 g Li
  - Oven Temp: 600-680°C
  - Rate: 1mg/min - 80mg/min

Impact of lithium conditioning was investigated in 4-6 MW H-mode discharges

- 0.9 MA, 4.5 kG, 4-6 MW NBI
- High κ~2.3, δ~0.6 shape
- Biased DN with δr_{sep}=6-8 mm

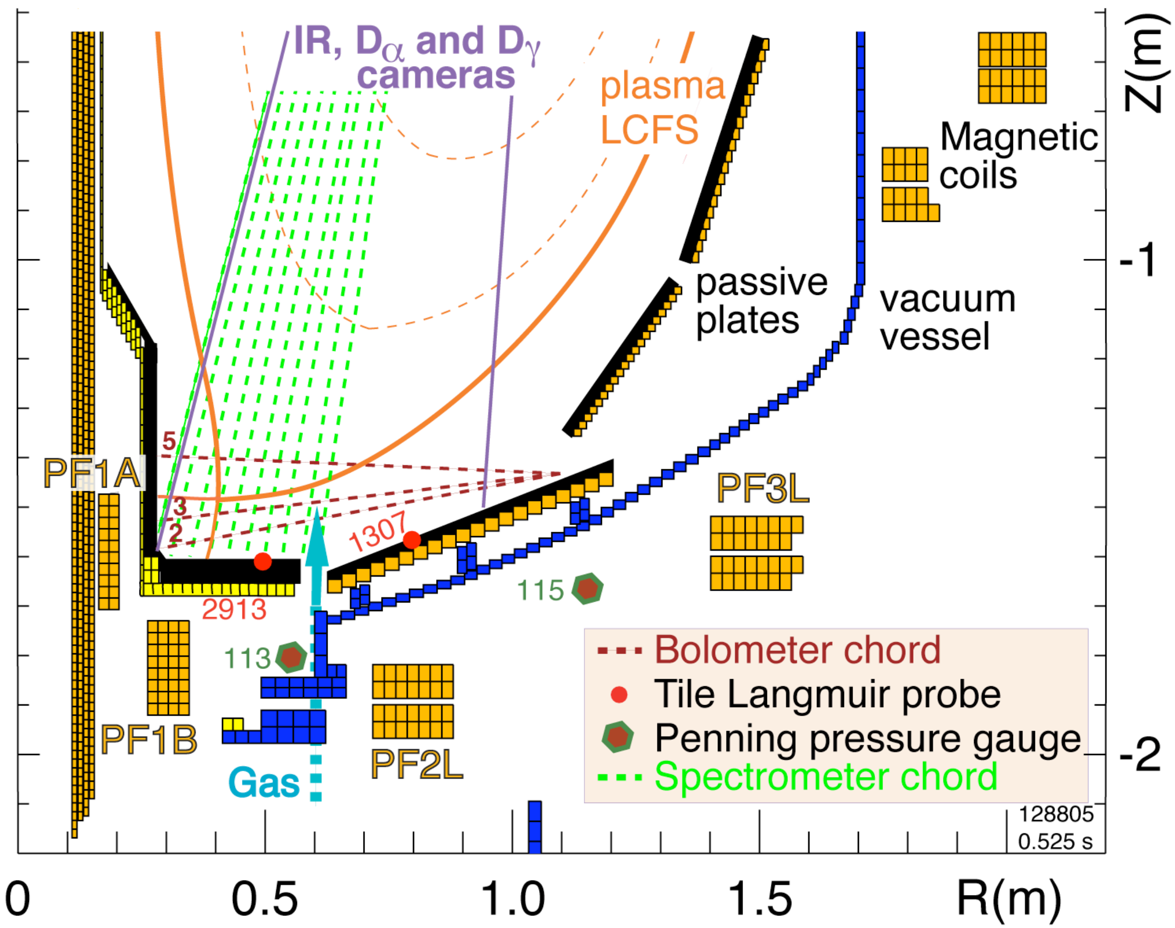


No lithium (129013)
190 mg Lithium (129061)
600 mg lithium (129064)

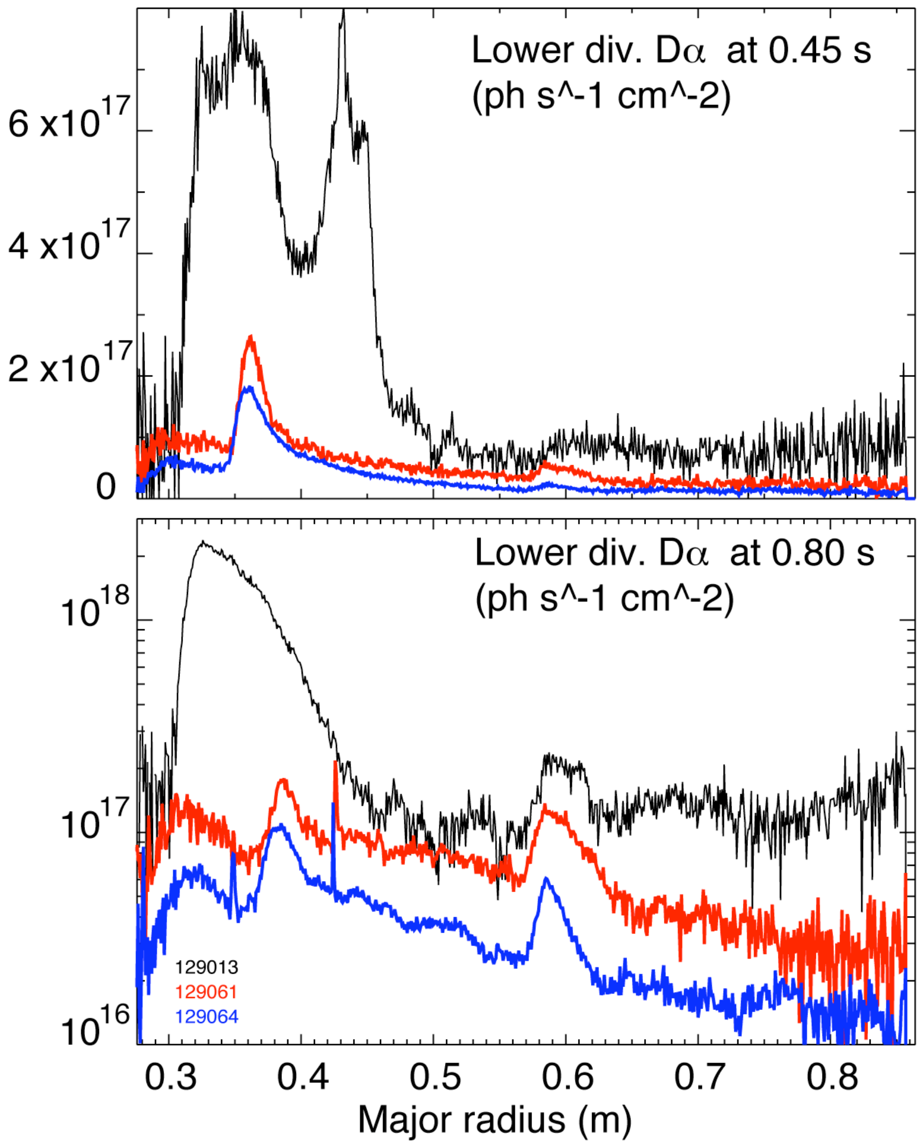


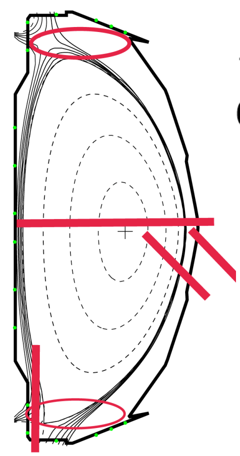
Multiple diagnostic measurements are analyzed to elucidate on divertor and SOL physics in NSTX

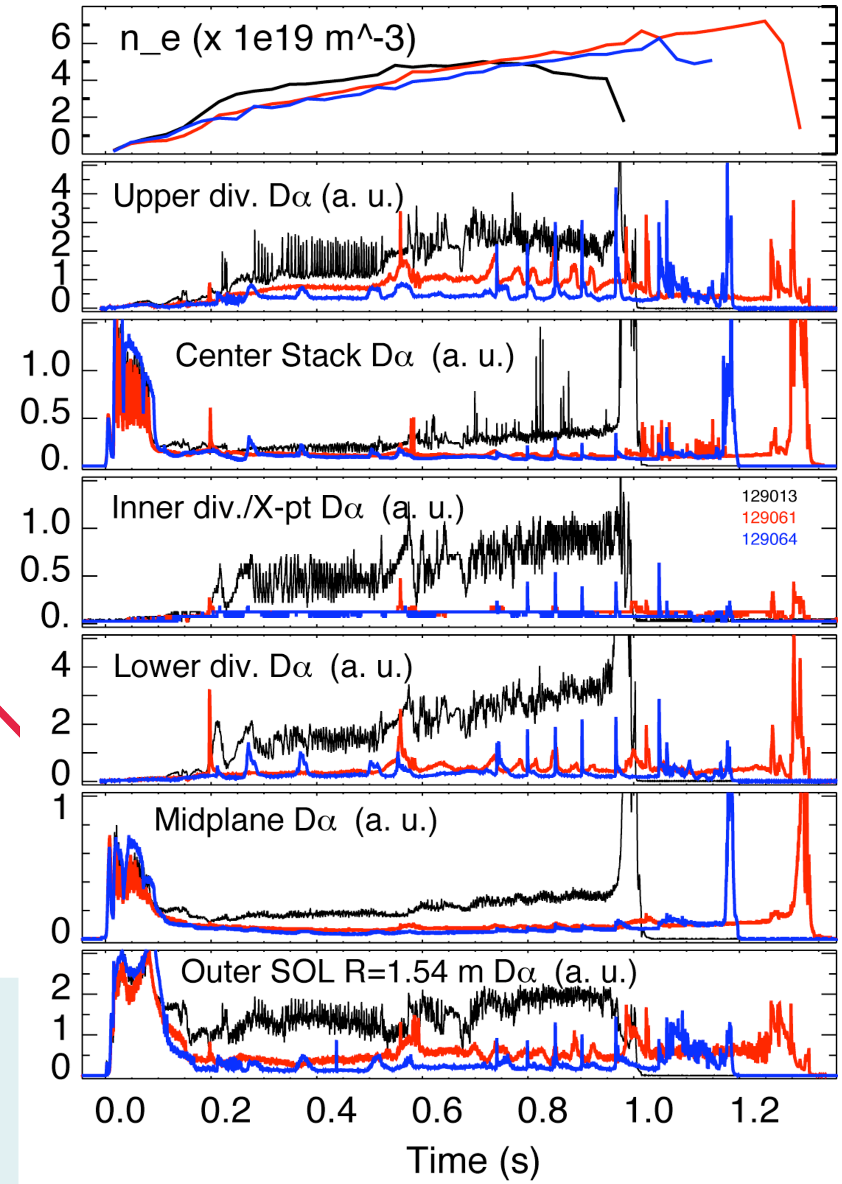
- Diagnostic set for divertor studies:
  - IR cameras
  - Bolometers
  - Neutral pressure gauges
  - Tile Langmuir probes
  - $D\alpha$, Li I filtered CCD arrays
  - Filterscopes
  - UV-VIS spectrometer (10 divertor chords)
- Midplane Thomson scattering and CHERS systems



Lithium had a profound and cumulative effect on poloidal recycling flux profile







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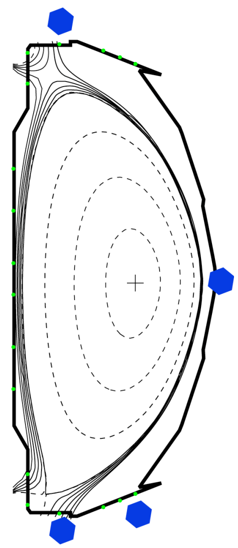
Neutral pressures in SOL and divertor were reduced after lithium application

$$\Gamma_{D_2} = \frac{1}{4} n_{D_2} \bar{v}$$

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}} \qquad P = n\,kT$$

$$\Gamma_D = 2 \times \frac{1}{2} \times \Gamma_{D_2} = \frac{1}{4} \frac{P}{kT} \sqrt{\frac{8kT}{\pi m}}$$



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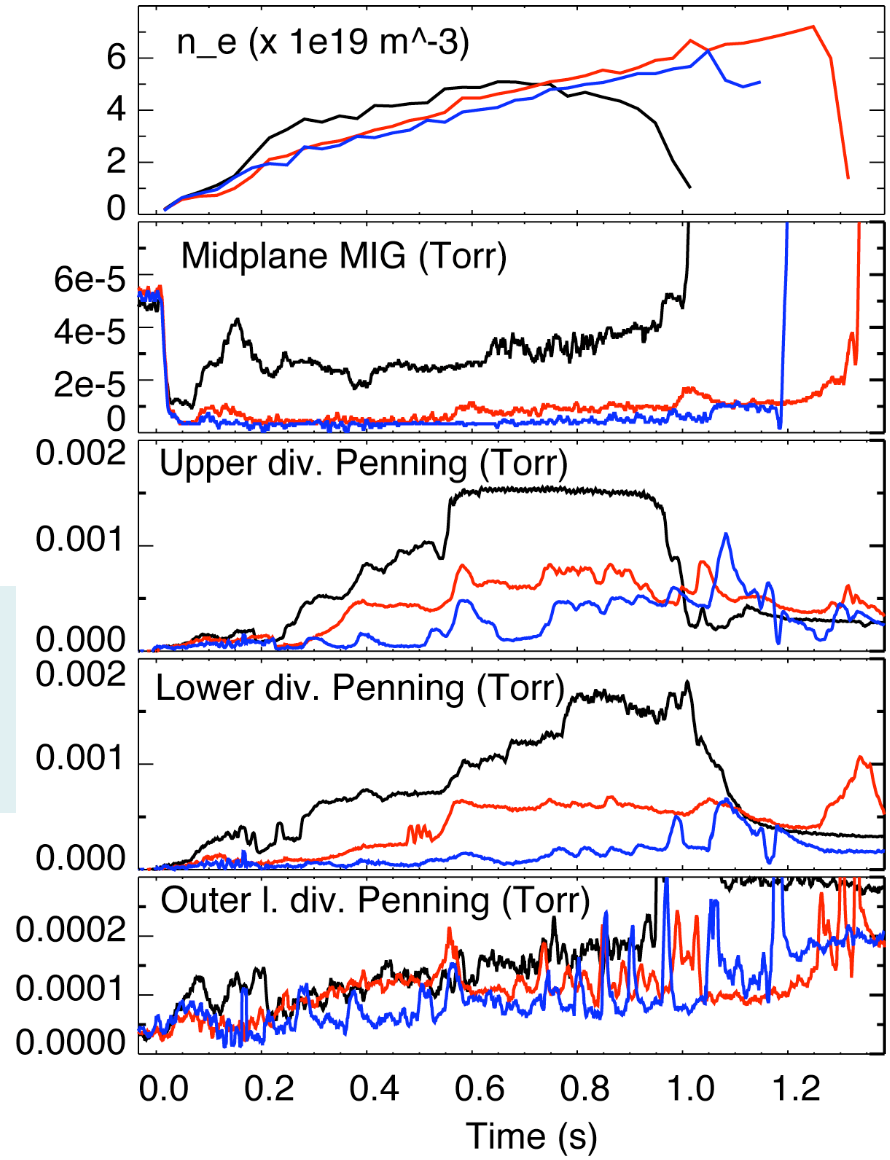

- "Standard" way to estimate molecular / atomic fluxes from pressure neutral measurements
- Might be about factor of 2-3 overestimated (from MC simulations and / or kinetic simulations)

Ion outflux is measured by Langmuir probes

$$j_{sat} = \frac{I_{sat}}{A_{pr} \sin \alpha}$$

$$\Gamma_i = j_{sat}/e$$

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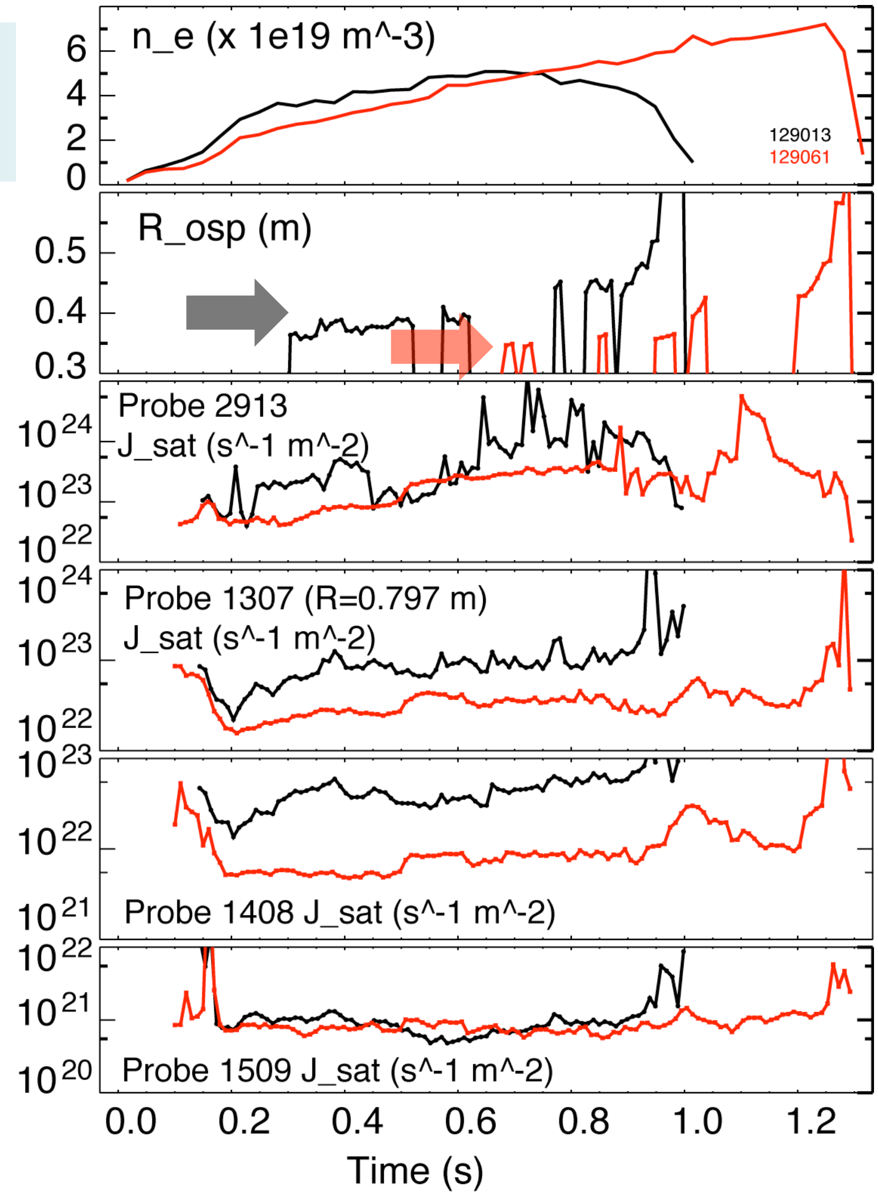

- Tile Langmuir probes are flush-mounted
- Main computational effort is to calculate α's accurately for shallow angles

  ($\alpha < 1\text{-}2^{o}$)
- On center stack, apparently large error bars in α's

Divertor heat flux measurements are complicated by lithium coatings

- Instrumental effects:
  - Thermal contact between lithium coating and bulk tile
  - Surface emissivity reduction
- Plasma effects:
  - Higher heat flux?

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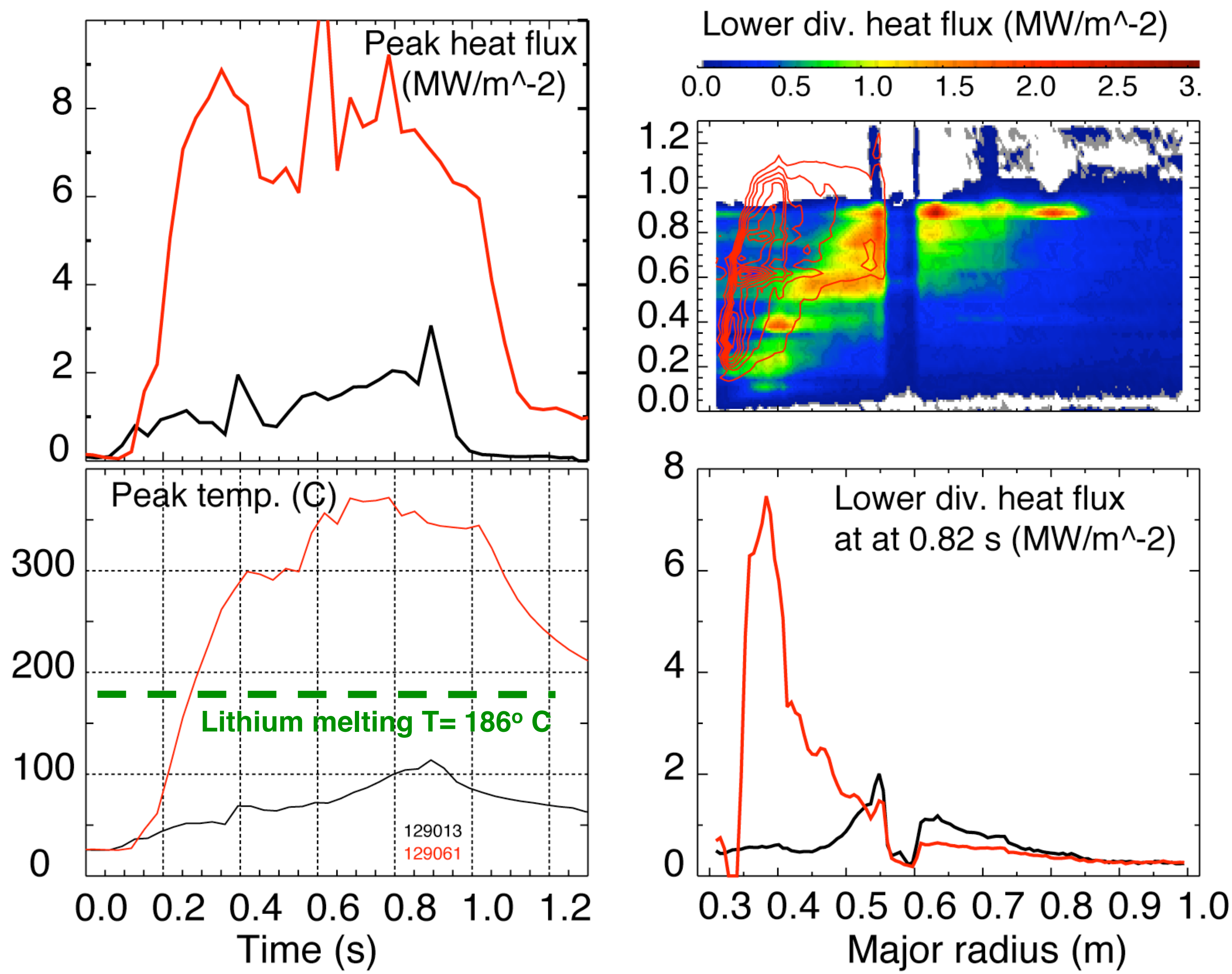

Lithium spectroscopy indicates higher lithium deposition on lower divertor and center stack

- Li I λ670 nm emission increase
  - x 10 in lower divertor
  - x 2-3 on center stack
  - little increase in upper divertor

- No systematic signs of accumulative effects

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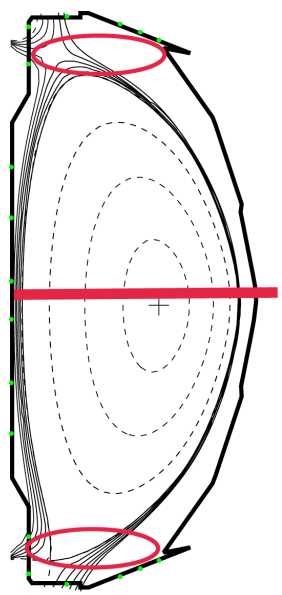
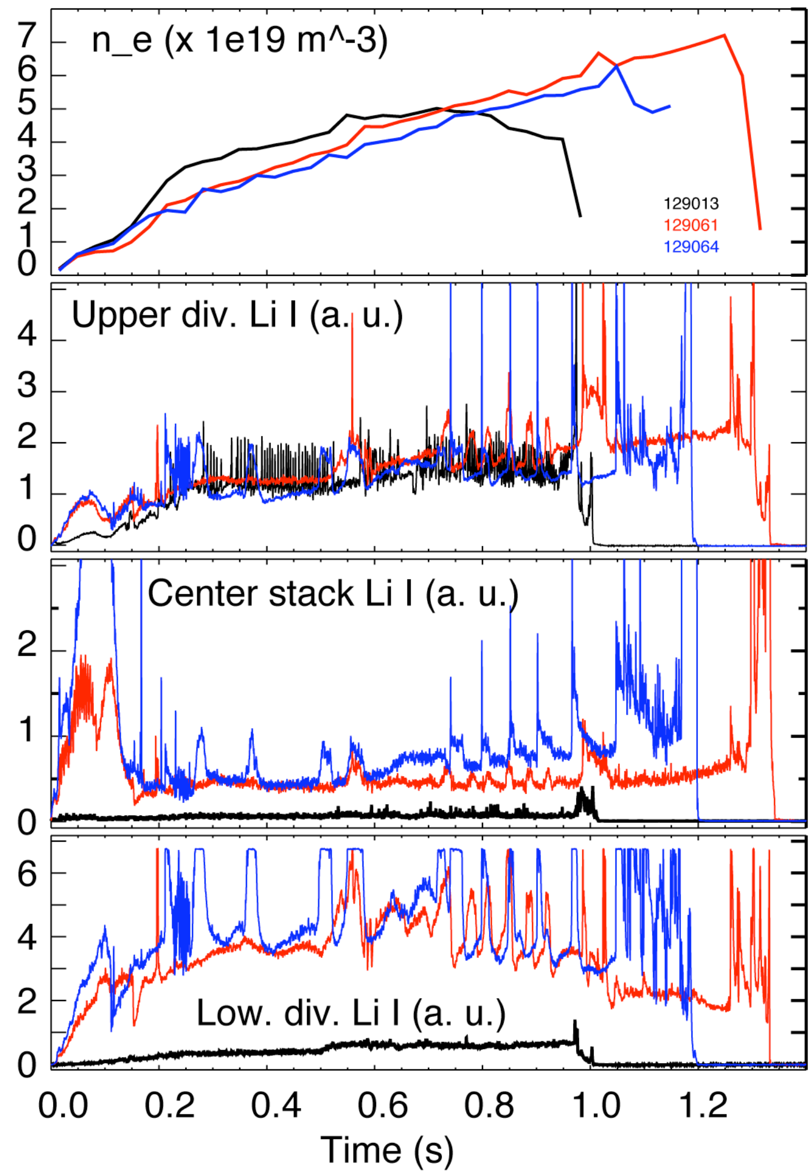
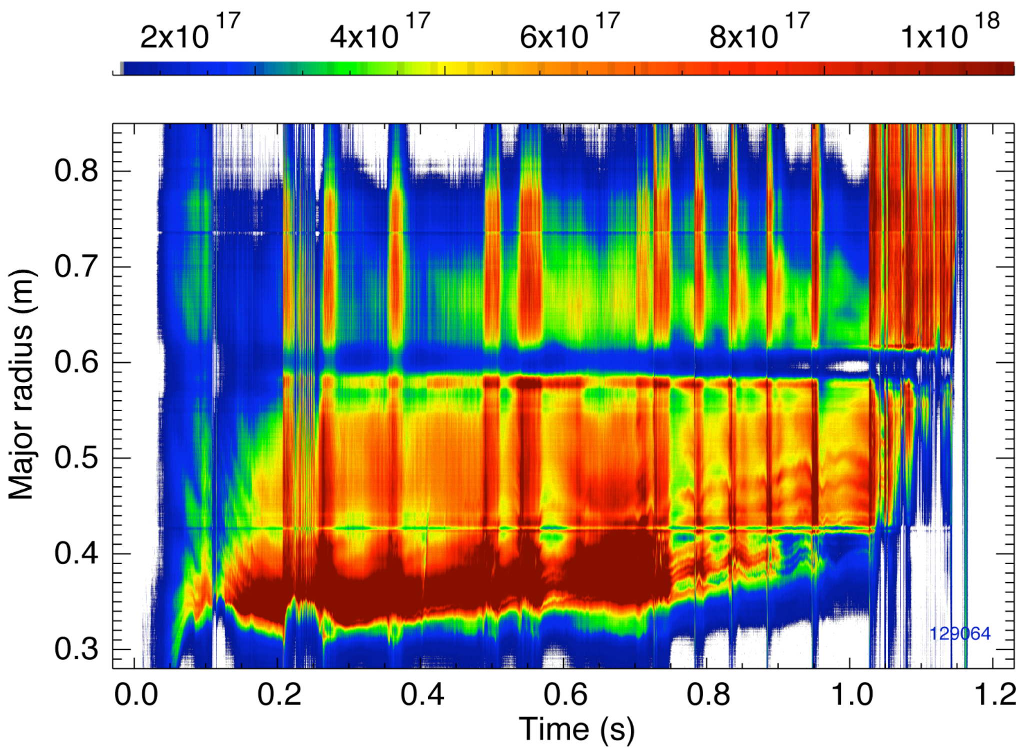
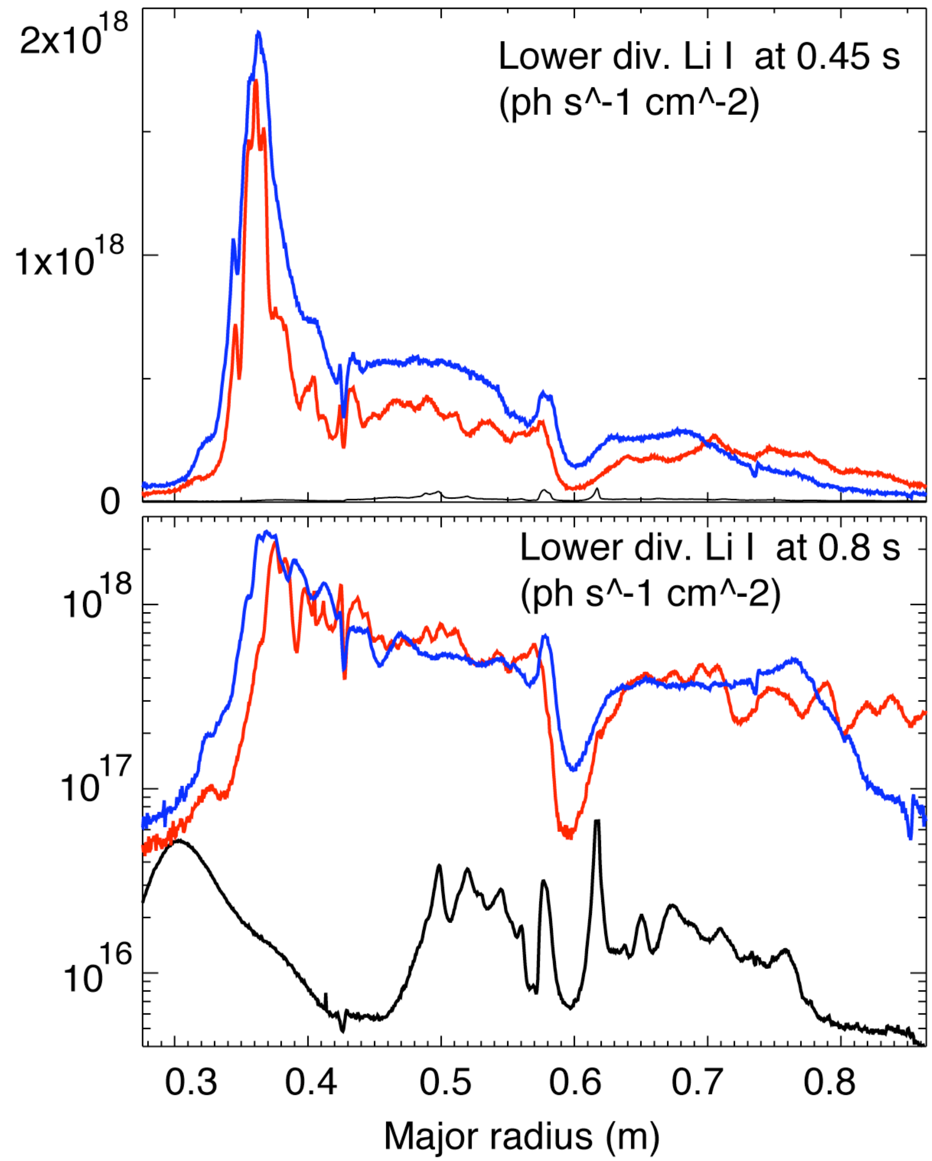




Li I emission profiles are highly peaked suggesting lithium melting in strike point region





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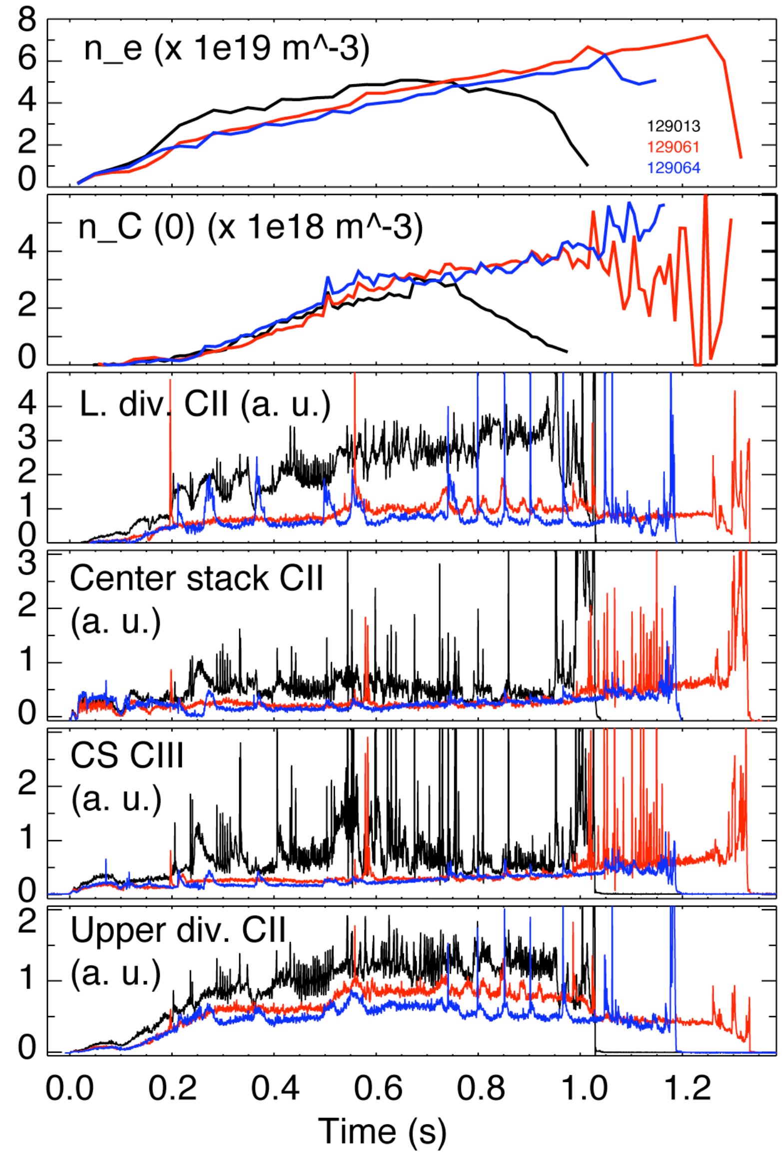
Reduction of carbon emission may suggest carbon source reduction w/ lithium

- C II emission reduction
  - x 2-3 in lower divertor
  - x 2 on center stack
  - x 1.5-2 in upper divertor
- C II anticorrelated with core C density
- Appears to be accumulative effect



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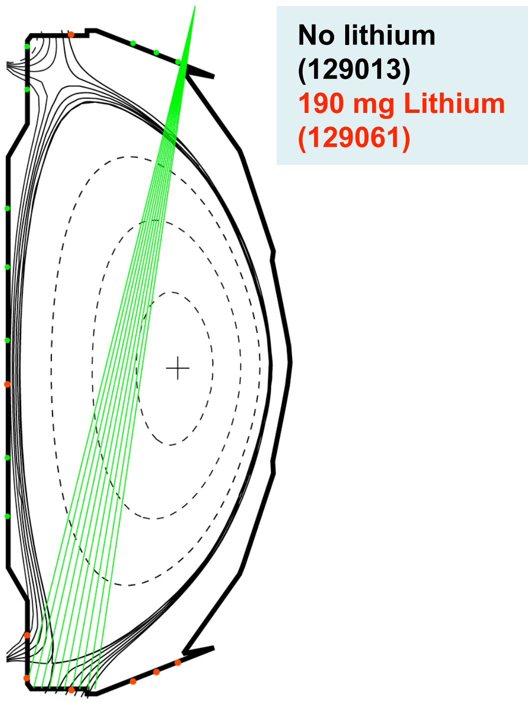
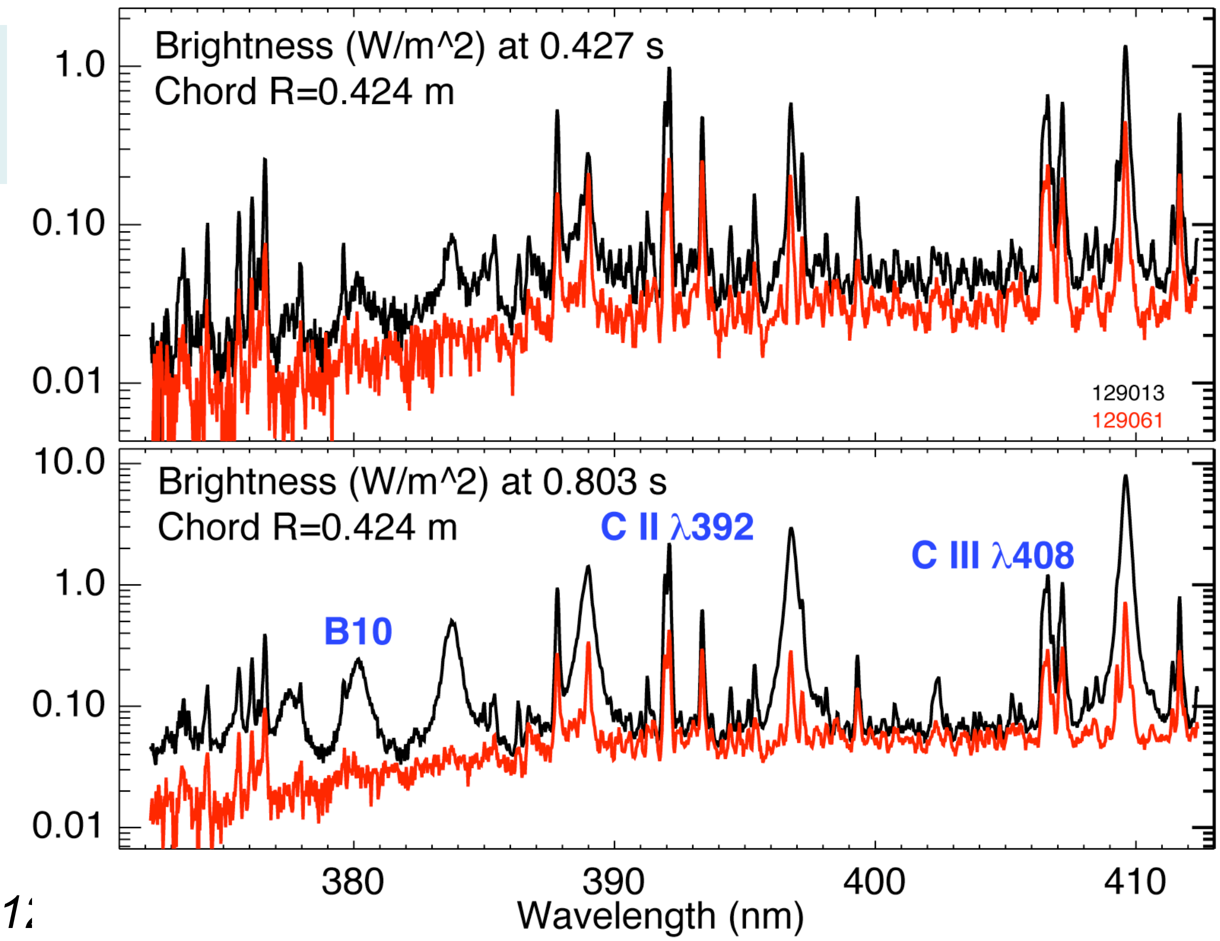
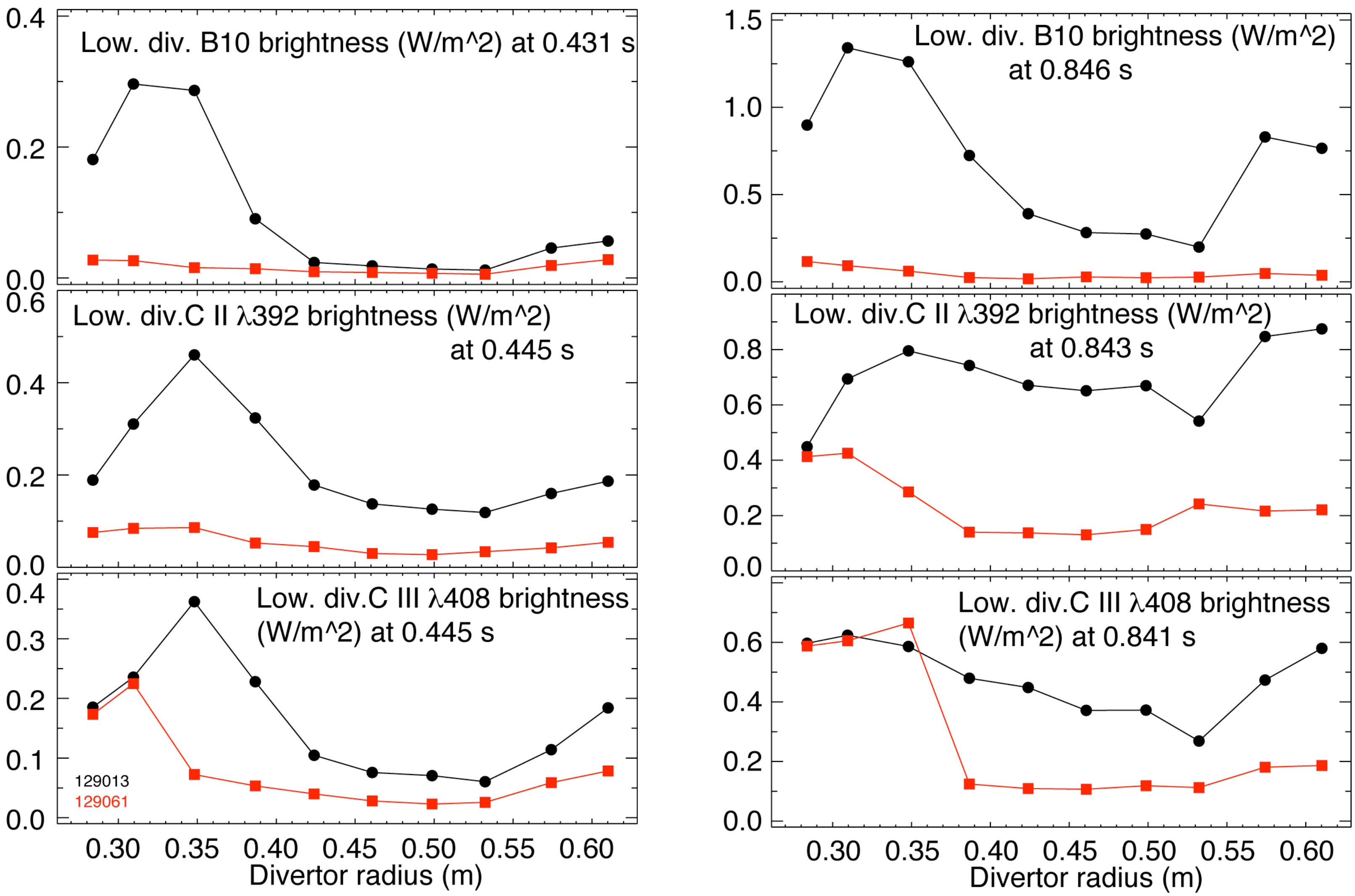
Divertor spectroscopy shows reduction in impurity emission and reduction in n_e





- Lines in spectra
  - C III λ408 nm
  - DI Balmer series *n=2 - 6…1*
  - C II λ392 nm (3p ^{2}P - 4s ^{2}S)
  - O I, O II, O III lines
  - LiD molecular band emission in the region 330-470 nm ($A^1\Sigma^+ - X^1\Sigma^+$)

Divertor profiles suggest significant reduction in n_e and an increase in T_e



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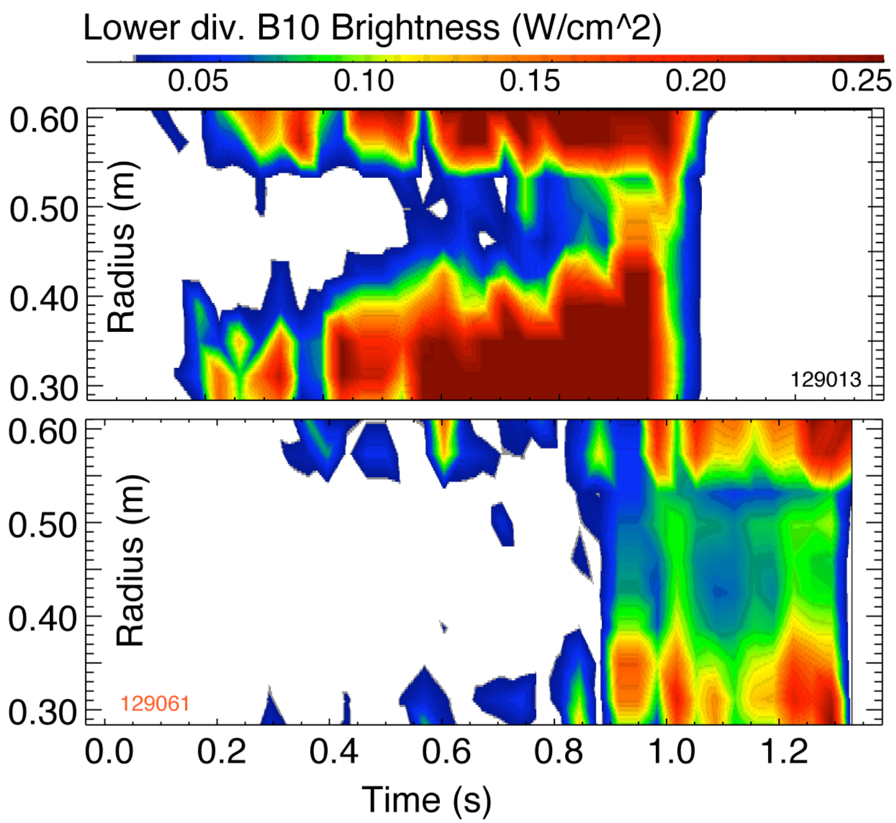
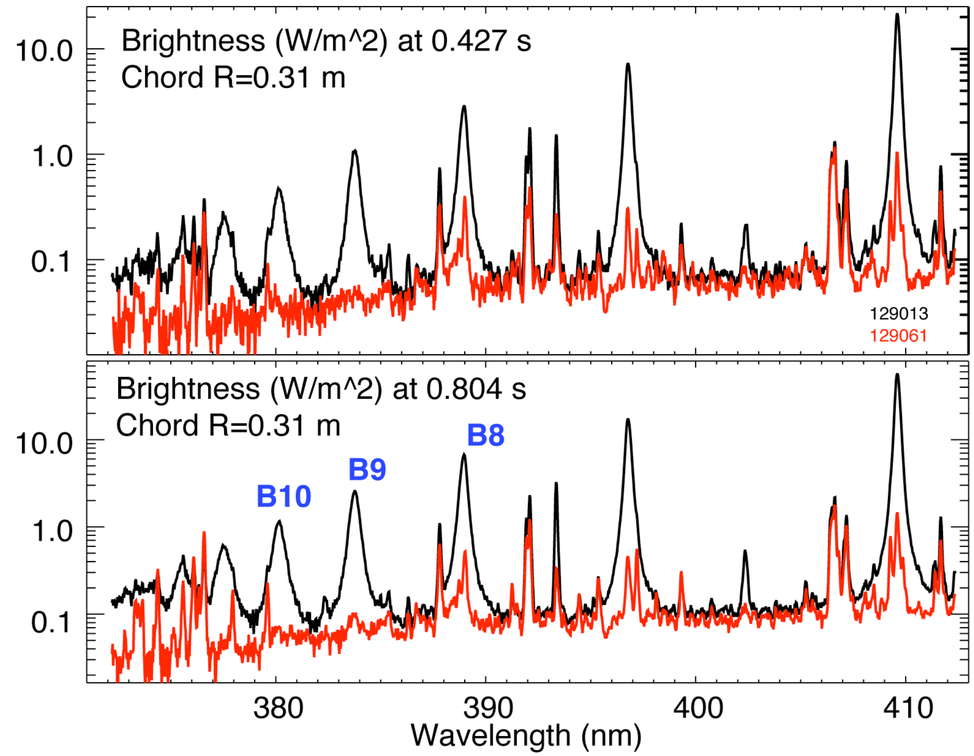
Lithium coatings reduced divertor density, eliminated X-point MARFEs and re-attached inner divertor SP





- **Poster PP8.00042: Modeling of Balmer series deuterium spectra with the CRETIN code for diagnosing the inner divertor re-attachment threshold in NSTX discharges with lithium coatings, F. Scotti et. al**

No lithium (129013)
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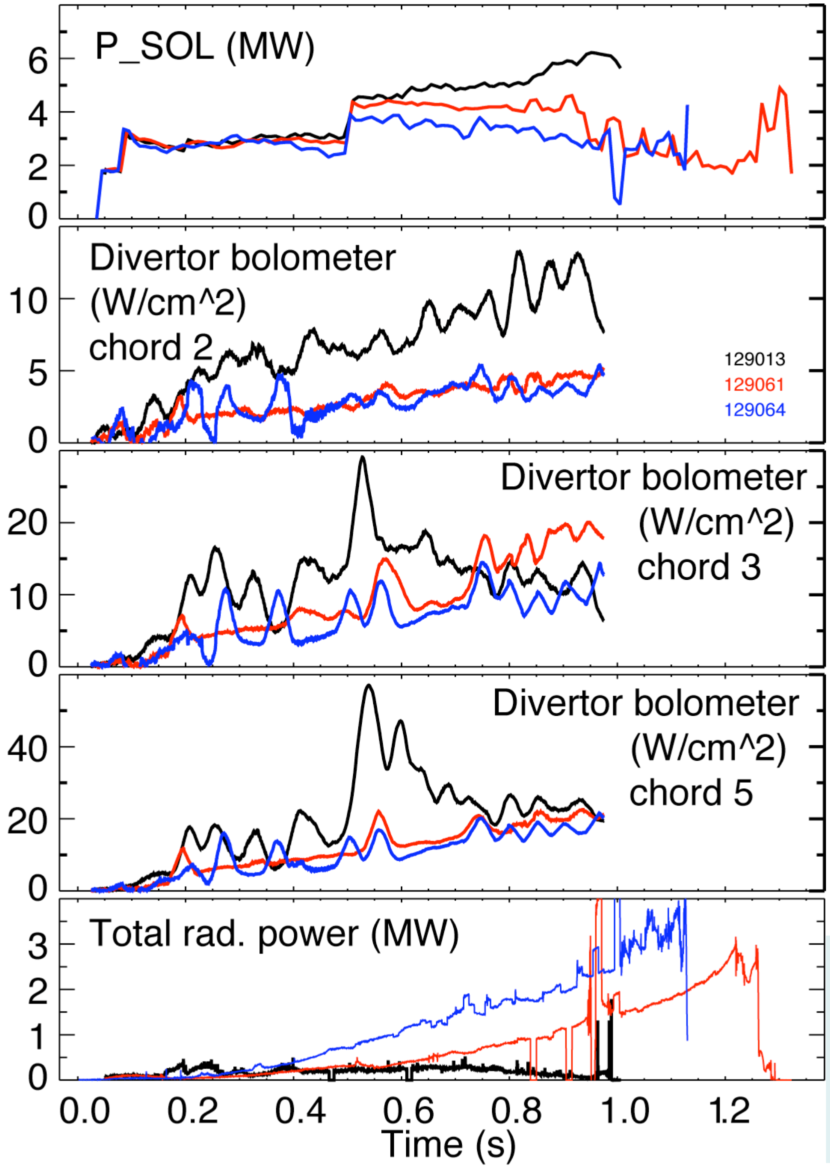
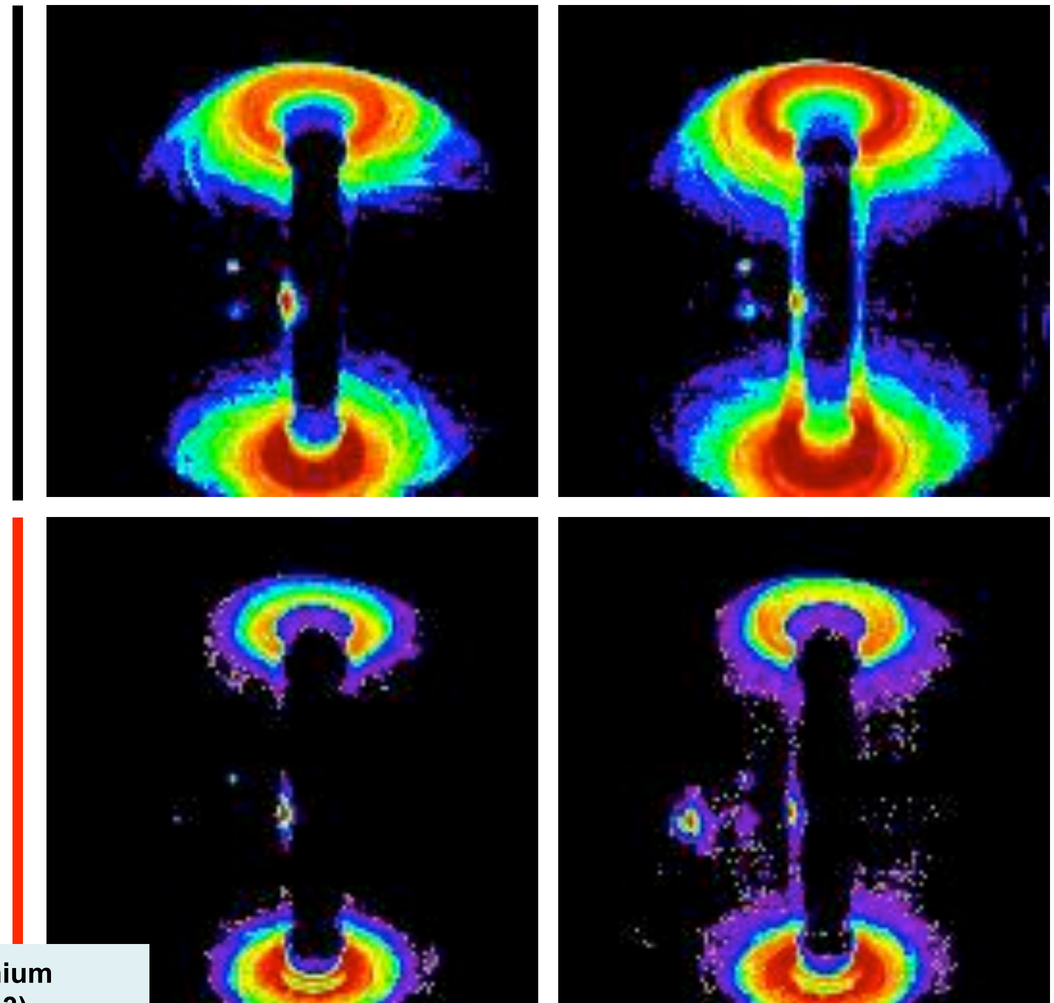
Divertor radiation was significantly reduced in discharges with lithium coatings





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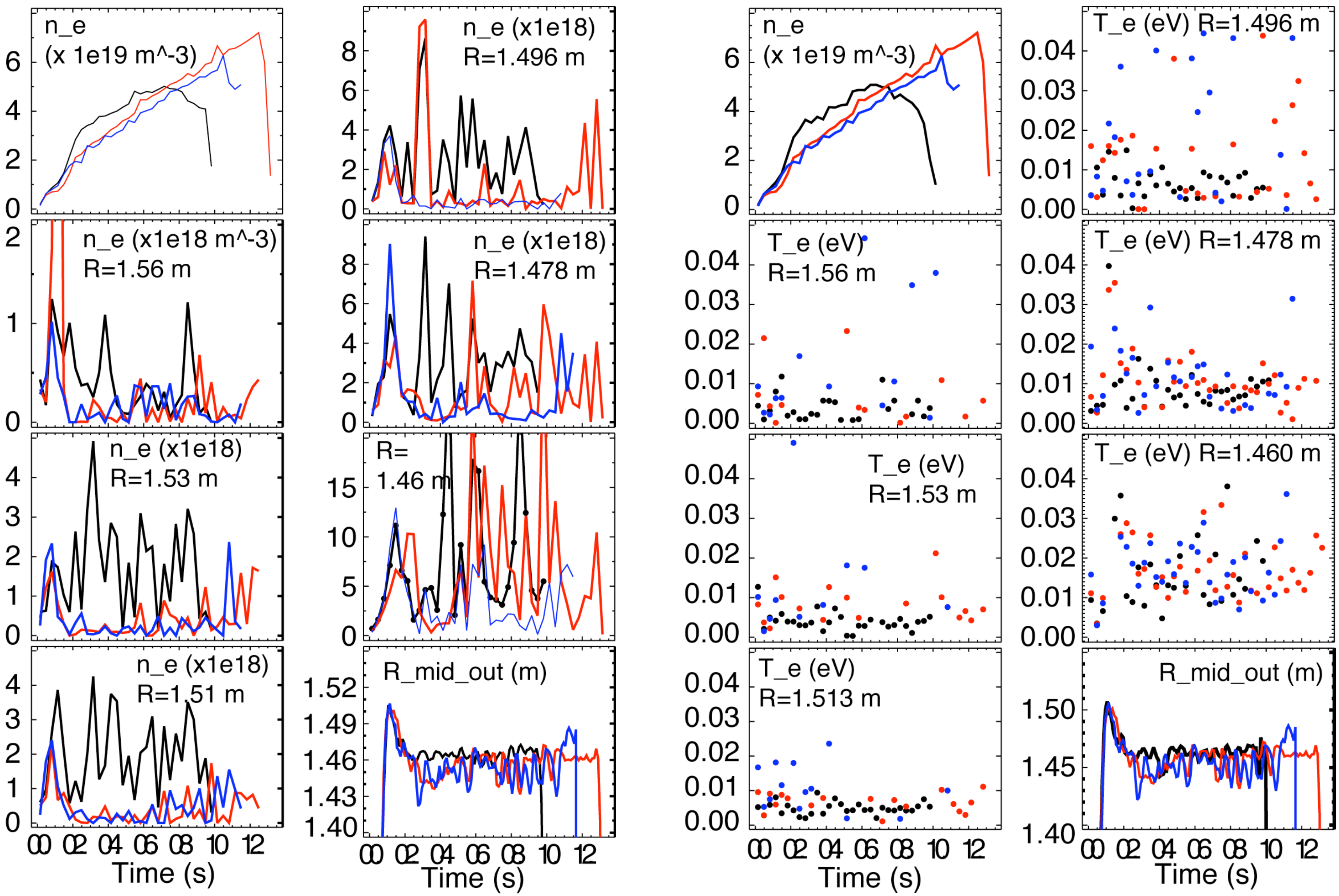
Unfiltered camera images at 0.450 s and 0.800 s

Midplane SOL T_e increased and n_e decreased with lithium coatings



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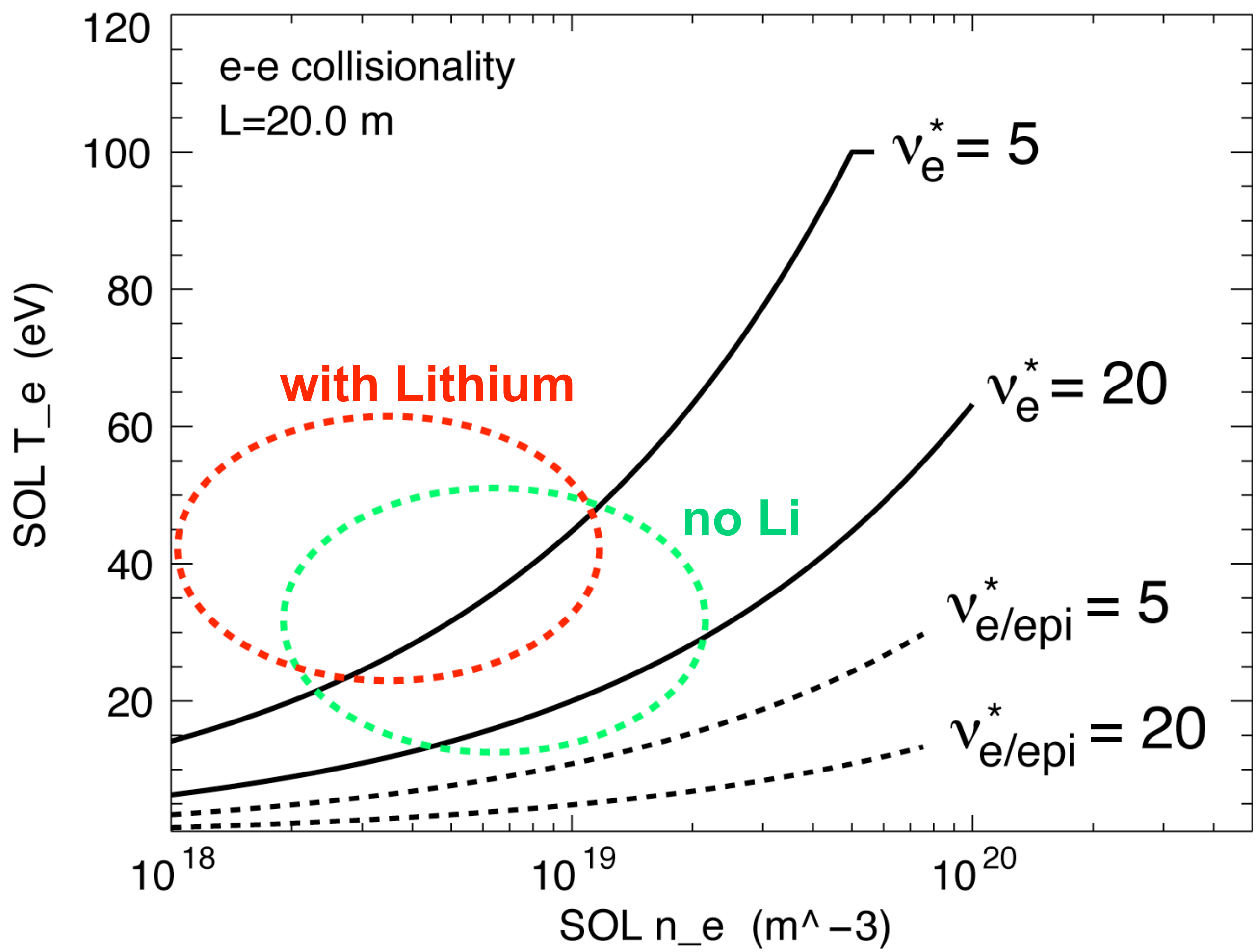
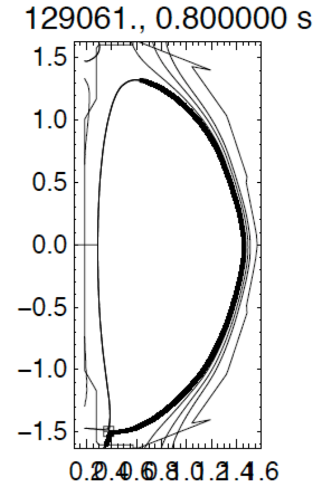
SOL collisionality decreased with lithium





Transition from conduction-limited (high recycling) regime to low-recycling (sheath-limited)

S/XB technique is used to estimate particle influx from spectroscopic measurements

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

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

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

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

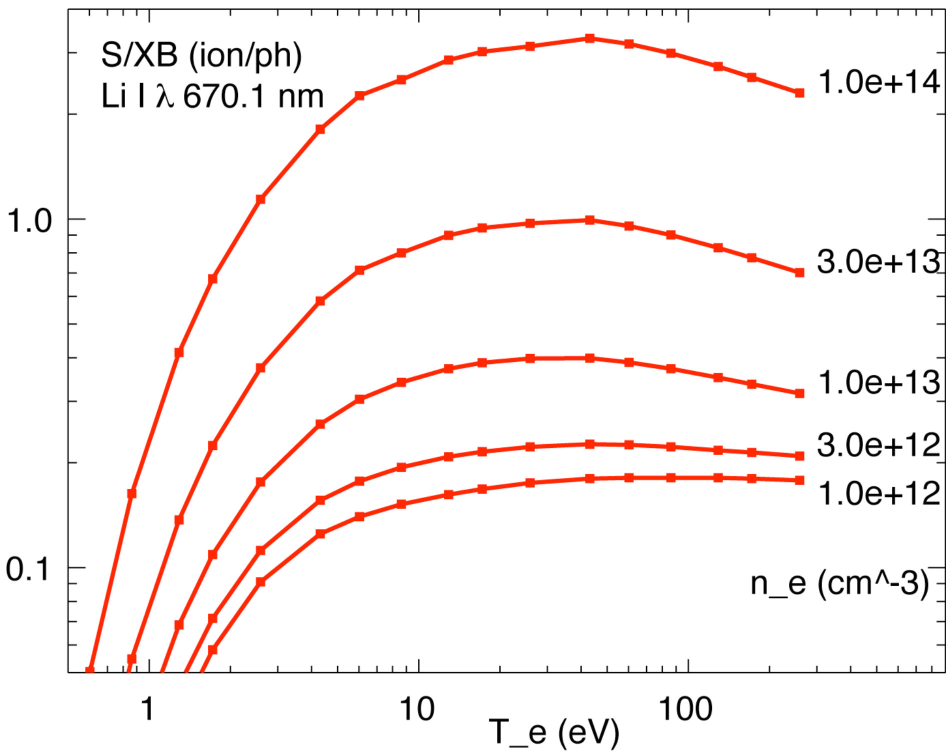
$$\Gamma_i = \frac{S}{X \, B} \Gamma_{ph}$$

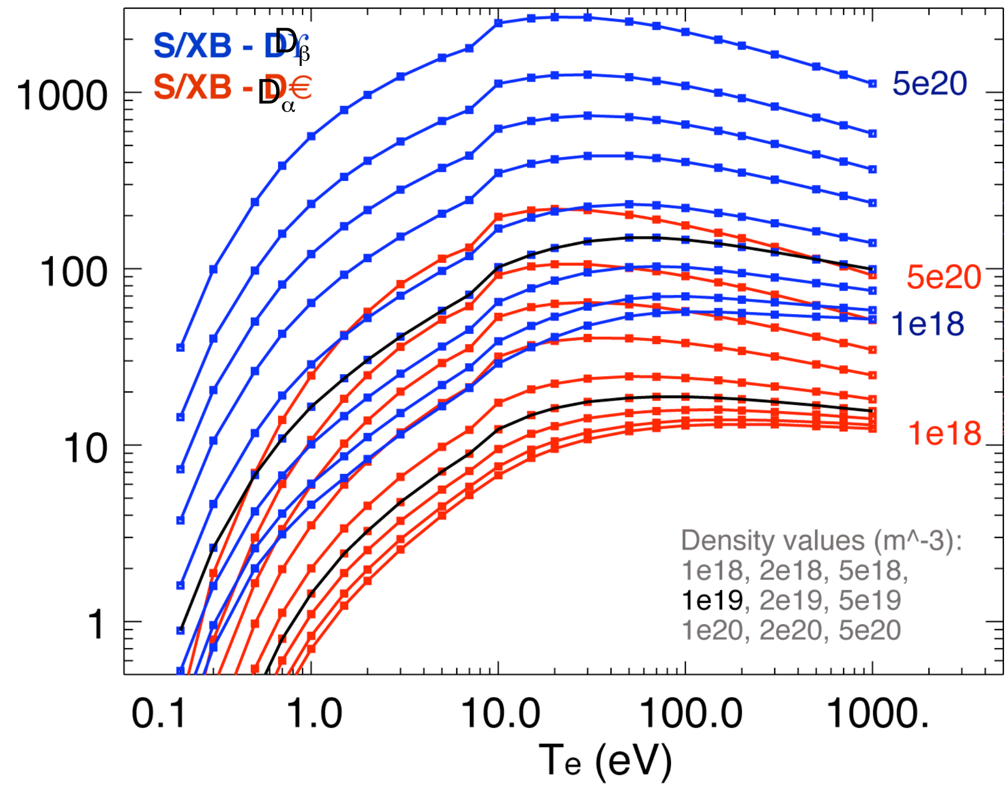
- Technique originally developed by L. C. Johnson & E. Hinnov, and further by A. Kallenbach
- Used for deuterium and impurities

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

ADAS S/XB factors are used

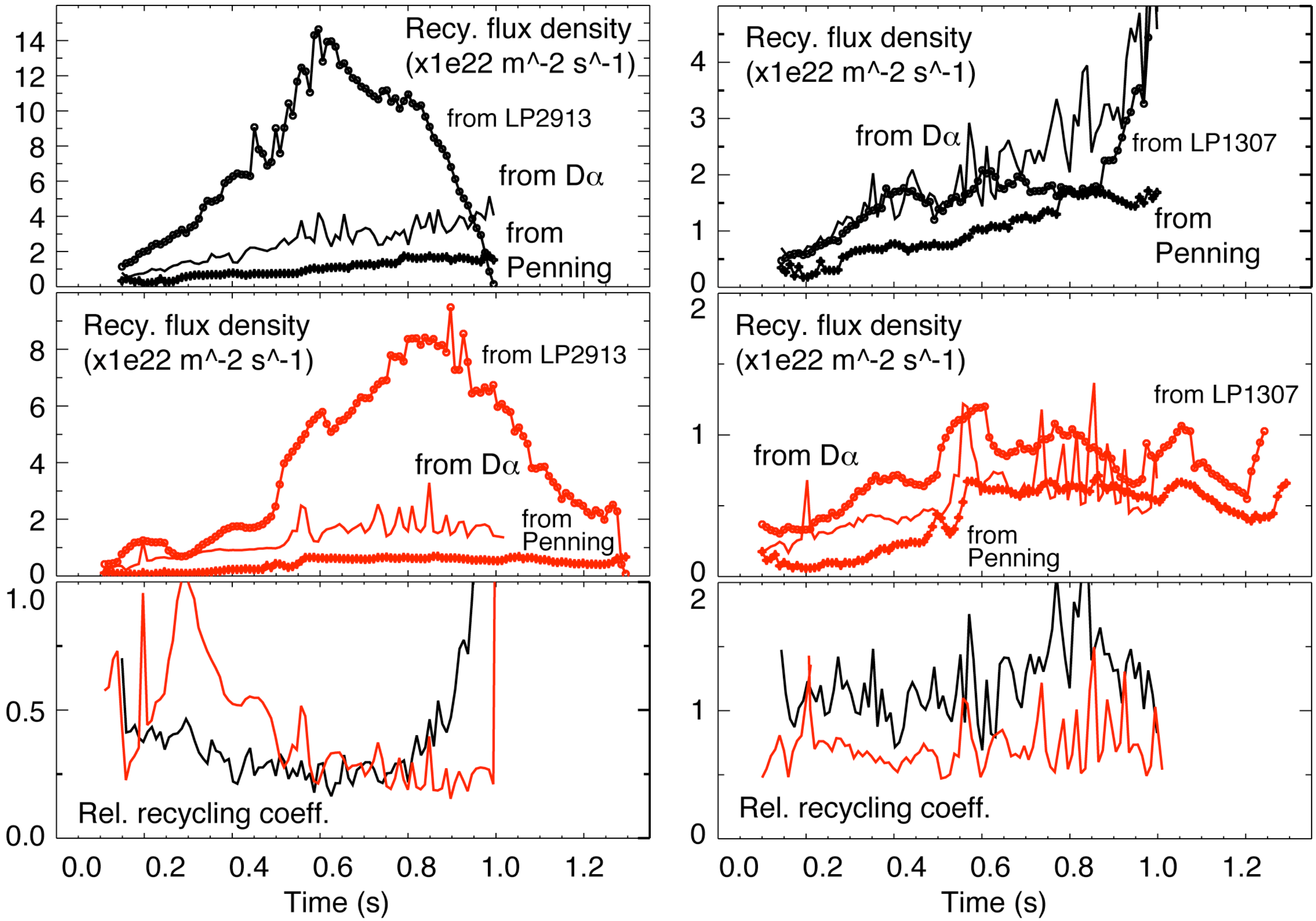
- ADAS database use courtesy of ORNL Controlled Fusion Atomic Data Center (CFADC)





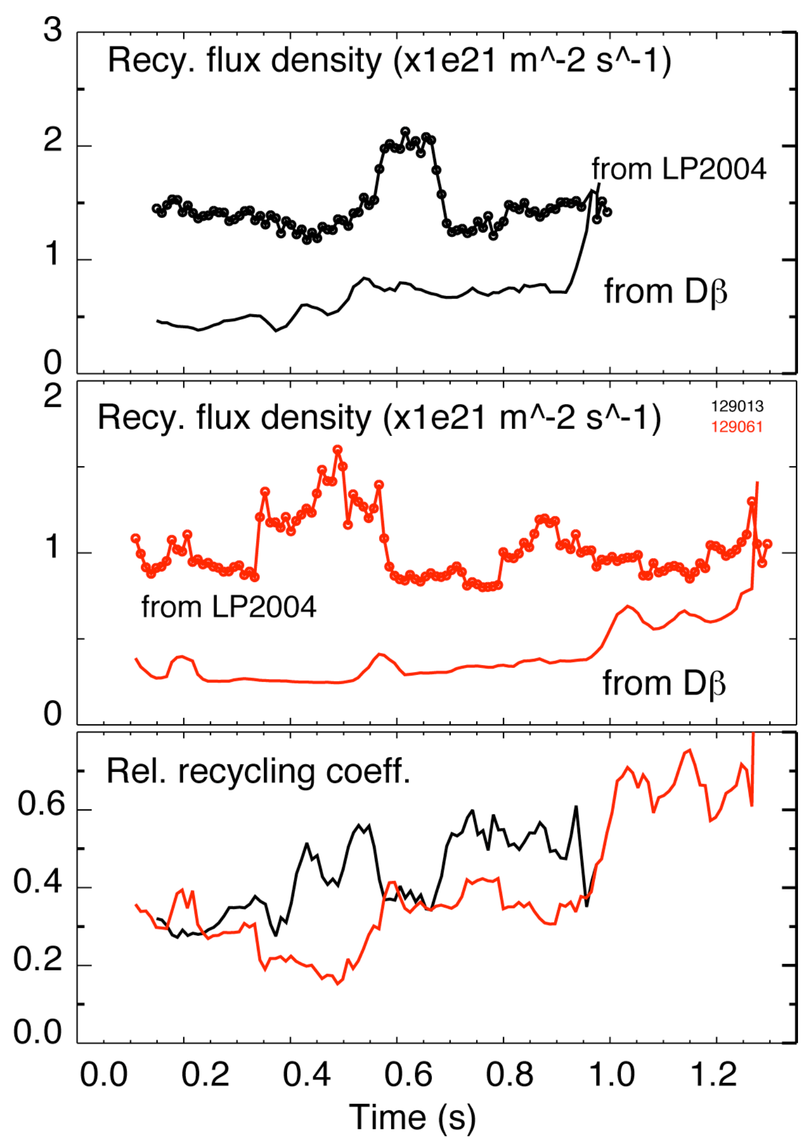
- Li I S/XB factors
  - very weak T_e dependence
  - strong n_e dependence
- D_α, D_β S/XB – weak T_e and n_e dependence

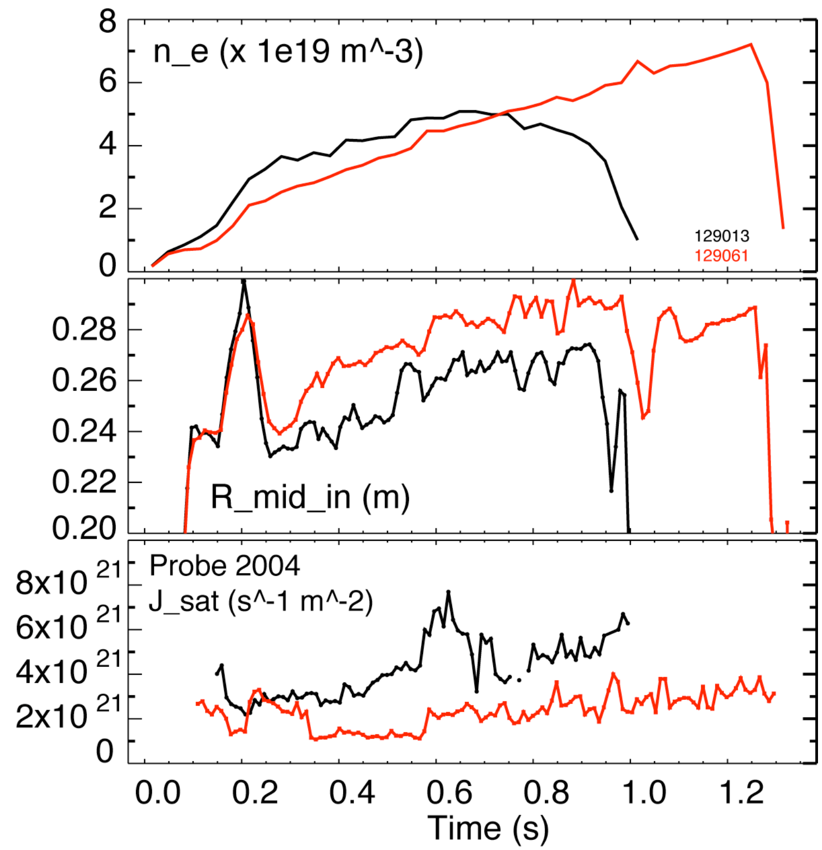
Estimates of particle fluxes suggest local recycling coefficient reduction in SOL but not at strike point



No lithium
(129013)
190 mg Lithium
(129061)

Estimates of particle fluxes suggest local recycling coefficient reduction on center stack





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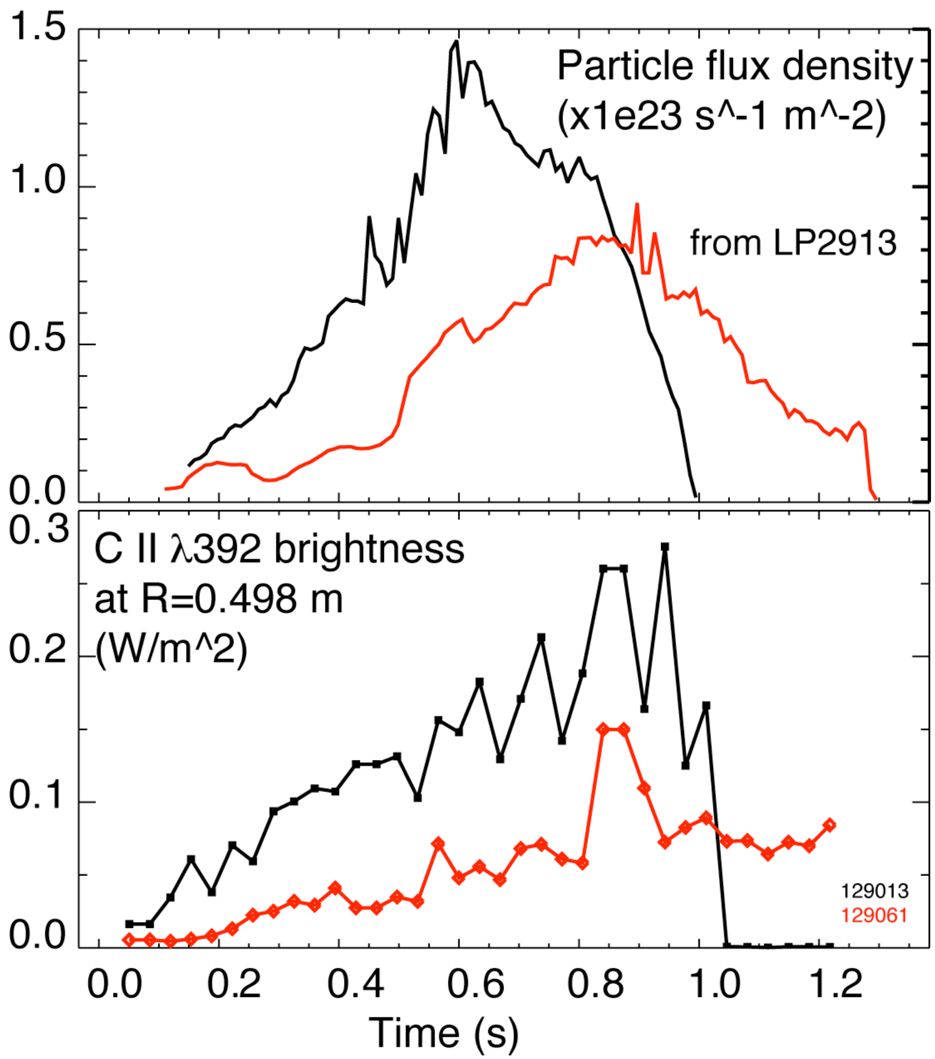
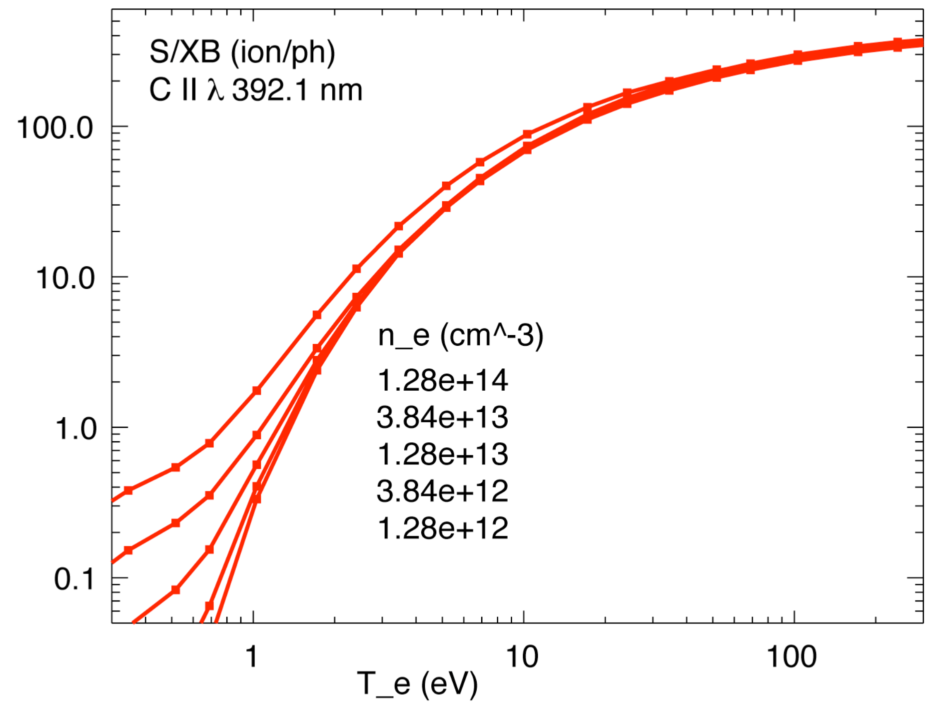
Spectroscopic measurements suggest that divertor physical sputtering yield for carbon does not increase





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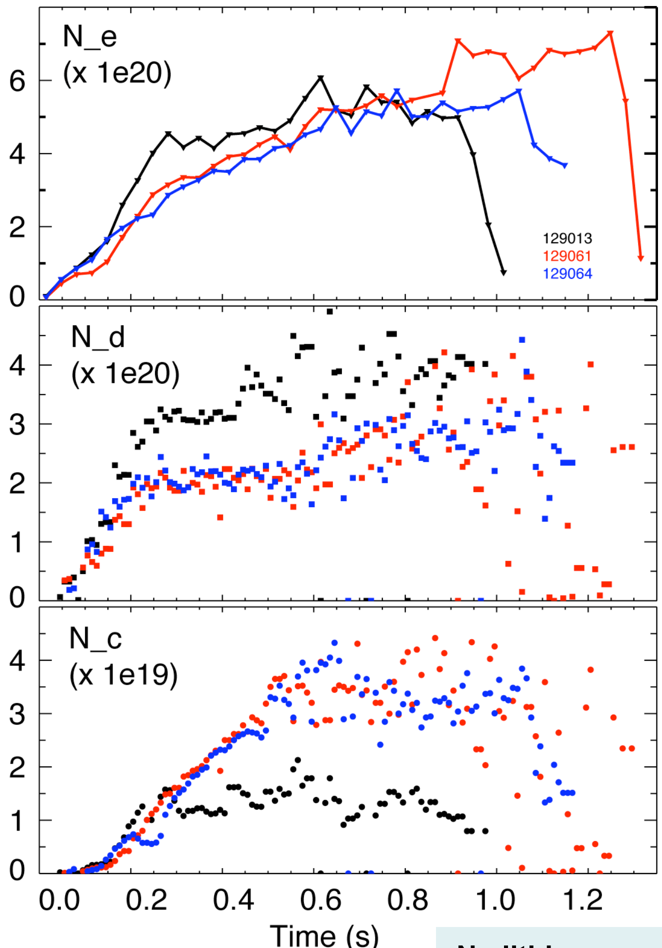
Ion inventory is well controlled in discharges with lithium, core carbon accumulates, lithium is screened out



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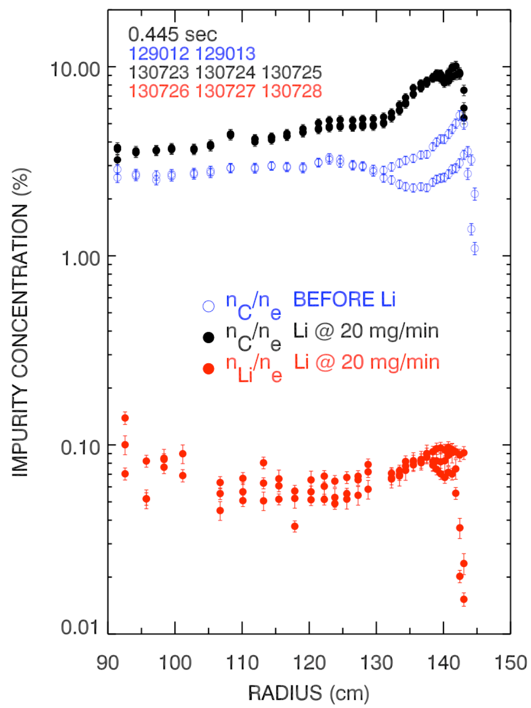

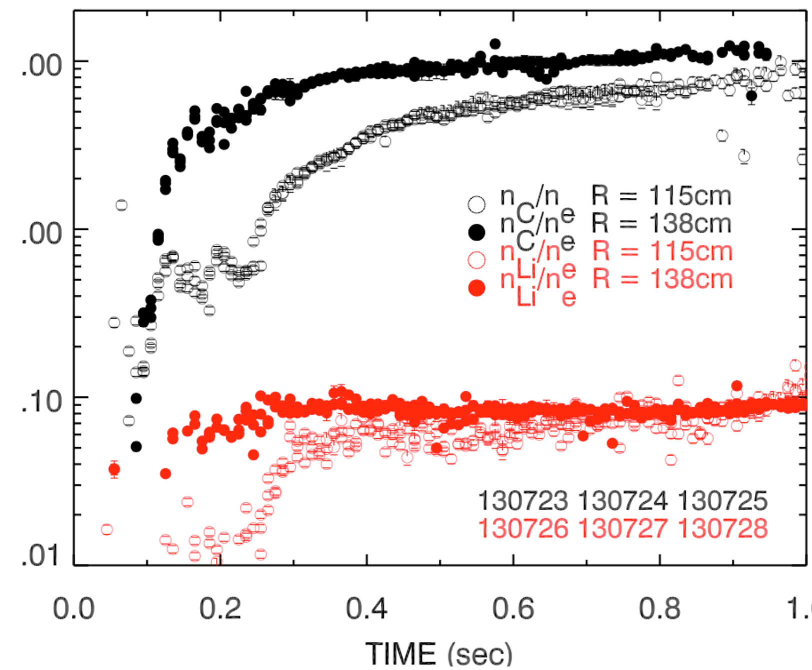

- Impurity density profiles from CHERS
  - C VI, n = 8-7 transition, 529.1 nm
  - Li III, n = 7-5 transition, 516.7 nm
- Lithium concentration much lower than carbon concentration
  - $n_C/n_{Li} \sim 100$
- Carbon increases with Li evaporation

Dynamic particle balance model indicates strong pumping by lithium

$$\frac{dN_p}{dt} = \Gamma_{gas} + \Gamma_{NBI} + \Gamma_{NBI\_cold} + \Gamma_{NBI\_cryo} + \Gamma_{wall} + \Gamma_{pump} + \frac{dN_n}{dt}$$

Change of particle inventory — *Gas feed rate* — *NBI fueling rate* — *NBI cryopump rate*

Ion density $n_i = n_e \frac{Z - Z_{eff}}{Z - 1}$

Fueling efficiency $\eta = \frac{N_p(t)}{N_{src}(t)}$

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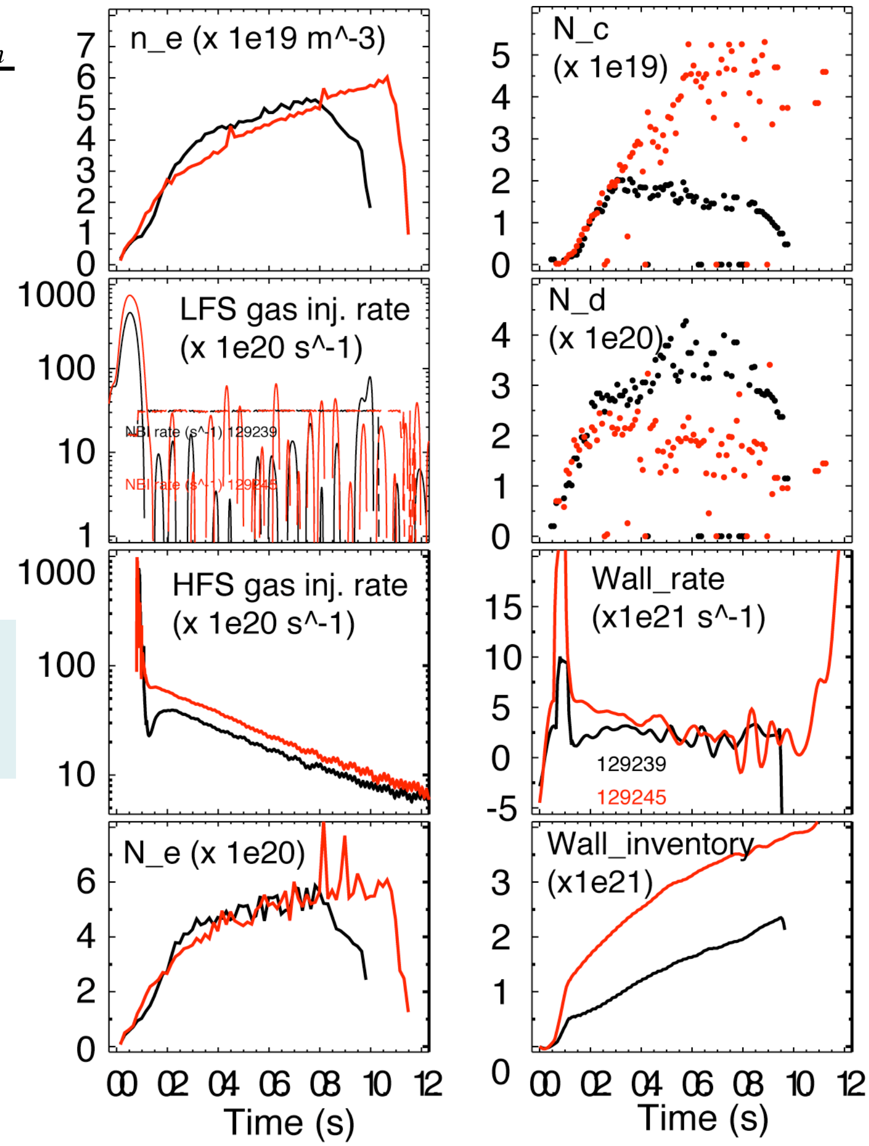
Rewrite global particle balance equation as:

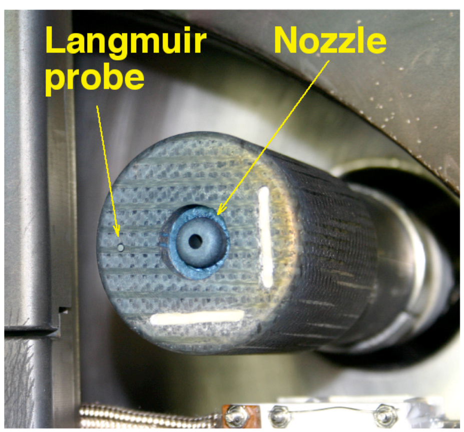
$$\frac{dN_p}{dt} = \eta_{gas} S_{gas} + \eta_{NBI} S_{NBI} + S_{recy} - \frac{N_p}{\tau_p}$$

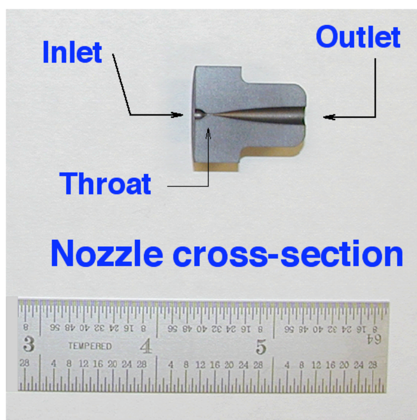


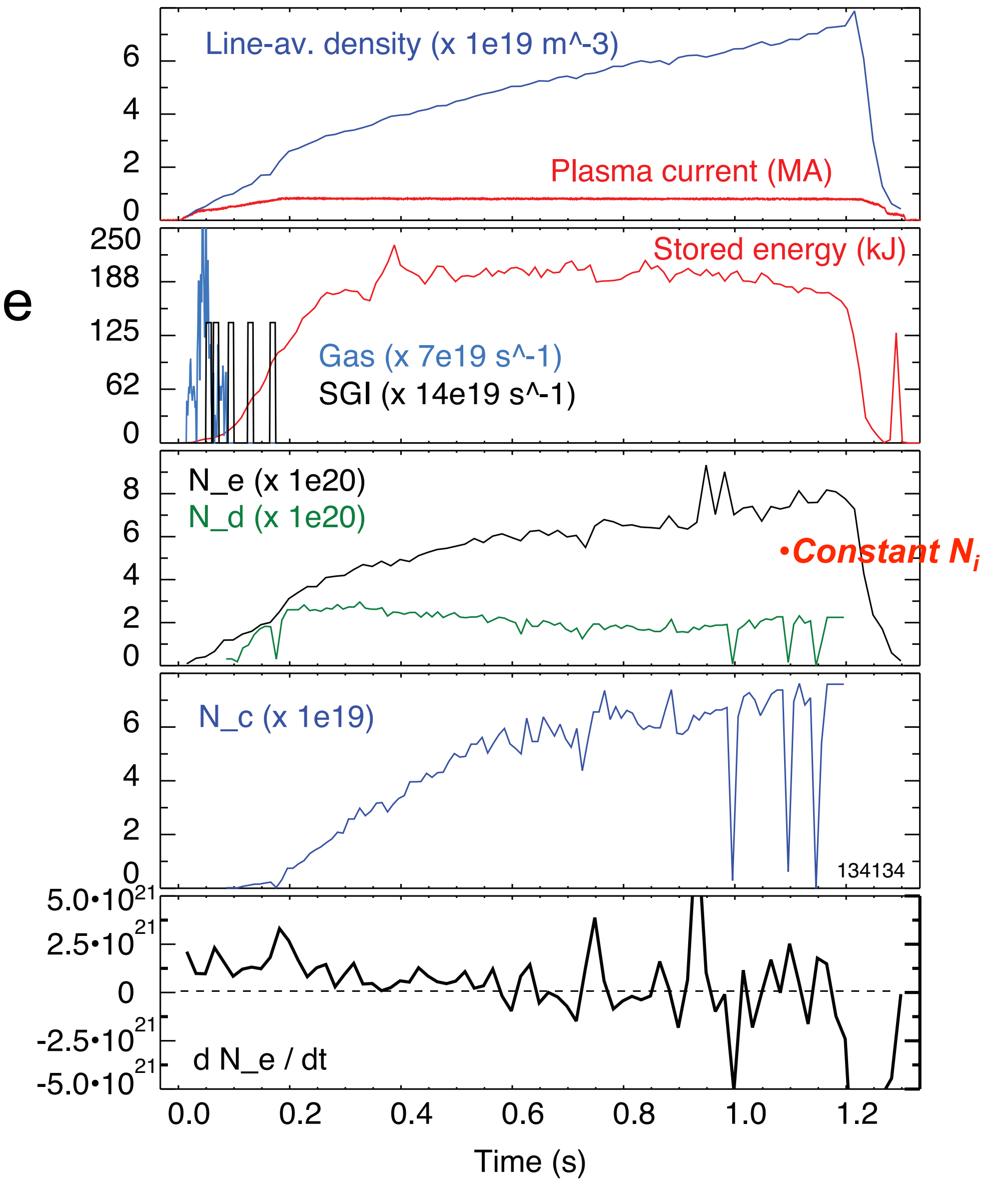
A long pulse H-mode discharge scenario with SGI fueling and controlled N_i was developed

- Used SGI-only fueling
- LITER rate 6-9 mg/min
- Ion density control
- N_i constant, while N_e is rising due to carbon

- SGI=Supersonic gas injector





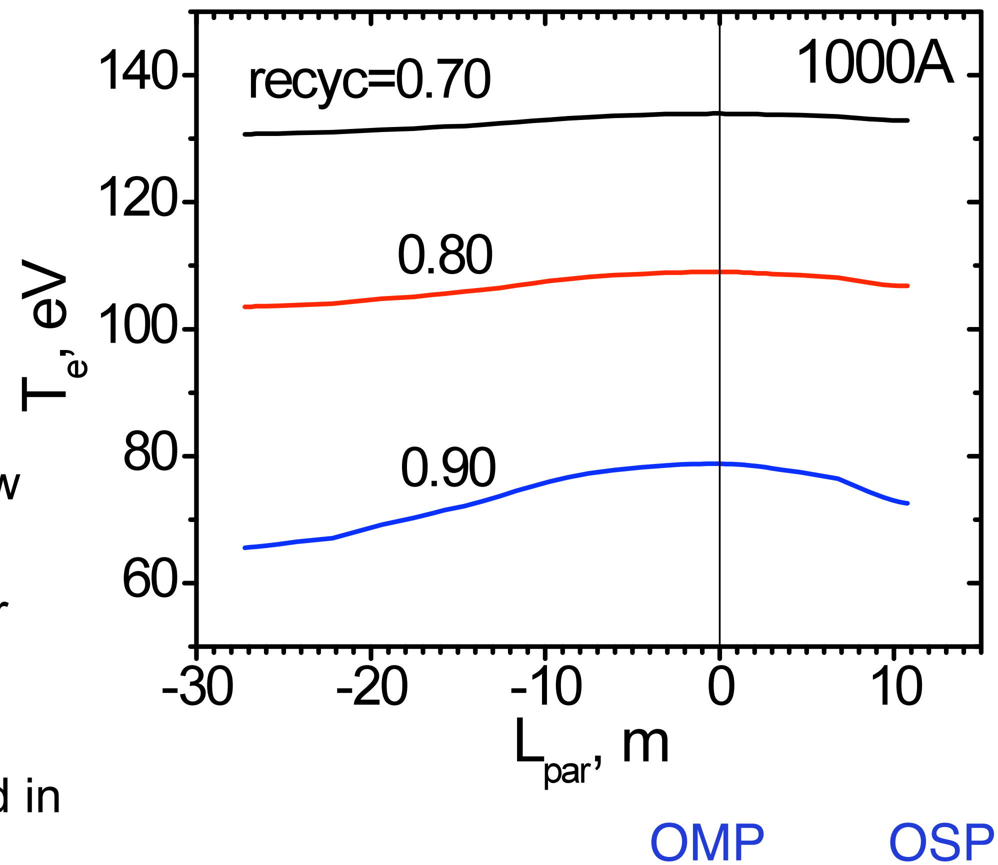


UEDGE modeling reproduces many features of the observed low-recycling divertor regime

- **Poster PP8.00041: Modeling of low-recycling divertor with lithium coating in NSTX, by R.D. Smirnov, A.Yu. Pigarov et. al**

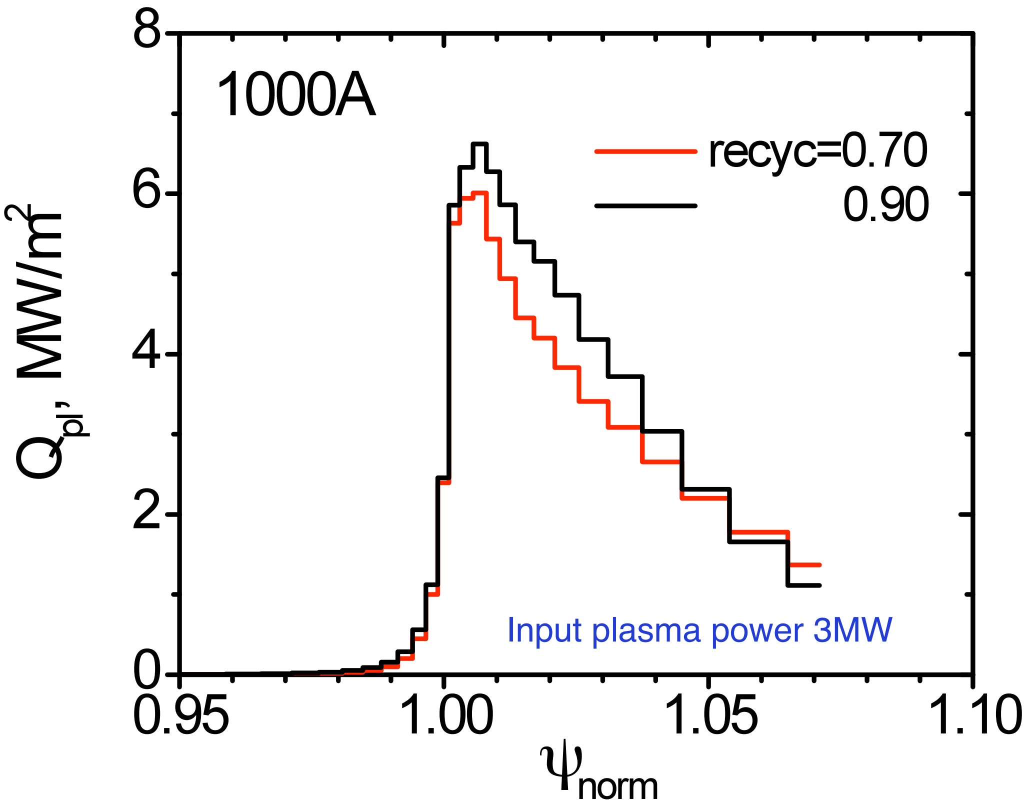
- In the UEDGE model of low-recycling regime
  - ✓ Small parallel T_e gradients
  - ✓ Relatively high divertor T_e and low n_e
  - ✓ Small particle (ion) flux to divertor plates, i.e., external fueling dominates
  - ✓ Lithium sputtered and evaporated in the divertor is retained in the divertor region

Parallel profiles of electron temperature along separatrix



UEDGE model of low-recycling divertor with lithium predicts high divertor heat flux

Radial profiles of the heat load to the outer divertor plate



- Heat in the SOL is carried by the electron conduction
- The profile narrows in the low-recycling regimes due to faster parallel transport
- In the low-recycling regime, the peak heat flux to outer plate can be high enough to melt Li around the strike point

Comparison with cryo-pumps

- Cryo-pumping (e.g., DIII-D experience)
  - Significant in-vessel hardware modifications
  - Inflexibility in plasma shaping due to the need of proximity to strike point
  - Calibrated pumping rate
  - Demonstrated density control
  - Compatibility with radiative divertor

- Lithium coatings on graphite PFCs (NSTX LITER experience)
  - Flexibility in plasma shaping
  - Need for operational scenario development for each pumping and fueling rate
  - Multiple side effects (good and bad) on plasma core and edge