NSTX

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

The continuous improvement of H-mode discharges with progressively increasing lithium coatings in NSTX

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U Washington
U Wisconsin

R. Maingi Oak Ridge National Laboratory

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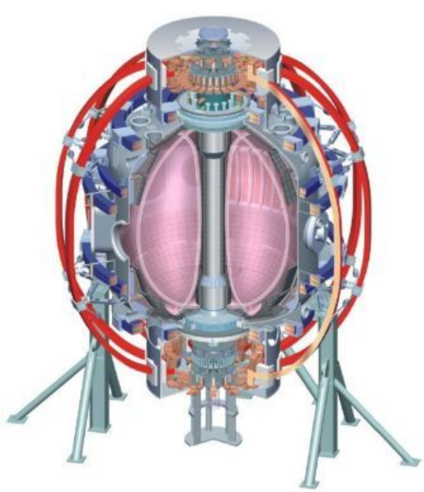
NSTX Physics Meeting
PPPL, Princeton NJ
June 13, 2011



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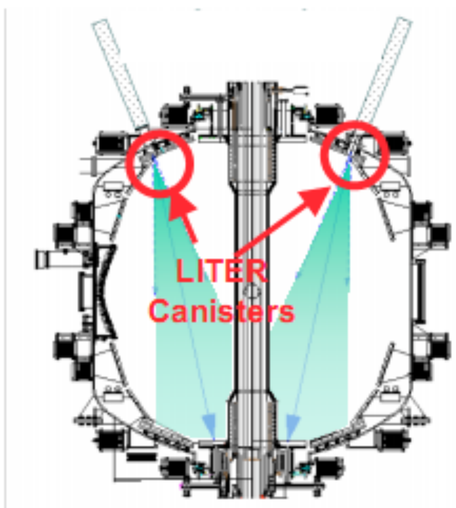
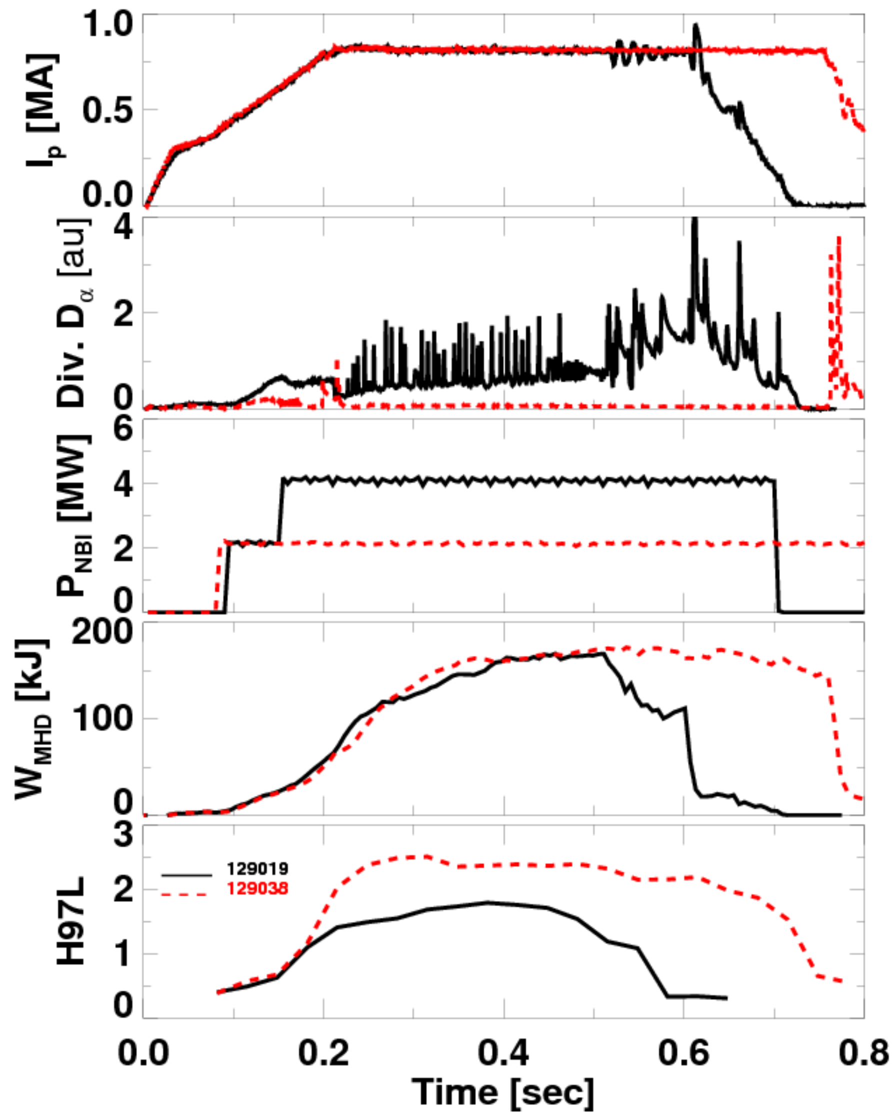
Type I ELMs eliminated, energy confinement improved with lithium wall coatings



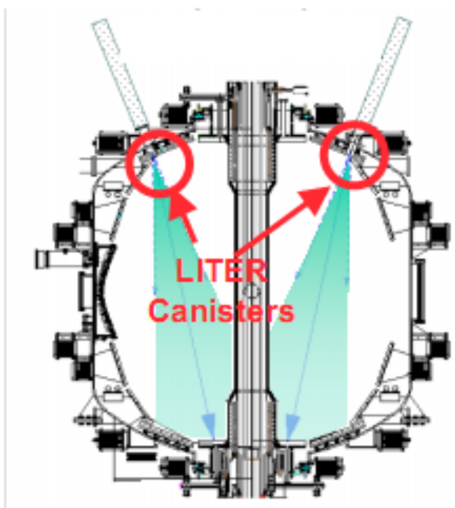
~ 700mg Li
between 129037
and 129038

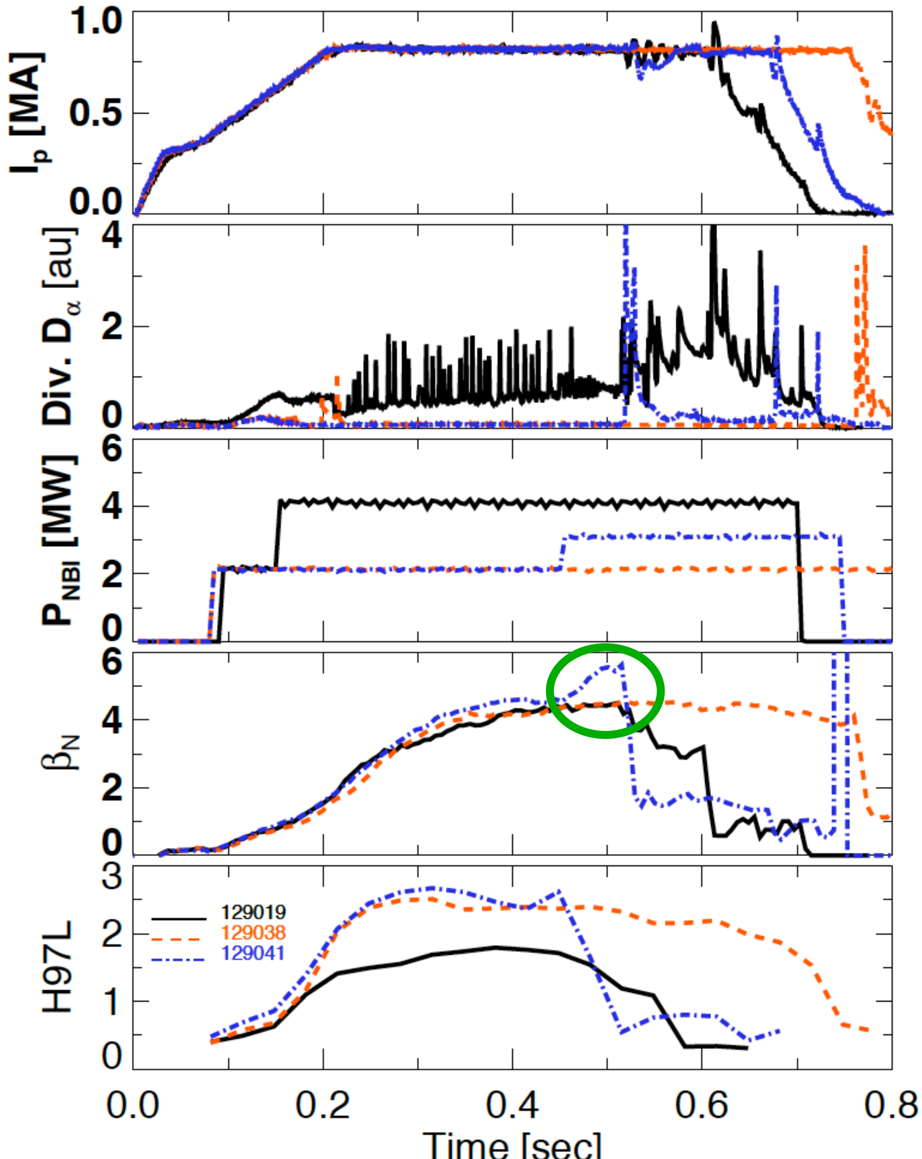


- Without Li, With Li
- ELM-free, reduced divertor recycling
- Lower NBI to avoid β limit
- Similar stored energy
- H-factor 40%↑

H. Kugel, PoP 2008
R. Kaita, IAEA 2008
M. Bell, PPCF 2009
D. Mansfield, JNM 2009
R. Maingi, PRL 2009

Edge stability limits pushed beyond global stability limits with lithium coatings in NSTX





- Without Li, With Li, With Li
- ELM-free, reduced divertor recycling
- Power scan to identify β limit
- Core β limit observed, but no ELMs

D. Mansfield, JNM 09

R. Maingi, PRL 09

Plasma characteristics change (mostly improve) continuously with increasing lithium evaporation

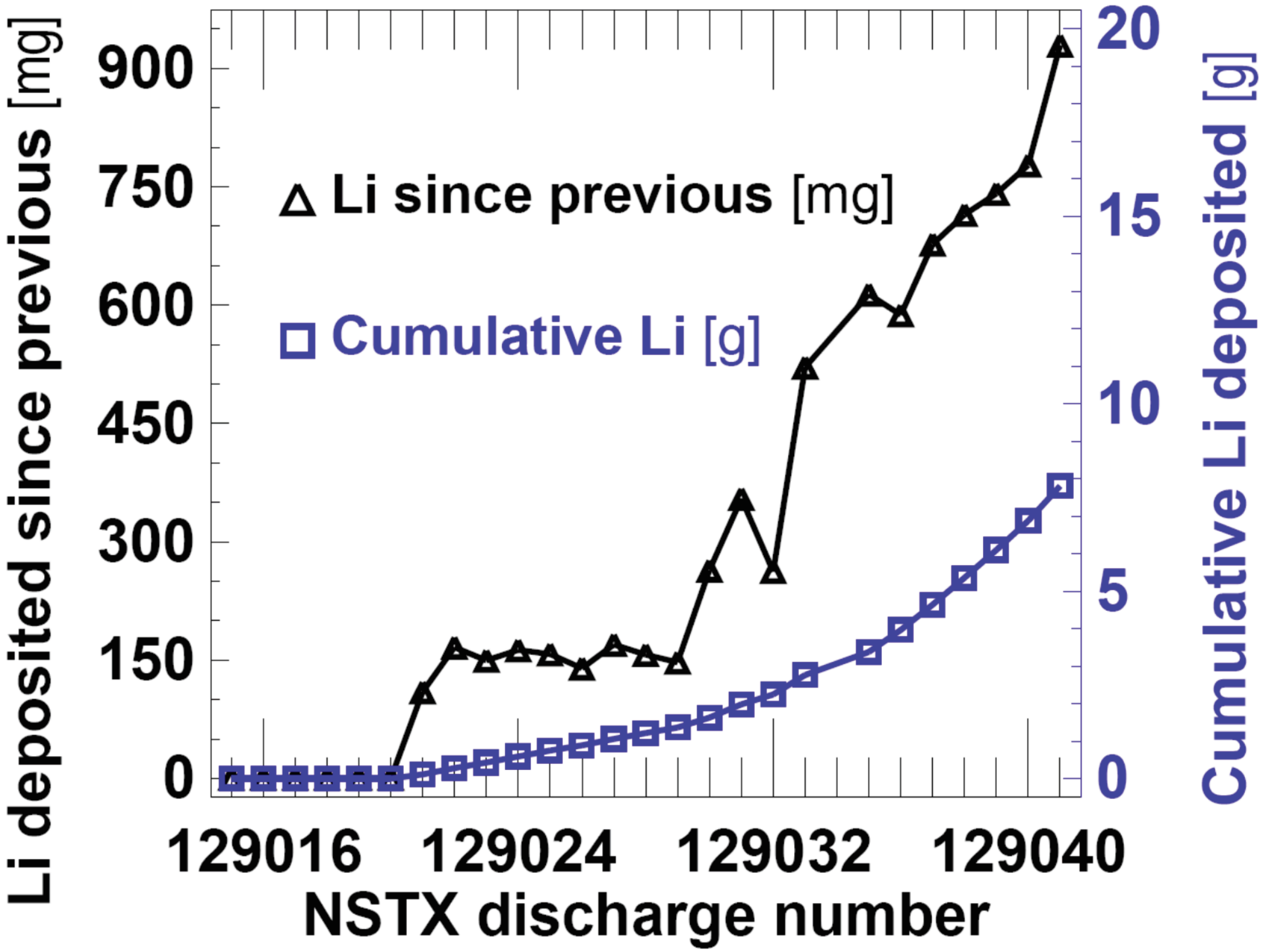
- Global characteristics change
  - Recycling: lower and upper divertor D_α at t=0.4 sec declines
  - Line average density at t=0.4 sec decline
  - Peak W_{MHD}, β_N, and H-factor increase at constant P_{NBI}
  - T_e and P_e profiles broaden; n_e profile peaks then broadens

R. Maingi, NF 2011 to be submitted

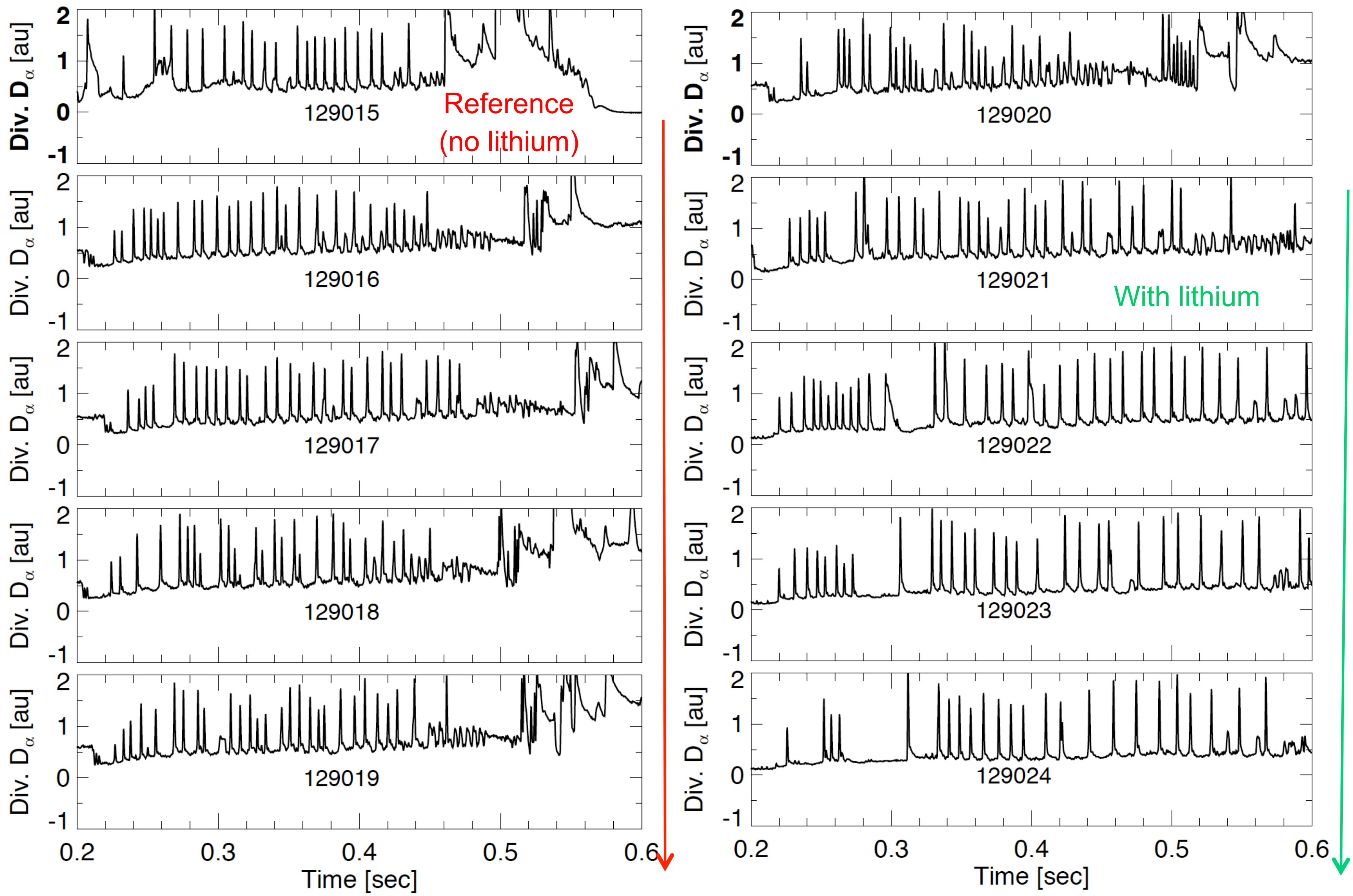
- Edge transport declines
  - TRANSP for transport a r/a=0.35, 0.7
  - SOLPS for transport for ψ_N > 0.8

- ELM frequency first declines, and then goes to 0
  - n_e profile shifts away from separatrix; pressure profile and bootstrap current follow, reducing drive for kink/peeling modes

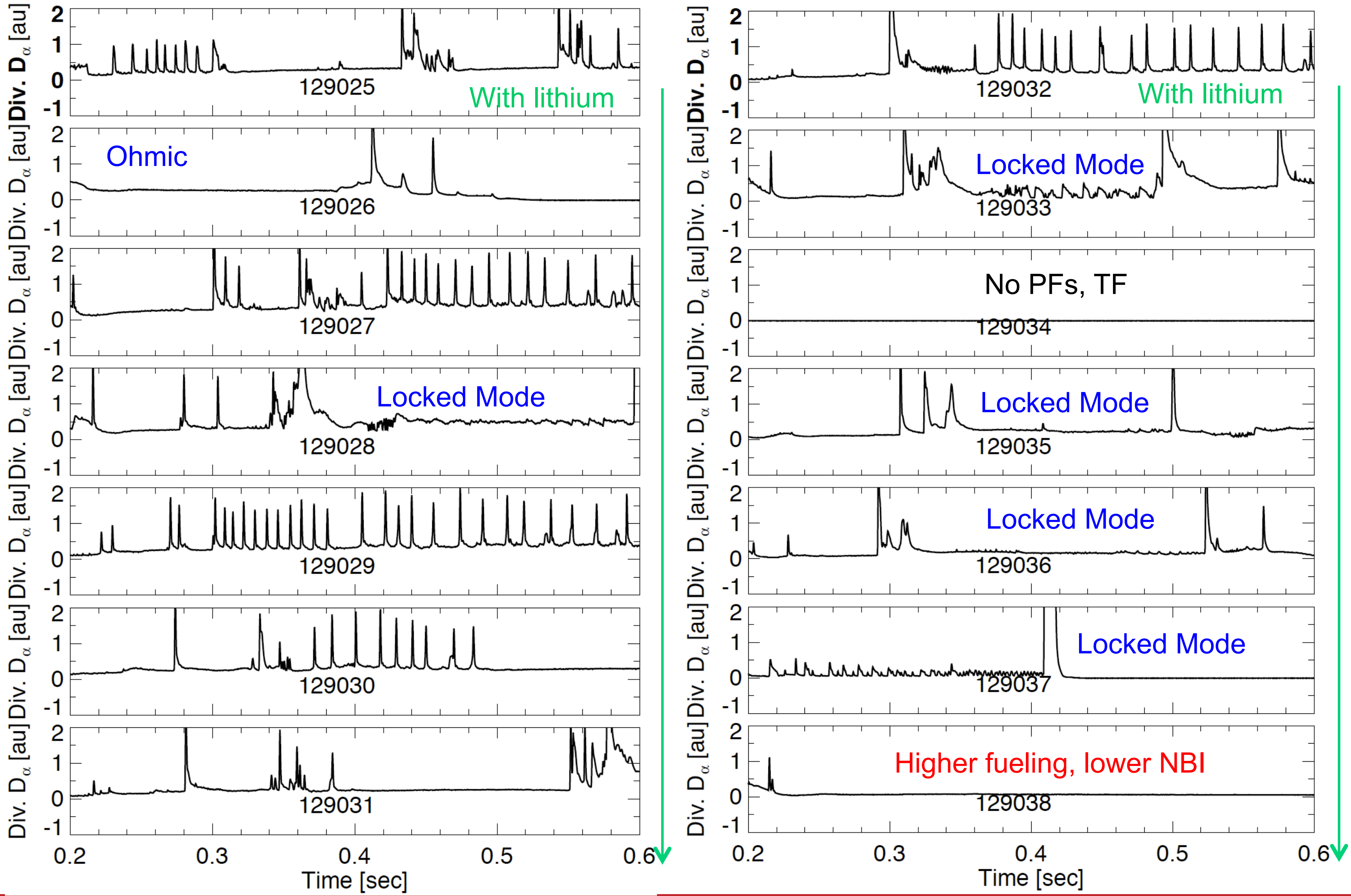
Lithium introduced methodically during experiment - first lithium in 2008 run campaign



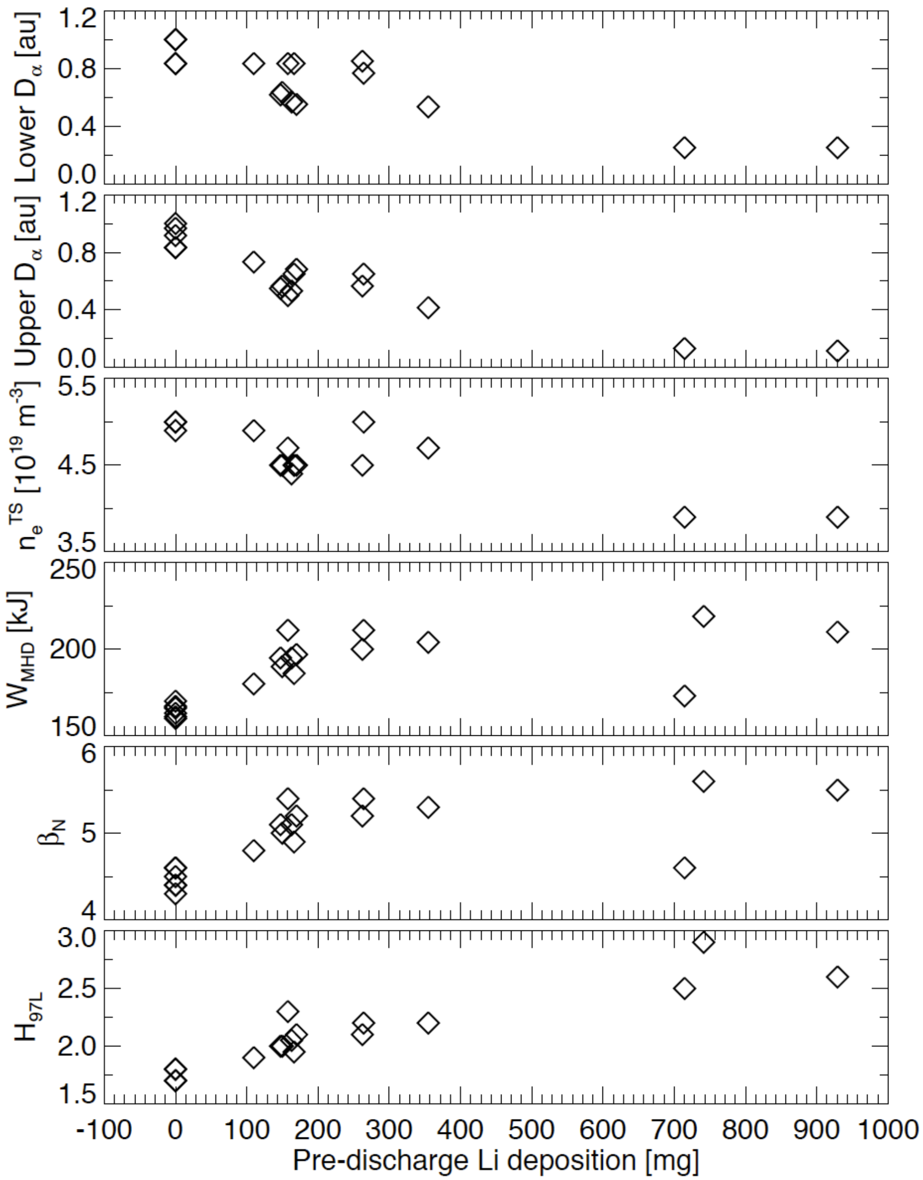
ELMs disappeared gradually during experiment in which pre-discharge Li deposition was varied



Transition to ELM-free discharges was not quite monotonic

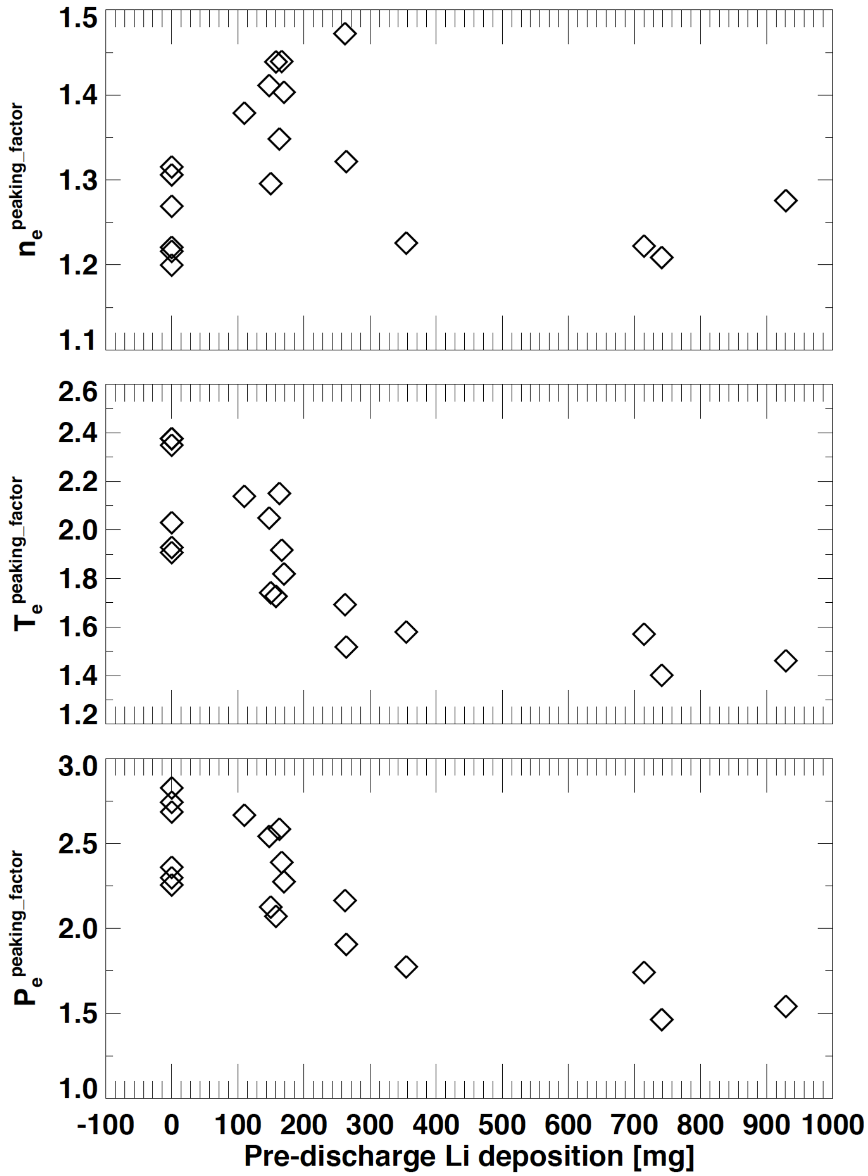


Global plasma performance improves nearly continuously with increasing lithium



- D_α and line-average density from Thomson n_e^{TS} evaluated at t=0.4 sec (fixed time)
- W_{MHD} β_N, and H97L (global τ_E, not thermal) evaluated at time of peak W_{MHD}

T_e and P_e profile peaking factors decrease with increasing lithium



- n_e profile peaking factor first increases as ELM v goes down, and then decreases as ELMs disappear and profile becomes hollow

- T_e and P_e profile peaking factors decrease ~ continuously, good for MHD stability

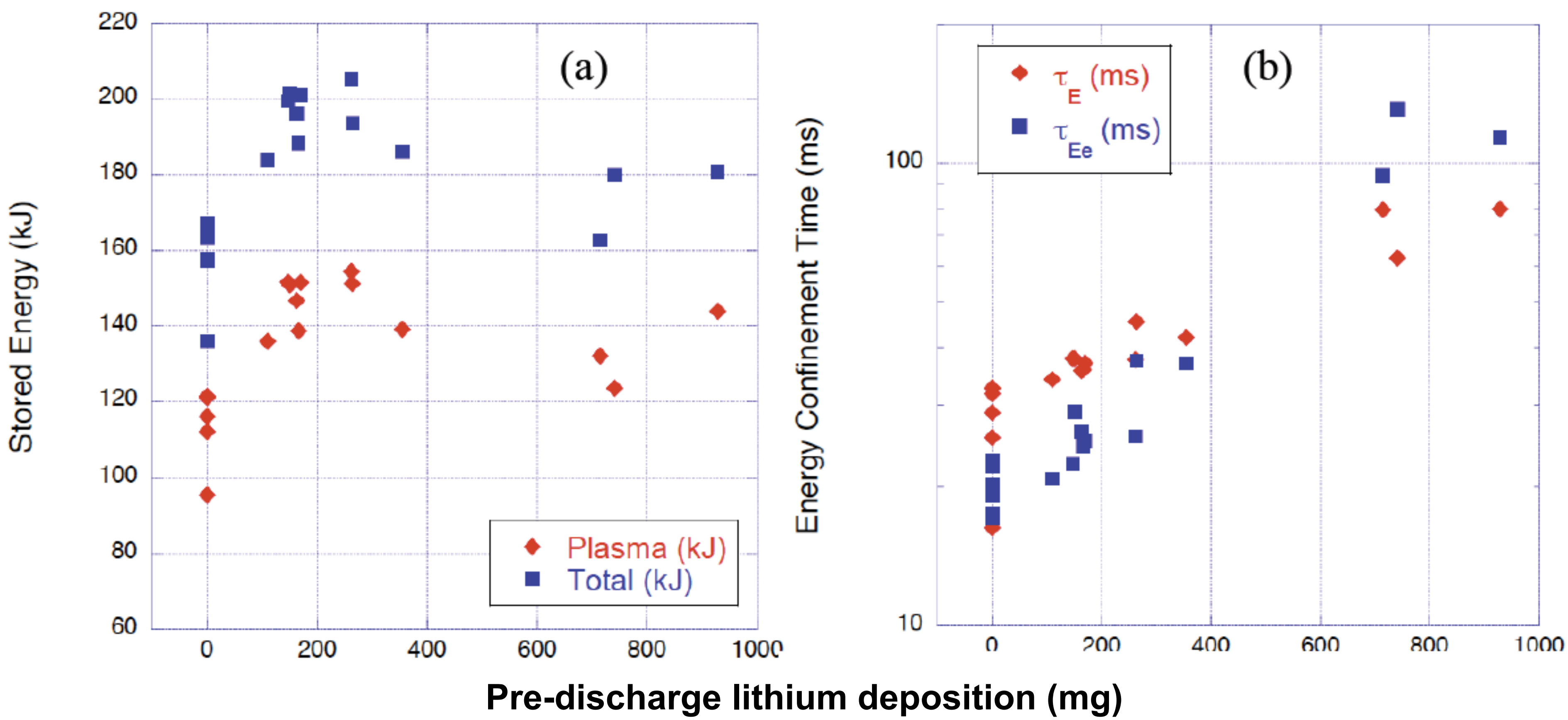
Outline

- Global characteristics change

- Edge electron transport declines
  - TRANSP for D, χ at r/a=0.35, 0.7
  - SOLPS for D, χ for $0.8 \leq \psi_N \leq 1$, including recycling changes
  - Ion transport increases modestly

- ELM frequency first declines, and then goes to 0
  - n_e profile shifts away from separatrix; pressure profile and bootstrap current follow, reducing drive for kink/peeling modes

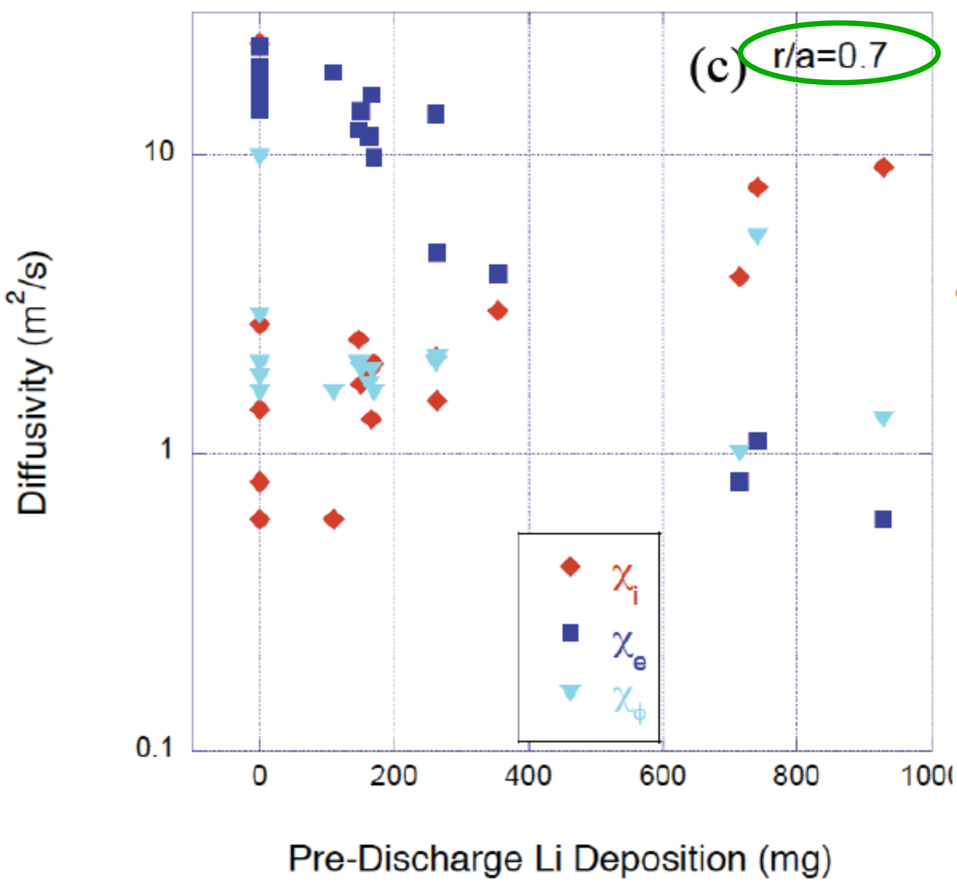
TRANSP used to evaluate plasma stored energy and separate global and electron confinement, τ_E and τ_{Ee}



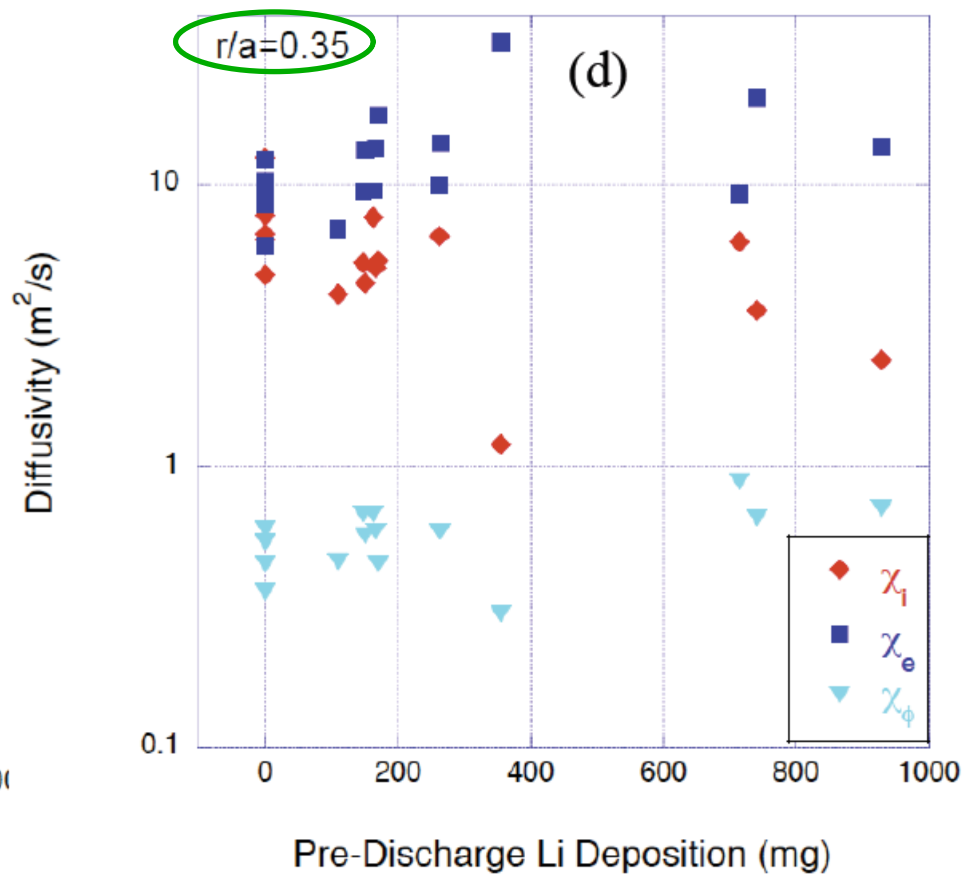
- Evaluated at time of peak stored energy, W_{MHD}

Edge χ_e goes down and χ_i goes up; core χ's unchanged

Edge

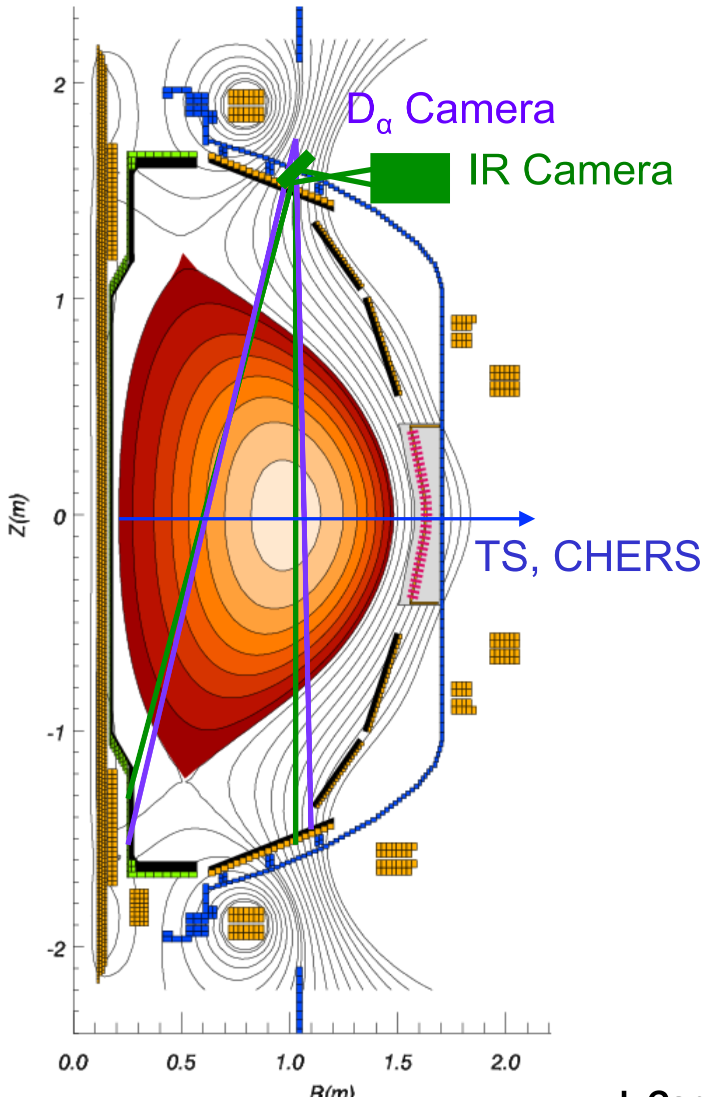


Core

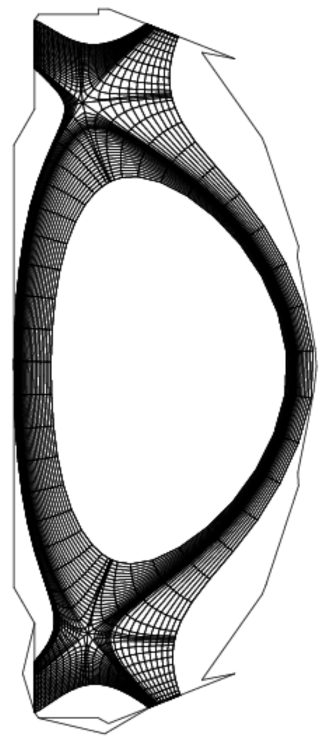


- Global increase in τ_E correlates with drop in edge χ_e

Divertor recycling and far edge cross-field transport quantified with data-constrained SOLPS modeling



SOLPS Grid



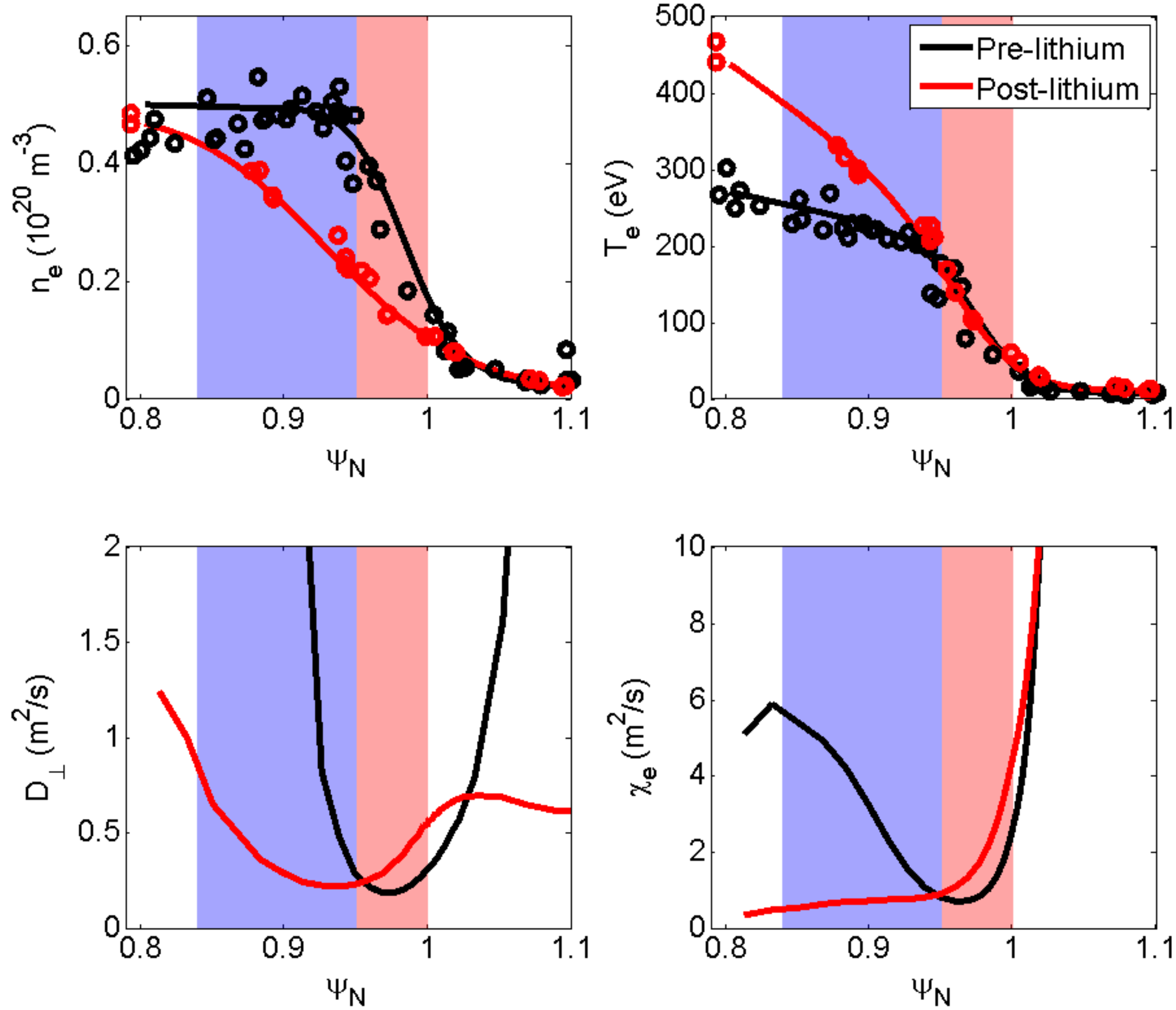
J. Canik PoP 2011

- SOLPS (B2-EIRENE: 2D fluid plasma + MC neutrals) used to model NSTX experimental data
  - Iterative Method
  - ✓ Neutrals, impurities contributions
  - ✓ Recycling changes due to lithium

Parameters adjusted to fit data	Measurements used to constrain code
Radial transport coefficients $D_\perp$, χ_e, χ_i	Midplane n_e, T_e, T_i profiles
Divertor recycling coefficient	Calibrated D_α camera
Separatrix position/ T_e^{sep}	Peak divertor heat flux

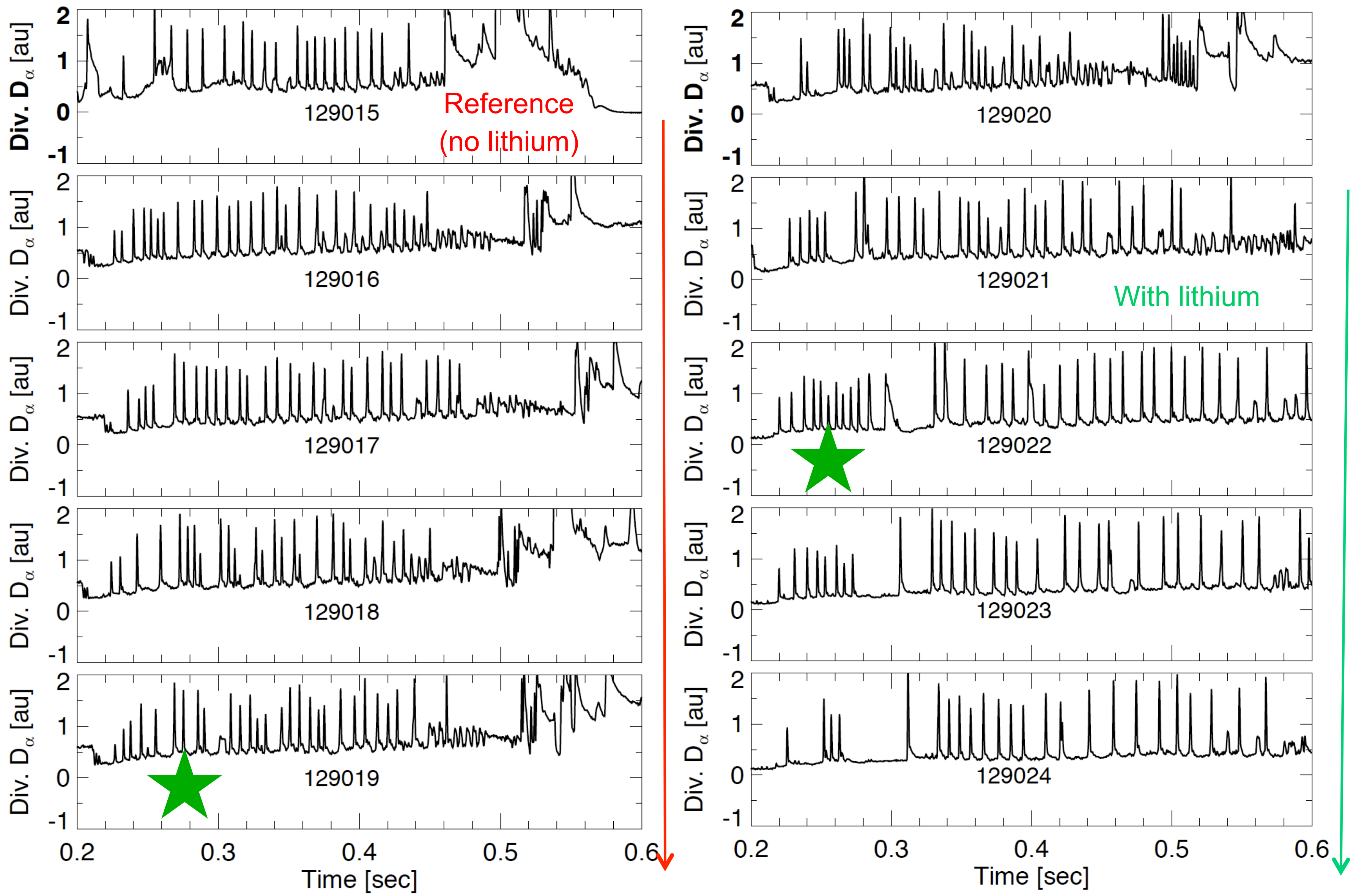
Transport barrier widens with lithium coatings, broadening pedestal (end points of lithium scan)

- Pre-lithium case shows typical H-mode structure
  - Barrier region in D, χ_e just inside separatrix
- Pedestal is much wider with lithium
  - $D_\perp$, χ_e slightly higher outside of ψ_N~0.95
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)
- Changes to profiles with lithium are due to reduced fluxes combined with wide transport barrier

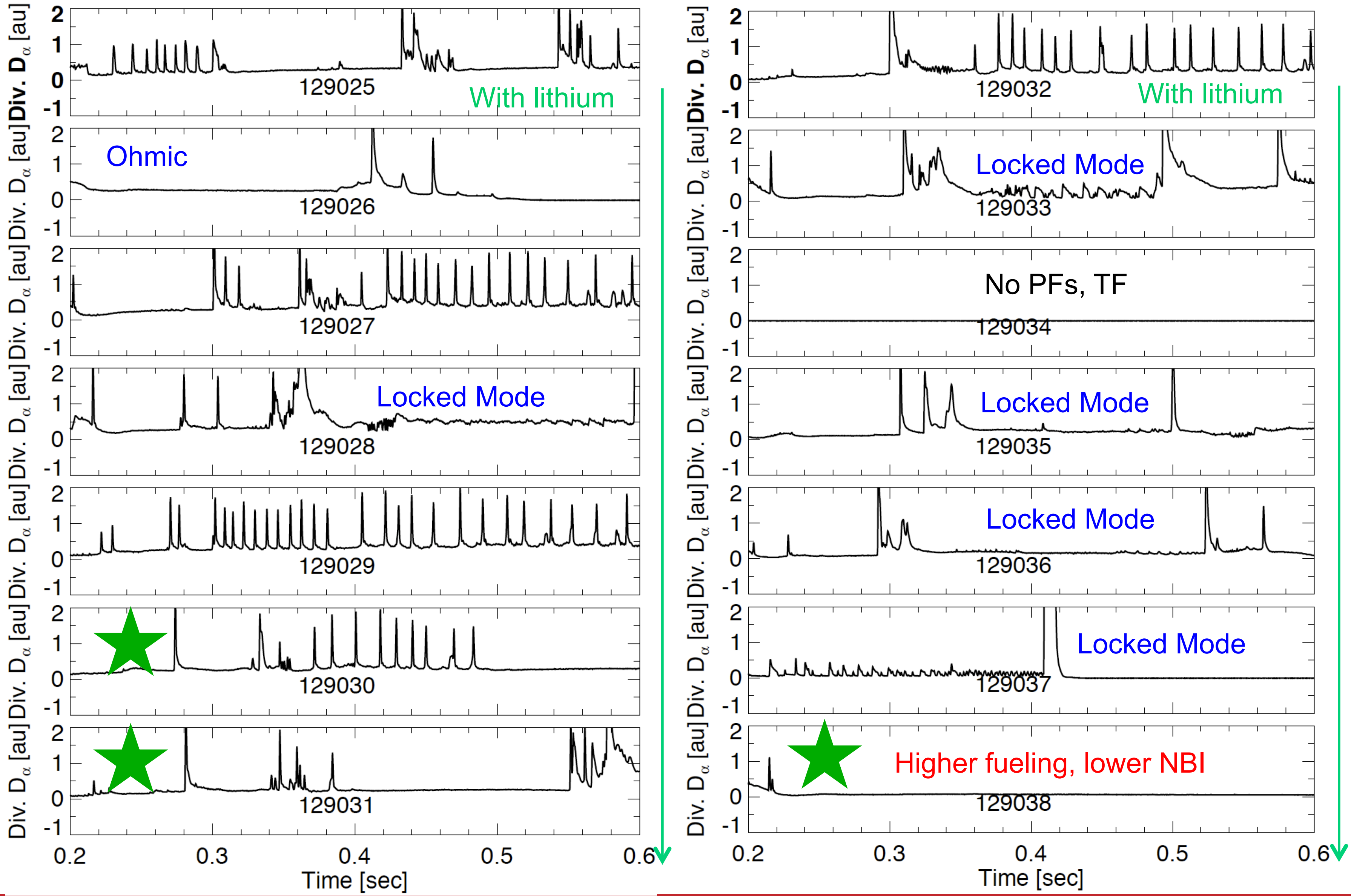


J. Canik PoP 2011

Discharge Sequence

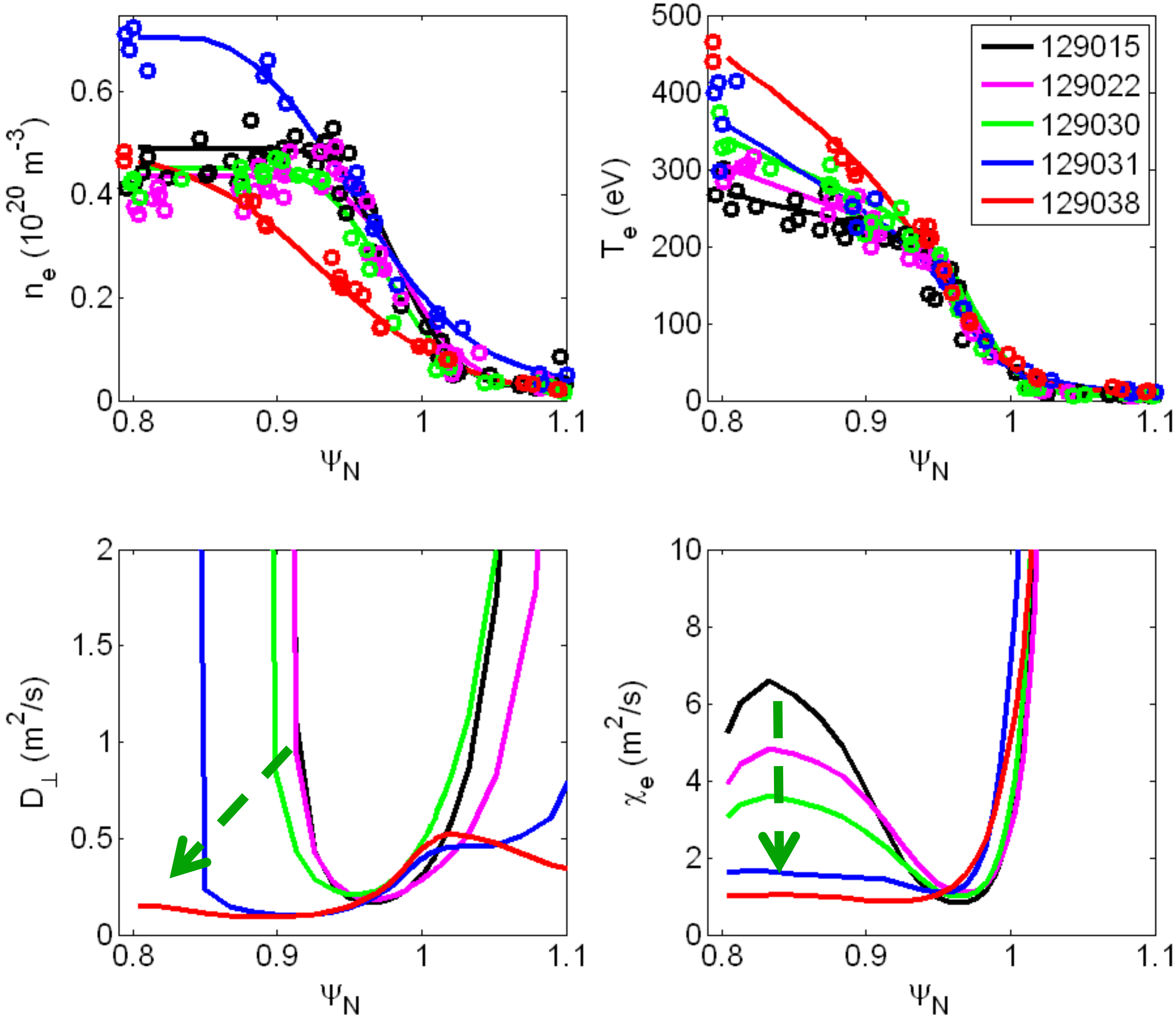


Discharge Sequence



Inner region: as lithium coatings thicken, transport barrier widens, pedestal-top χ_e reduced

- Several shots analyzed with increasing lithium thickness (direction of arrow) ➔
- ELMy to reduced frequency to ELM-free
- T_e gradient clamped



J. Canik PoP 2011

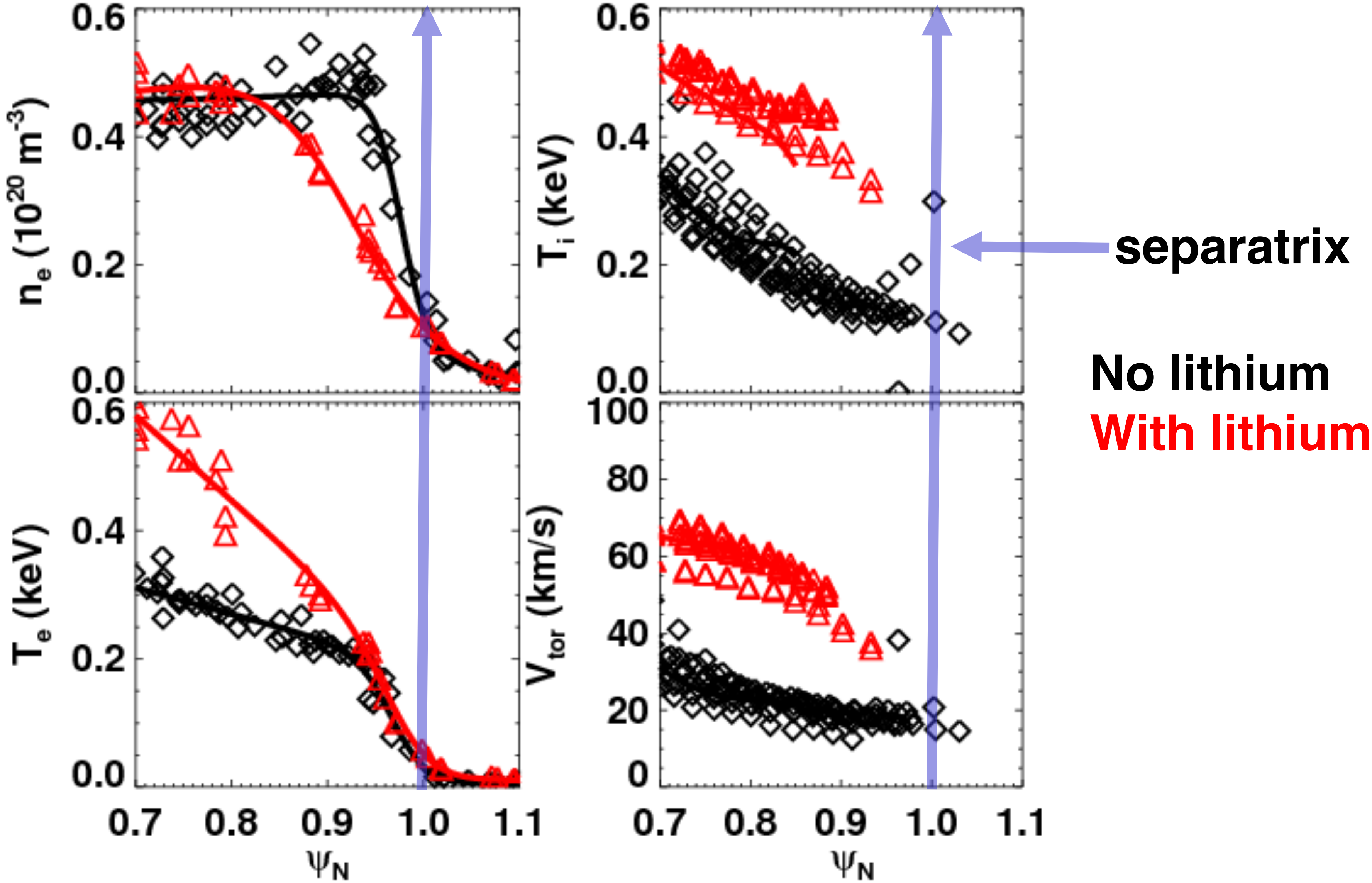
Outline

- Global characteristics change

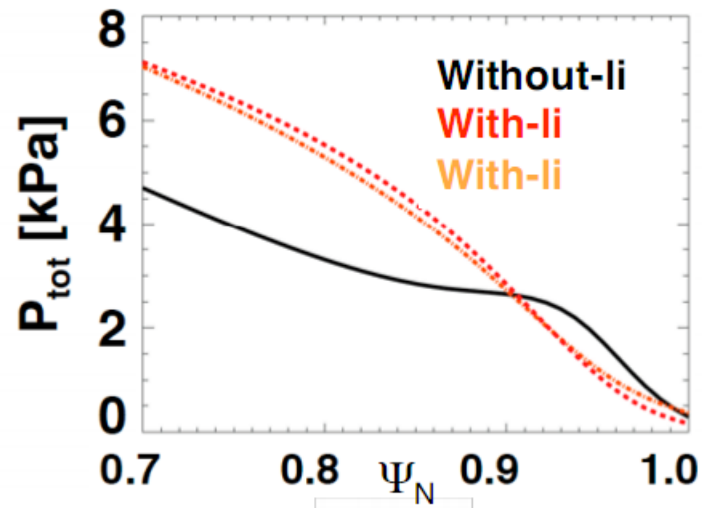
- Edge transport declines

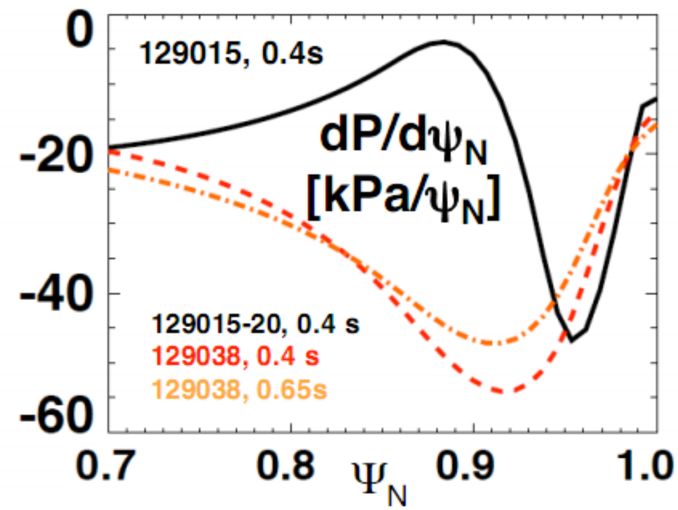
- ELM frequency first declines, and then goes to 0
  - n_e profile shifts away from separatrix; pressure profile and bootstrap current follow, reducing drive for kink/peeling modes
  - n_e profile modification appears to be the key first step, but T_e gradient clamping an important ingredient

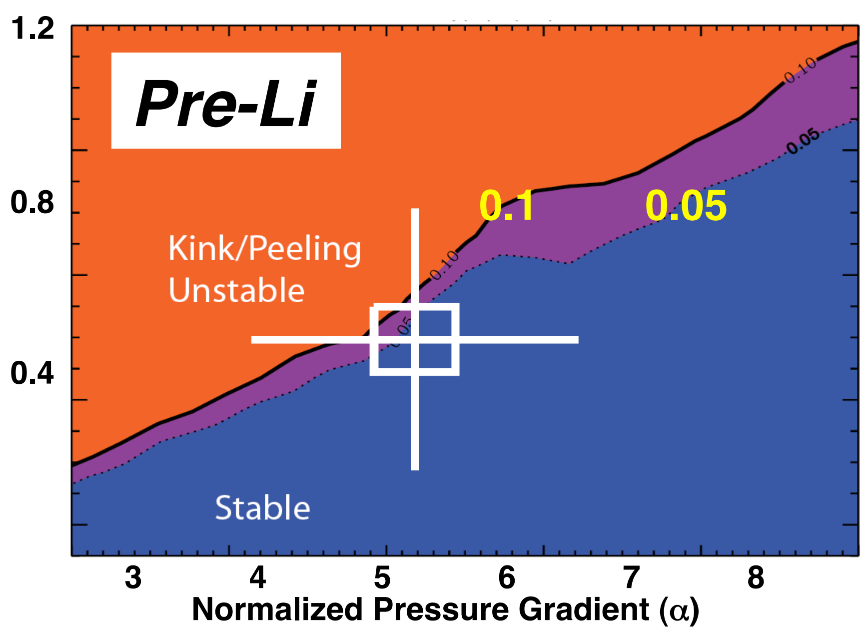
T_e, T_i increased and edge n_e decreased with lithium coatings (end points of lithium scan)



Pre-lithium discharge near the kink/peeling boundary (end points of lithium scan)

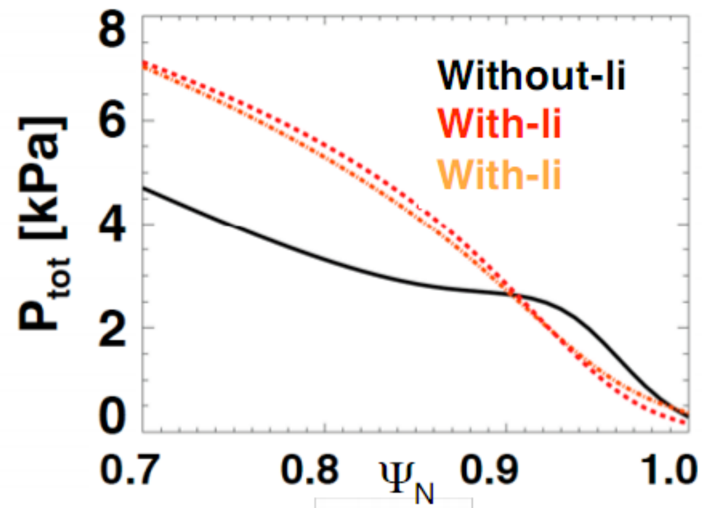


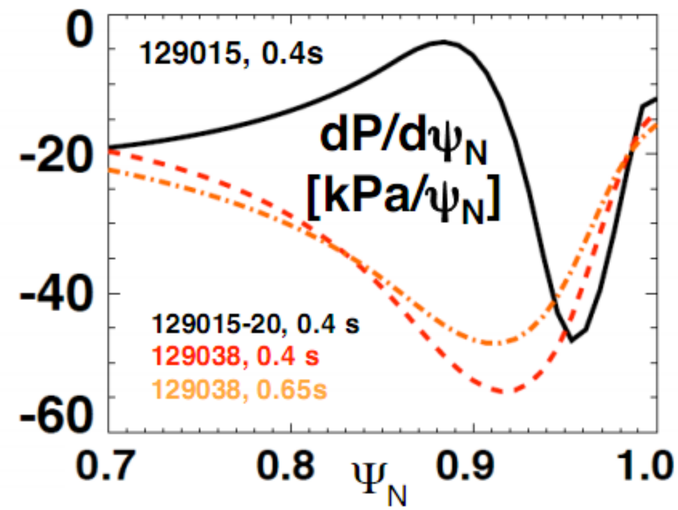


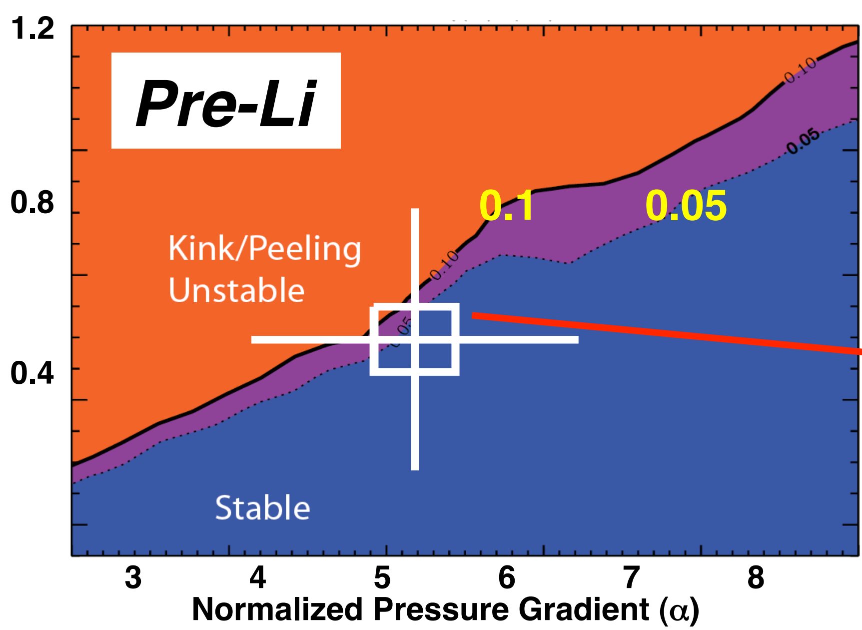


R. Maingi, PRL 2009

Pre-lithium discharge near the kink/peeling boundary (end points of lithium scan)

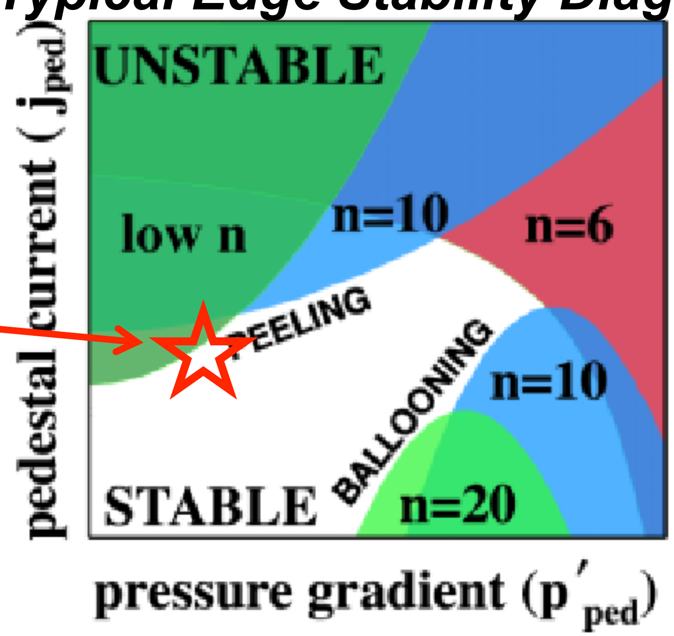




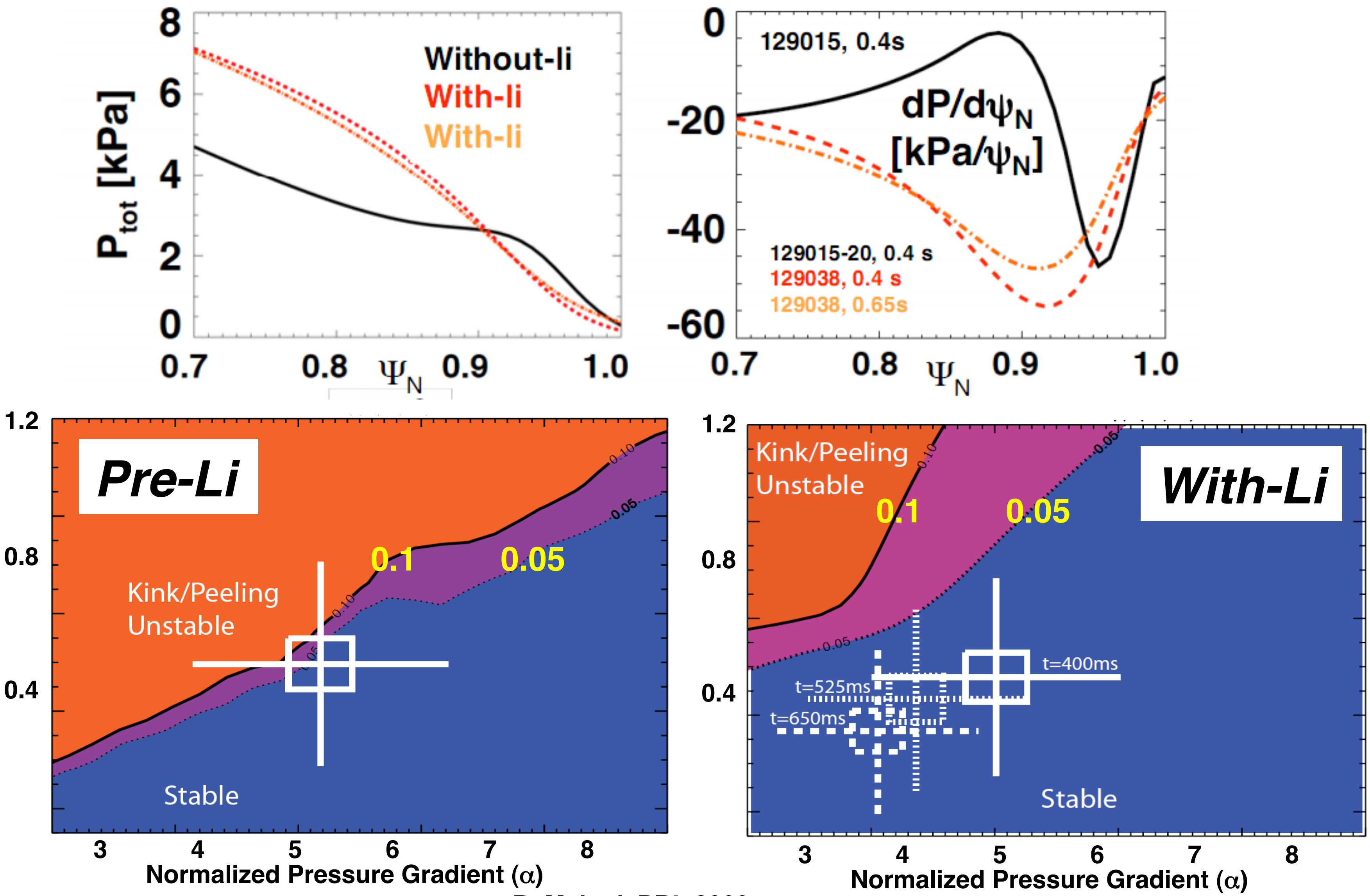


R. Maingi, PRL 2009

Typical Edge Stability Diagram

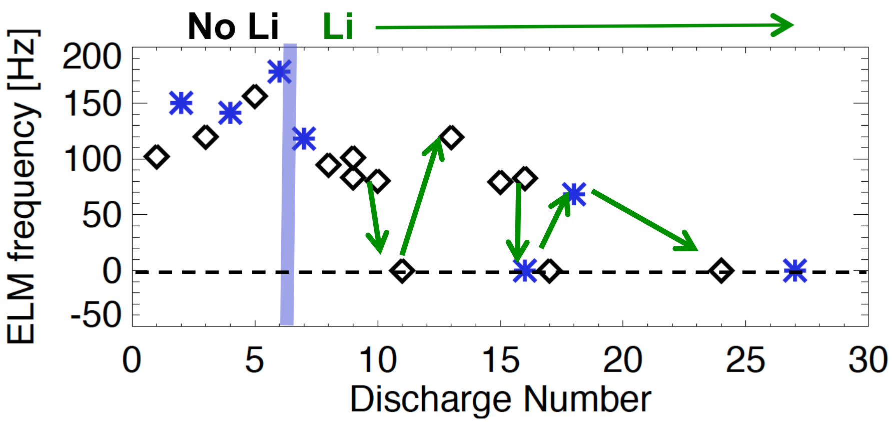


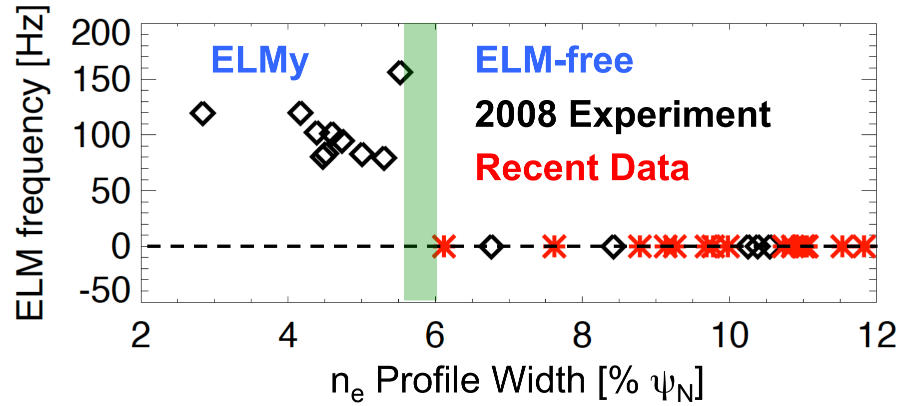
Peak pressure gradient moves inwards, p' and j reduced outside ψ_N~0.95, reduces kink/peeling drive

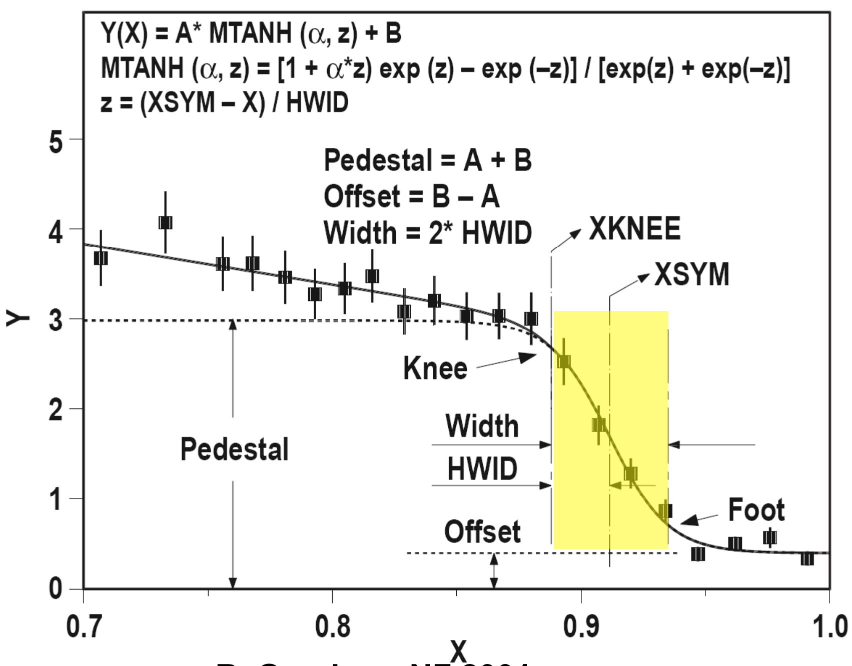


R. Maingi, PRL 2009

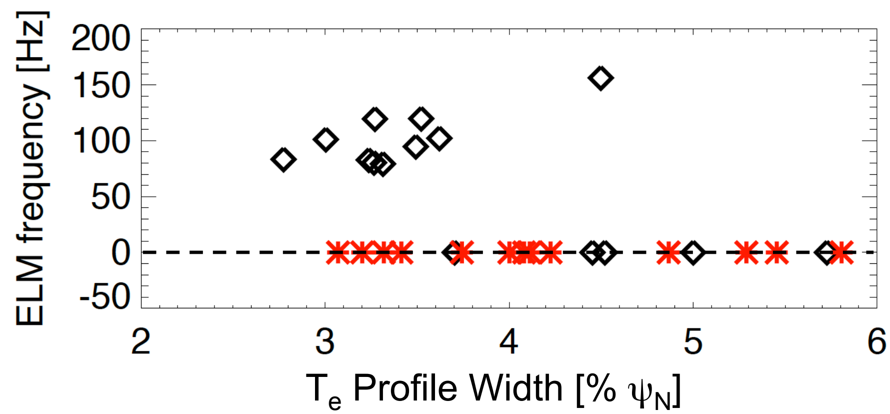
ELM suppression correlates with broadening of the density profile, but not the temperature profile





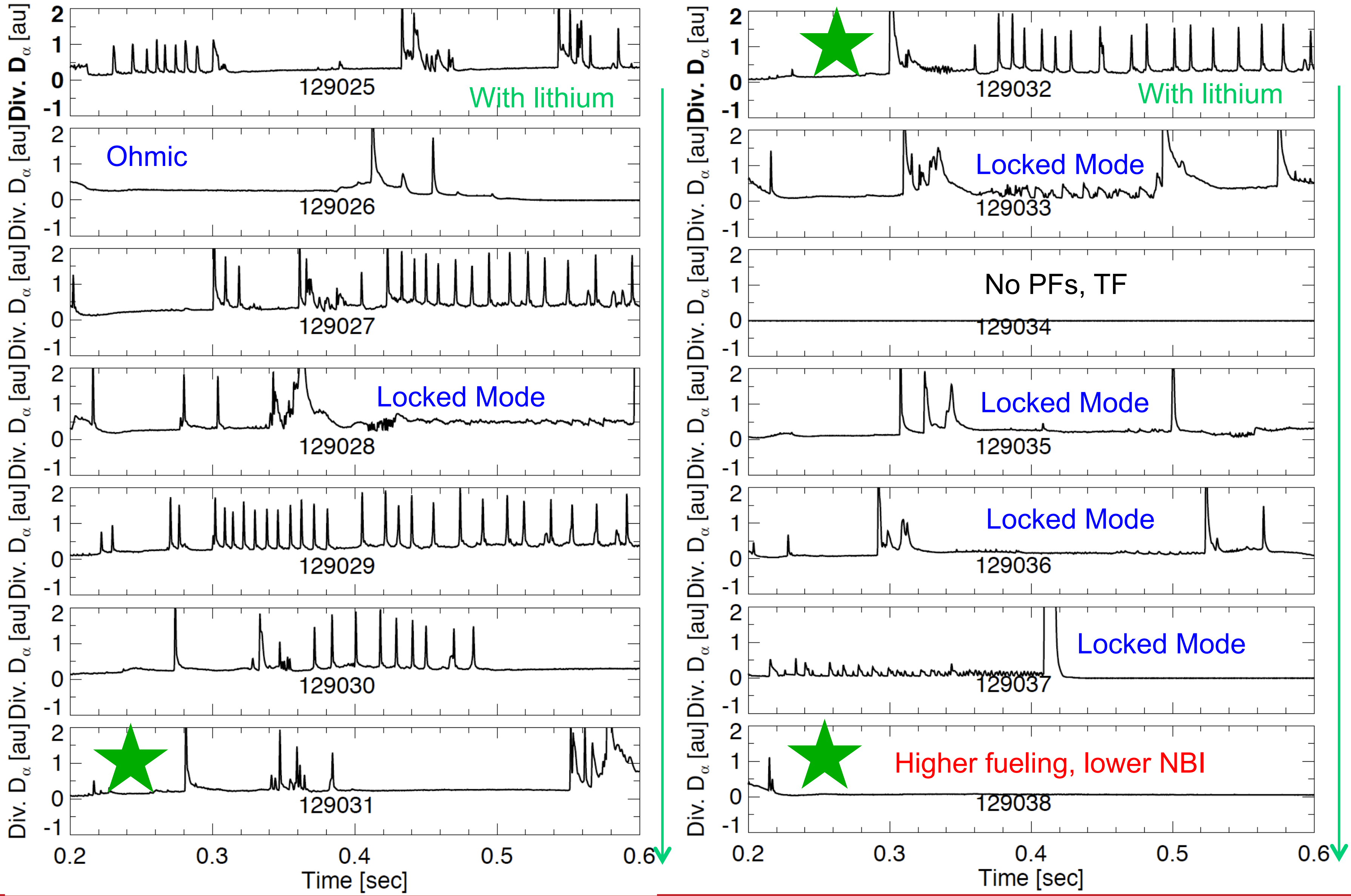


R. Groebner NF 2001

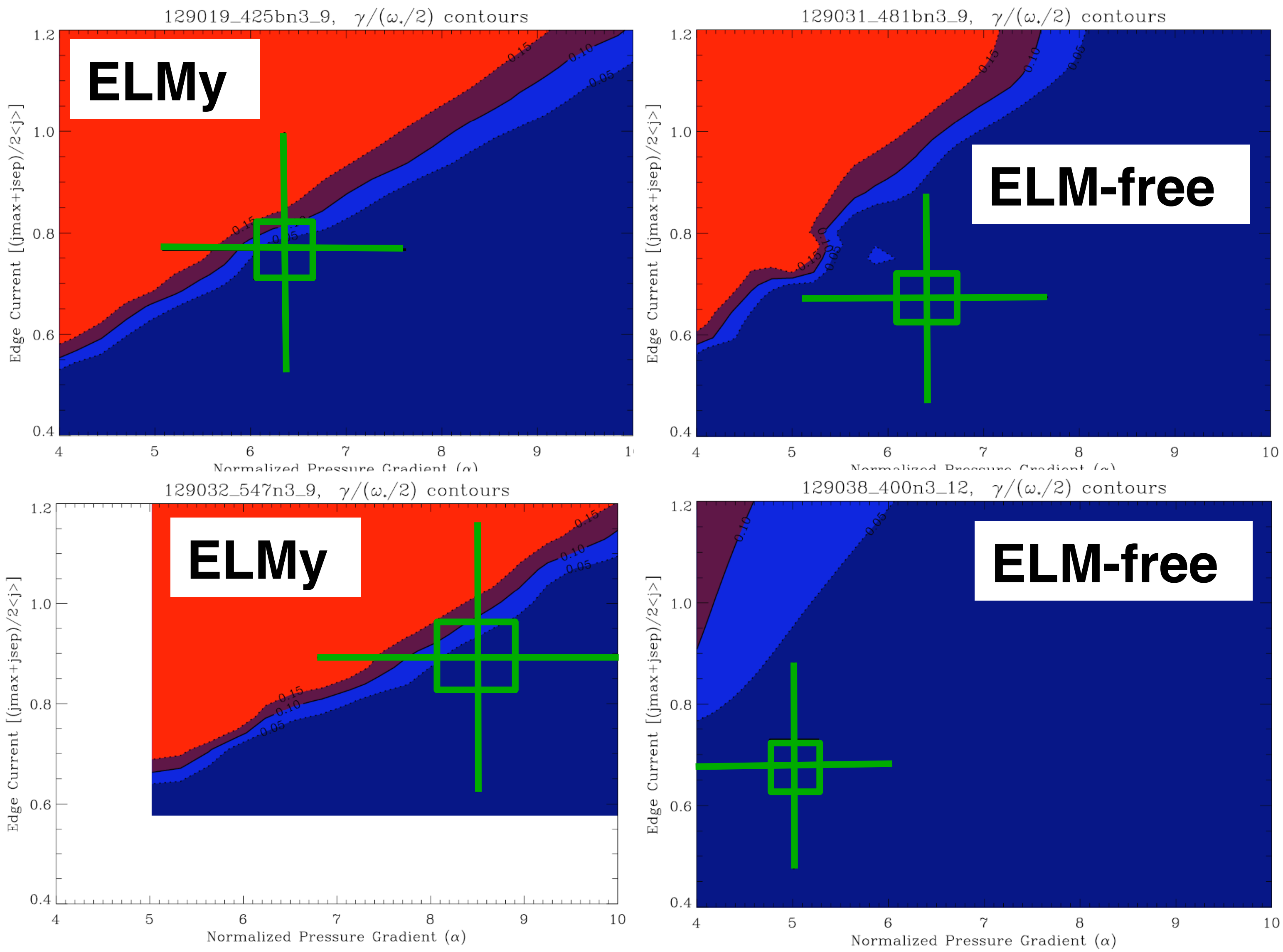


D. Boyle PPCF 2011 submitted

Discharge Sequence

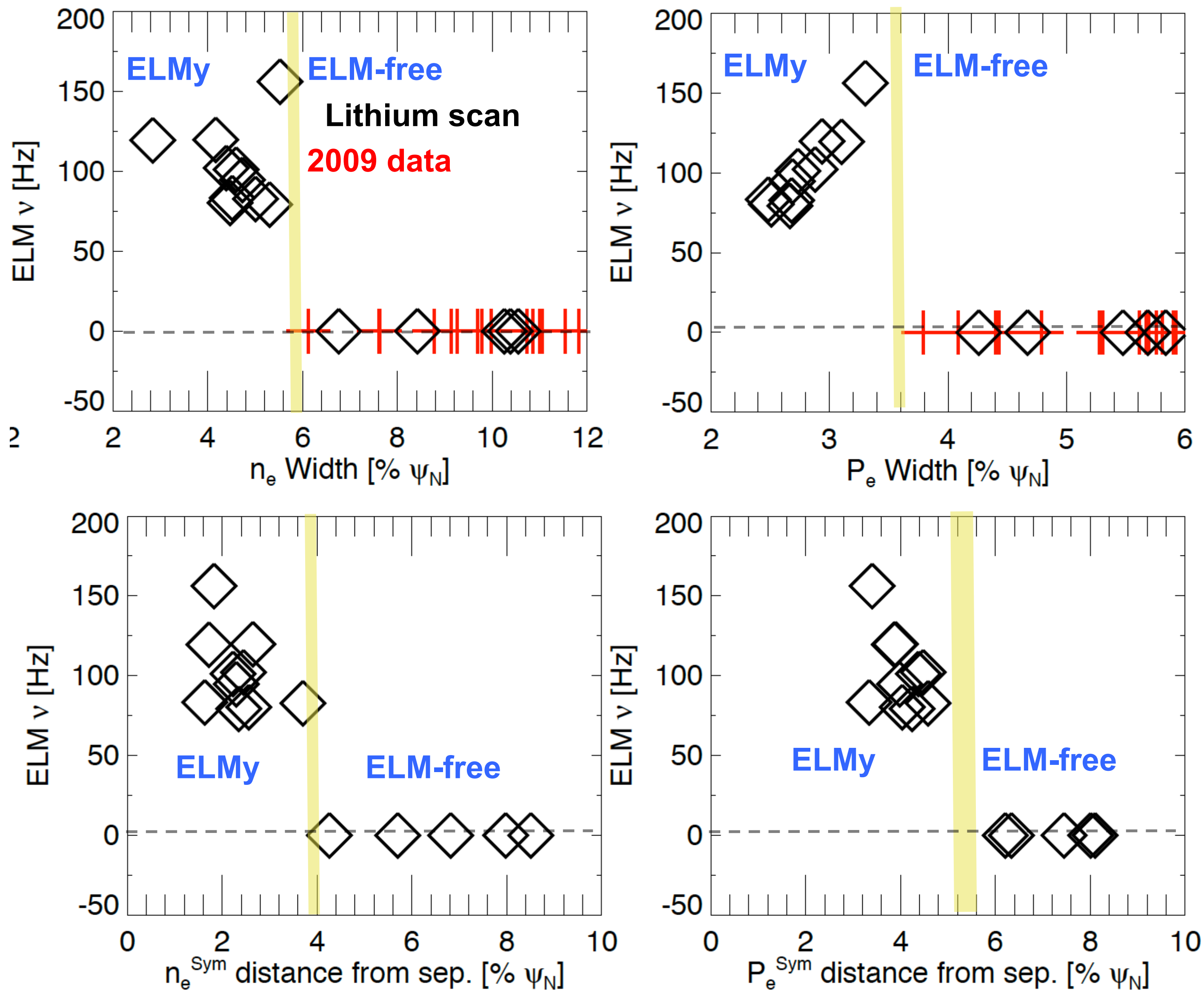


ELMy discharges close to the kink/peeling mode stability boundary, while ELM-free discharges are farther away



D. Boyle
PPCF 2011
submitted

Widening of pedestal widths also correlates with movement of the peak gradient locations farther from separatrix



Density profile modification to lithium pumping the key in changing edge stability

Lithium reduces recycling → Core fueling reduced and edge density reduced → Density gradient reduced and profile broadened

Density profile modification to lithium pumping the key in changing edge stability

Lithium reduces recycling

→ Core fueling reduced and edge density reduced

→ Density gradient reduced and profile broadened

→ Edge T_e profile clamped; Peak edge P' moves farther from separatrix

→ Edge bootstrap and parallel current modified

→ Kink/peeling stability improved -> ELMs suppressed

What causes this nearly continuous dependence of recycling, transport, and stability on increasing lithium?

- Nominal evaporation was ~ 150nm at the outer strike point at ~0.8m at the lowest 110mg rate
  - Toroidal variation gives ~ 60nm minimum deposition
  - Maximum deposition ~ 9x higher, or 500-1400nm! (900 mg)
- Surprising because implantation (pumping) depth expected to be < 10 nm
  - Brooks (JNM 2005) computed an implantation depth of 100 nm for 0.5 keV < E_i < 2 keV
  - Krstic (ISLA 2011) computed an implantation depth of 1 nm for E_i < 30 eV
  - Simple extrapolation for 150-200 eV (about $5*T_e^{div}$) yields implantation depth < 10 nm
  - *These are all 'ideal' calculations - actual surface chemistry of reactive lithium may alter these results*

A few hypotheses

- Lithium intercalating into bulk graphite pores?
  - No evidence of this from post-mortem tile analysis by Wampler; lithium confined to first μm of surface
- Lithium evaporation highly asymmetric?
  - In-situ quartz deposition monitors seem to confirm modeling by Zacharov: toroidal variation at most a factor of two, radial distribution is Gaussian with a 23^0 spread
- Lithium pumping complex - surface chemistry?
  - In-situ MAPP from JP Allain, and off-site measurements
- Non-divertor PFCs critical in this? (longer time scales)
- Electric fields or other effects increase ion impact energy, and thus implantation depth (J. Harris)
  - How to test this?

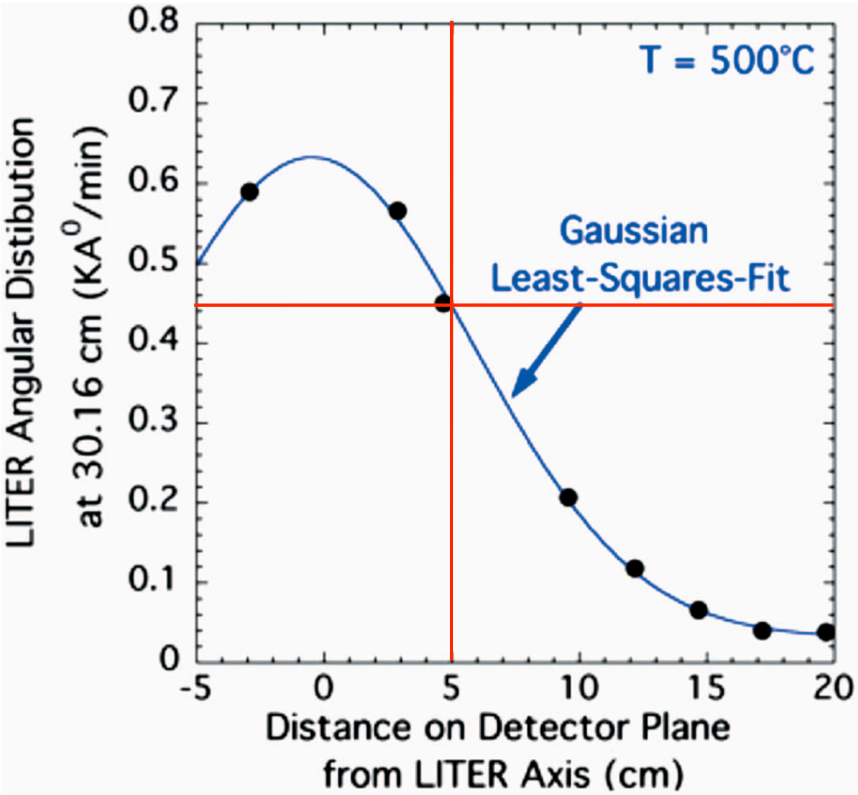
Plasma characteristics change continuously with increasing lithium evaporation

- Recycling decreases, normalized energy confinement improves, profiles become less peaked
- Edge electron transport is reduced
  - Electron channel responsible for global τ_E increase
  - More than just the drop in recycling source term
- Edge stability improves as density profile and bootstrap current shifts away from separatrix
- *Need work to connect these effects to the PWI with lithium, since even the minimum coating thickness is beyond the expected implantation range*

Backup

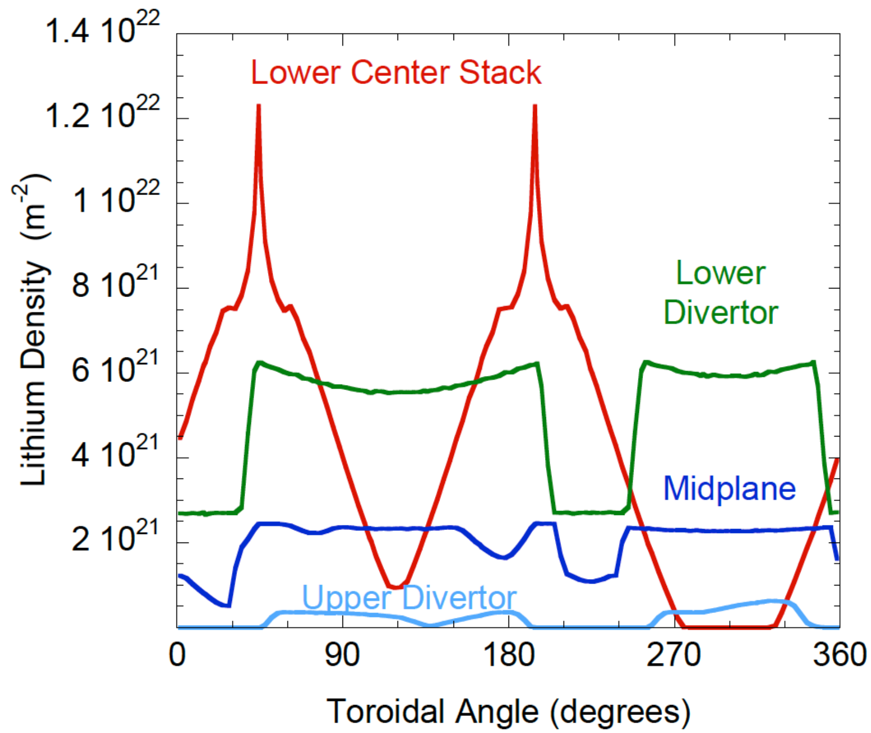
LiTER deposition has toroidal and poloidal variation

- 30cm distance from LiTER to surface
- in NSTX, x-axis should be multiplied by 10x
- For R_{OSP}~0.8m, deposition 1/3 less than max.



H. Kugel PoP 2008

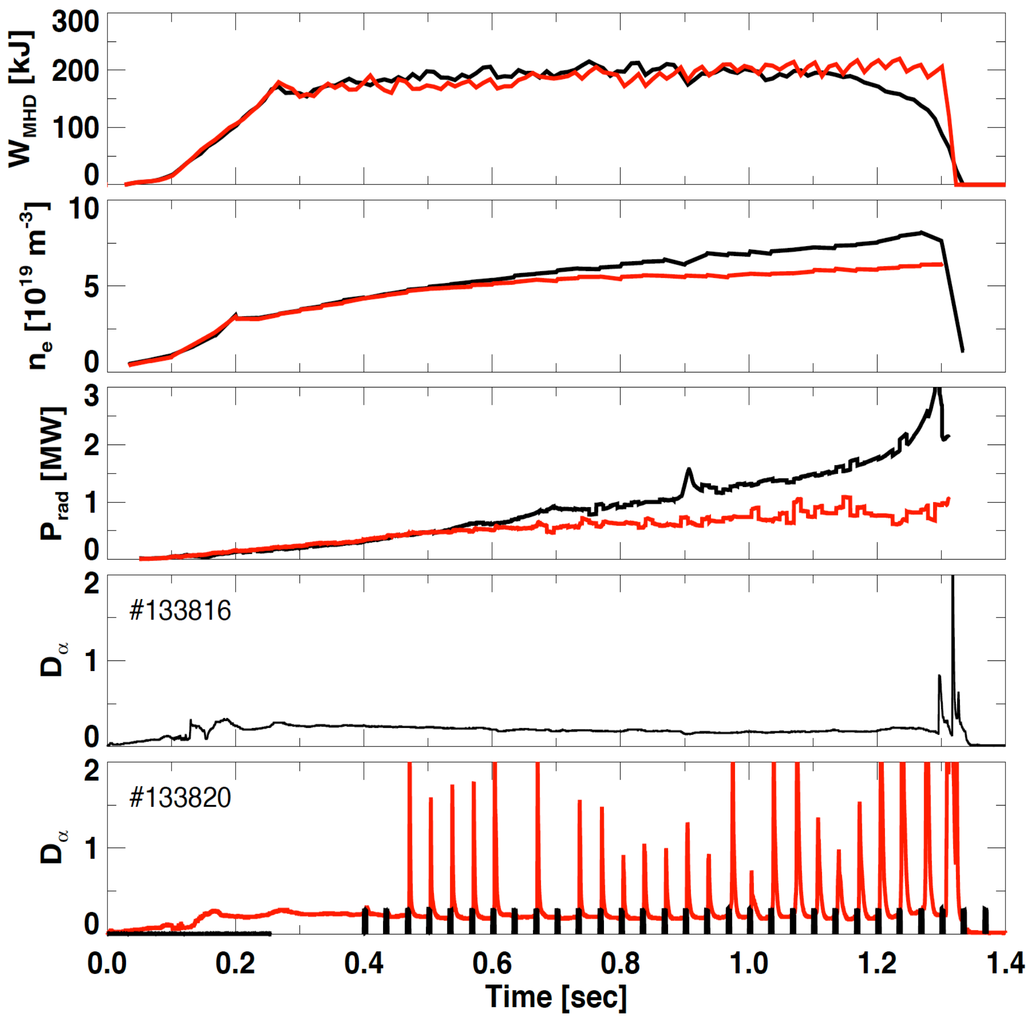
Vacuum Deposition with 1.3 gm Lithium



* From H. Kugel, source?

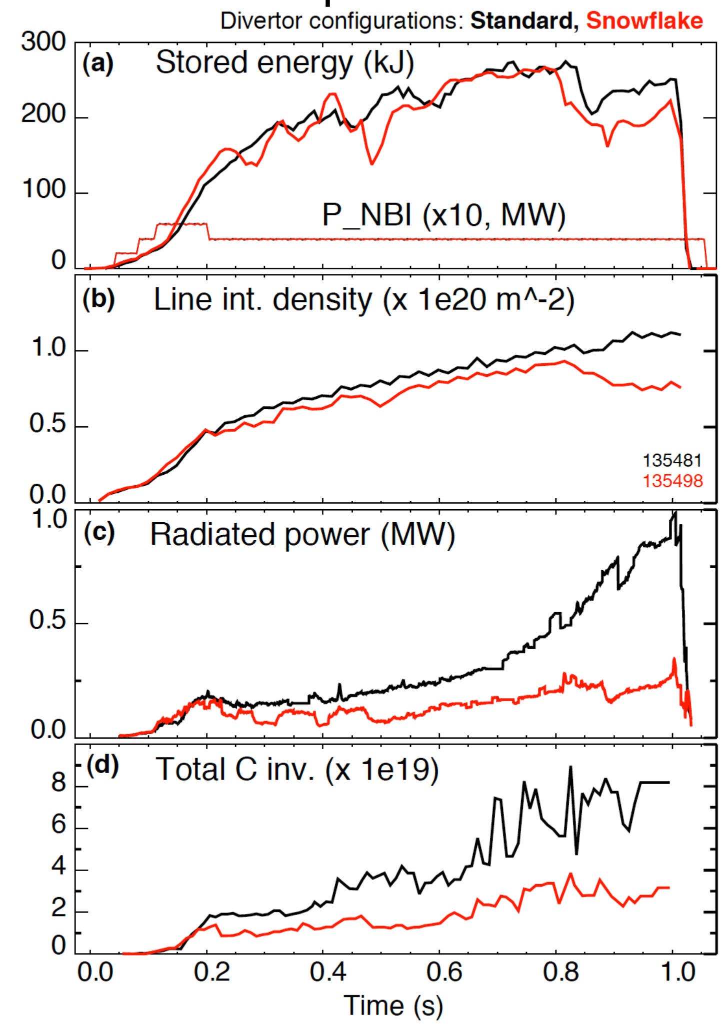
New group in NSTX (FY11-12) will focus on combining techniques to address impurity influx with high lithium

Type I ELMs triggered for impurity control (post-lithium, n=3)



J. Canik, PRL 2010

"Snowflake" divertor reduced impurities



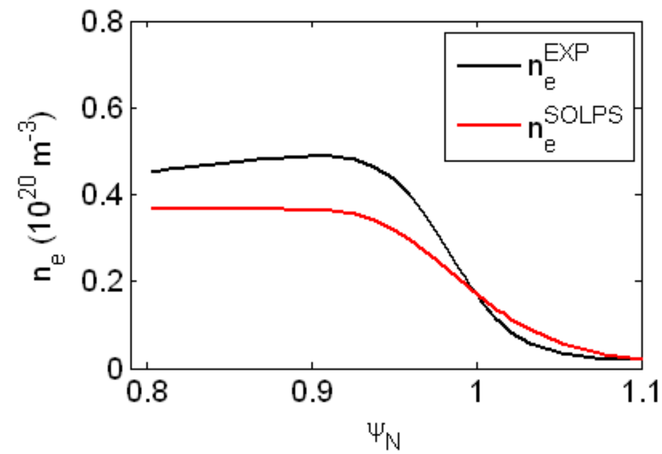
V. Soukhanovskii, NF 2011

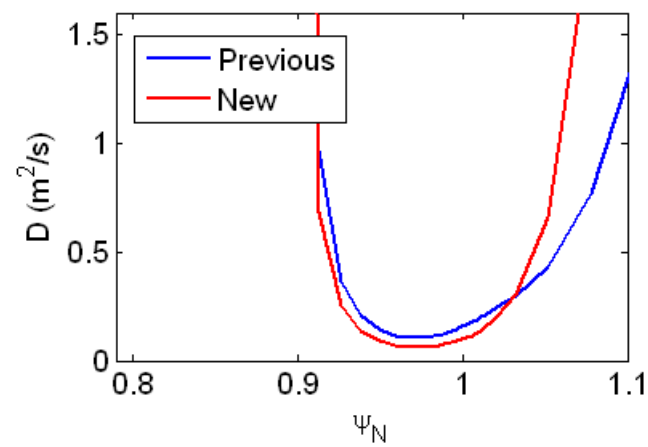
Possible directions in NSTX

- Increase the film thickness everywhere: does trend persist?
  - A liquid lithium divertor module was installed in NSTX, which also provided the capability of a liquid plasma facing surface; initial results show LLD no better than lithium on graphite
- Increase the minimum film thickness everywhere, in case those interactions are responsible for the gradual dependence
  - Additional lithium delivery mechanisms to increase the coverage are being implemented, as is a technique to increase the overall coverage by evaporating lithium into a helium working gas
- Increase the film thickness in the divertor strike point regions with the most intense plasma-wall interactions, in case erosion during the discharge is responsible for the trend
  - Develop targeted lithium deposition near the strike point regions, possibly even during discharges, and new designs are being considered

Procedure for fitting midplane n_e, T_e, T_i profiles

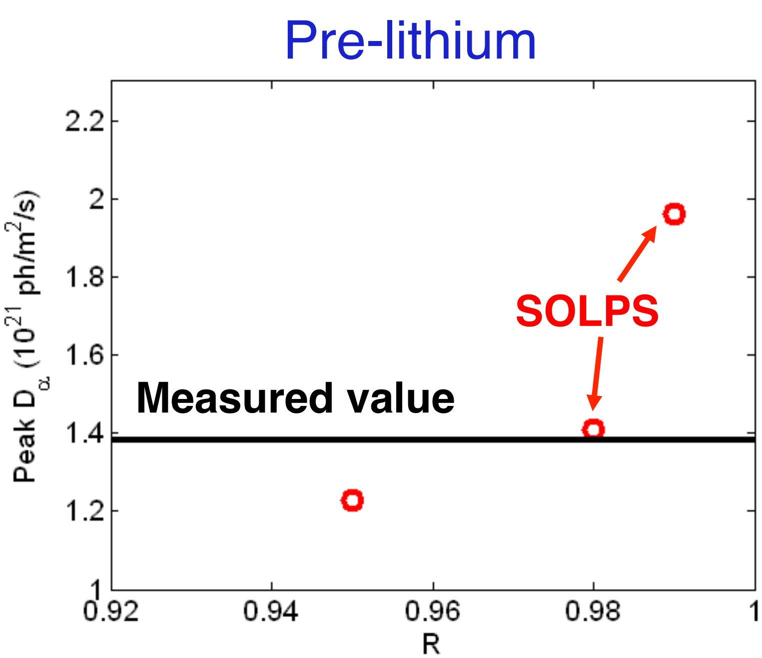
- Start with initial guess for $D_\perp$, χ_e,χ_i
- Run simulation for ~10% of confinement time
- Take radial fluxes along 1-D slice at midplane from code
  - Γ^{SOLPS}, $q_e^{\ SOLPS}$, $q_i^{\ SOLPS}$
- Update transport coefficients using SOLPS fluxes and *experimental* profiles
  - E.g., $D^{new} = - \Gamma^{SOLPS}/\text{grad}(n_e^{EXP})$
  - Here we use fits to profiles used in stability calculations (Maingi PRL '09)
- Repeat until $n_e/T_e/T_i^{SOLPS} \sim n_e/T_e/T_i^{EXP}$

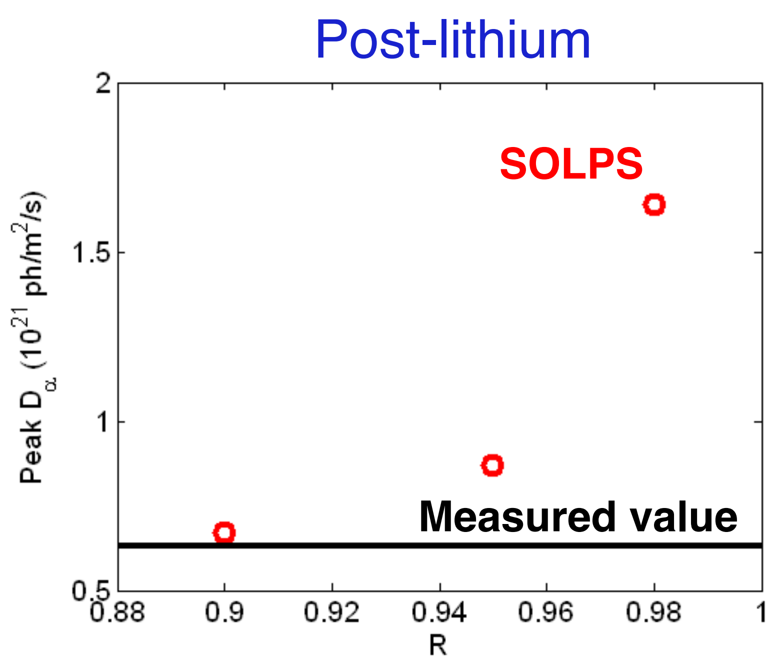




Peak D_α brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces R from ~.98 to ~.9

- For each discharge modeled, PFC recycling coefficient R is scanned
  - Fits to midplane data are redone at each R to maintain match to experiment
- D_α emissivity from code is integrated along lines of sight of camera, compared to measured values
  - Best fit indicates reduction of recycling from R~0.98 to R~0.9 when lithium coatings are applied





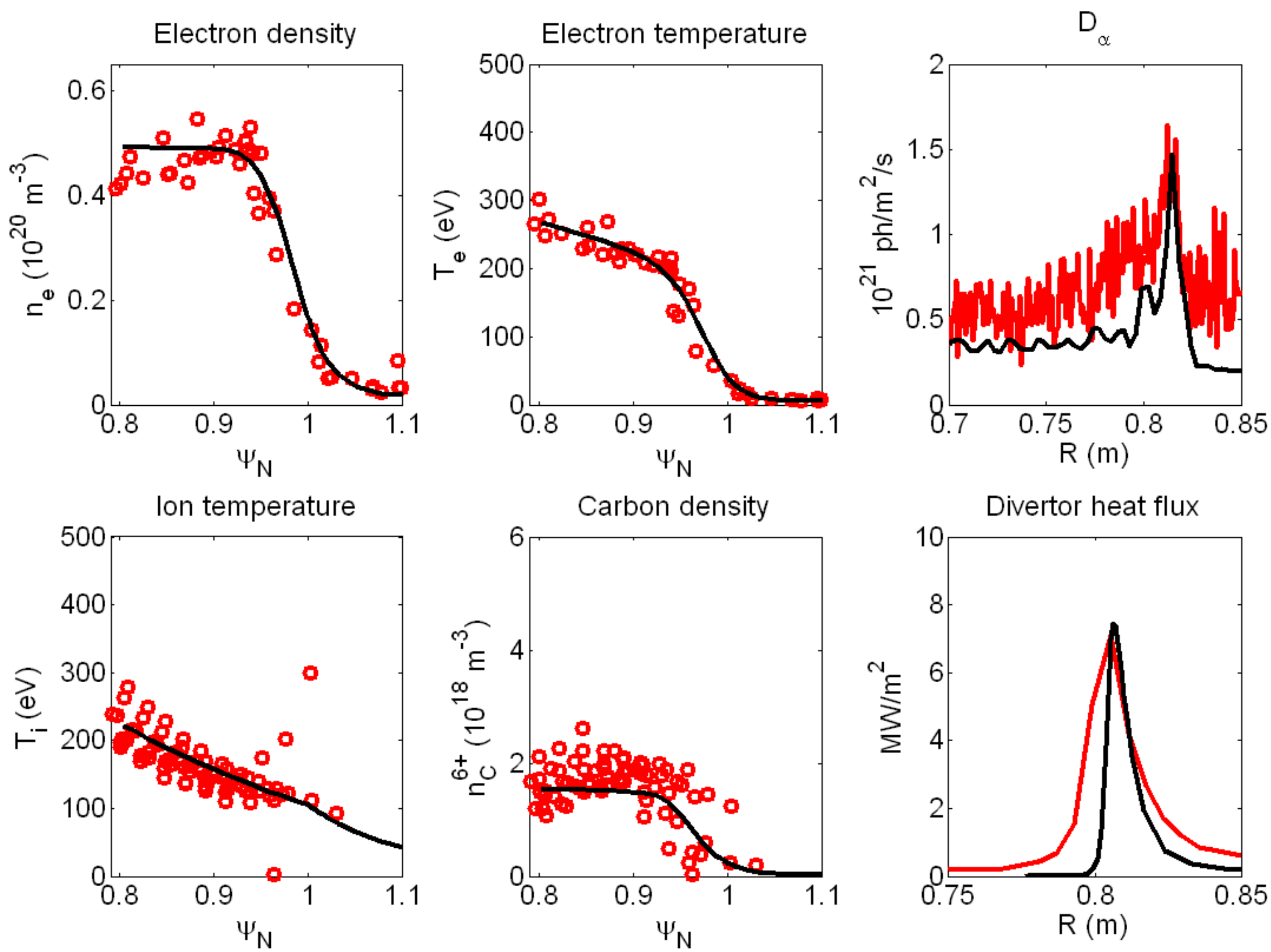
Midplane and divertor profiles from modeling compare well to experiment for the pre-lithium case

- P=3.7 MW
- R=0.98

- Good match to midplane profiles

- Carbon included: sputtering from PFCs, inward convection to match measured n_C^{6+}

- Heat flux and D_α, radial decay sharper than experiment



J. Canik PoP 2011 at press

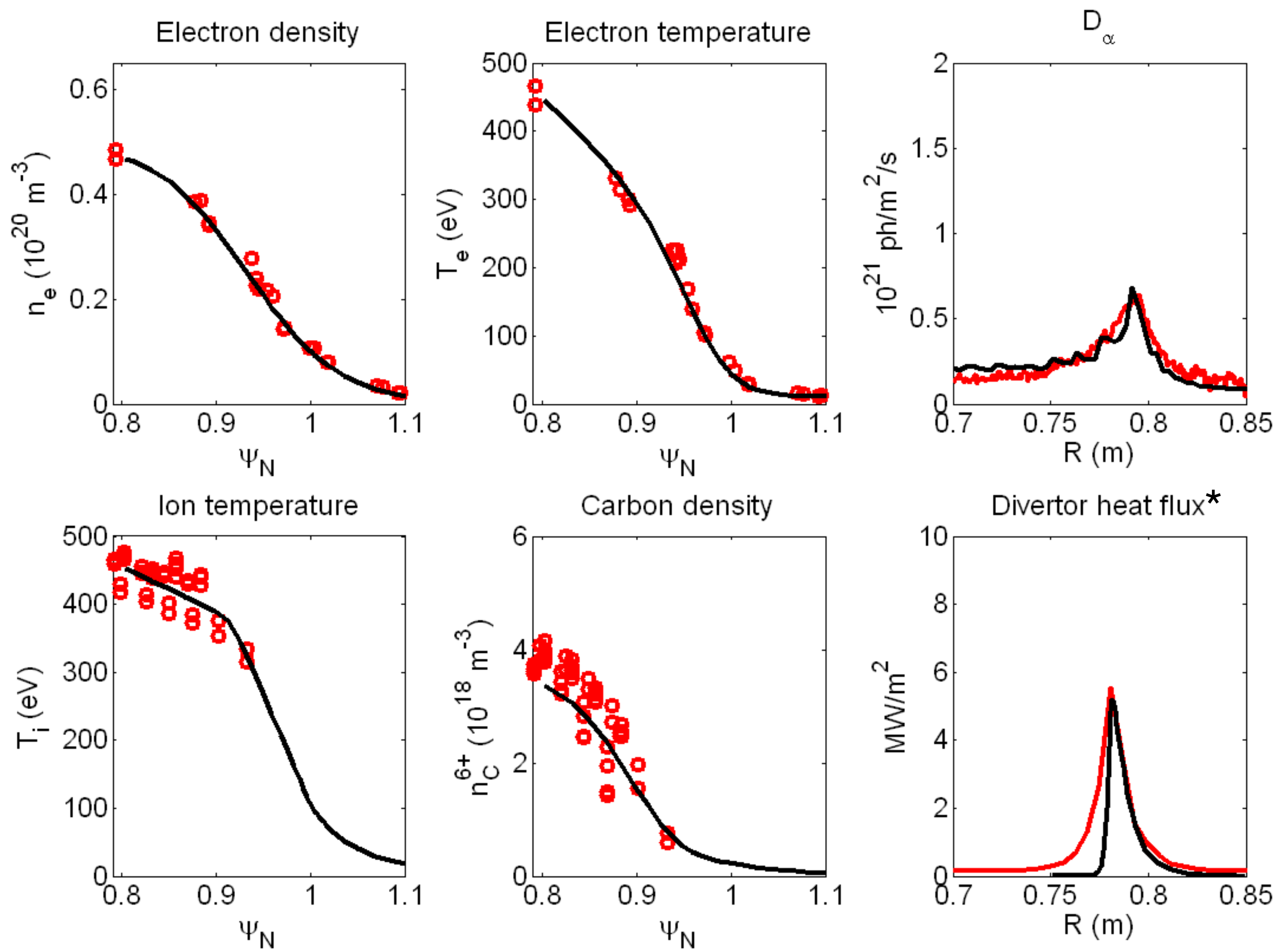
Combining reduced recycling and transport changes gives match to measurements with lithium

- P=1.9 MW
- R=0.90

- Transport coefficients adjusted to recover fit to upstream data

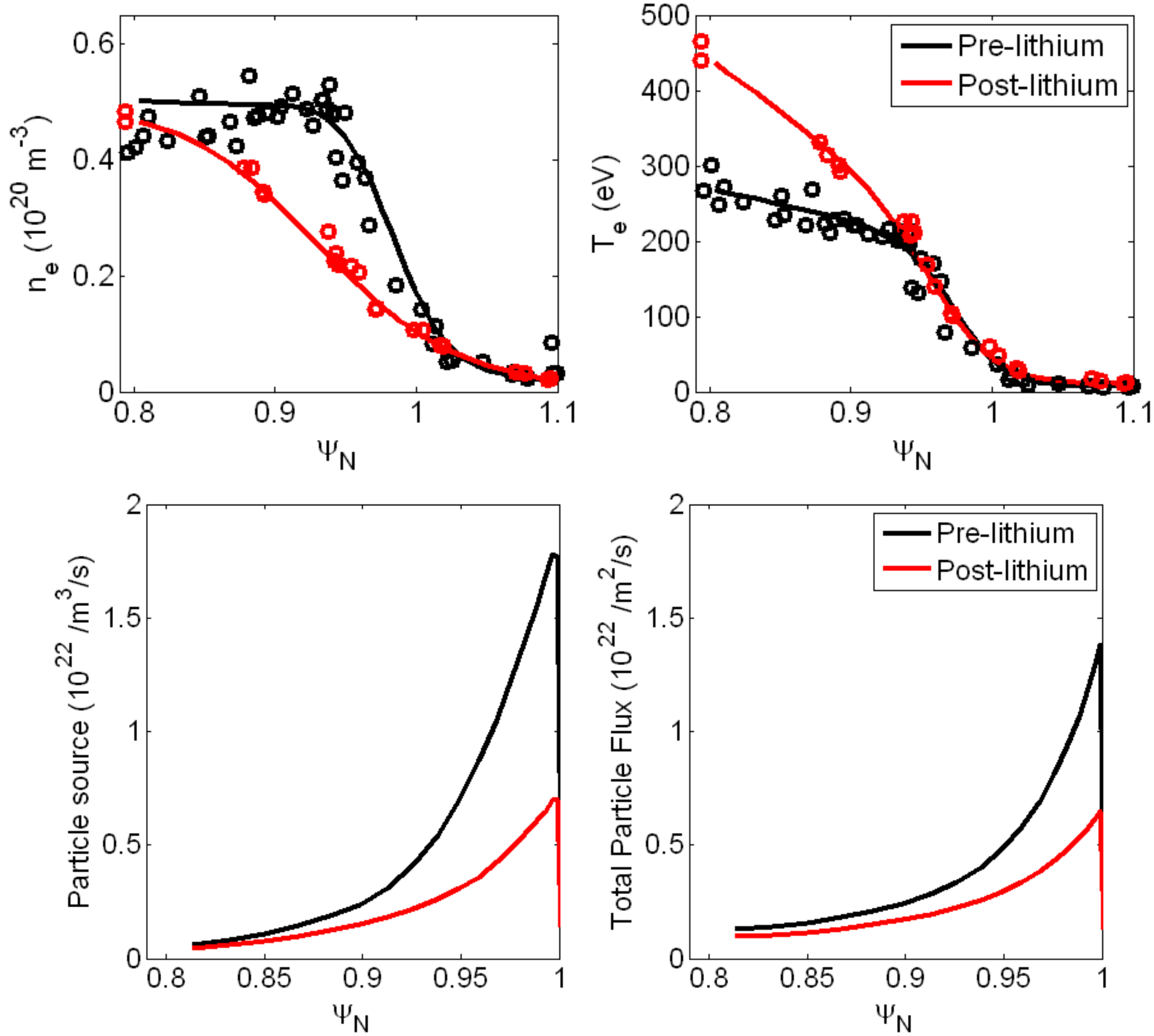
- Good match to both peak and profile for heat flux and D_{α} (except PFR)

*Uncertainty exists in IR measurements, due to emissivity change with lithium films

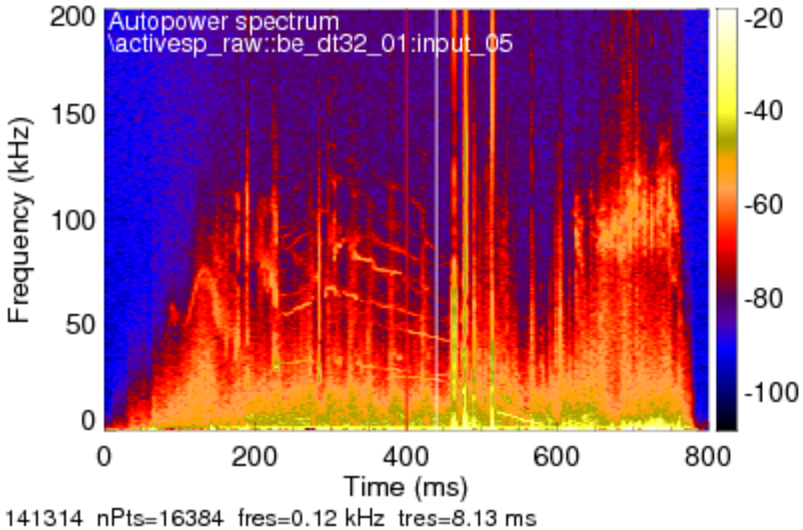


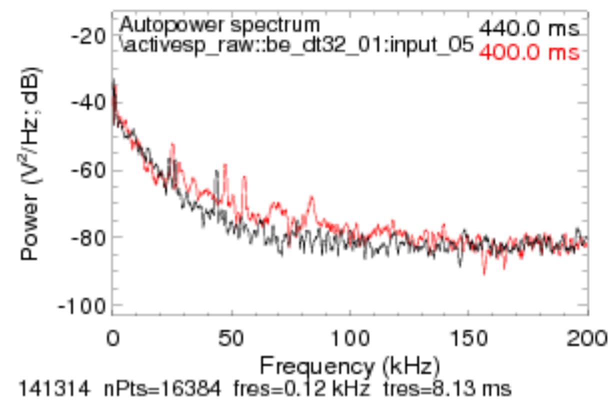
Particle and heat sources are reduced with lithium

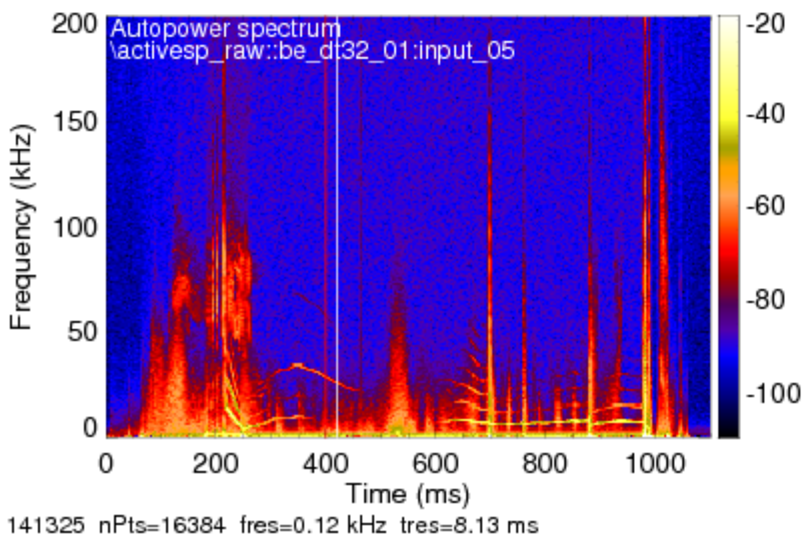
- Pre-lithium case shows typical H-mode structure
  - Barrier region in D, χ_e just inside separatrix
- Pedestal is much wider with lithium
  - $D_\perp$, χ_e similar outside of ψ_N~0.95
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)
- Changes to profiles with lithium are due to reduced fluxes combined with wide transport barrier

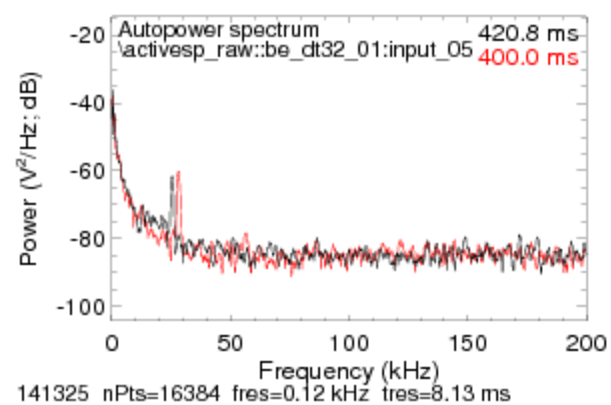


BES also shows reduced turbulence levels in post-lithium discharges





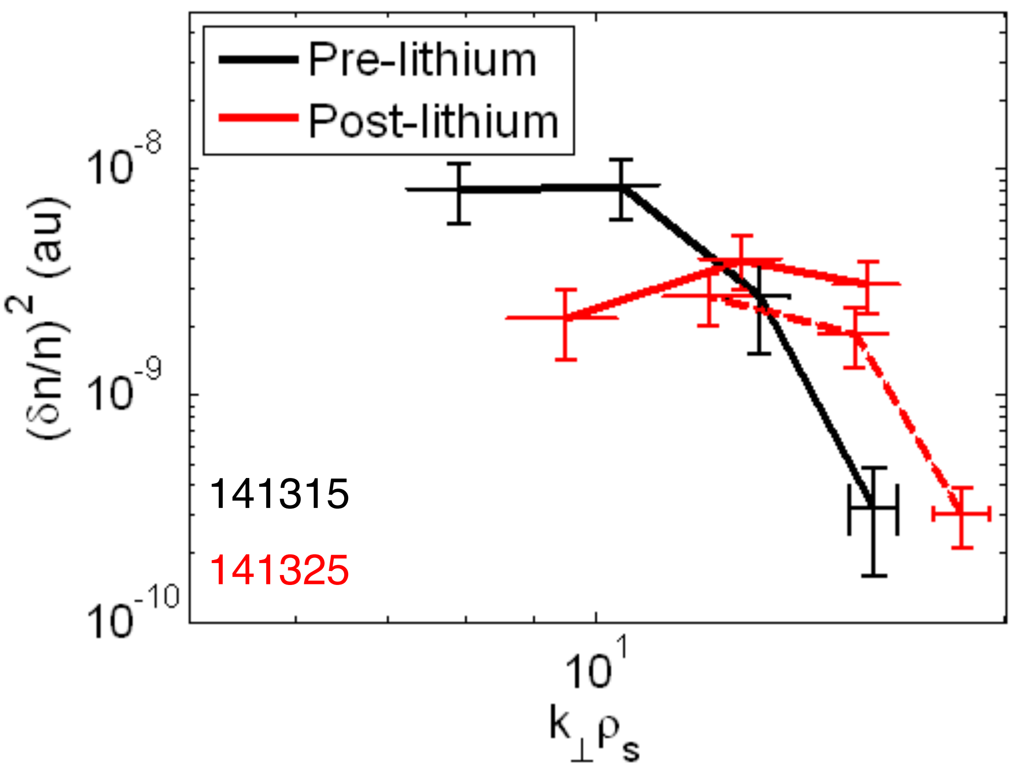


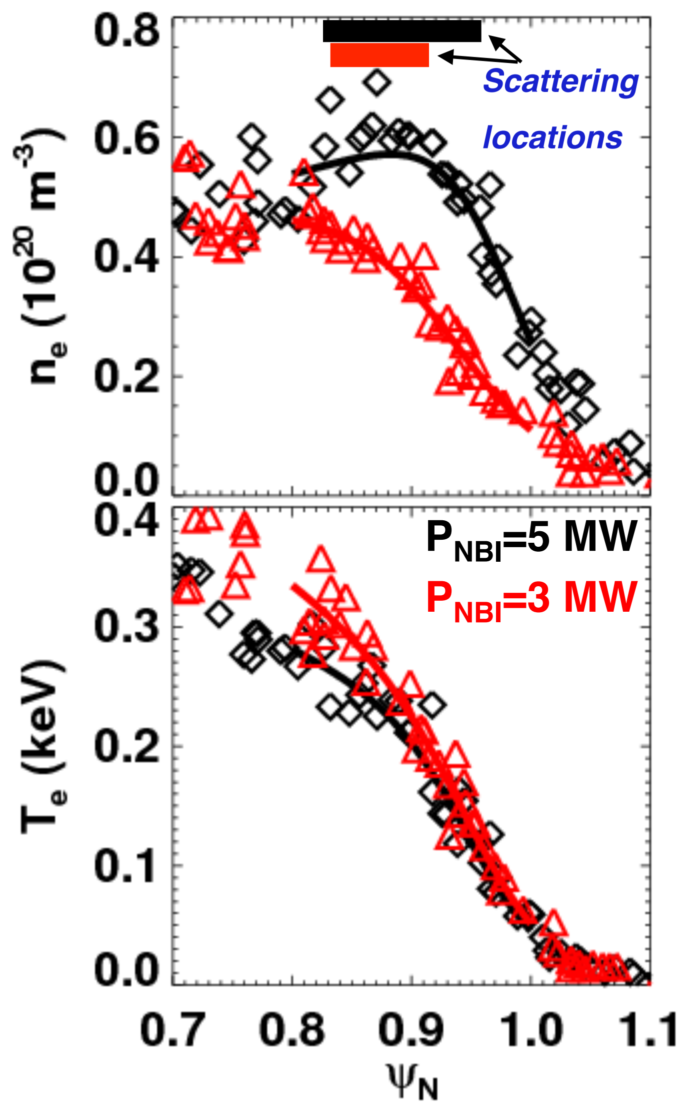


***Courtesy D.R. Smith, UW**

High-k scattering diagnostic shows little change in fluctuation amplitude at $k\rho_s > 10$

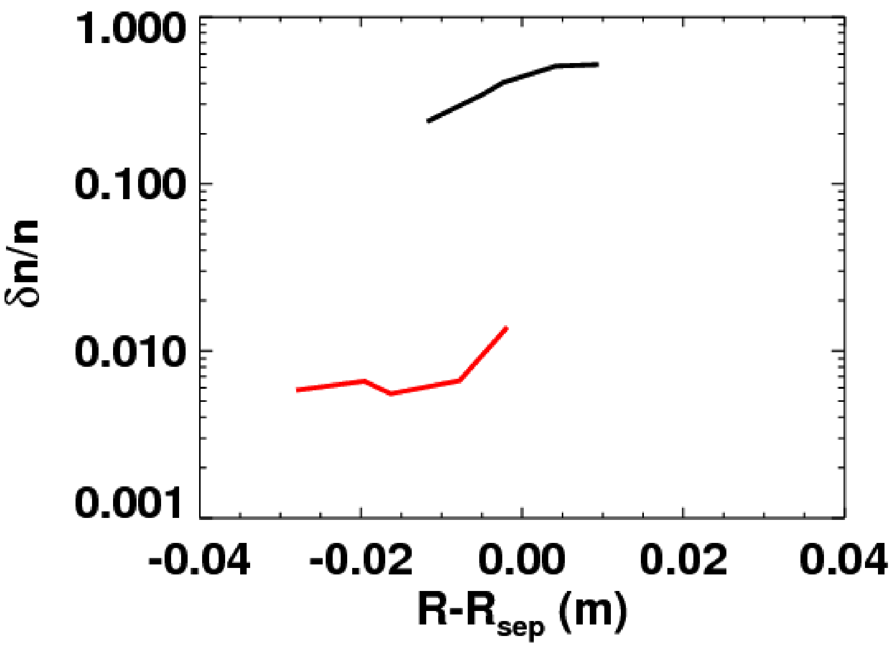
- Pre-to-post lithium transition repeated, similar profile changes observed
- Fluctuations similar for $k\rho_s > 10$, some reduction at lower k for the with-lithium case





Edge reflectometry near pedestal top shows reduced density fluctuations with lithium

- Reduced transport in inner region->higher pedestal top pressure
- Reflectometer shows reduced fluctuation level
  - Pre-lithium: strong amplitude/phase fluct.
  - With-lithium: little amplitude fluctuation
  - 3D simulations using Kirchoff integral indicate turbulence level reduced from ≥10% to ≤1% with lithium



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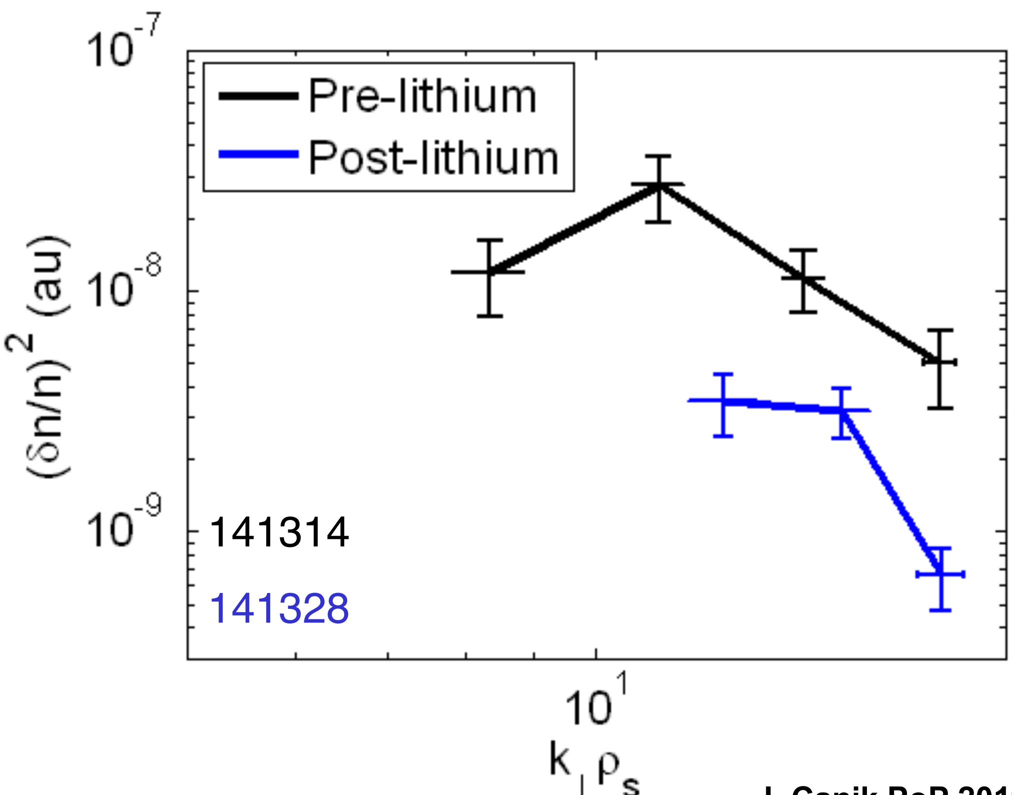
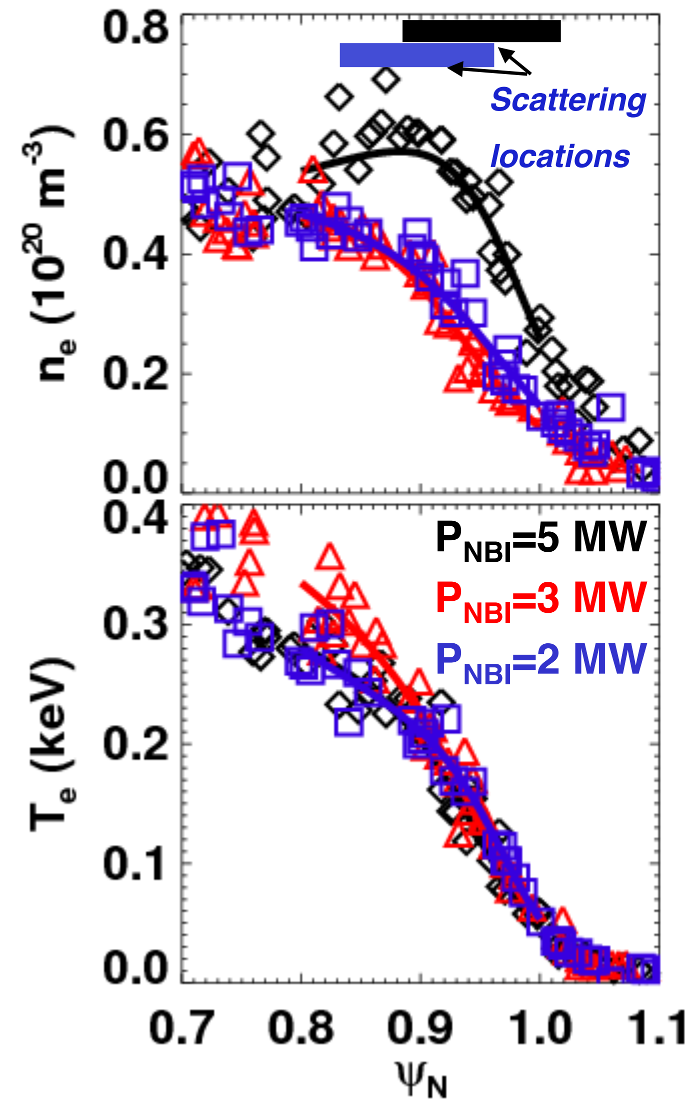
With power reduced so T_e profile matches pre-lithium case, fluctuation amplitudes show broad reduction

- Power reduced to 2 MW
- T_e profile similar to pre-lithium
- Fluctuation amplitude reduced across measured $k\rho_s$





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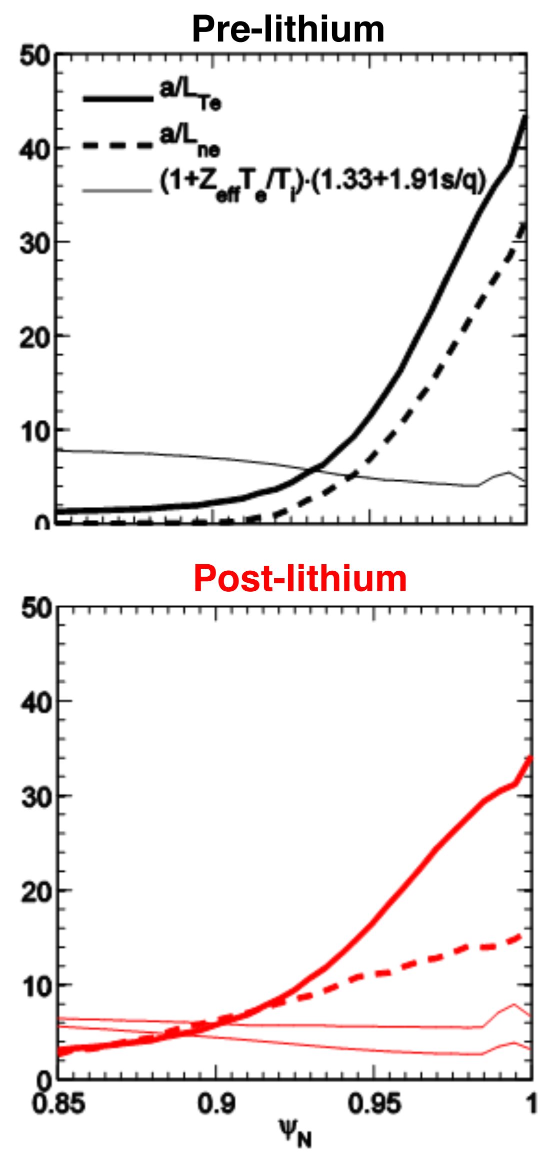
ETG is unstable in steep gradient edge

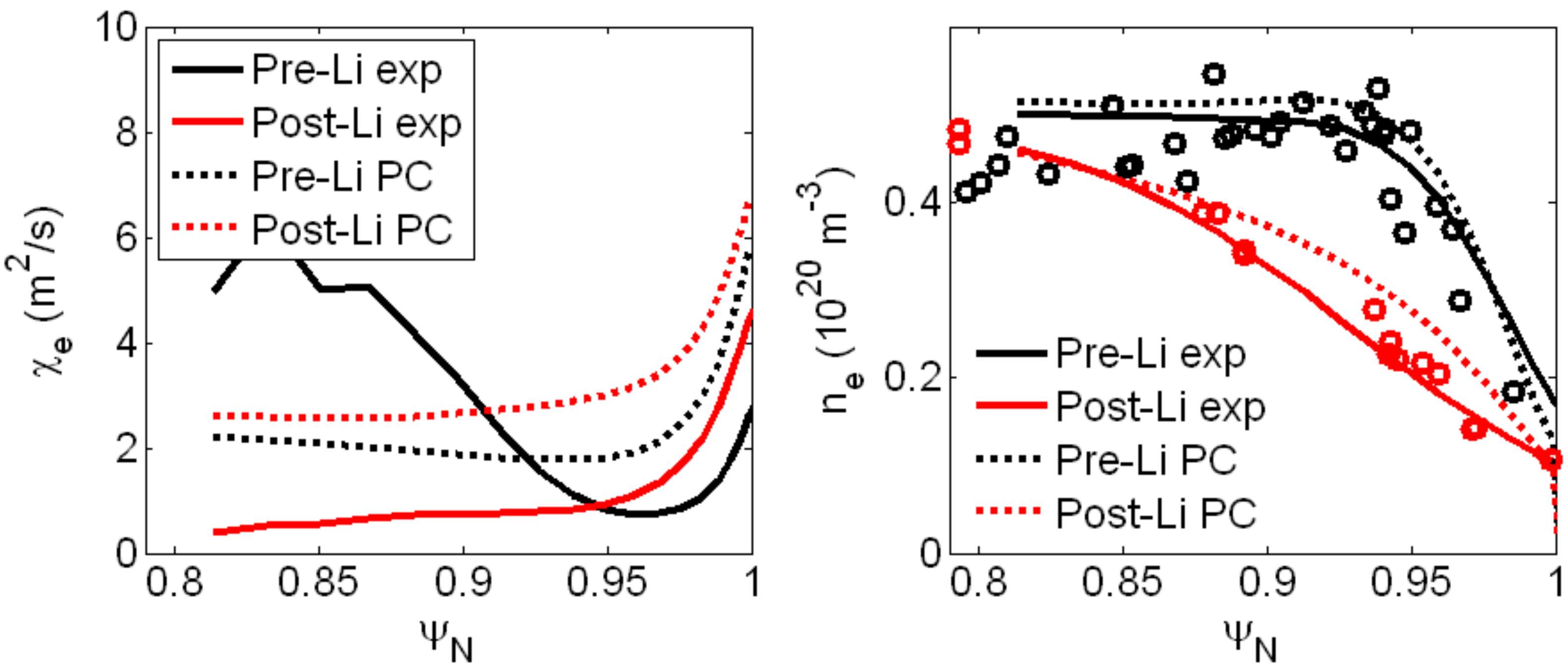
- Investigating ETG stability with GYRO [1]
  - $\chi_e \sim 2\text{-}5\ (\rho_e^2 v_{te}/L_{Te})$, within range of nonlinear expectations
  - Electrons satisfy gyrokinetic ordering $\rho_e/L_{Te} < 1/400$
- ETG unstable in steep gradient region ($\psi_N > 0.92$)
  - Threshold likely set by density gradient
  - $\eta_{e,crit} \sim 1\text{-}1.25$ calculated in AUG edge [2], compared to core criteria $\eta_{e,crit} \sim 0.8$ [3]
- ETG stable at top of pedestal ($\psi_N = 0.88$)
  - Smaller density gradient, threshold likely sensitive to $Z_{eff}T_e/T_i$ and s/q
- *Calculating thresholds and transport are work-in-progress*



[1] J. Candy & R.E. Waltz, PRL (2003); [2] D. Told et al., PoP (2008);
[3] F. Jenko et al., PoP (2001)

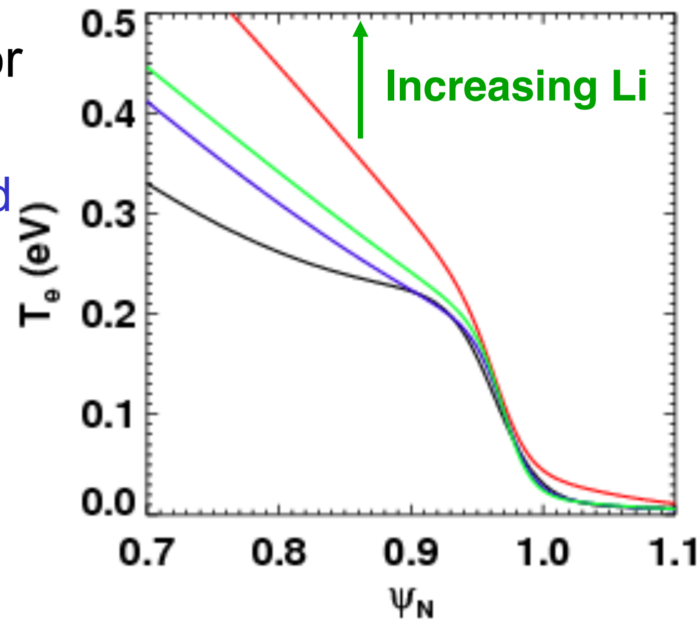
Measured pedestal modifications are consistent with paleoclassical transport

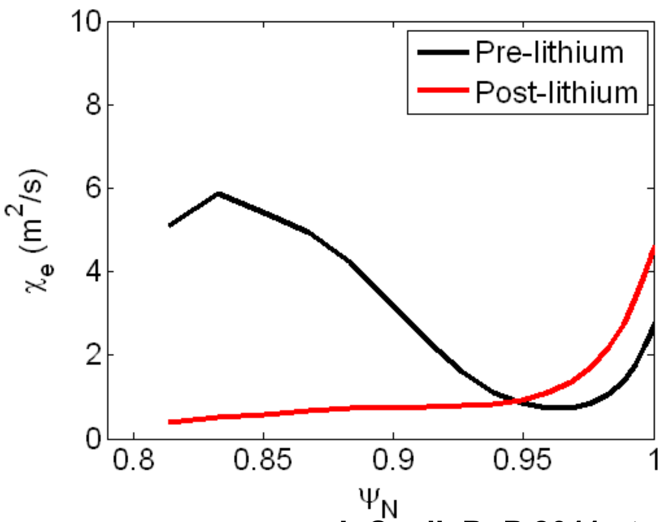
- Pedestal structure model based partly on paleoclassical transport proposed
  - J.D. Callen, UW-CPTC 10-9
  - Depends on resistivity profile->Z_{eff} changes important
- Model recovers χ_e magnitude, shape, rise near separatrix, as well as modest increase with lithium outside ψ_N~0.95
- Density profile shape changes with lithium also captured by model



Outer region: T_e gradient nearly constant outside of Ψ_N~0.95

- Key to ELM suppression: reduction of current for Ψ_N>.95
  - Density is reduced with lithium, but T_e unchanged
  - Pressure gradient is reduced->less bootstrap current
- Edge ∇T_e ~ constant, critical gradient?
  - Intermediate stages shown have less lithium, same P_{NBI} as pre-lithium case





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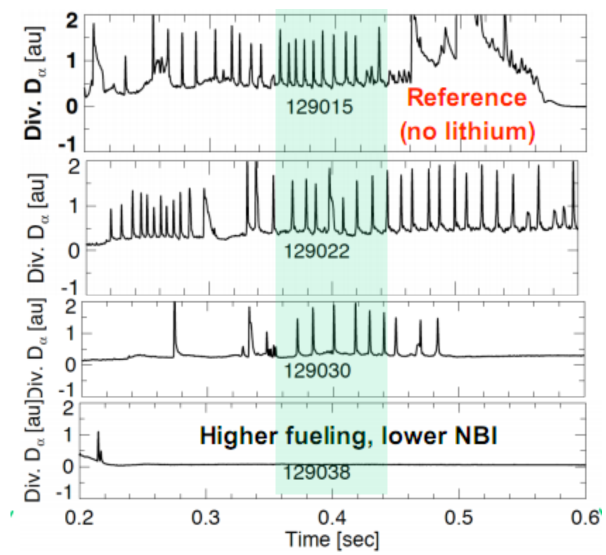
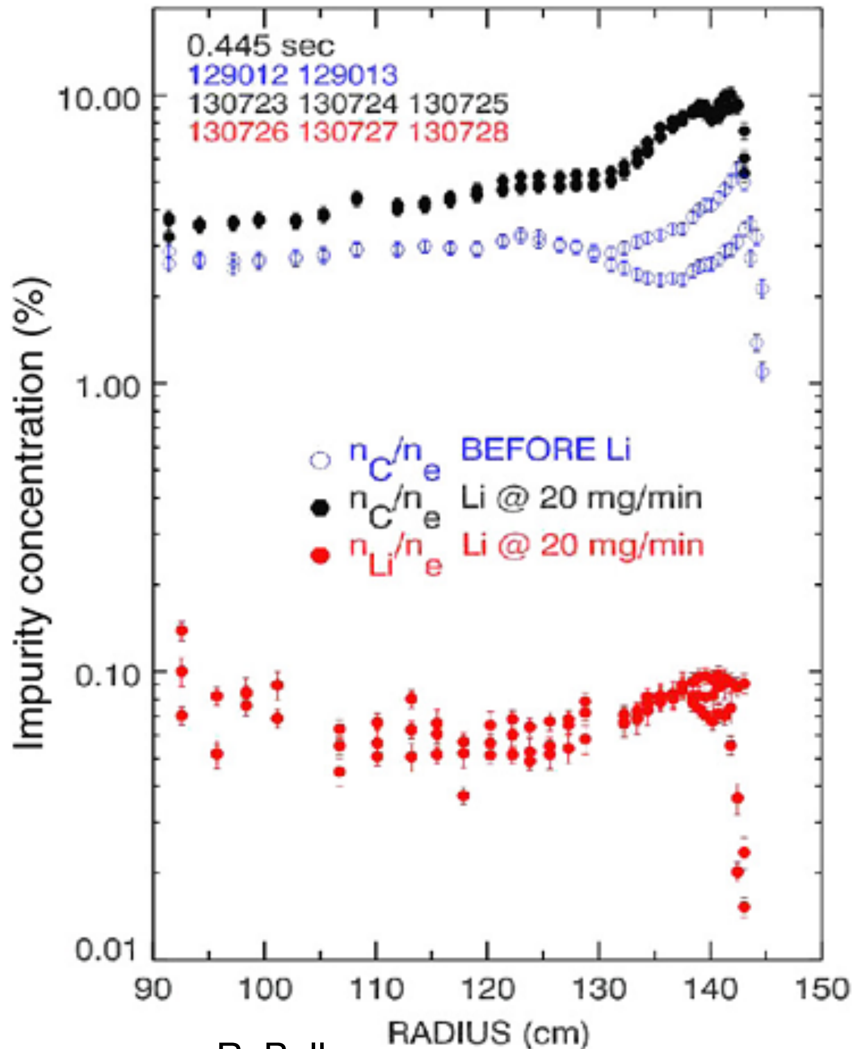


Carbon is the dominant impurity species with lithium coatings

- Measured lithium concentration is much less than carbon
  - Carbon concentration ~100 times higher
  - Carbon increases when lithium coatings are applied
  - Neoclassical effect: higher Z accumulates, low Z screened out

- Increase in n_C due to lack of ELMs
  - Can be mitigated by triggering ELMs



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