NSTX

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Effect of Lithium Coatings on Edge Plasma Profiles, Transport, and ELM Stability in NSTX

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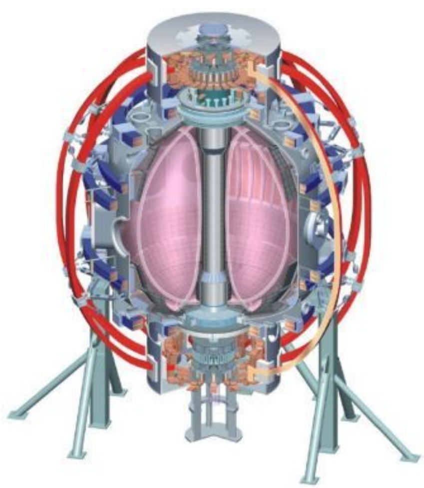

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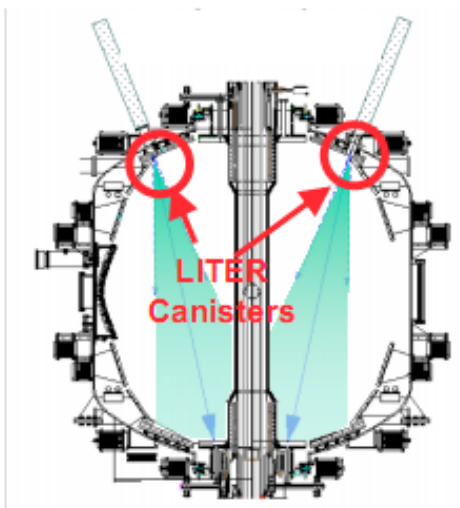
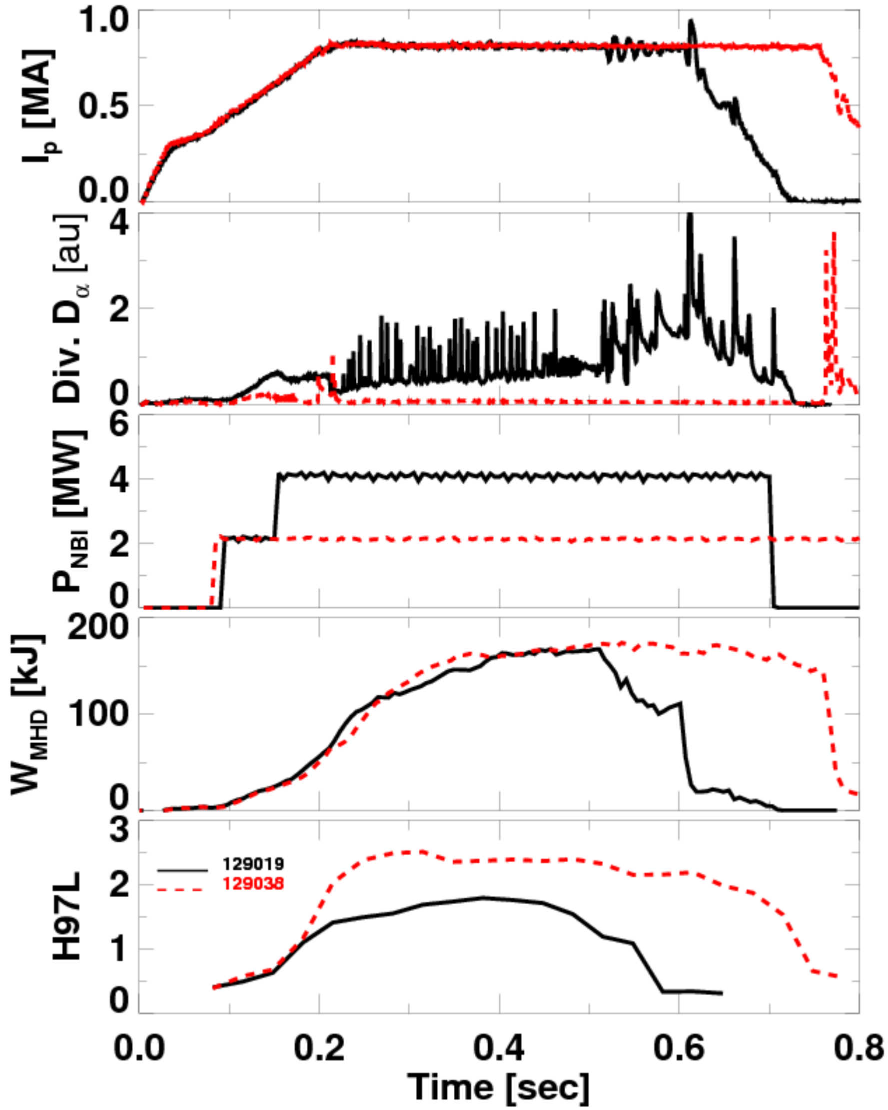
Evaporated Li coatings provide edge plasma profile and stability control in NSTX

- This talk describes a pre-LLD experiment with systematic and slow increase in lithium wall coating between discharges
  - "Medium" coatings level used to study Edge Localized Modes (ELM) stability physics
    - "Larger" coatings reproducibly suppress ELMs on ~ every discharge
  - Global energy confinement improved and ELMs stabilized
  - Operating regime achieved in which global stability limits observed before edge stability limits
- Region of reduced edge particle and electron thermal transport (aka H-mode transport barrier) broadened
  - Depends ~*continuously* on amount of pre-discharge Li deposition
- ELM frequency also depends nearly continuously on amount of pre-discharge Li deposition
  - n_e profile broadening critical component

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



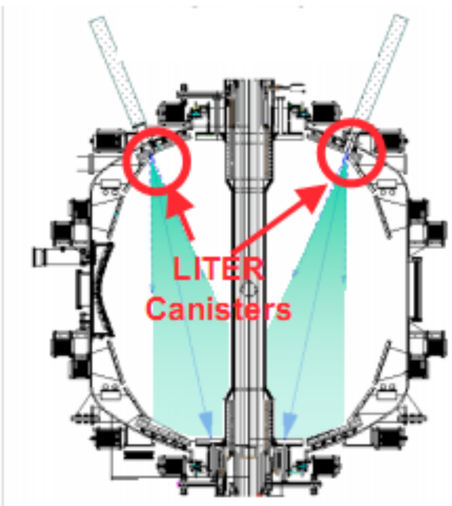
~ 700mg Li between 129037 and 129038

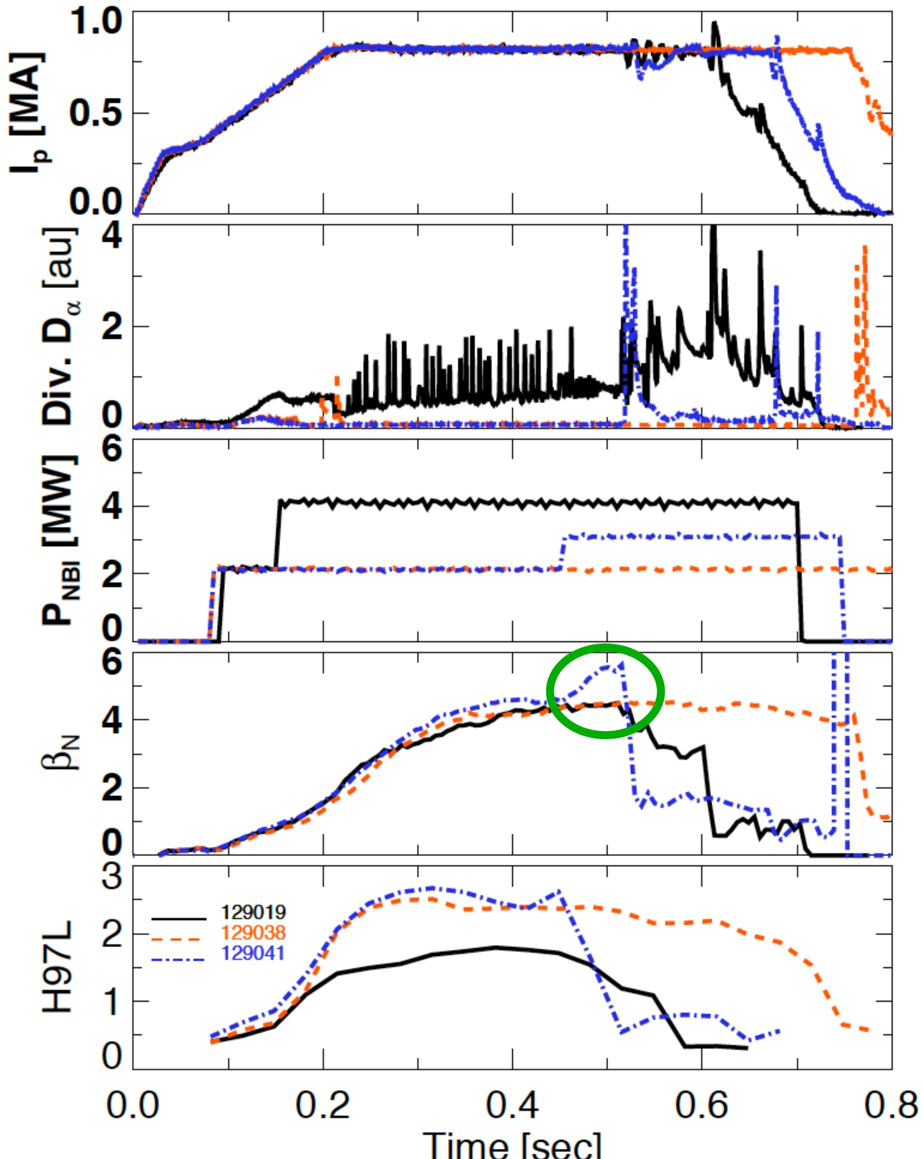


- Without Li, With Li
- ELM-free, reduced divertor recycling
- Lower NBI to avoid β limit
- Similar stored energy
- H-factor 40%↑

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

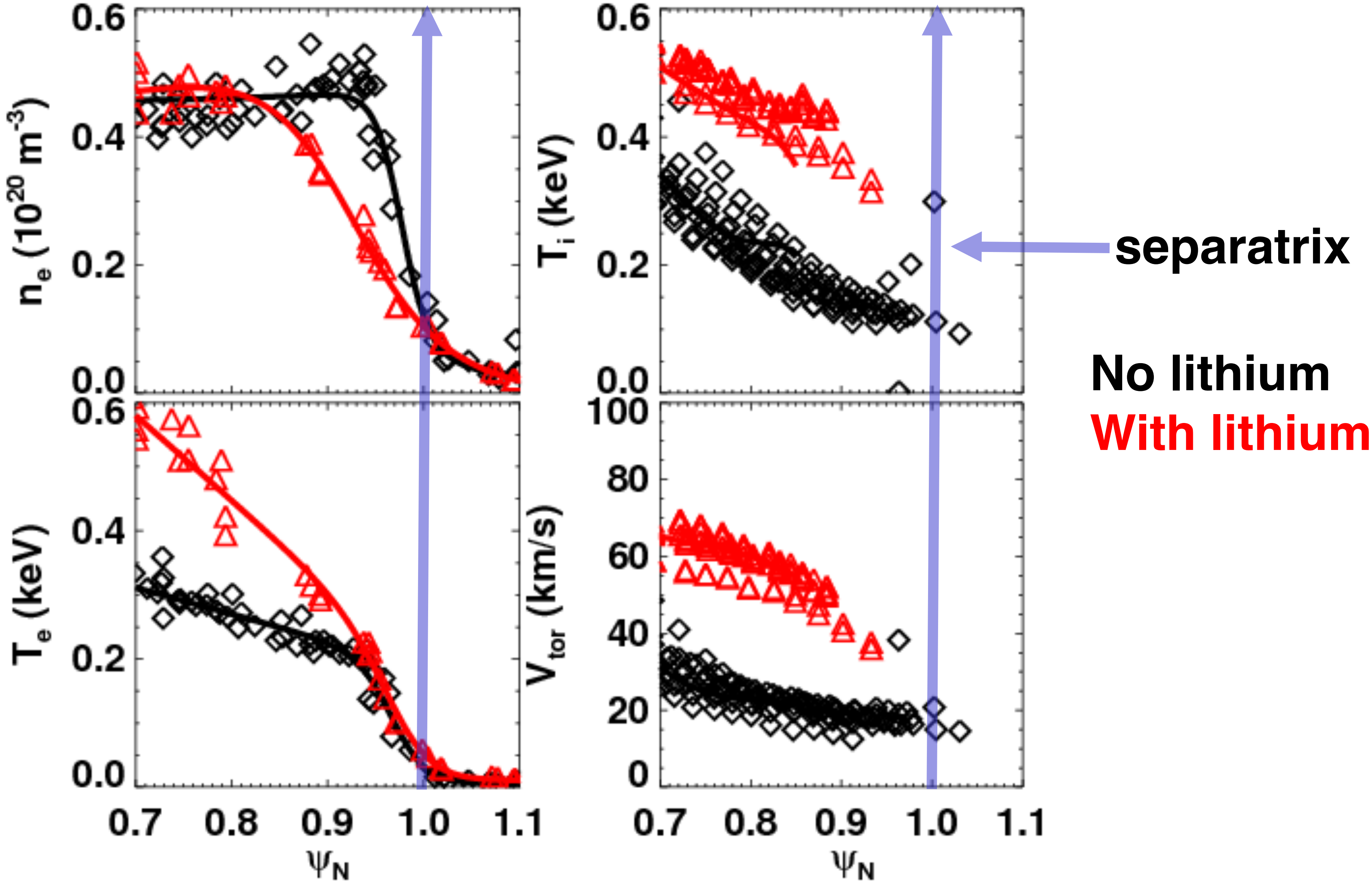




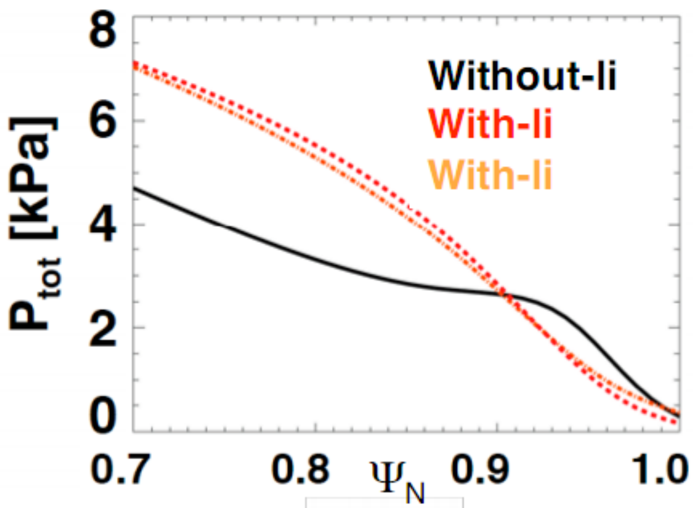
- Without Li, With Li, With Li
- ELM-free, reduced divertor recycling
- Power scan to identify β limit
- Core β limit observed, but no ELMs

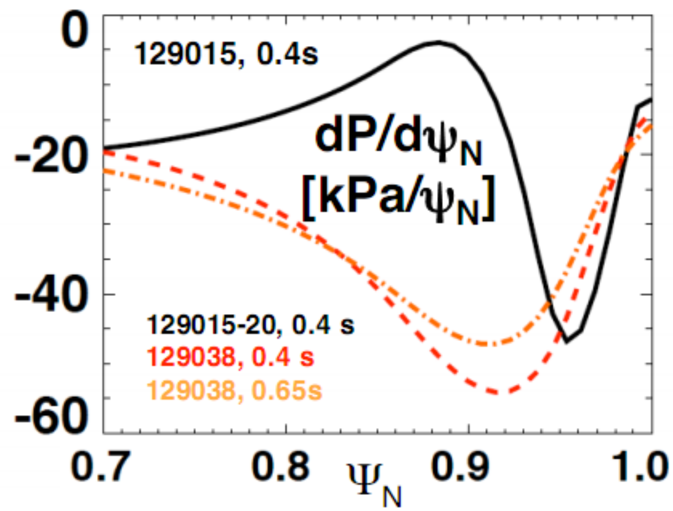
D. Mansfield, JNM 09
R. Maingi, PRL 09

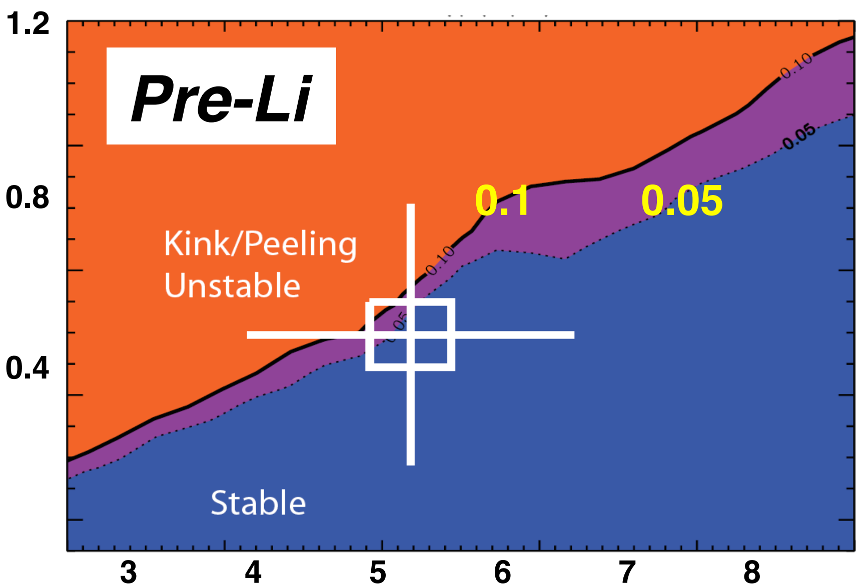
T_e, T_i increased and edge n_e decreased with lithium coatings



Pre-lithium discharge near the kink/peeling boundary

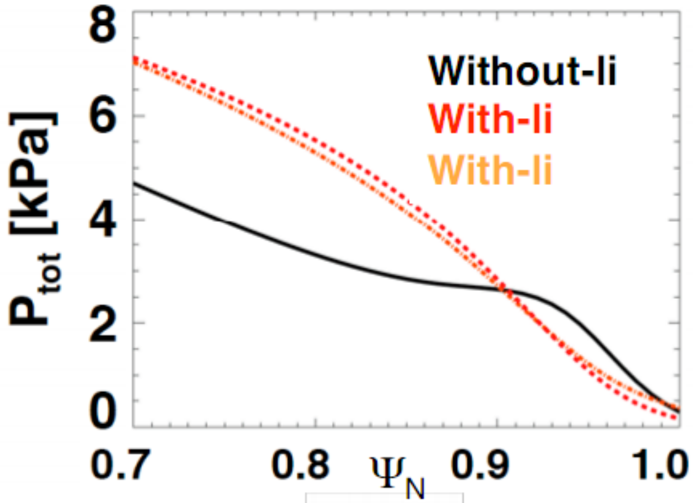


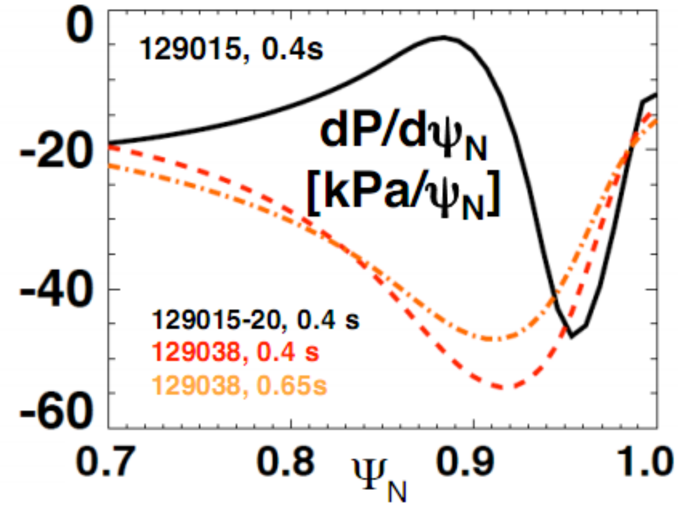


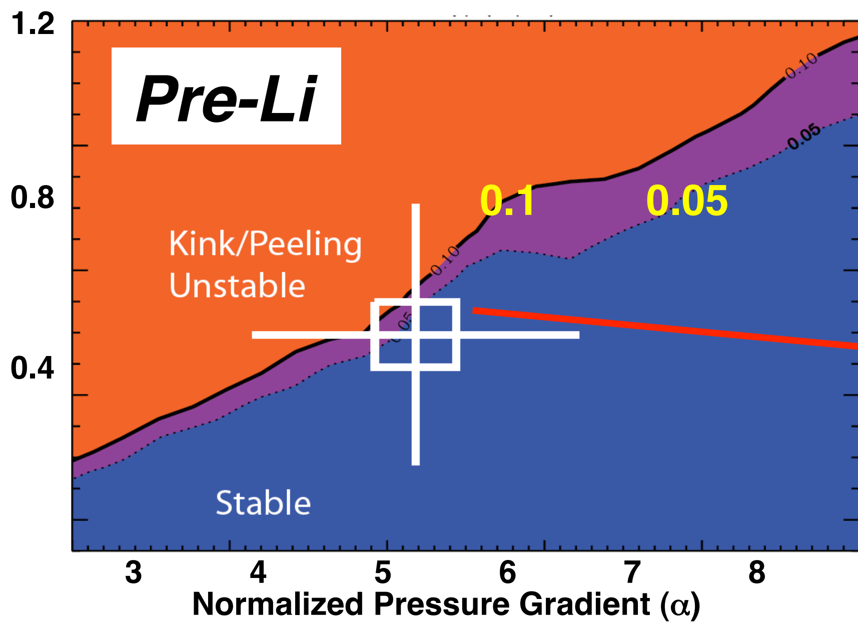


R. Maingi, PRL 2009

Pre-lithium discharge near the kink/peeling boundary

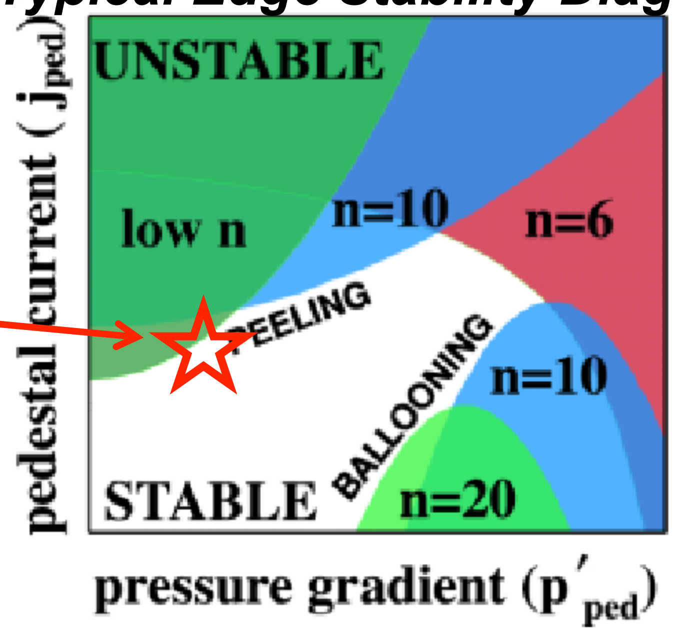




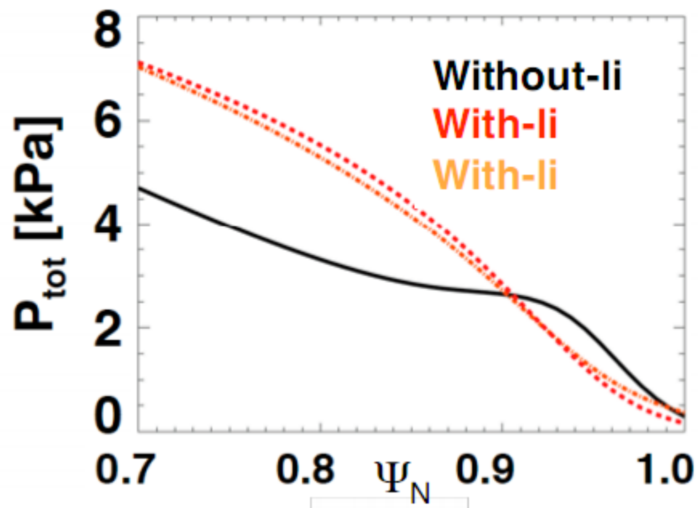


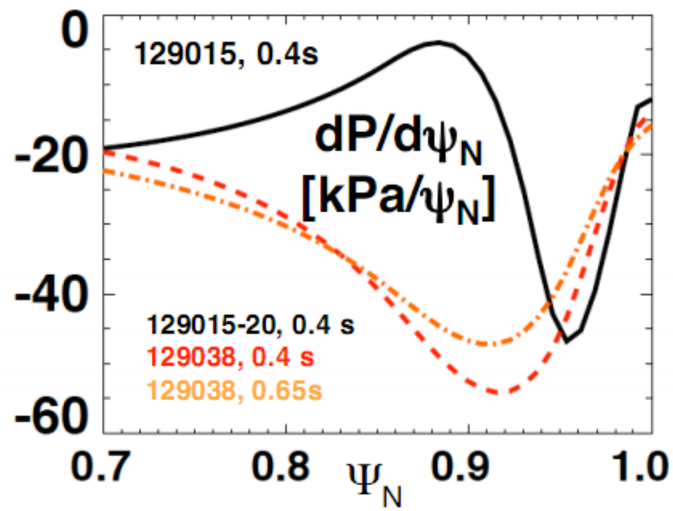
R. Maingi, PRL 2009

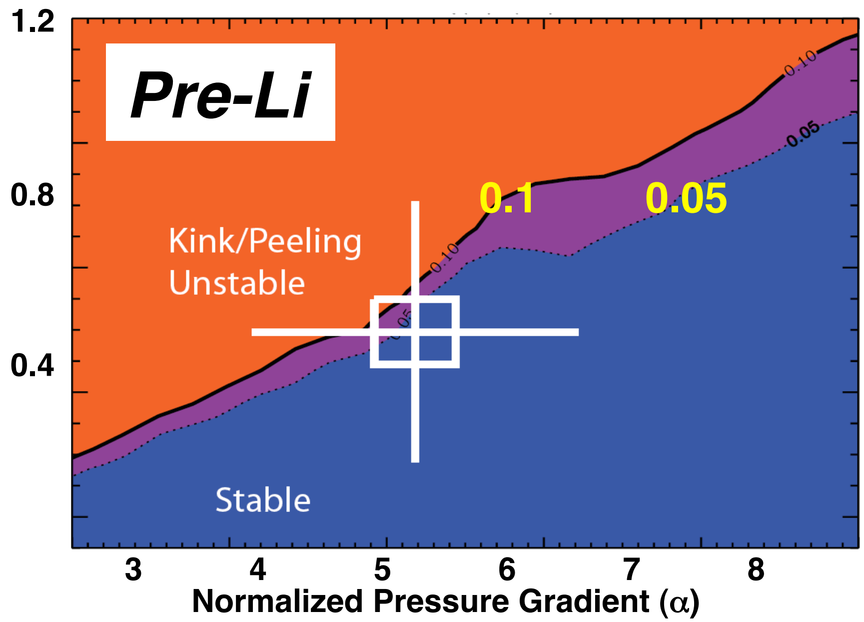
Typical Edge Stability Diagram

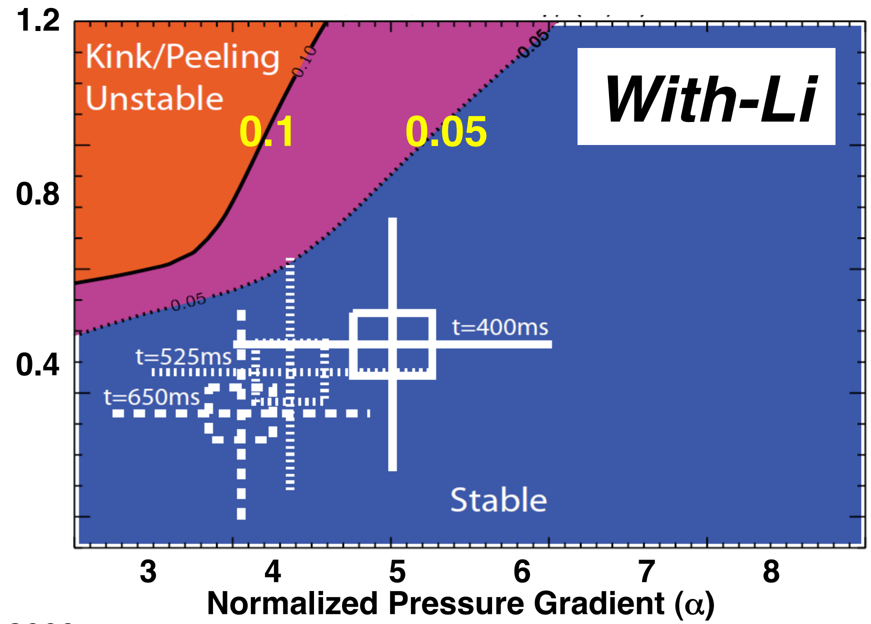


Peak pressure gradient moves inwards, p’ and j reduced outside ψ_N~0.95







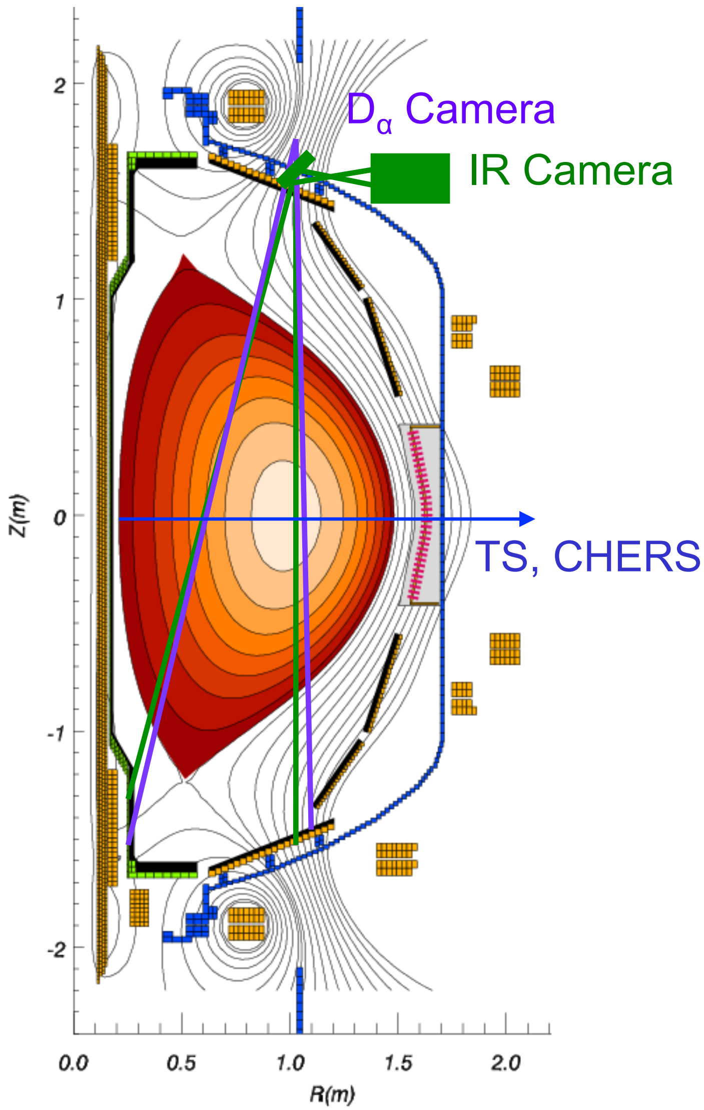


R. Maingi, PRL 2009

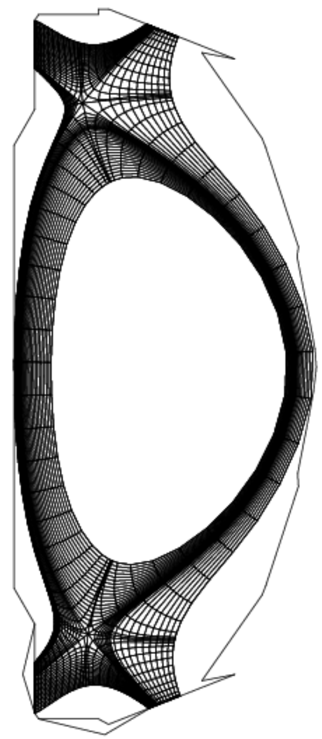
Outline

- Global energy confinement improved and Edge Localized Modes (ELMs) stabilized
  - Operating regime achieved in which global stability limits observed before edge stability limits
- Region of reduced edge particle and electron thermal transport (aka H-mode transport barrier) broadened
  - Depends ~*continuously* on amount of pre-discharge Li deposition
  - Pedestal fluctuations reduced with lithium
  - Transport near separatrix actually increases: stiff T_e profiles
- ELM frequency also depends nearly continuously on amount of pre-discharge Li deposition
  - n_e profile broadening critical component

Divertor recycling and cross-field transport coefficients quantified with data-constrained interpretive modeling



SOLPS Grid



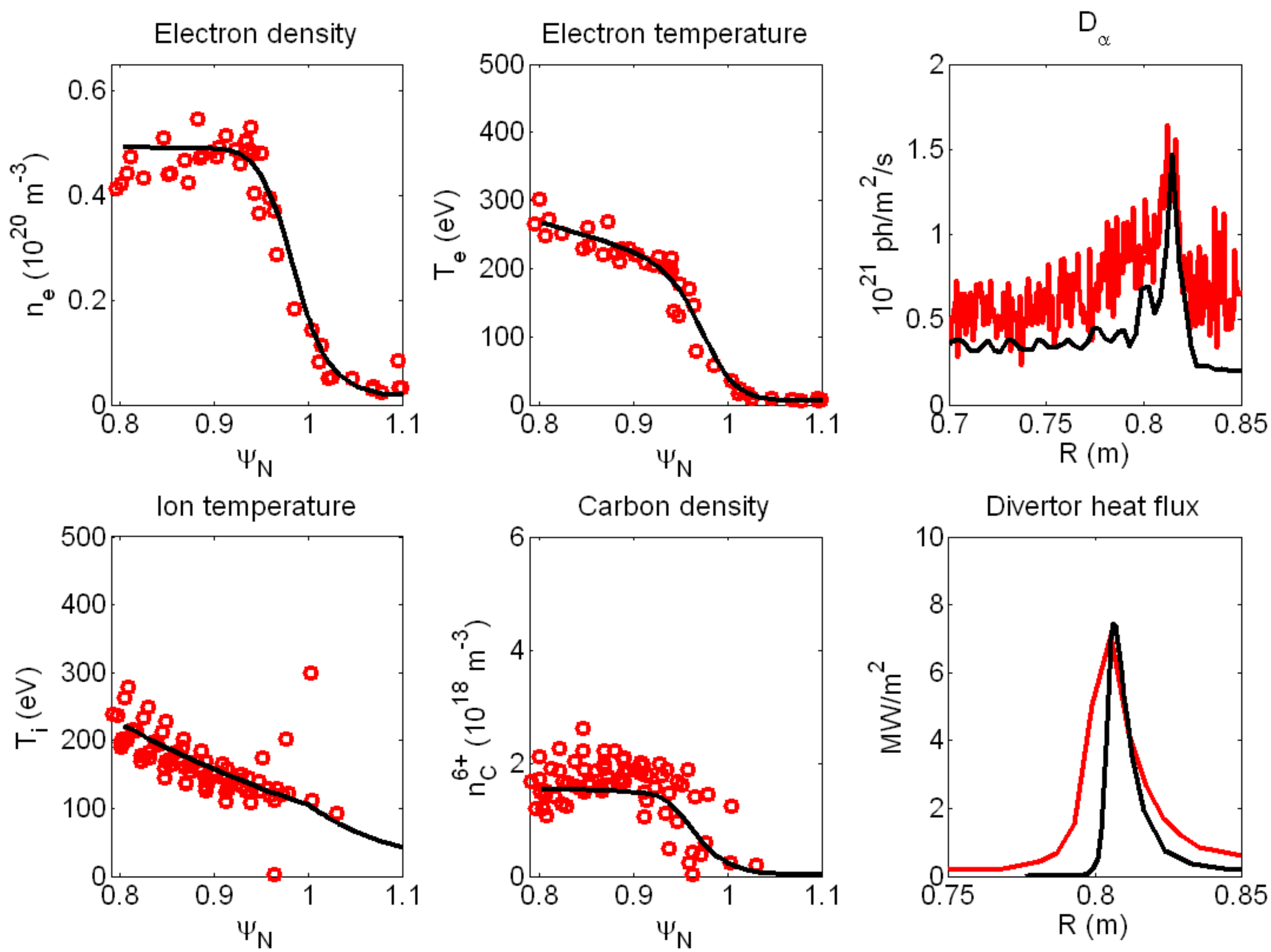
- SOLPS (B2-EIRENE: 2D fluid plasma + MC neutrals) used to model NSTX experimental data
  - Iterative Method
  - ✓ Neutrals, impurities contributions
  - ✓ Recycling changes due to lithium

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

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

- P=3.7 MW
- R=0.98

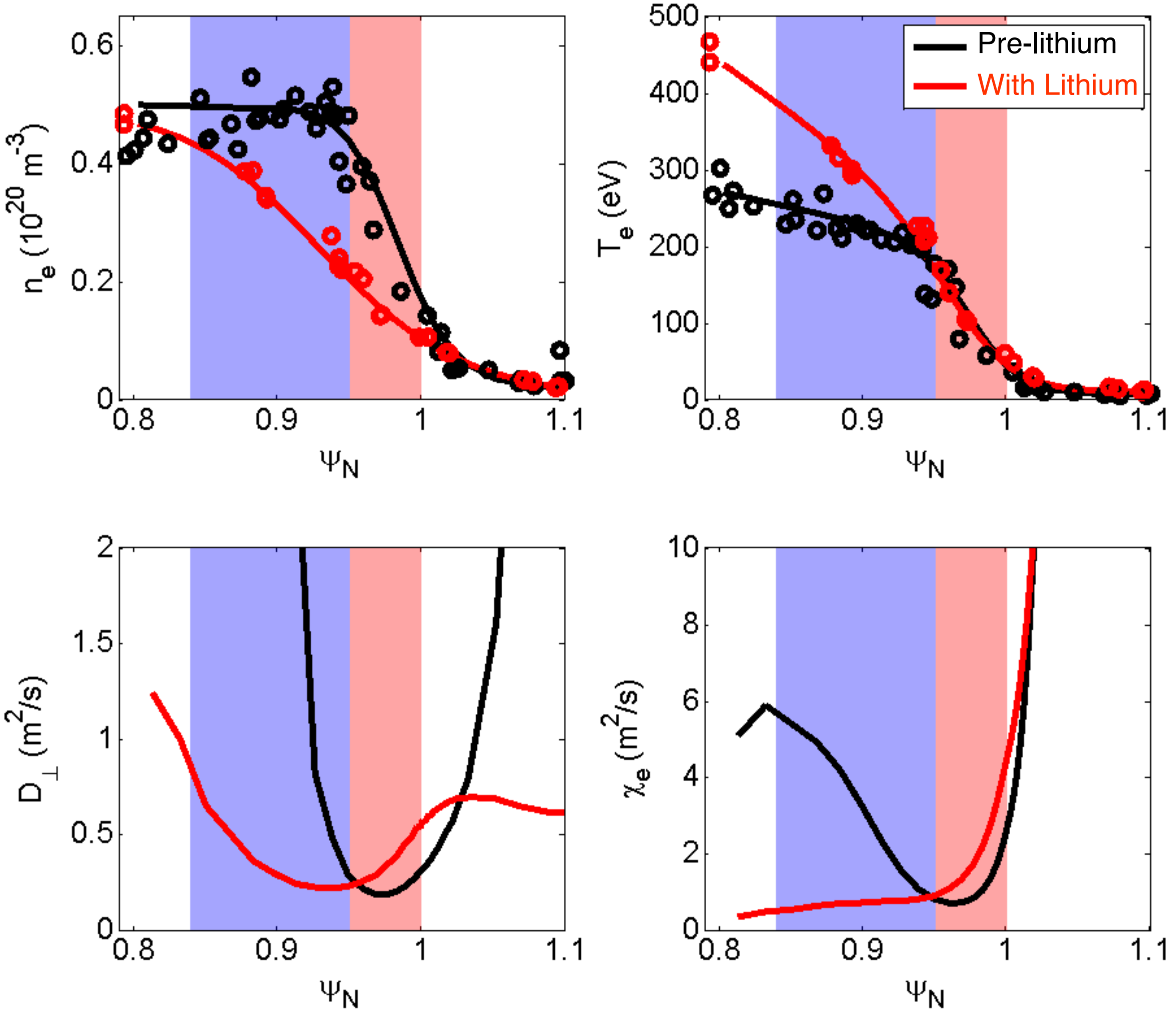
- Good match to midplane profiles
- Carbon included: sputtering from PFCs, inward convection to match measured n_C^{6+}
- Heat flux and D_α, radial decay sharper than experiment



J. Canik PoP 2011 at press

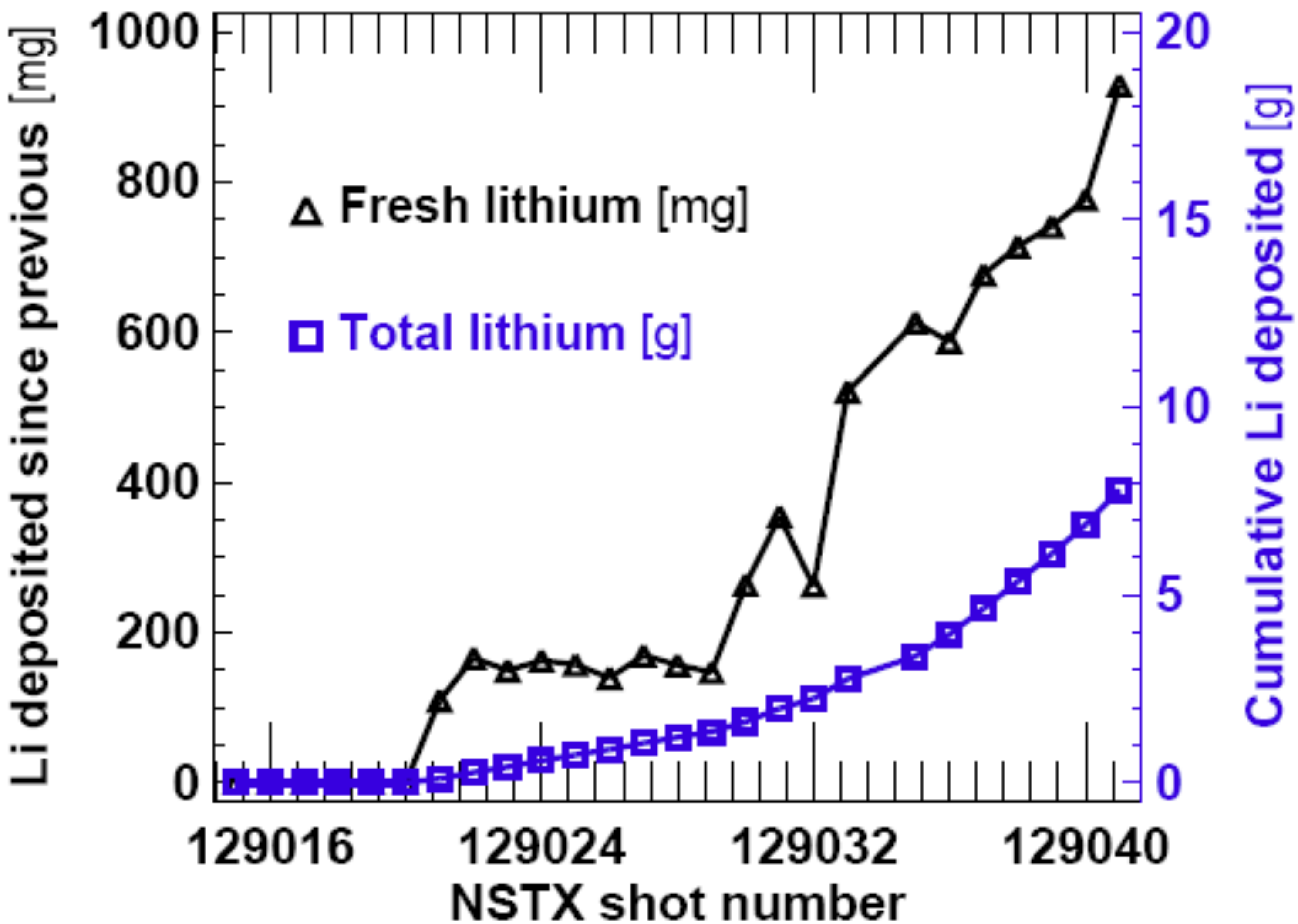
Transport barrier widens with lithium coatings, broadening pedestal

- 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

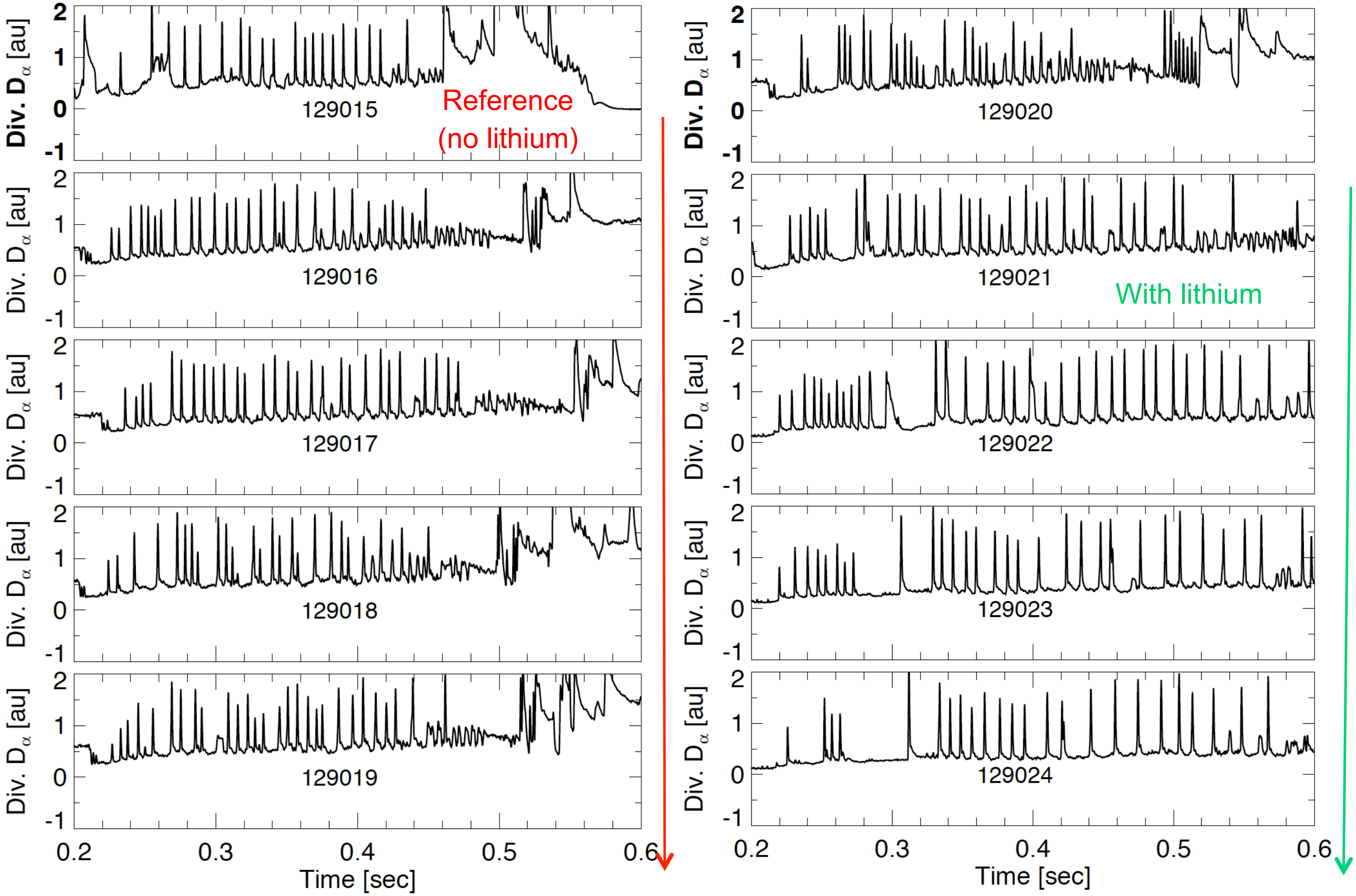


J. Canik PoP 2011 at press

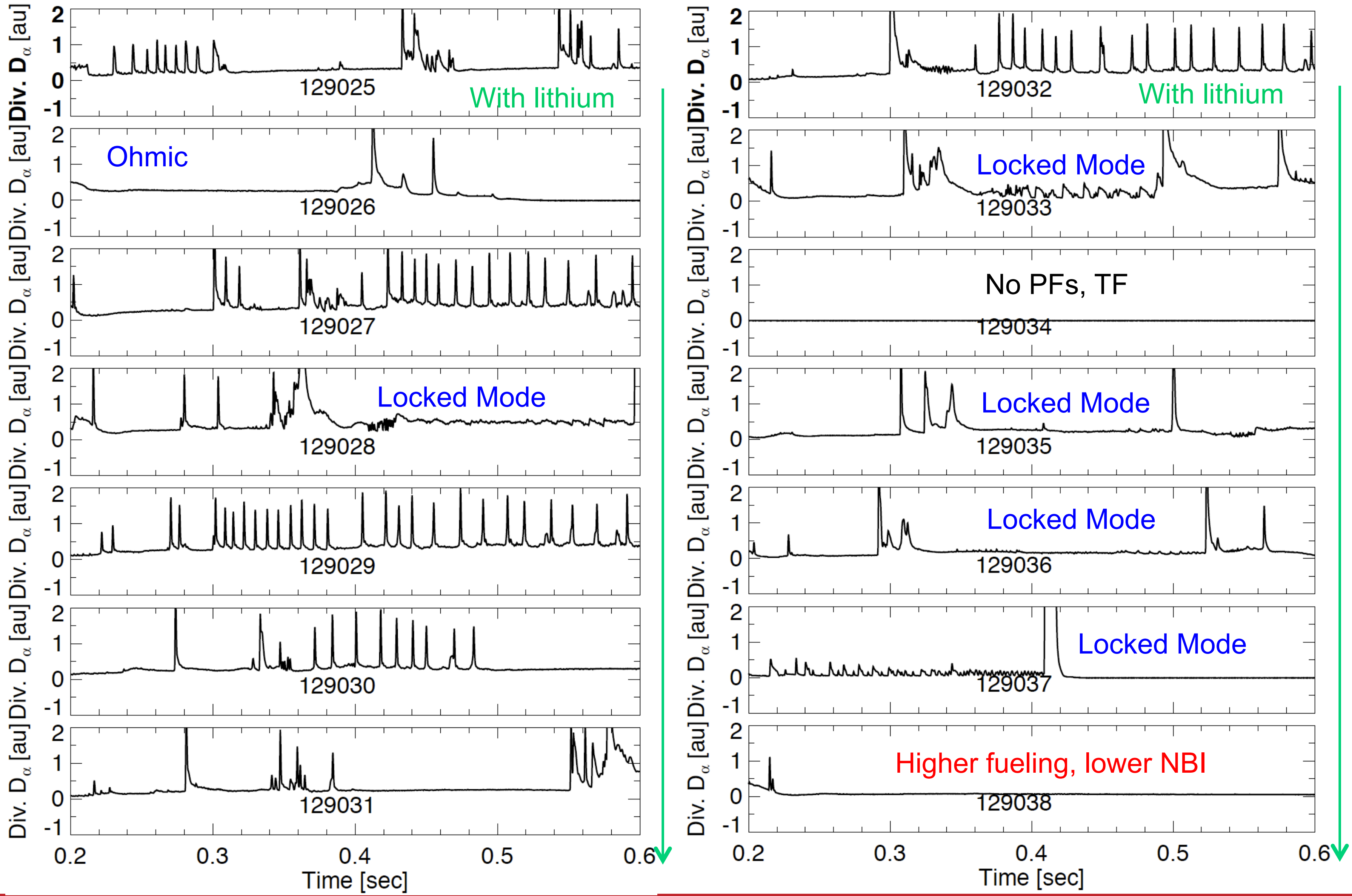
Experiment conducted in which pre-discharge Li deposition was varied systematically



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



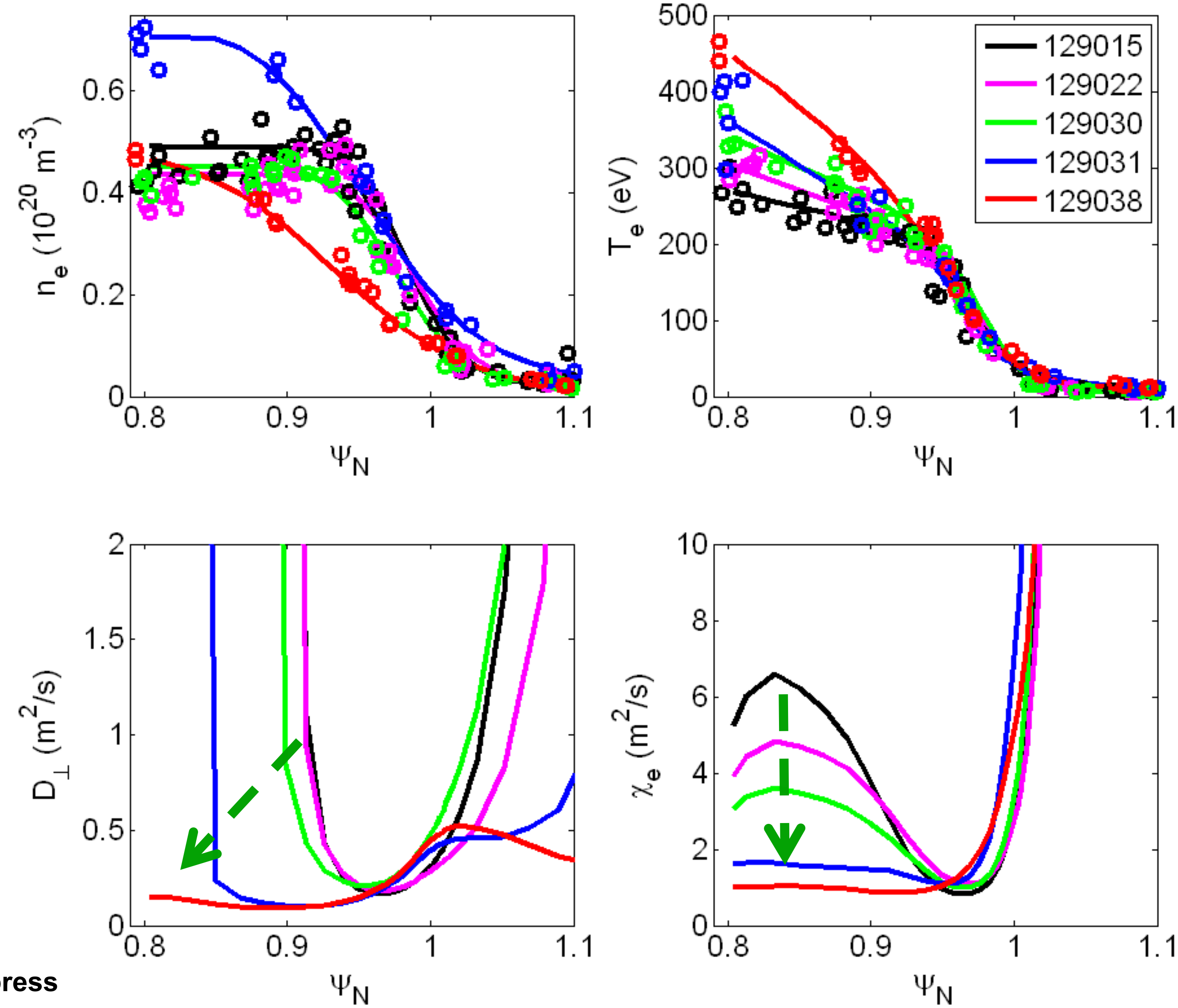
Transition to ELM-free discharges was not monotonic



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



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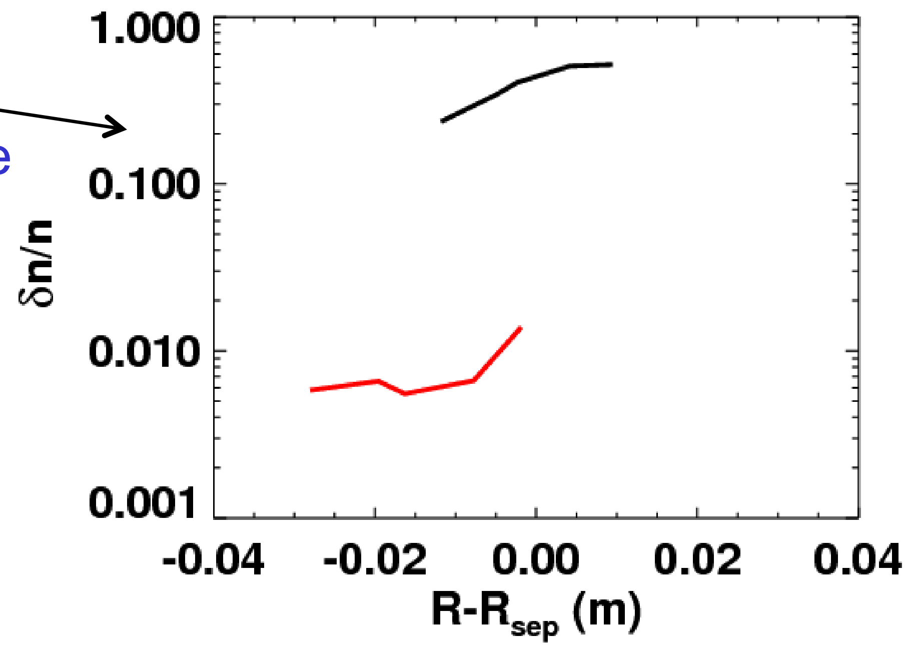
Edge reflectometry near pedestal top shows reduced density fluctuations with lithium

- 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



- Fluctuations with $k_\perp \rho_s$ > 10 from high-k scattering also reduced

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Outline

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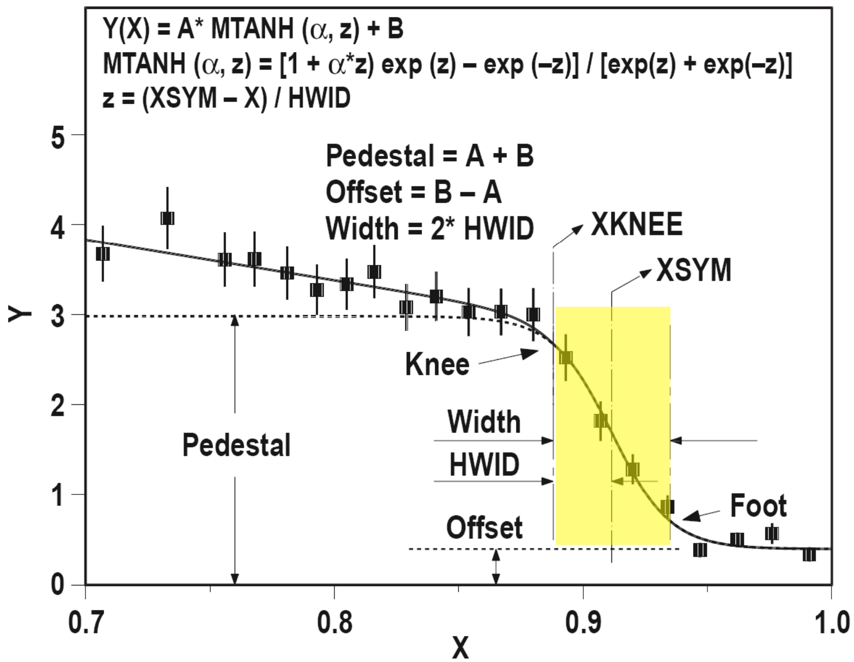
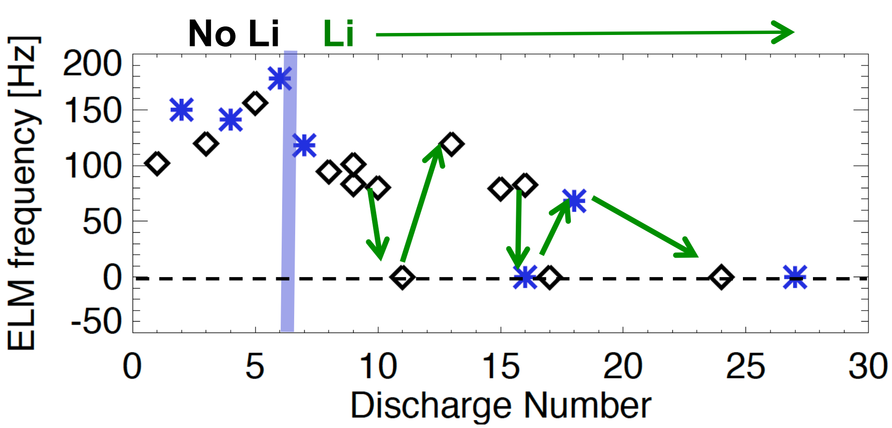
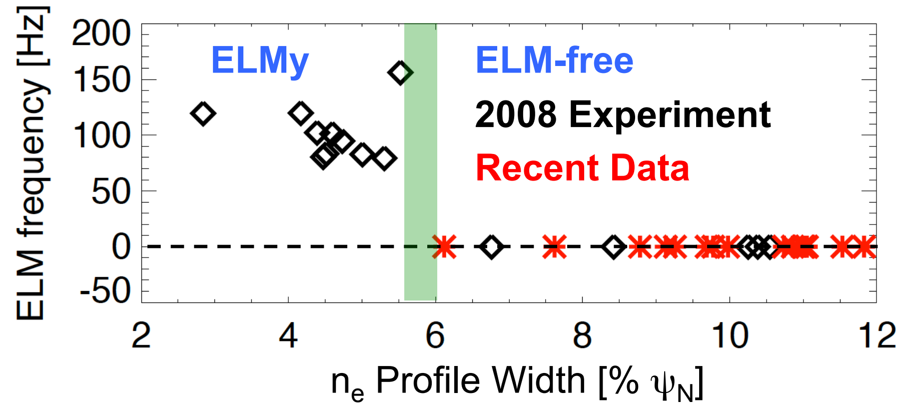
  - Operating regime achieved in which global stability limits observed before edge stability limits
- Region of reduced edge particle and electron thermal transport (aka H-mode transport barrier) broadened
  - Depends ~*continuously* on amount of pre-discharge Li deposition
- ELM frequency also depends nearly continuously on amount of pre-discharge Li deposition
  - (Consistent with ELITE edge stability calculations)
  - n_e profile broadening critical component

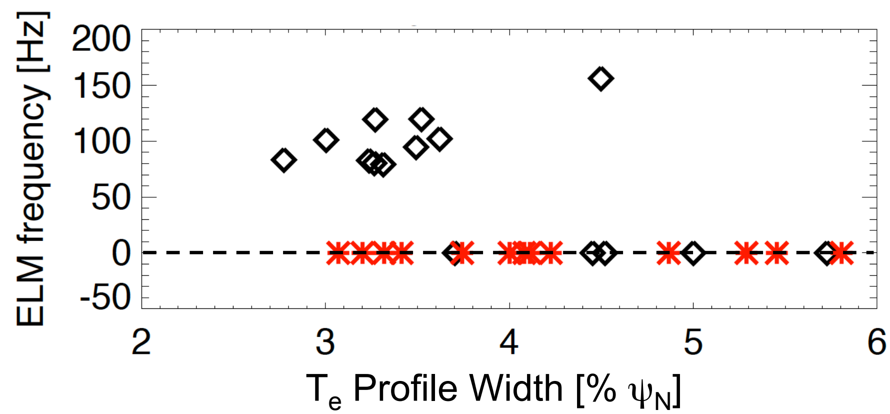
ELM suppression correlates with broadening of the density profile, but not the temperature profile



R. Groebner NF 2001





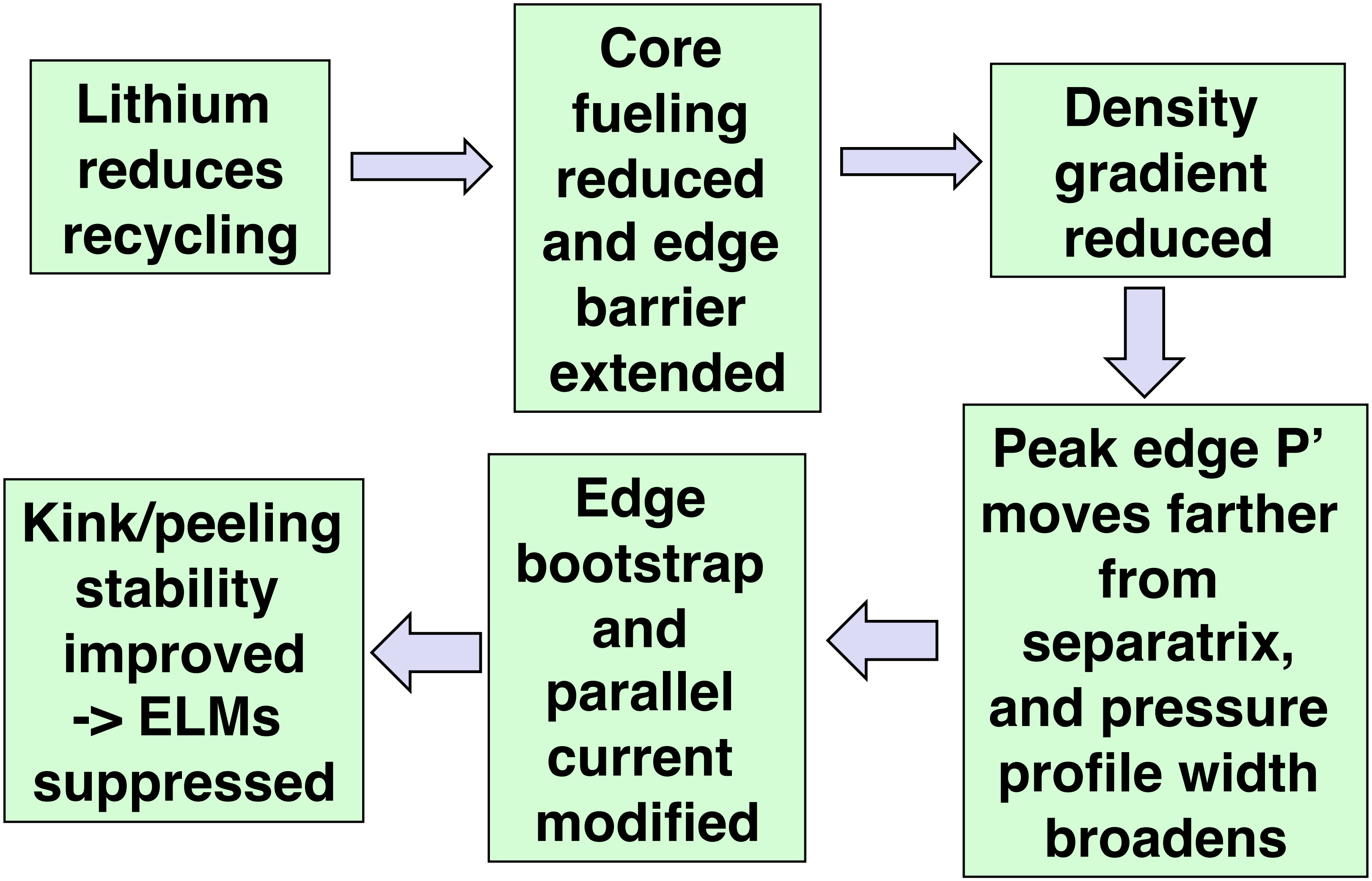


D. Boyle PPCF 2011 to be submitted

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

Lithium reduces recycling → **Core fueling reduced and edge barrier extended** → **Density gradient reduced**

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



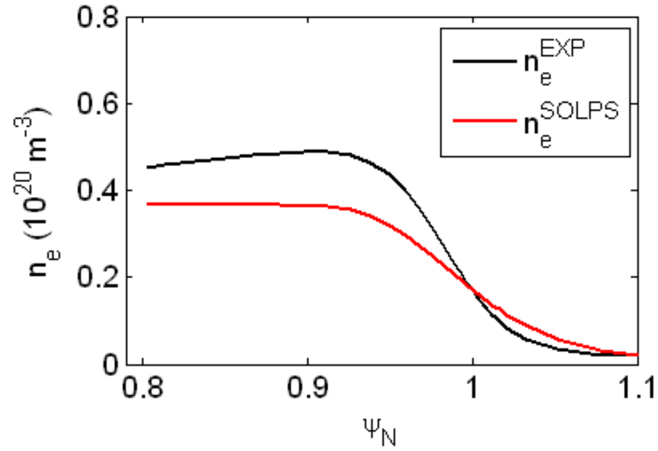
Use of lithium wall coatings between discharges increased global τ_E and stabilized ELMs in NSTX

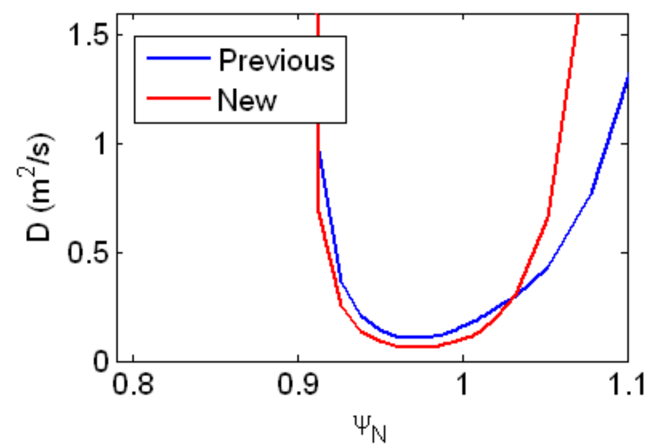
- Region of reduced edge particle and electron thermal transport grew inward from edge of reference H-mode
  - "Width" of transport barrier increased ~*continuously* with amount of pre-discharge Li deposition
  - Pedestal fluctuations reduced with lithium
- ELM frequency also depended nearly continuously on amount of pre-discharge lithium deposition, with ELM-free discharges at end of lithium coating scan
  - Global stability limits observed before edge stability limits
  - n_e profile broadening critical component

Copies (email address)

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., $D^{new} = - \Gamma^{SOLPS}/grad(n_e^{EXP})$
  - Here we use fits to profiles used in stability calculations (Maingi PRL '09)
- Repeat until $n_e/T_e/T_i^{SOLPS} \sim n_e/T_e/T_i^{EXP}$

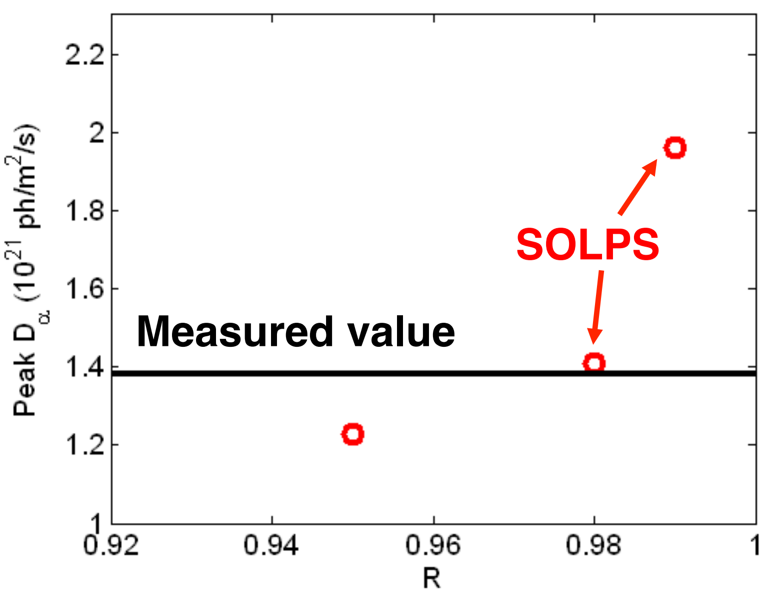




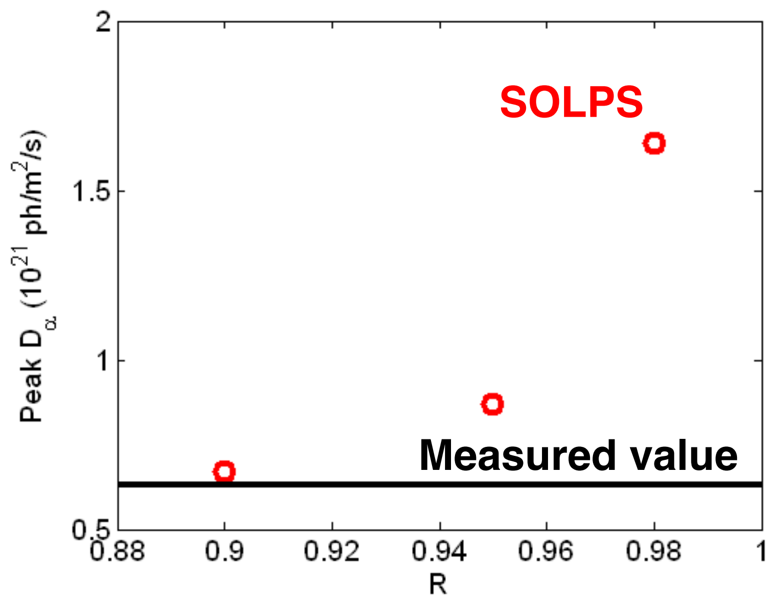
Peak D_α brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces R from ~.98 to ~.9

- 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

Pre-lithium



With lithium



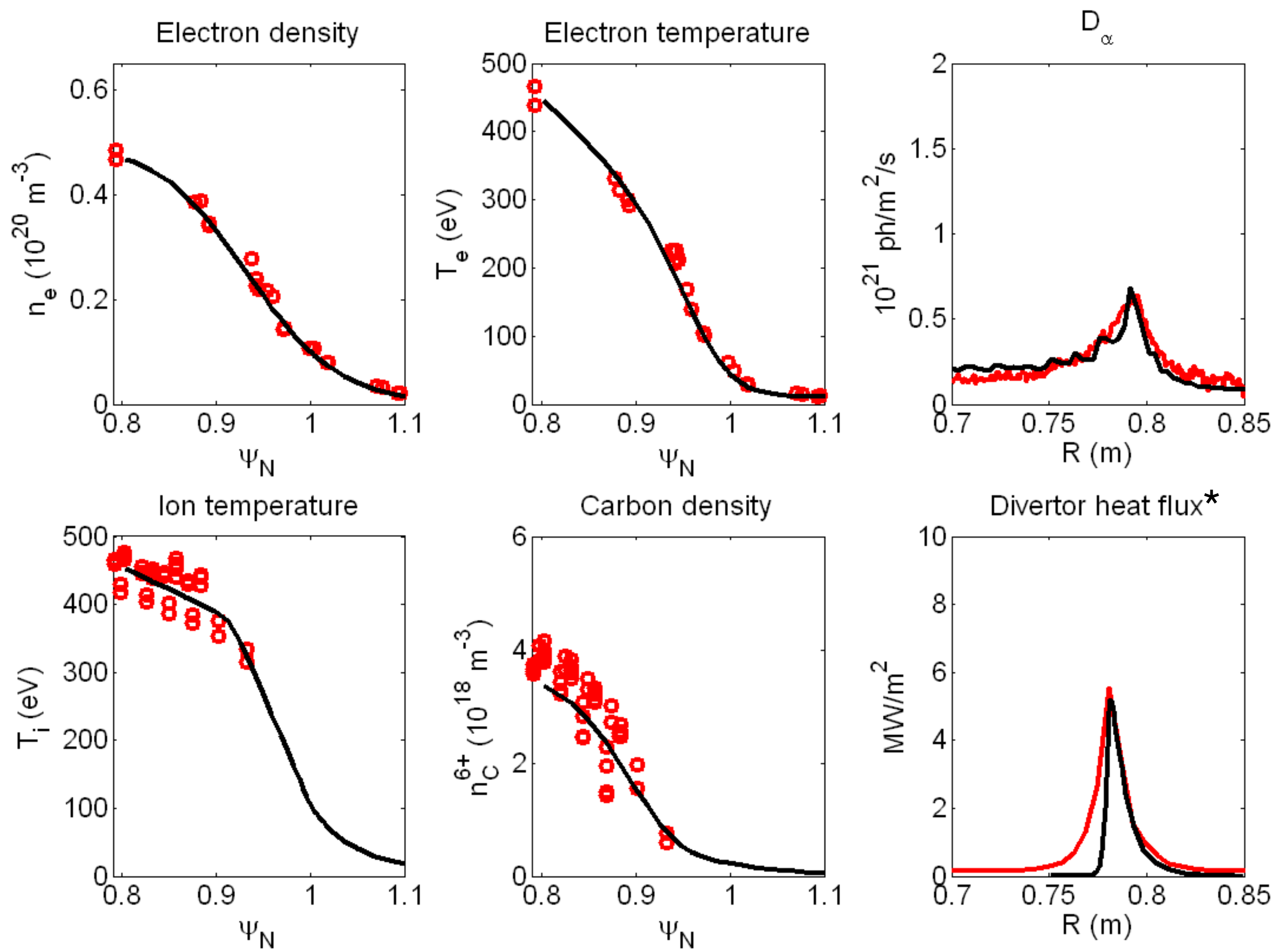
Combining reduced recycling and transport changes gives match to measurements with lithium

- 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)
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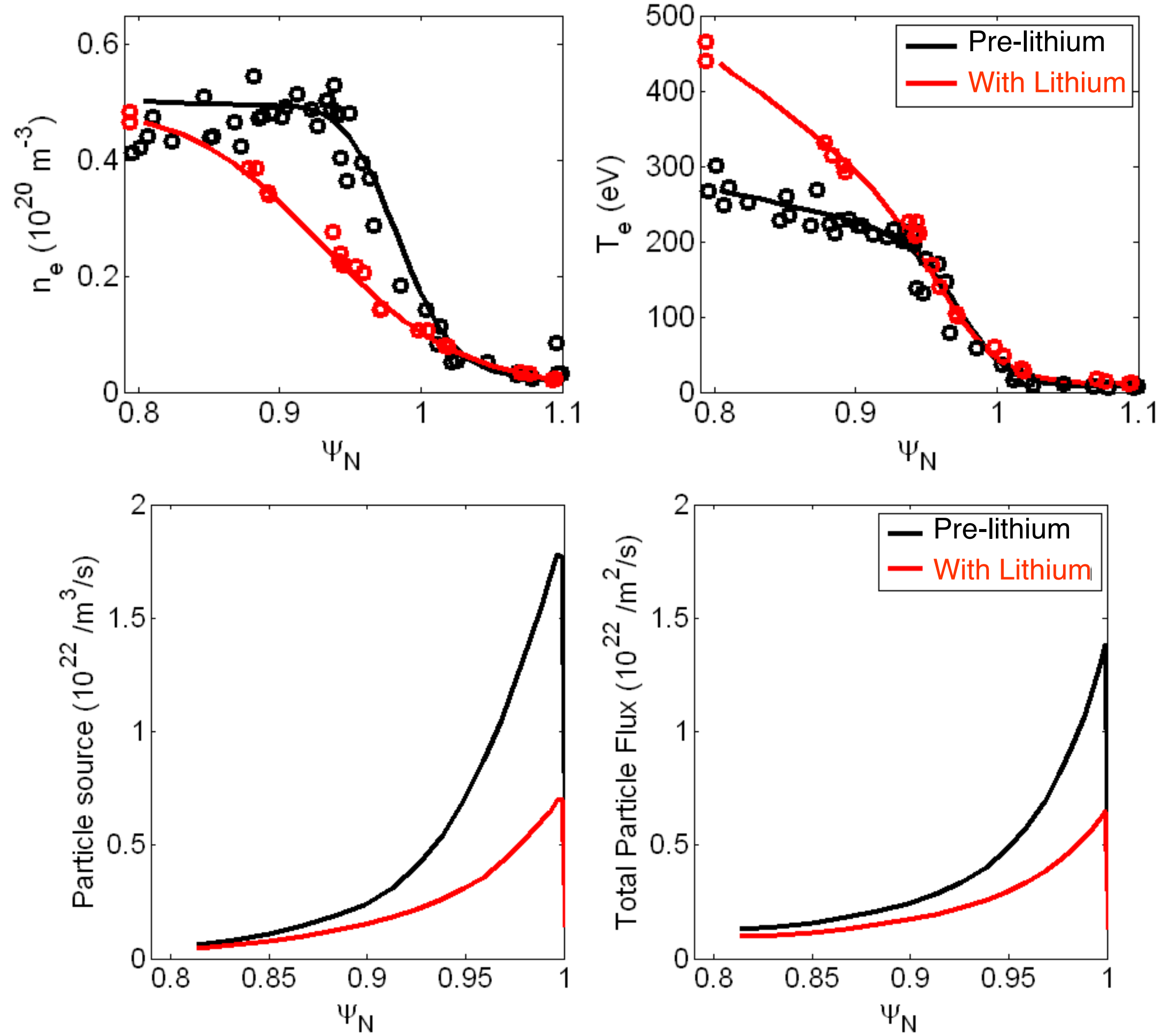
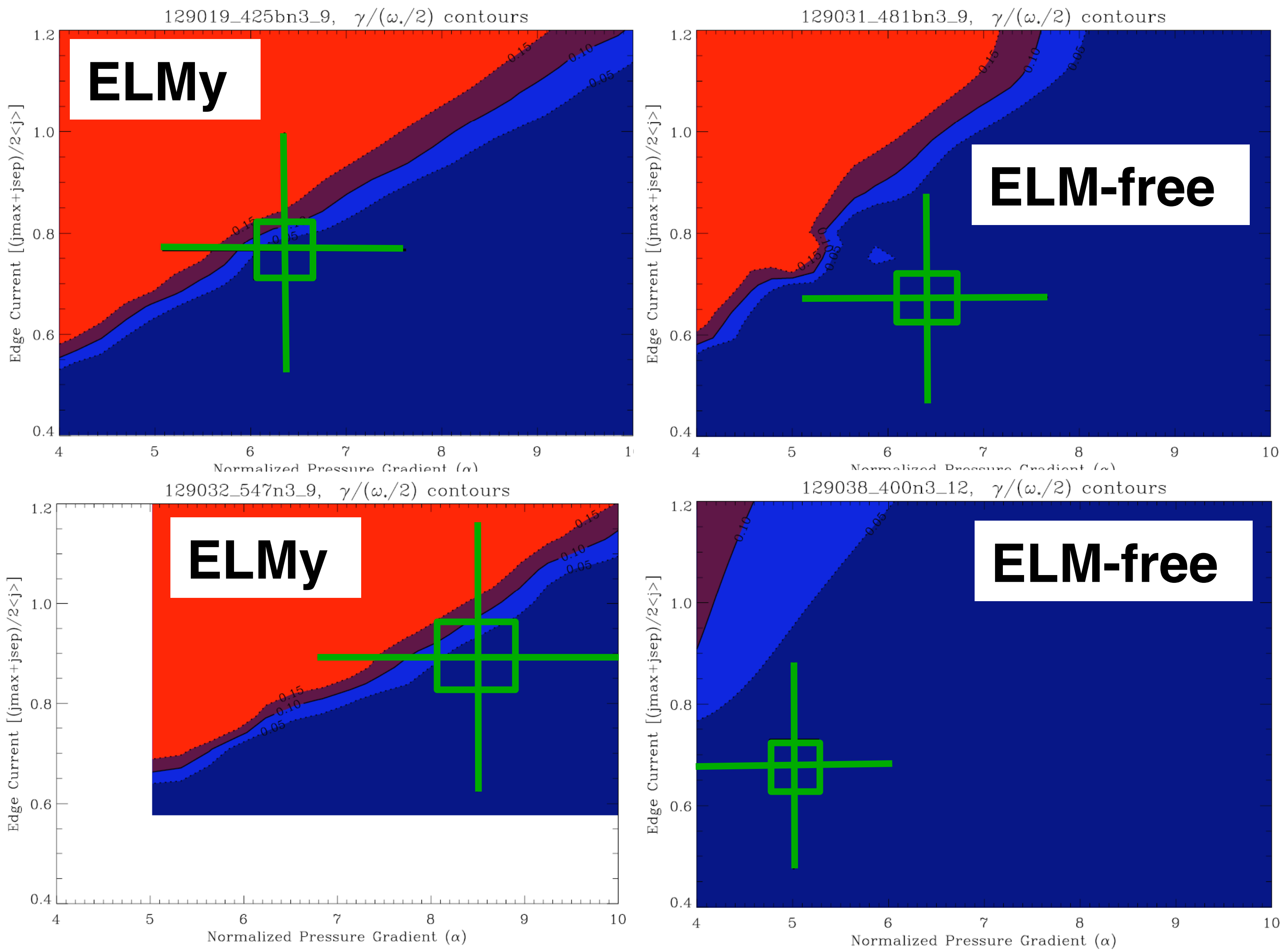
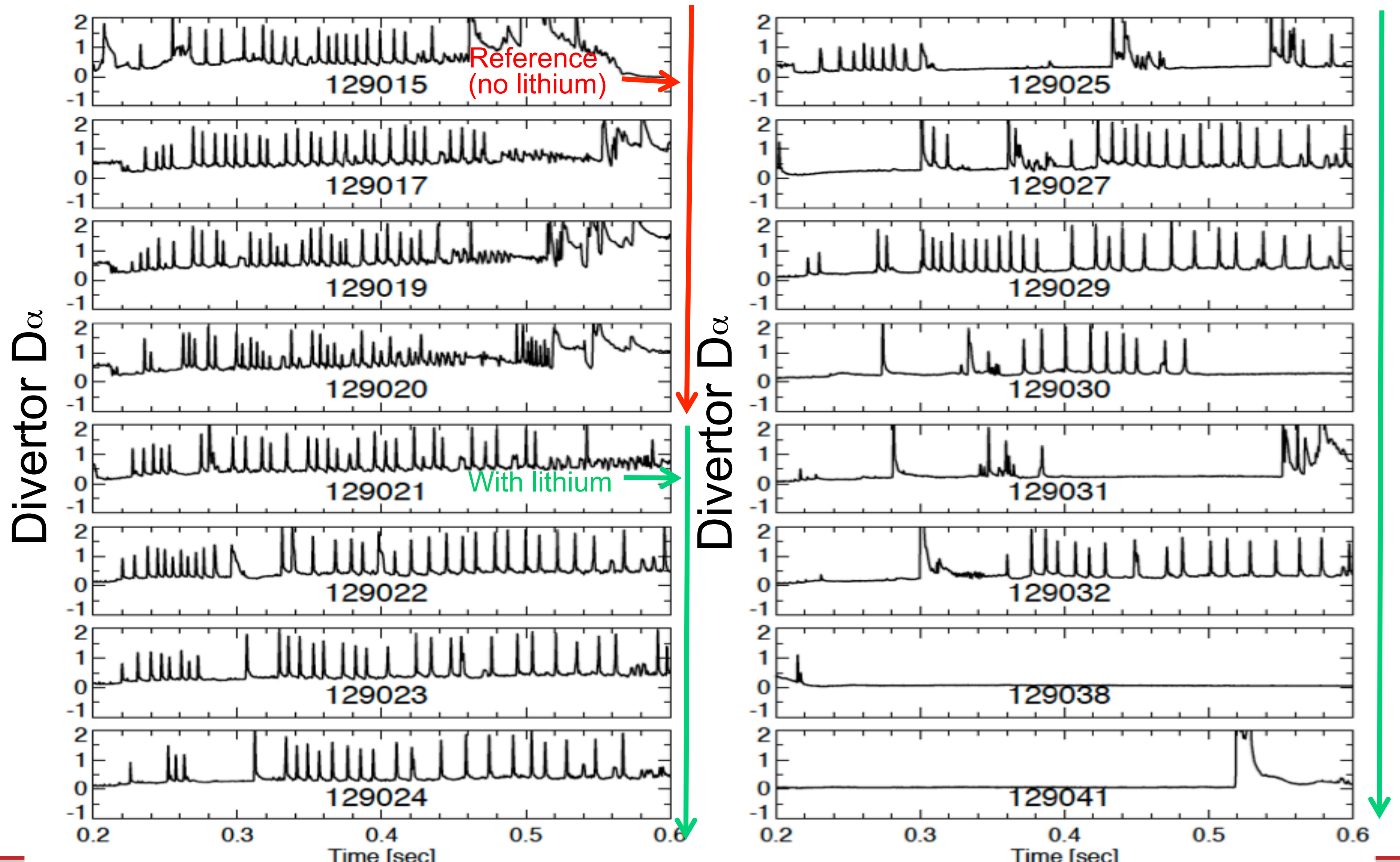


ELMy discharges close to the kink/peeling mode stability boundary, while ELM-free discharges are farther away



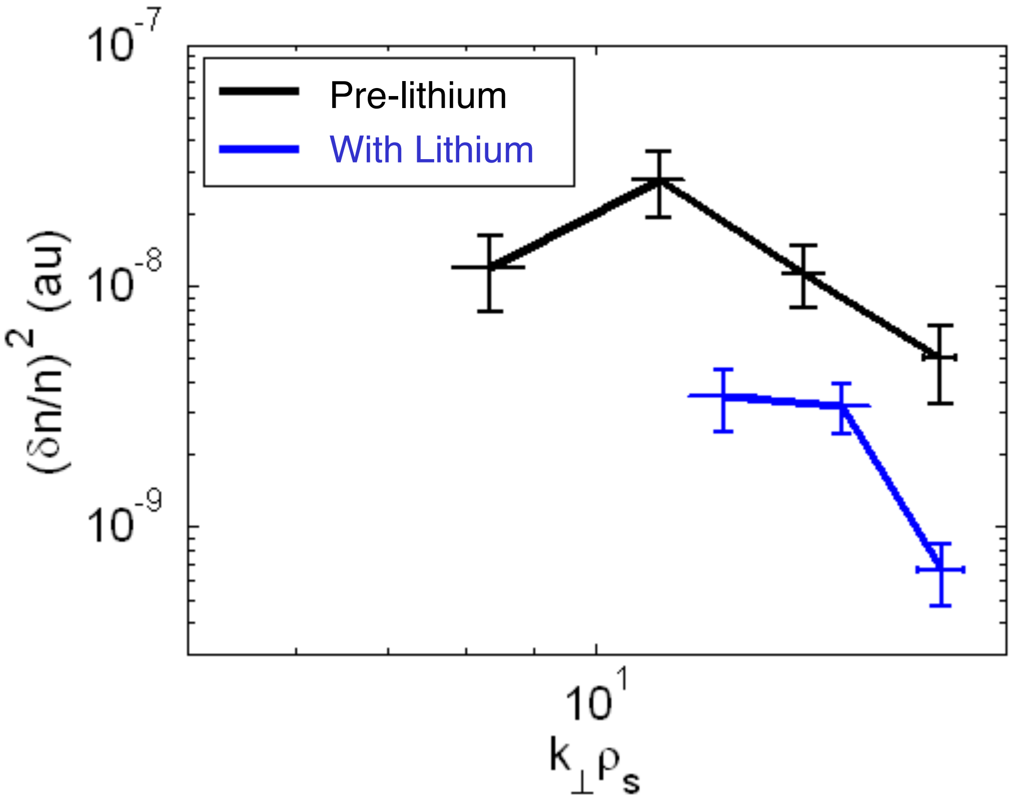
D. Boyle PPCF 2011 to be submitted

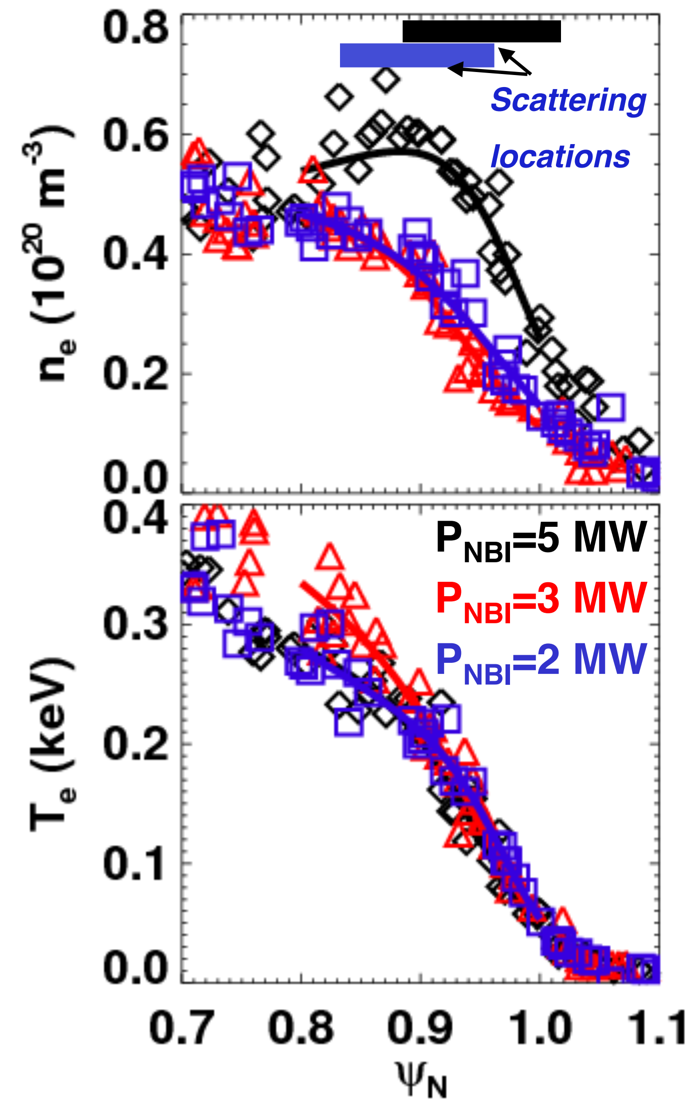
ELMs disappeared gradually during experiment in which pre-discharge Li deposition was varied



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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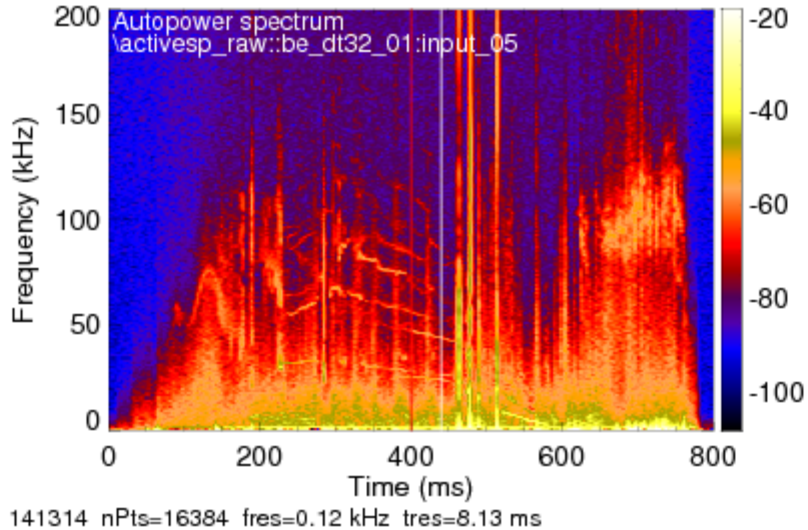
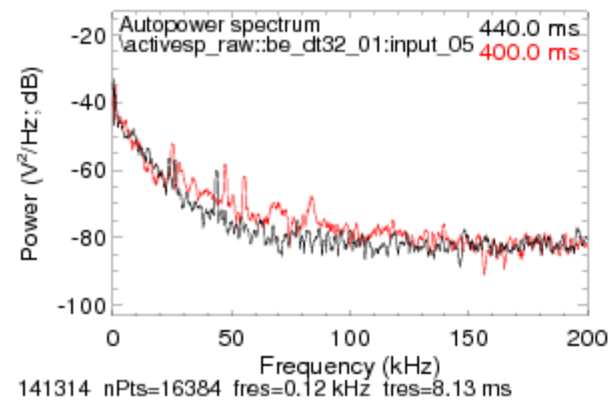
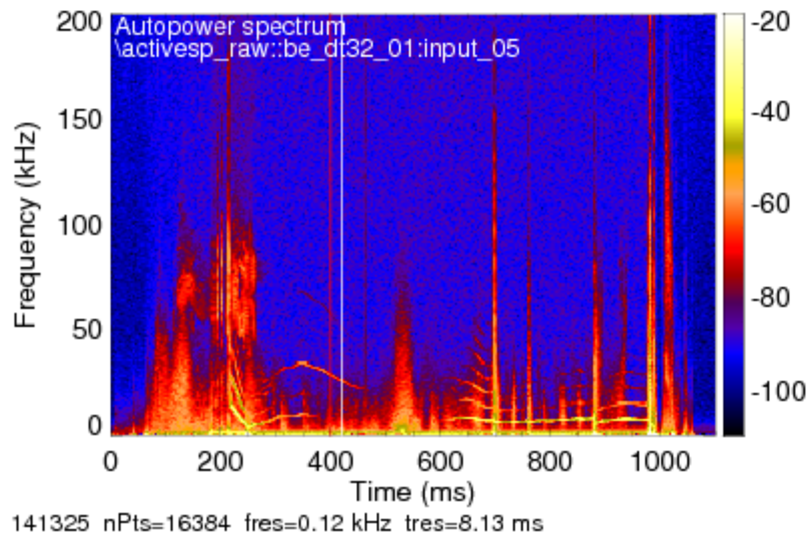
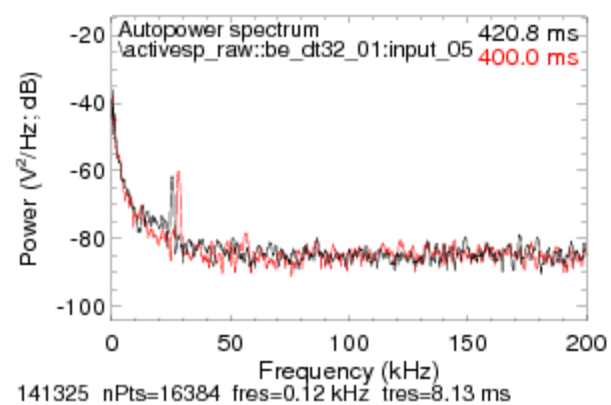
BES also shows reduced turbulence levels in post-lithium discharges





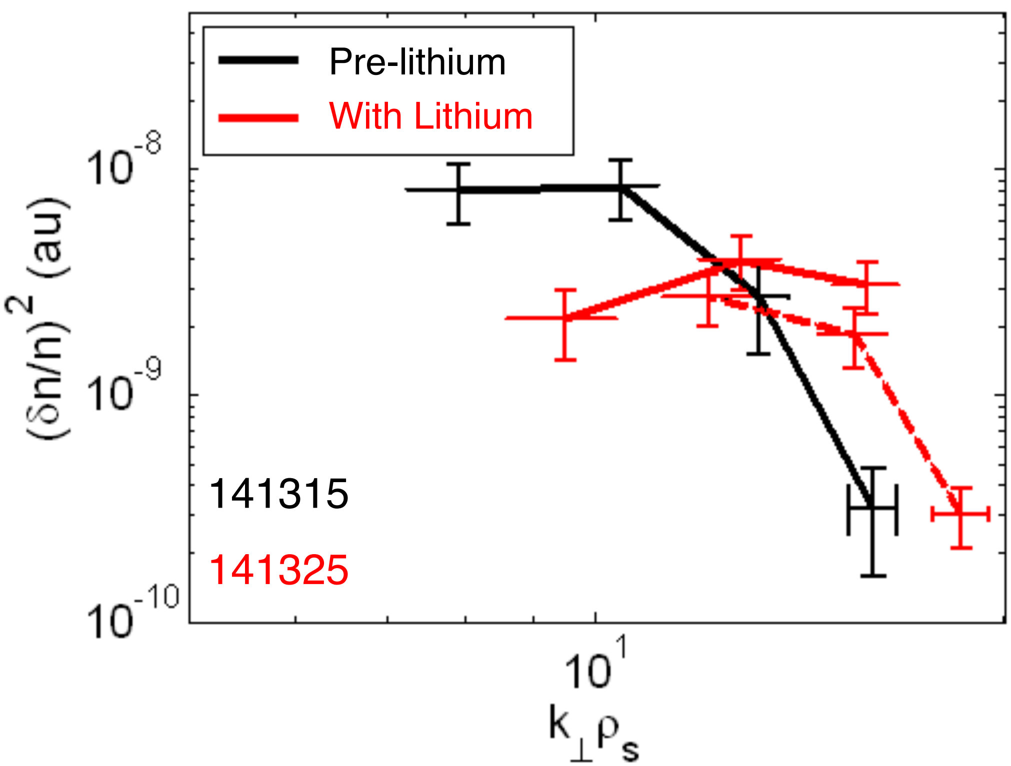


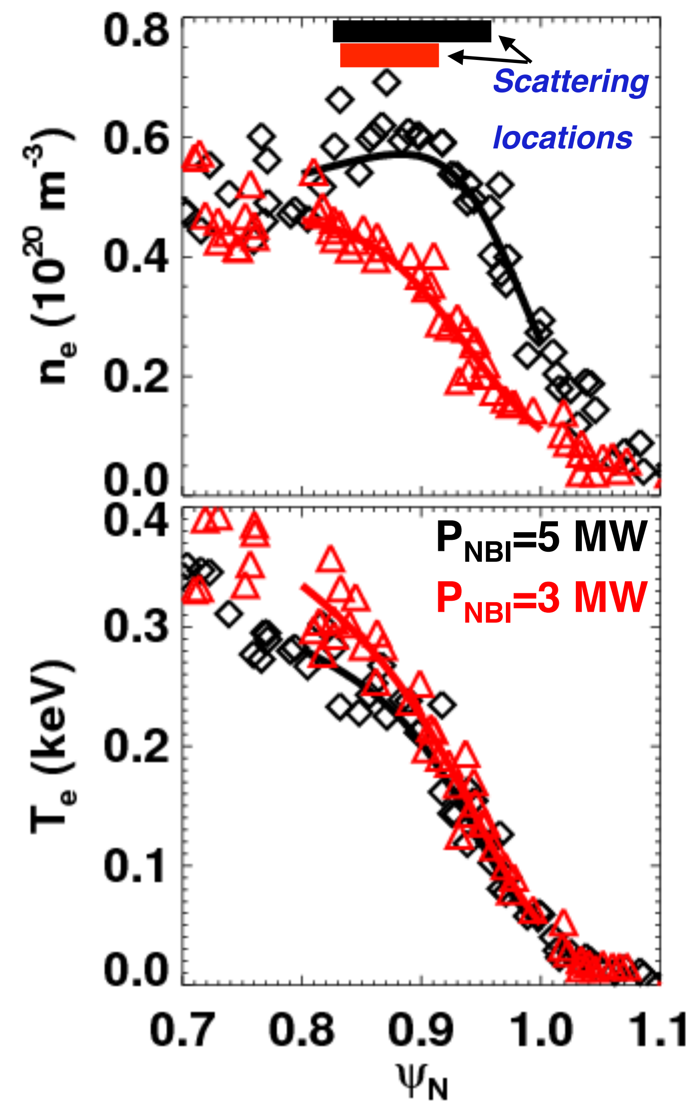


***Courtesy D.R. Smith, UW**

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

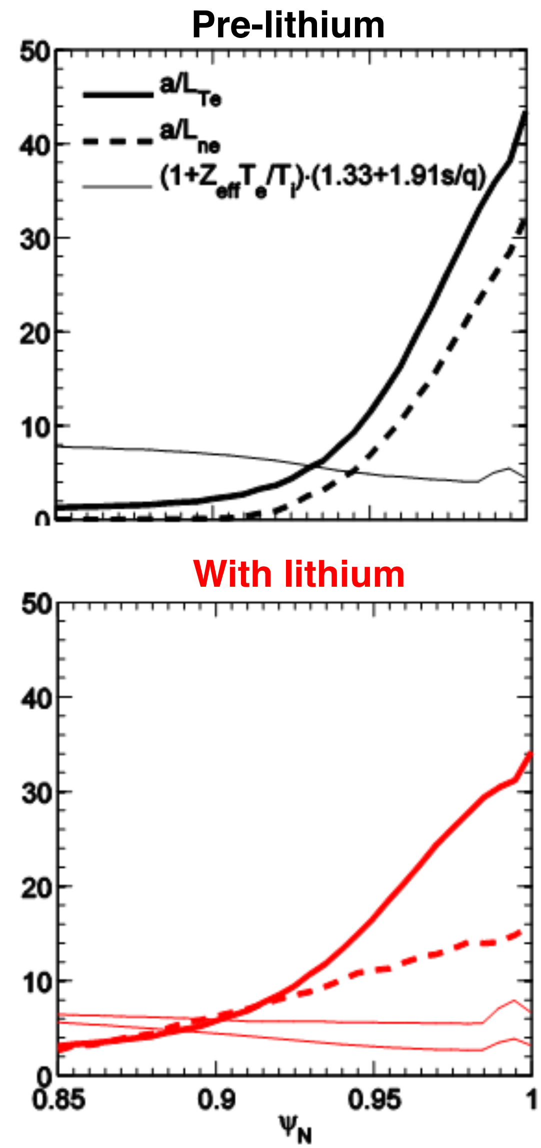
- Pre-to-post lithium transition repeated, similar profile changes observed
- Fluctuations similar for $k\rho_s > 10$, some reduction at lower k for the with-lithium case





ETG is unstable in steep gradient edge

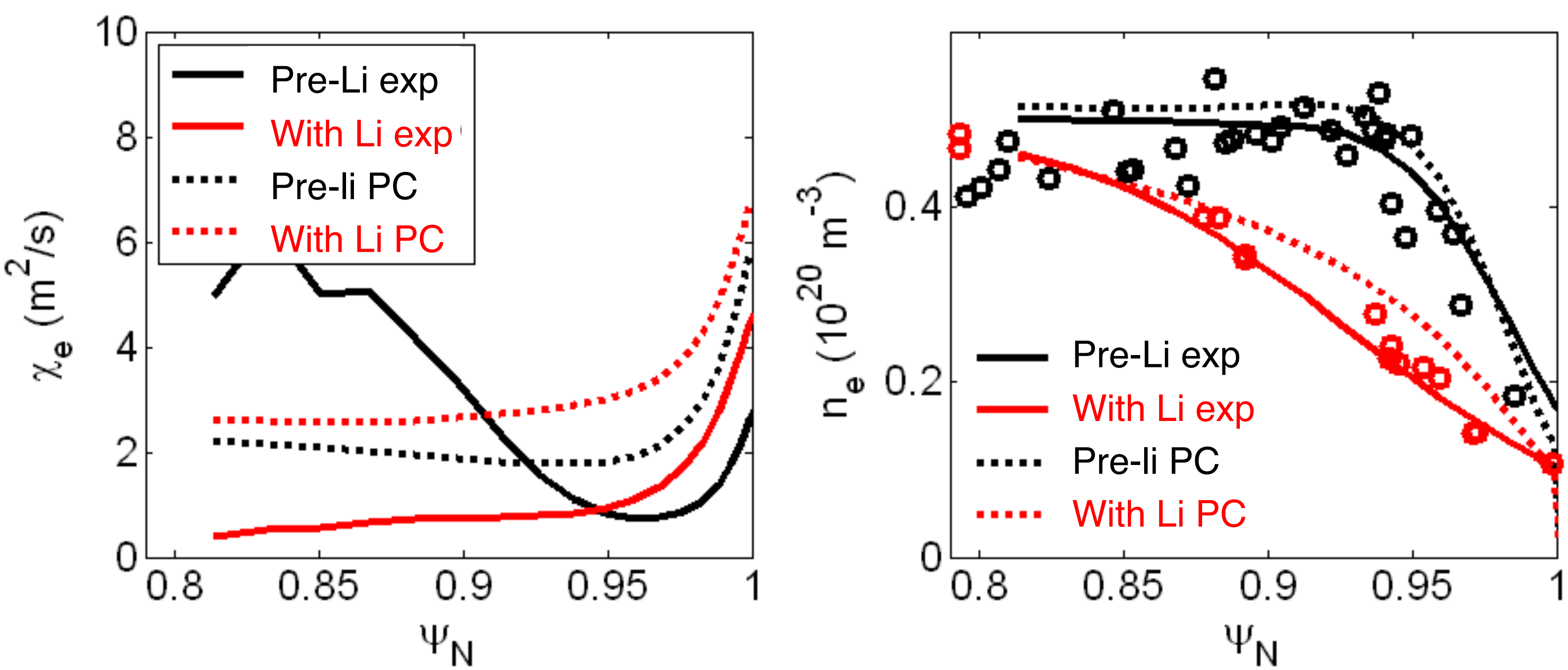
- Investigating ETG stability with GYRO [1]
  - $\chi_e \sim 2\text{-}5\ (\rho_e^2 v_{te}/L_{Te})$, within range of nonlinear expectations
  - Electrons satisfy gyrokinetic ordering $\rho_e/L_{Te} < 1/400$
- ETG unstable in steep gradient region ($\psi_N > 0.92$)
  - Threshold likely set by density gradient
  - $\eta_{e,crit} \sim 1\text{-}1.25$ 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*



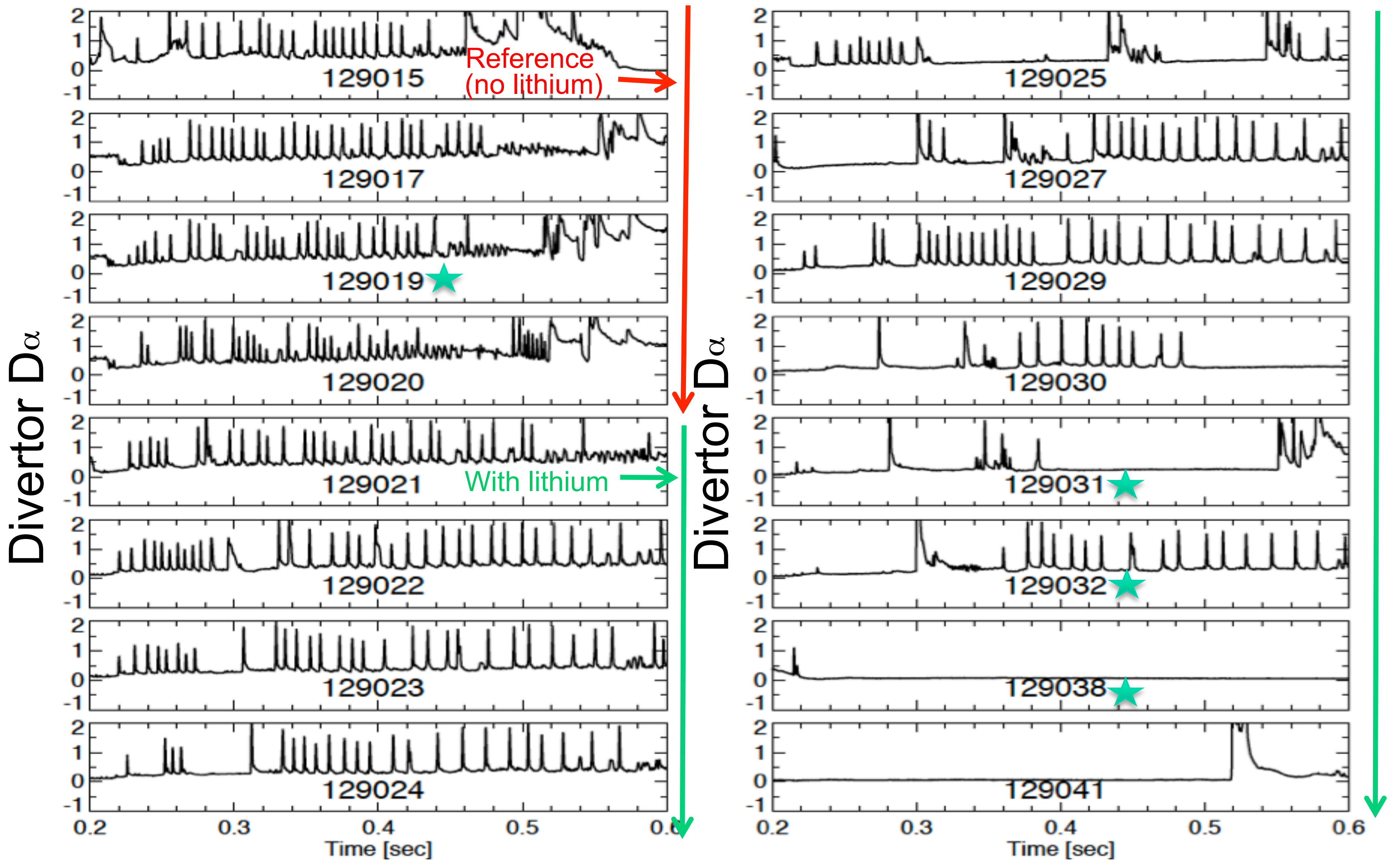
[1] J. Candy & R.E. Waltz, PRL (2003); [2] D. Told et al., PoP (2008);
[3] F. Jenko et al., PoP (2001)

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

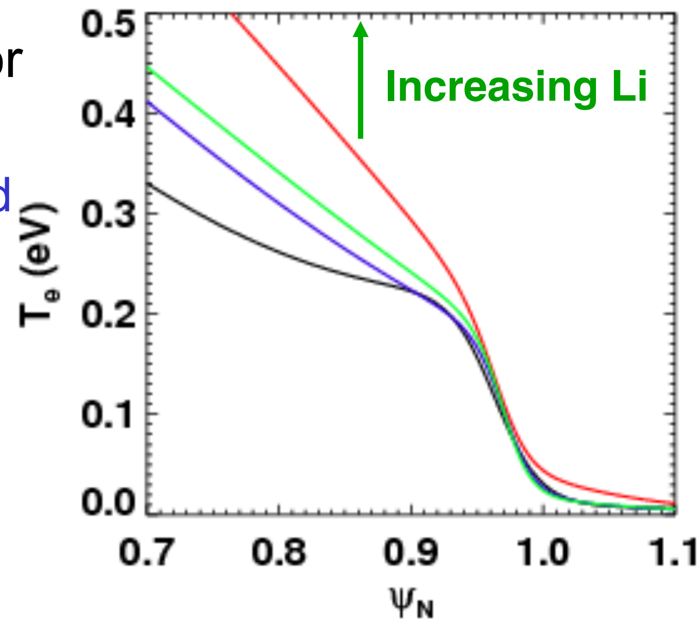


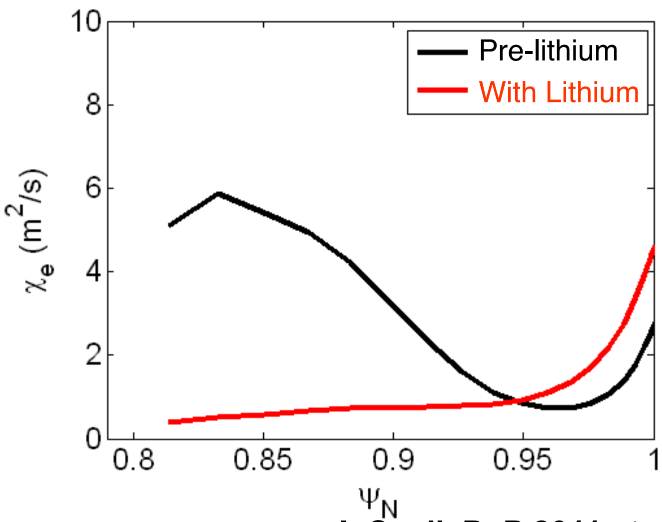
ELMs disappeared gradually during experiment in which pre-discharge Li deposition was varied



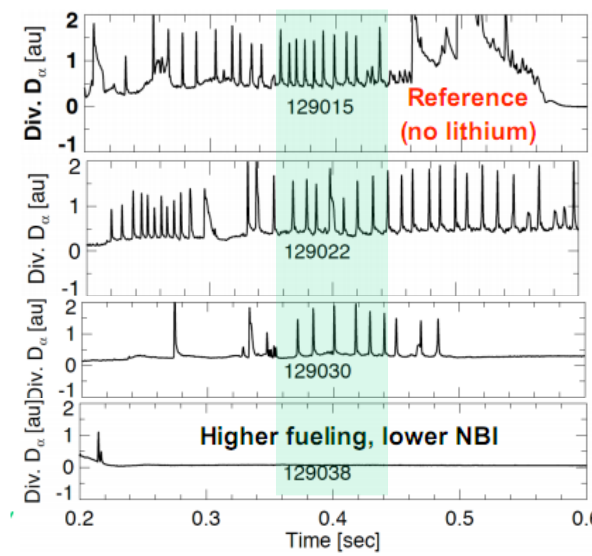
Outer region: T_e gradient nearly constant outside of Ψ_N~0.95

- 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





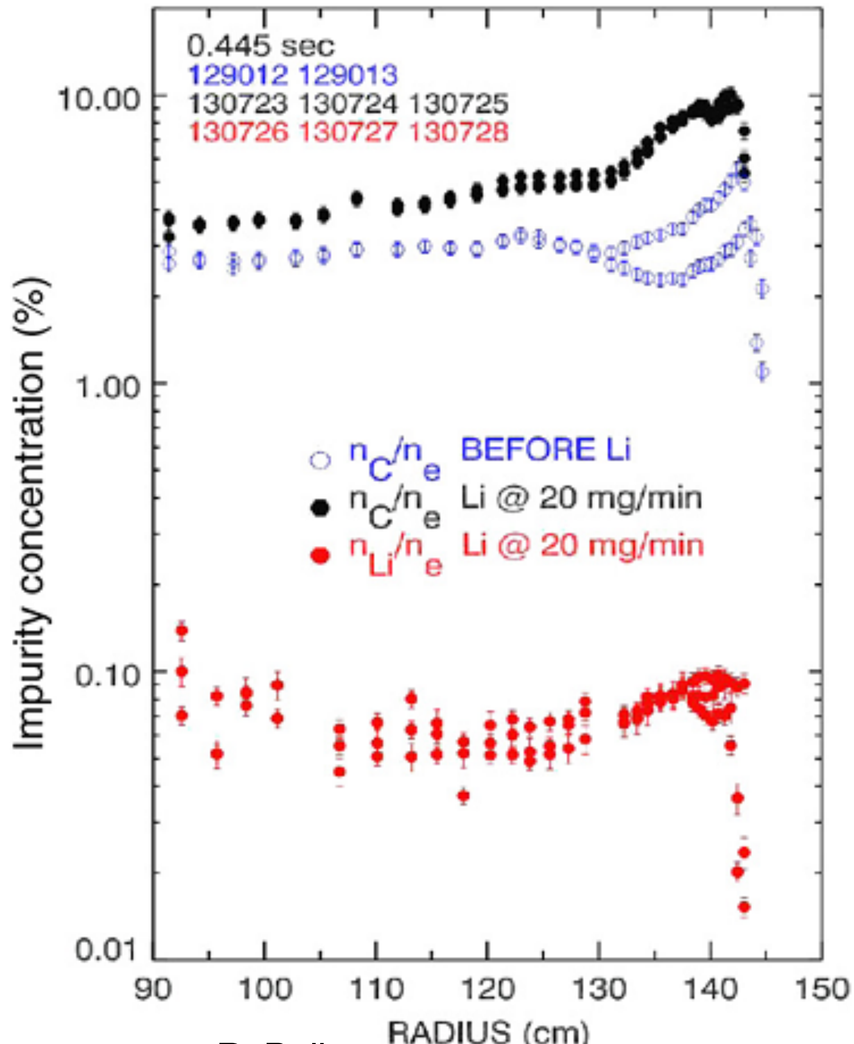
J. Canik PoP 2011 at press



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

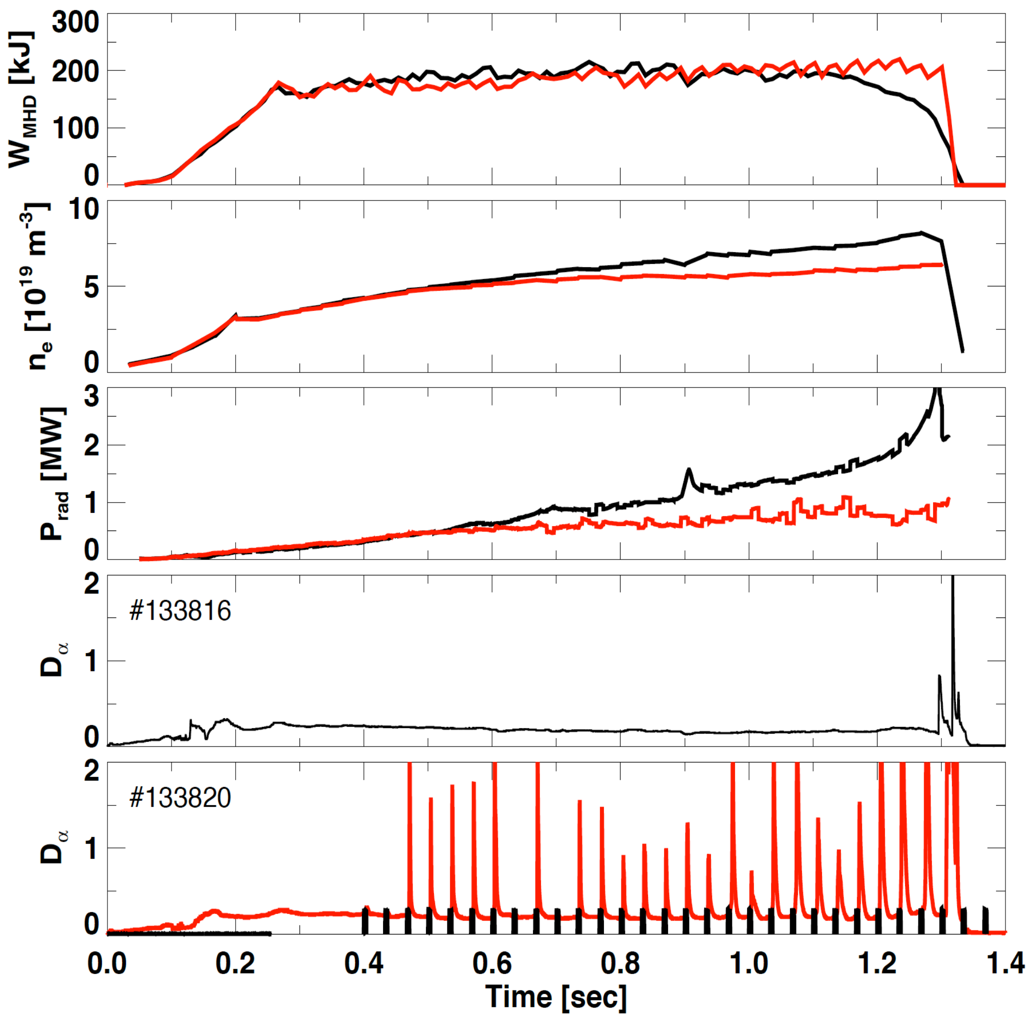


R. Bell

M. Bell, PPCF **51** (2009) 124054

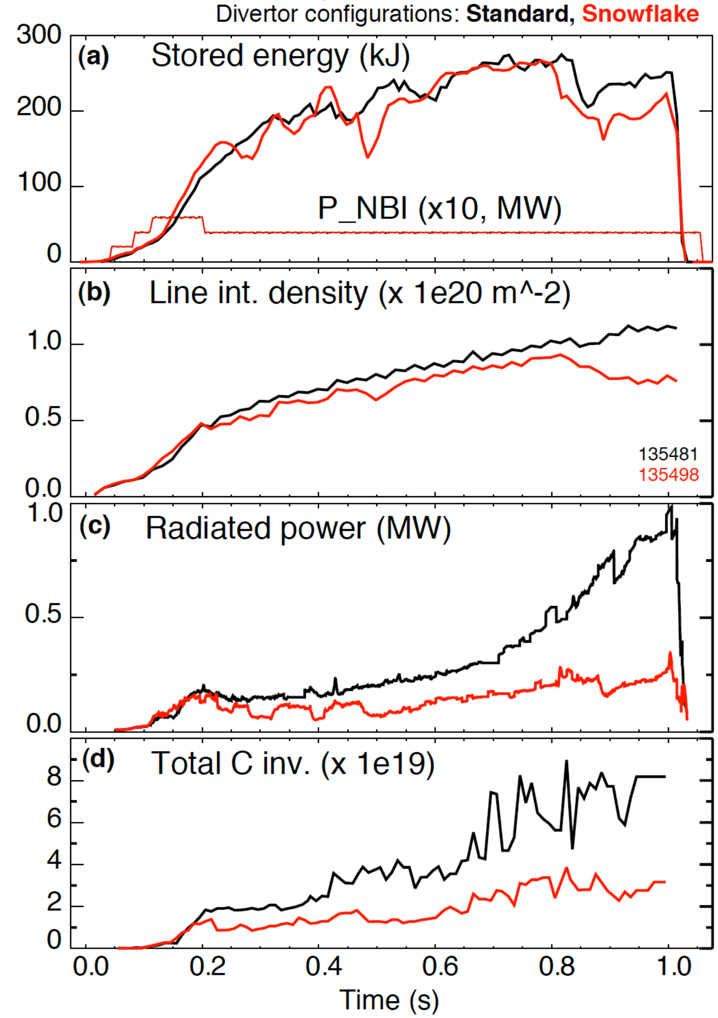
3D external fields used to trigger ELMs, prevent radiation buildup while keeping high energy confinement from lithium

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



J. Canik, PRL 2010, also this conf.

"Snowflake" divertor reduced impurities



V. Soukhanovskii, this conf.