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

Edge transport and turbulence reduction, and formation of ultra-wide pedestals with lithium coated PFCs in NSTX

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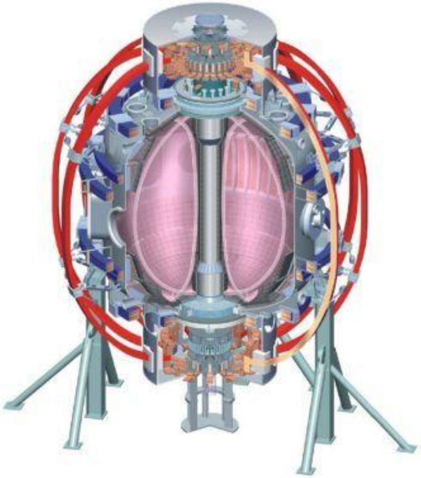
and the NSTX Research Team

52nd APS-DPP
Chicago, IL
Nov 9, 2010



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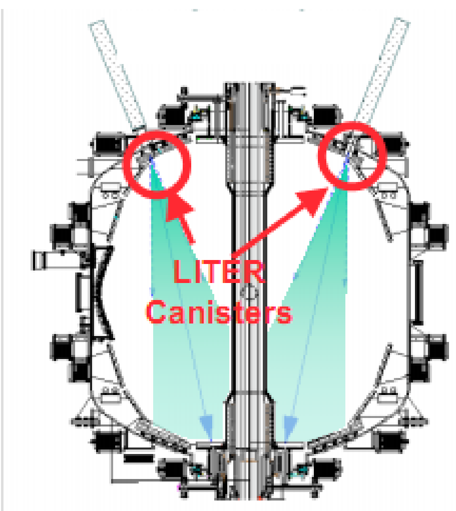
Outline

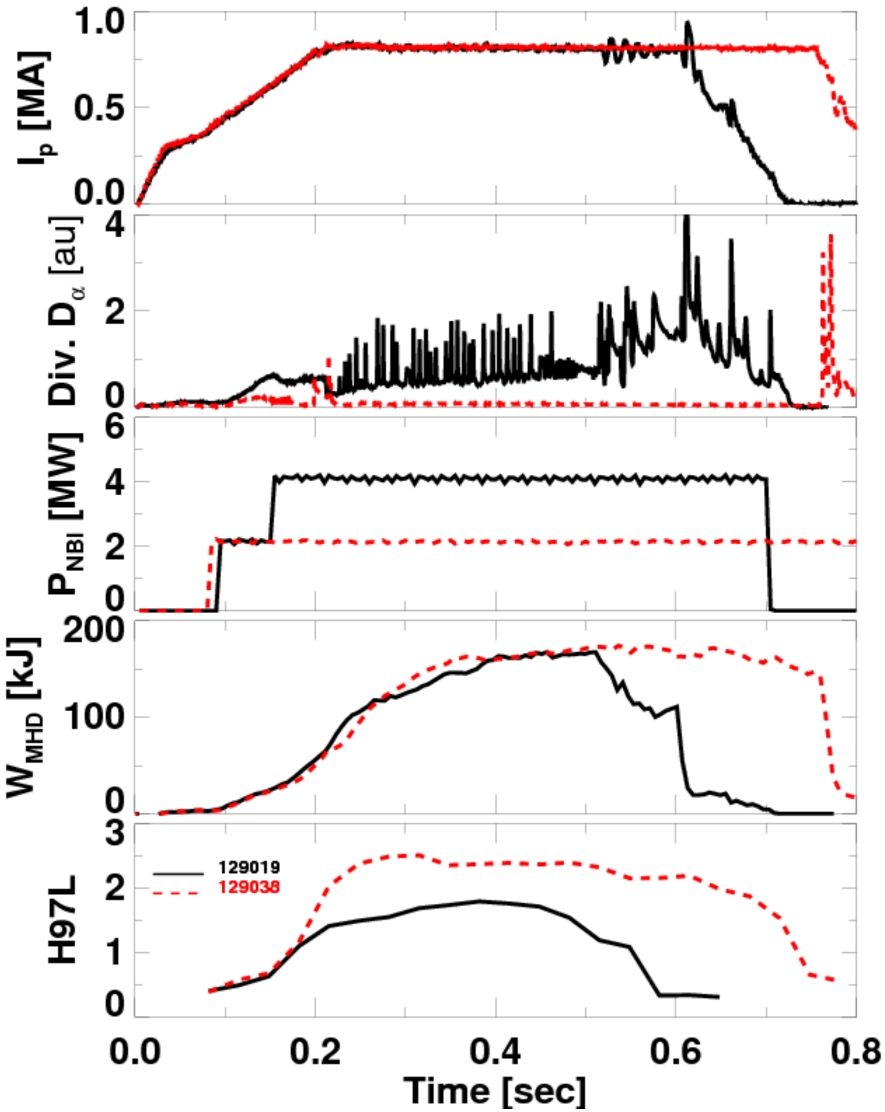
- Introduction: ELM elimination and pedestal profile changes with lithium coatings
- SOLPS is used for interpretive modeling of the edge plasma
- Lithium coatings lead to widening of edge transport barrier
  - Two regions: stiff T_e near separatrix, reduced transport at top of pedestal
  - Measurements show reduced fluctuations with lithium
- Discussion of candidate edge transport mechanisms

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

Predicted* by
L. Zakharov
in 2005



~ 700mg Li
between 129037
and 129038

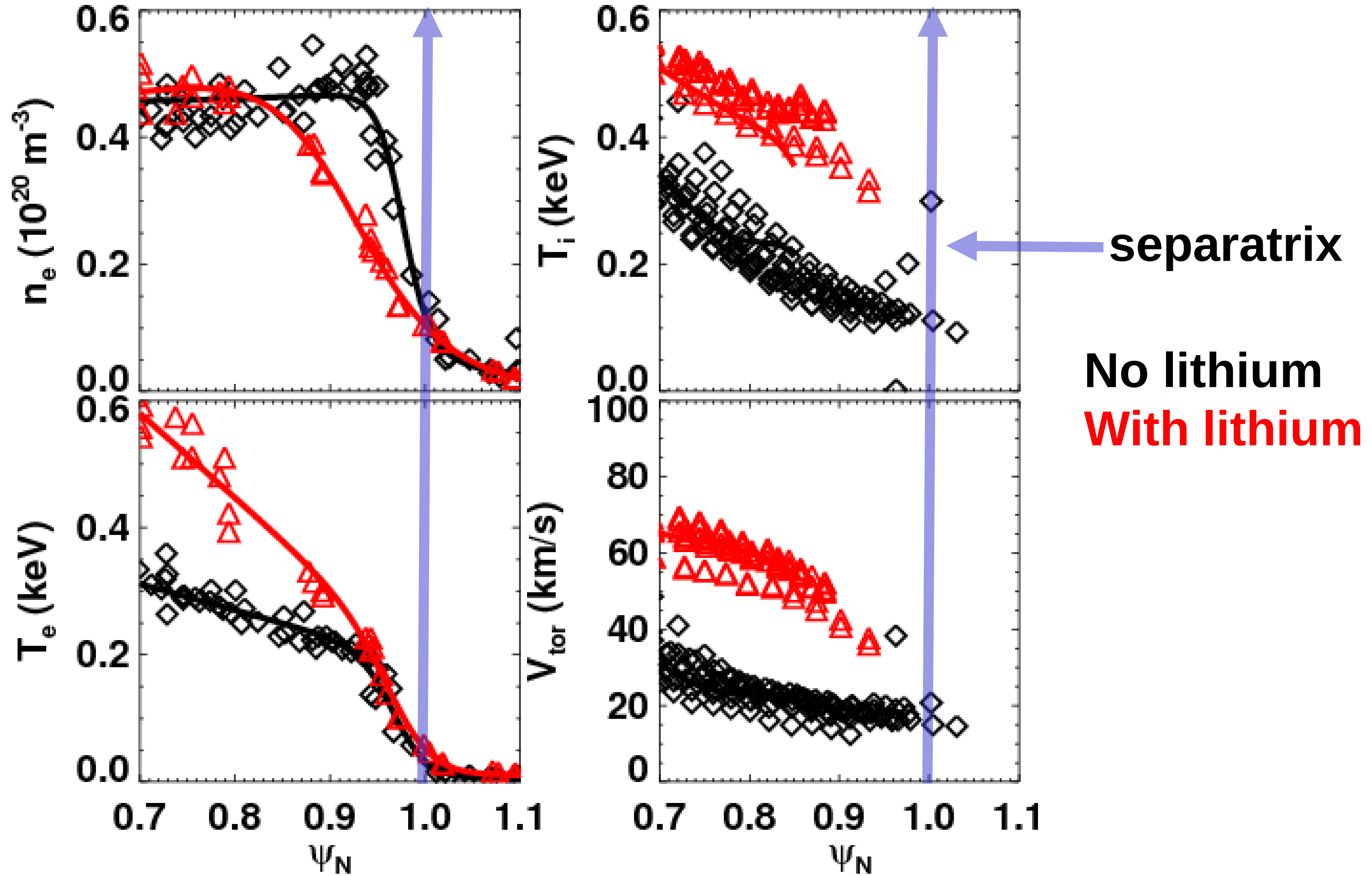


- Without Li, With Li
- ELM-free, reduced divertor recycling
- Lower NBI to avoid β limit
- Similar stored energy
- H-factor 40%↑

H. Kugel, PoP 2008
R. Kaita, IAEA 2008
M. Bell, PPCF 2009

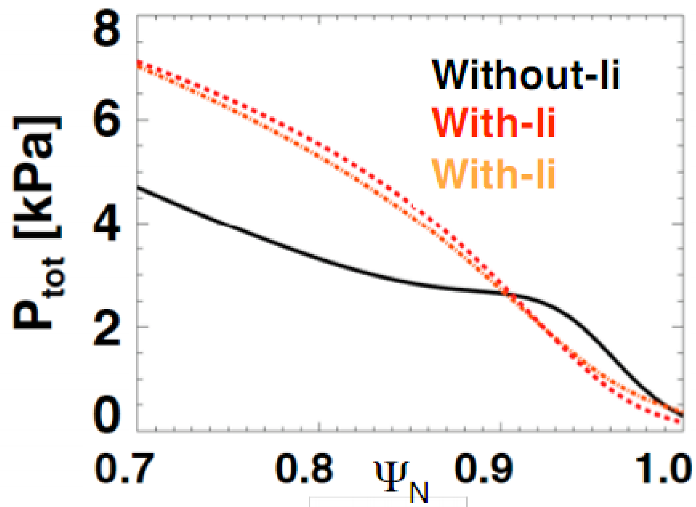
*** L. Zakharov, JNM 2007**

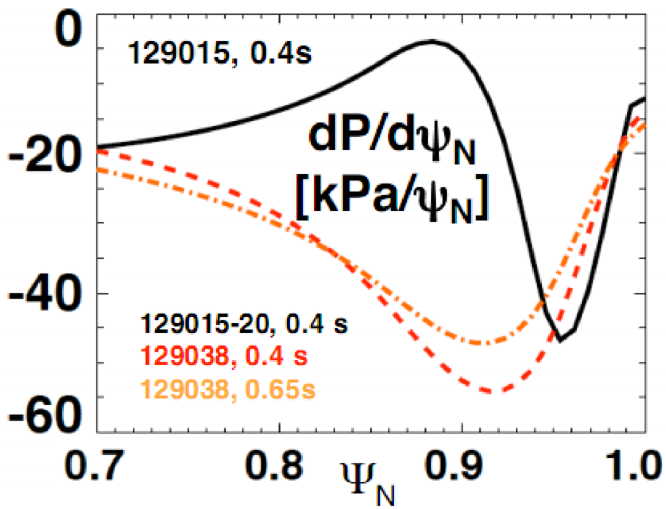
T_e, T_i increased and edge n_e decreased with lithium coatings

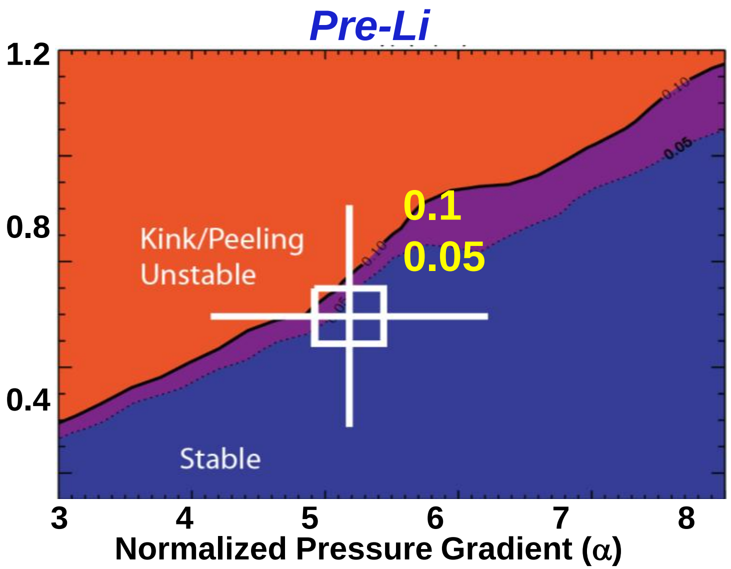


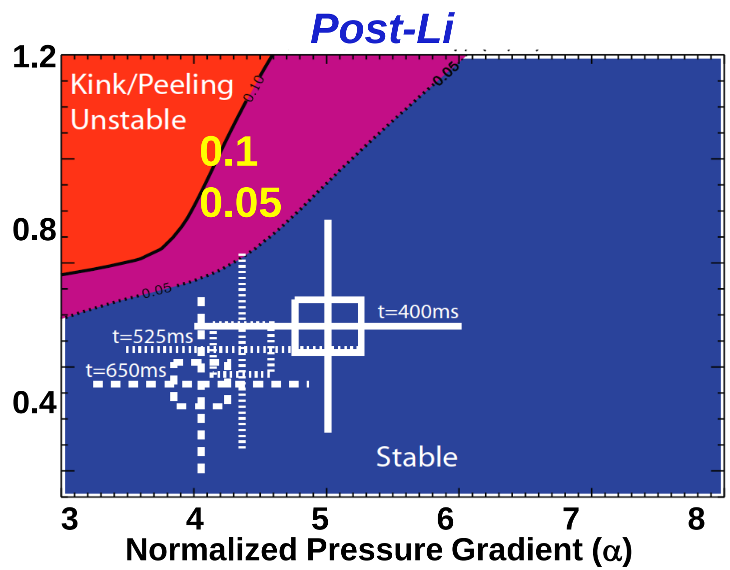
Peak pressure gradient moves inwards, p' and j reduced outside ψ_N~0.95

R Maingi, PRL 2009

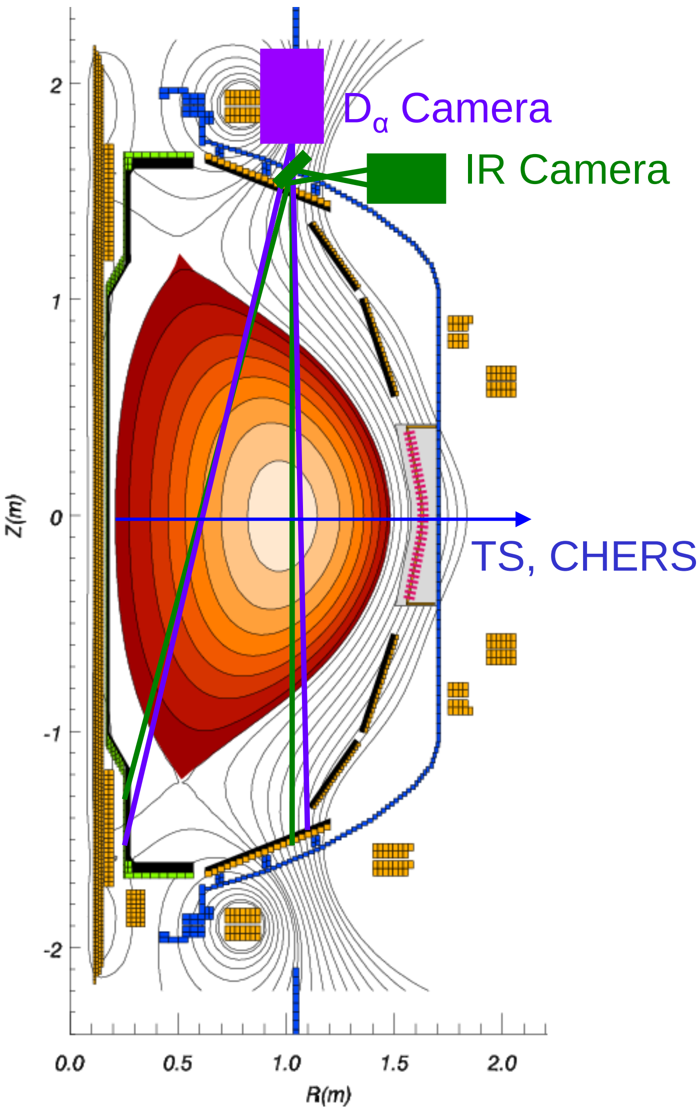




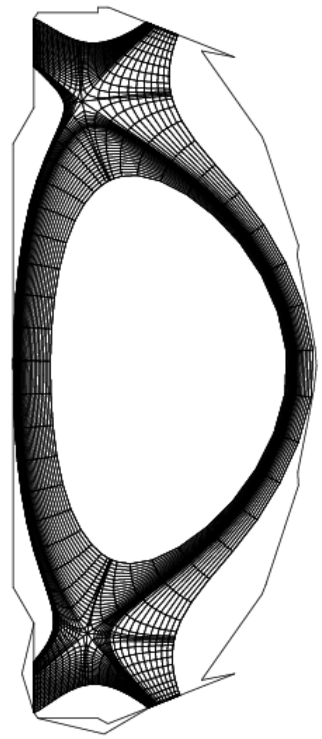




Pre- and post-lithium discharges are modeled using SOLPS



SOLPS Grid

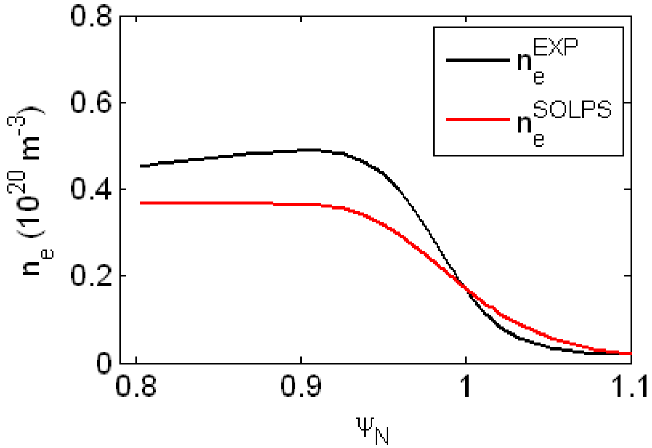


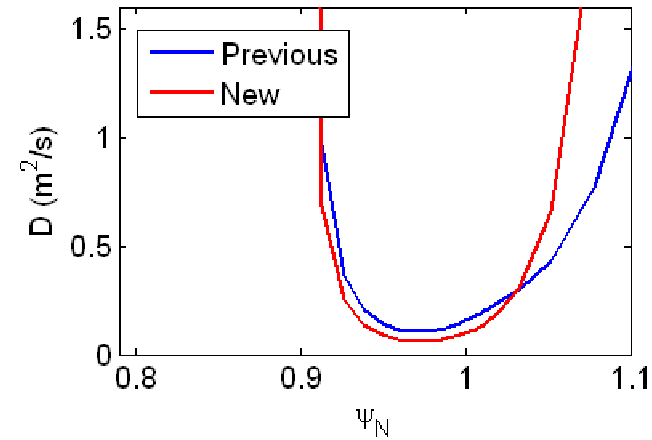
- SOLPS (B2-EIRENE: 2D fluid plasma + MC neutrals) used to model NSTX experimental data
  - ✓ Neutrals contributions
  - ✓ Recycling changes due to lithium

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

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 $n_e/T_e/T_i^{SOLPS} \sim n_e/T_e/T_i^{EXP}$

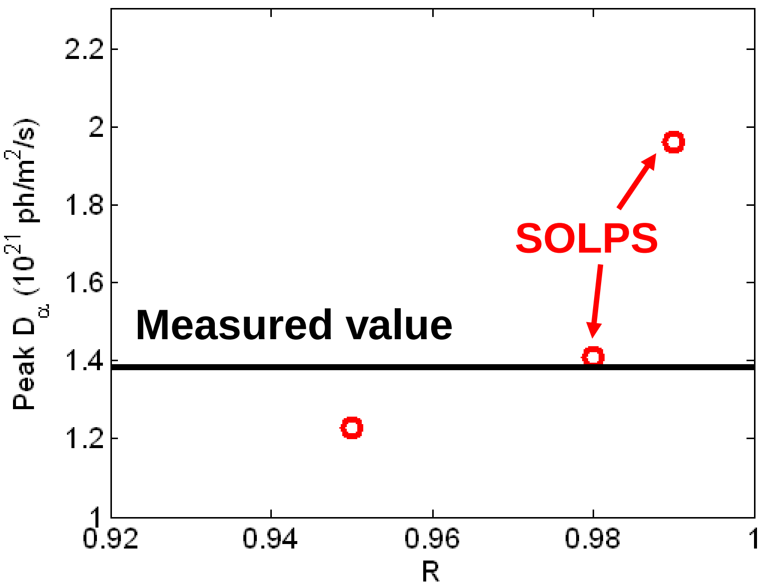




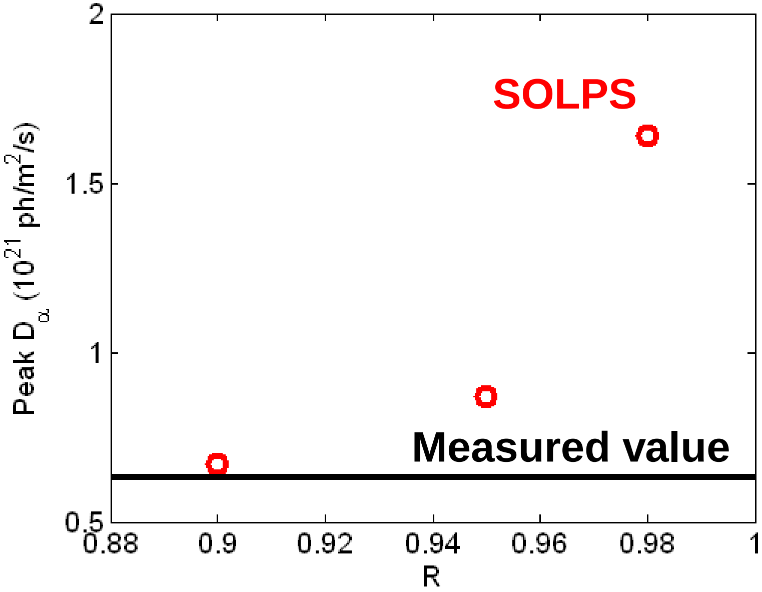
Peak D_α brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces R from ~.98 to ~.9

- 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

Pre-lithium



Post-lithium



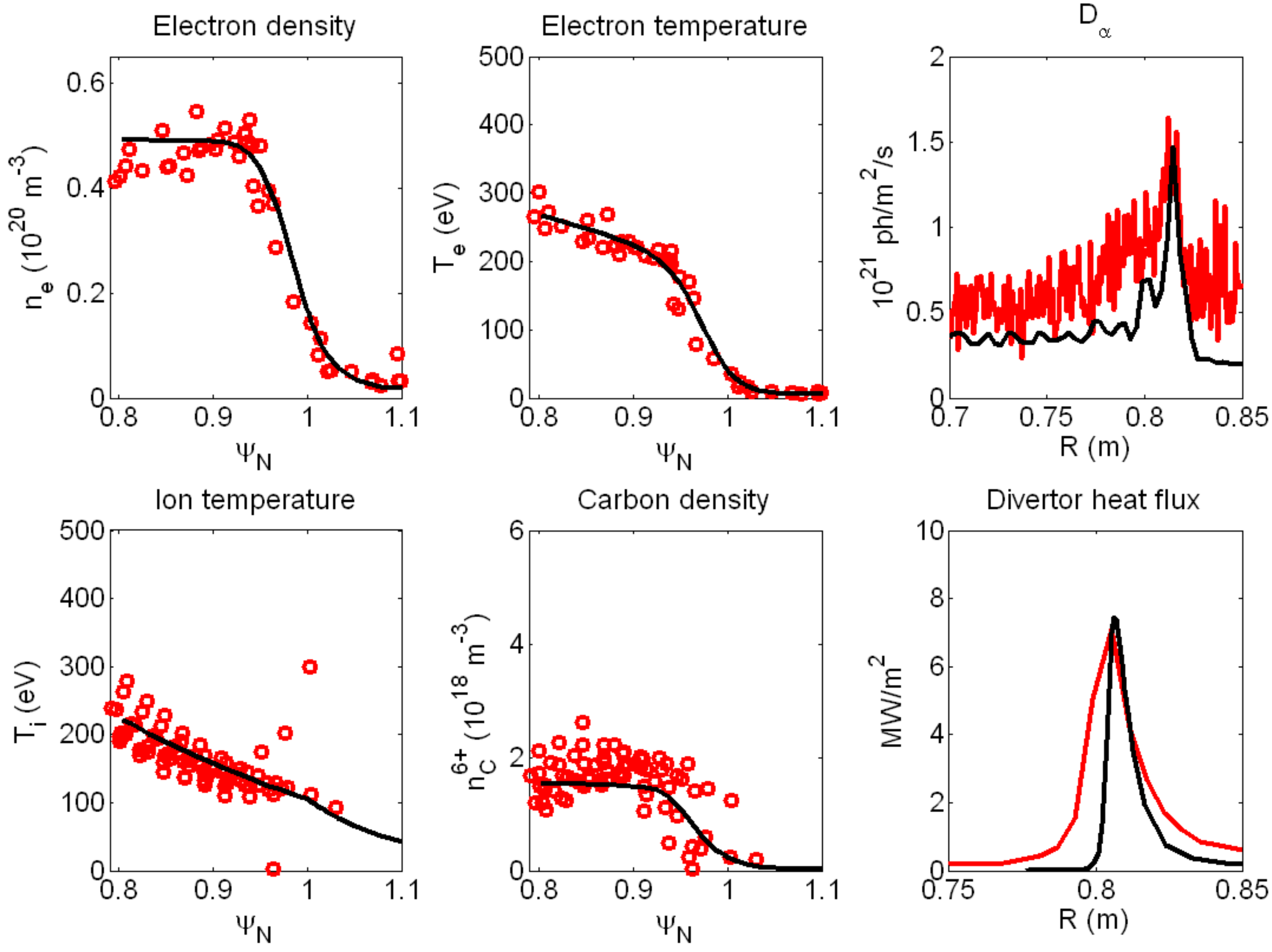
Midplane and divertor profiles from modeling compare well to experiment for the pre-lithium case

- 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



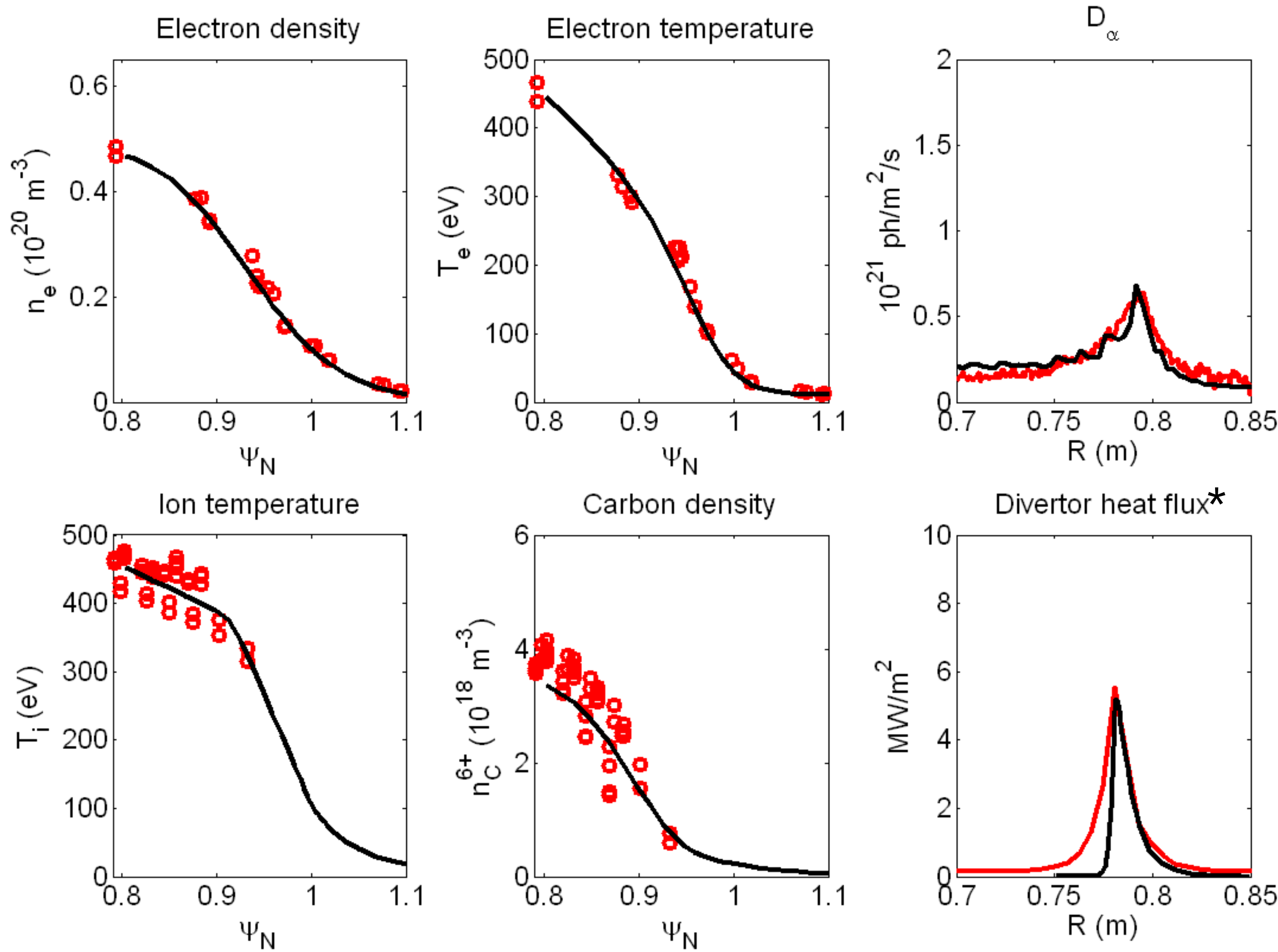
Combining reduced recycling and transport changes gives match to measurements with lithium

- P=1.9 MW
- R=0.90

- Transport coefficients adjusted to recover fit to upstream data

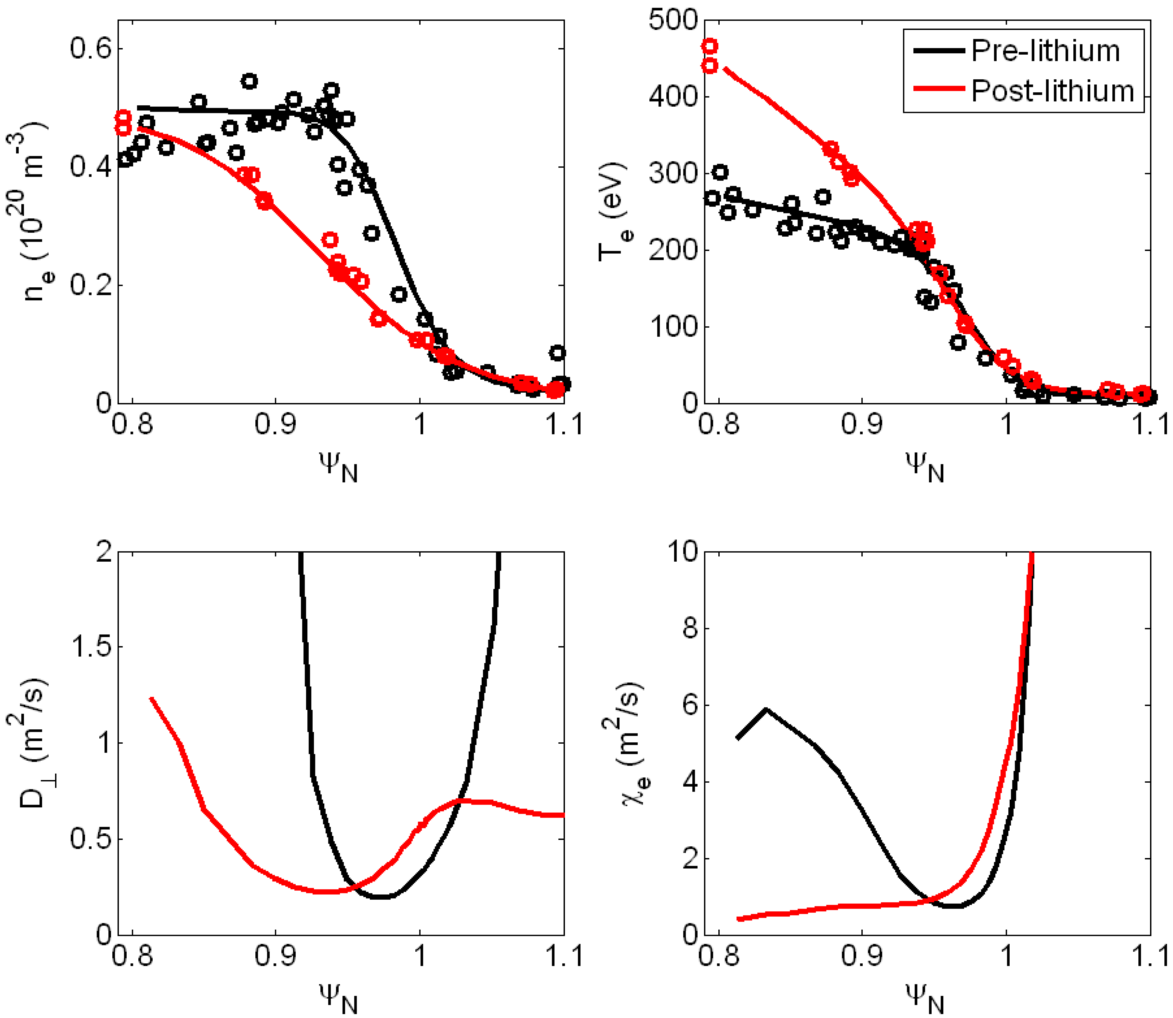
- Good match to both peak and profile for heat flux and D_α (except PFR)

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



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 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



Particle and heat sources are reduced with lithium

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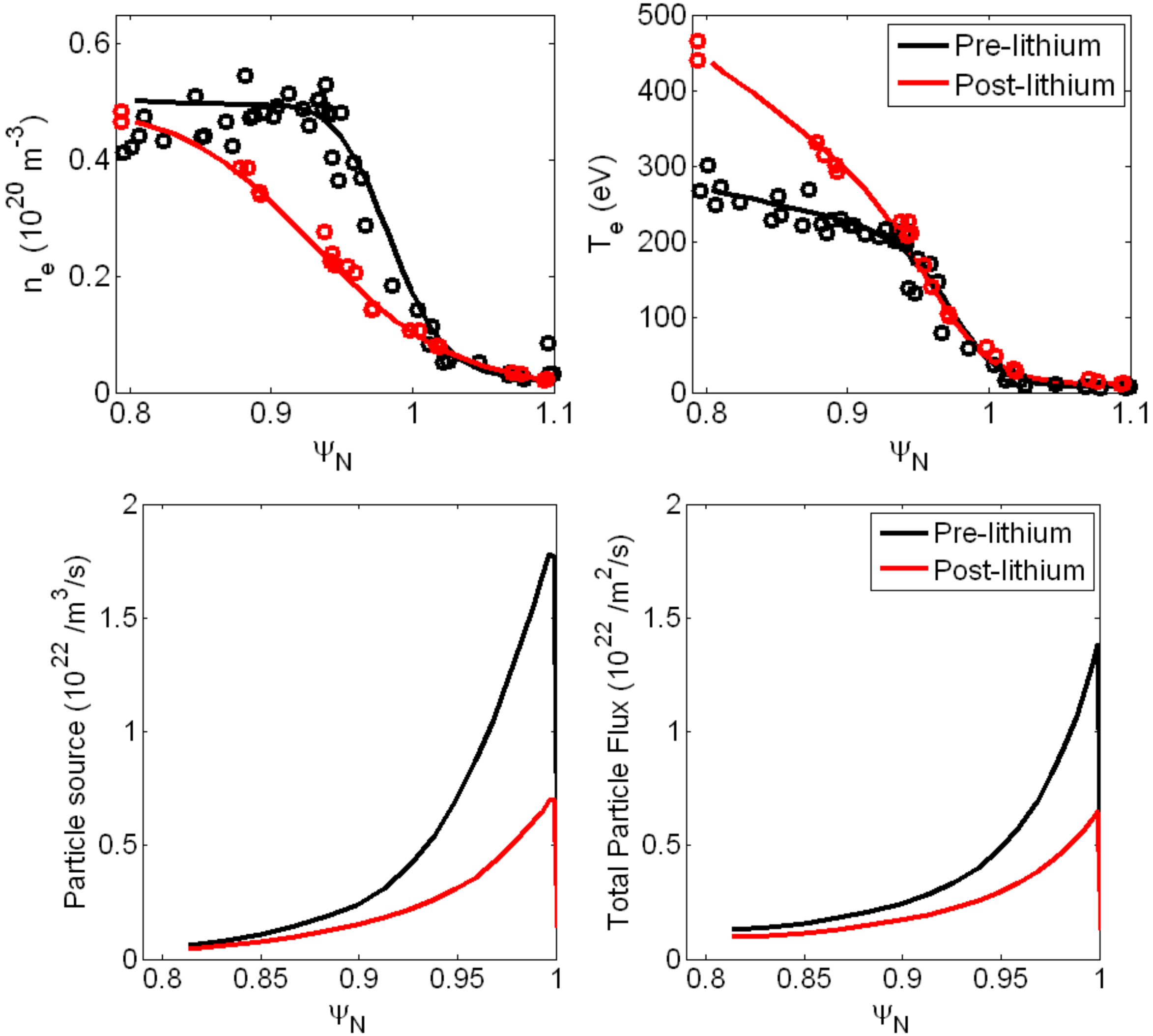
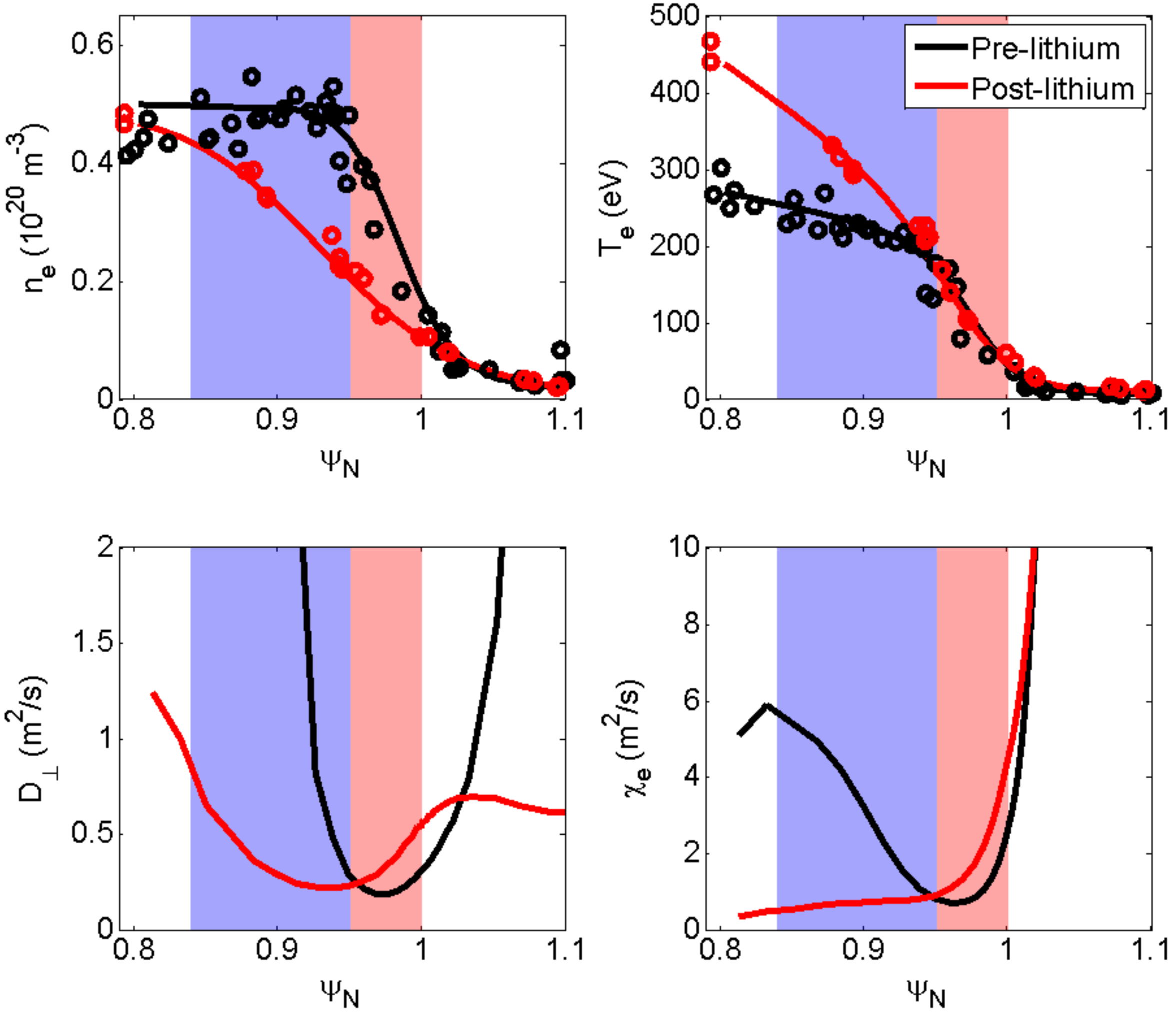
  - Barrier region in D, χ_e just inside separatrix
- Pedestal is much wider with lithium
  - $D_\perp$, χ_e similar outside of ψ_N~0.95
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)
- Changes to profiles with lithium are due to reduced fluxes combined with wide transport barrier



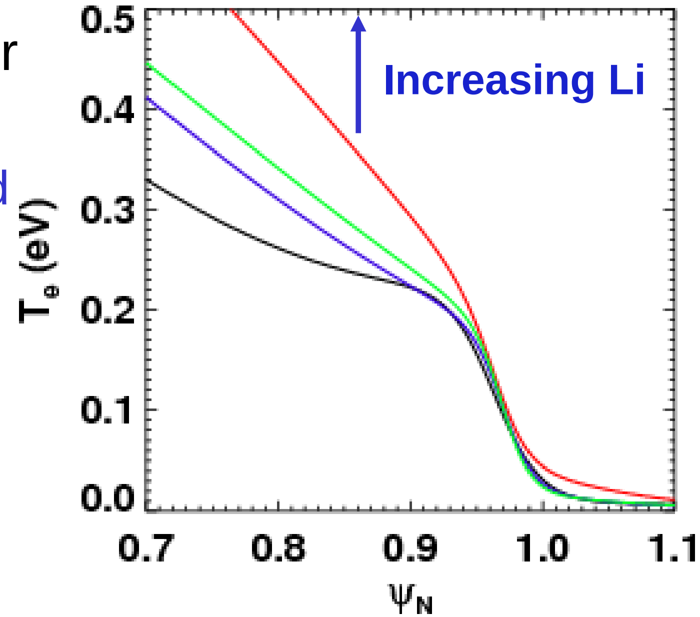
Transport barrier widens with lithium coatings, broadening pedestal

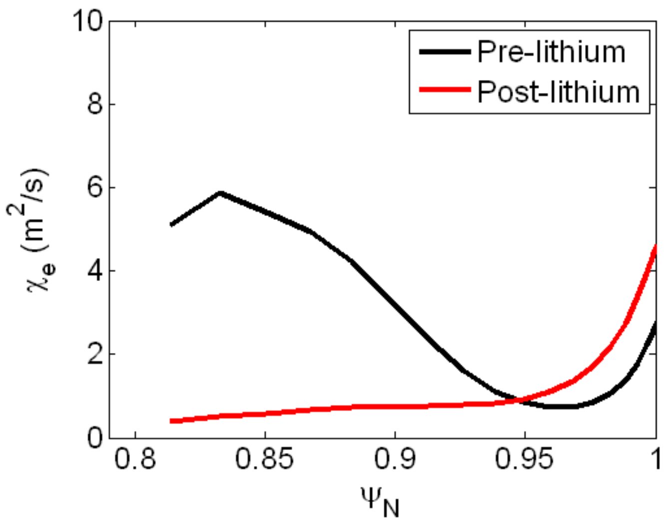
- Two regions considered
  - Top of pedestal
    - Large transport reduction
  - Bottom of pedestal
    - Transport similar with lithium

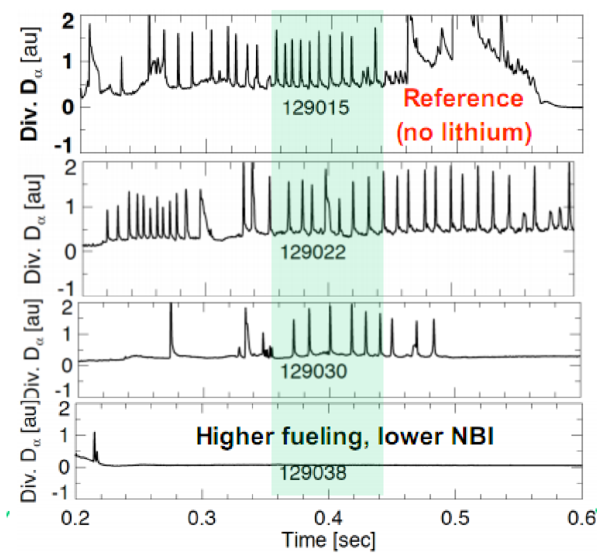


Outer region: T_e gradient nearly constant outside of Ψ_N~0.95

- 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

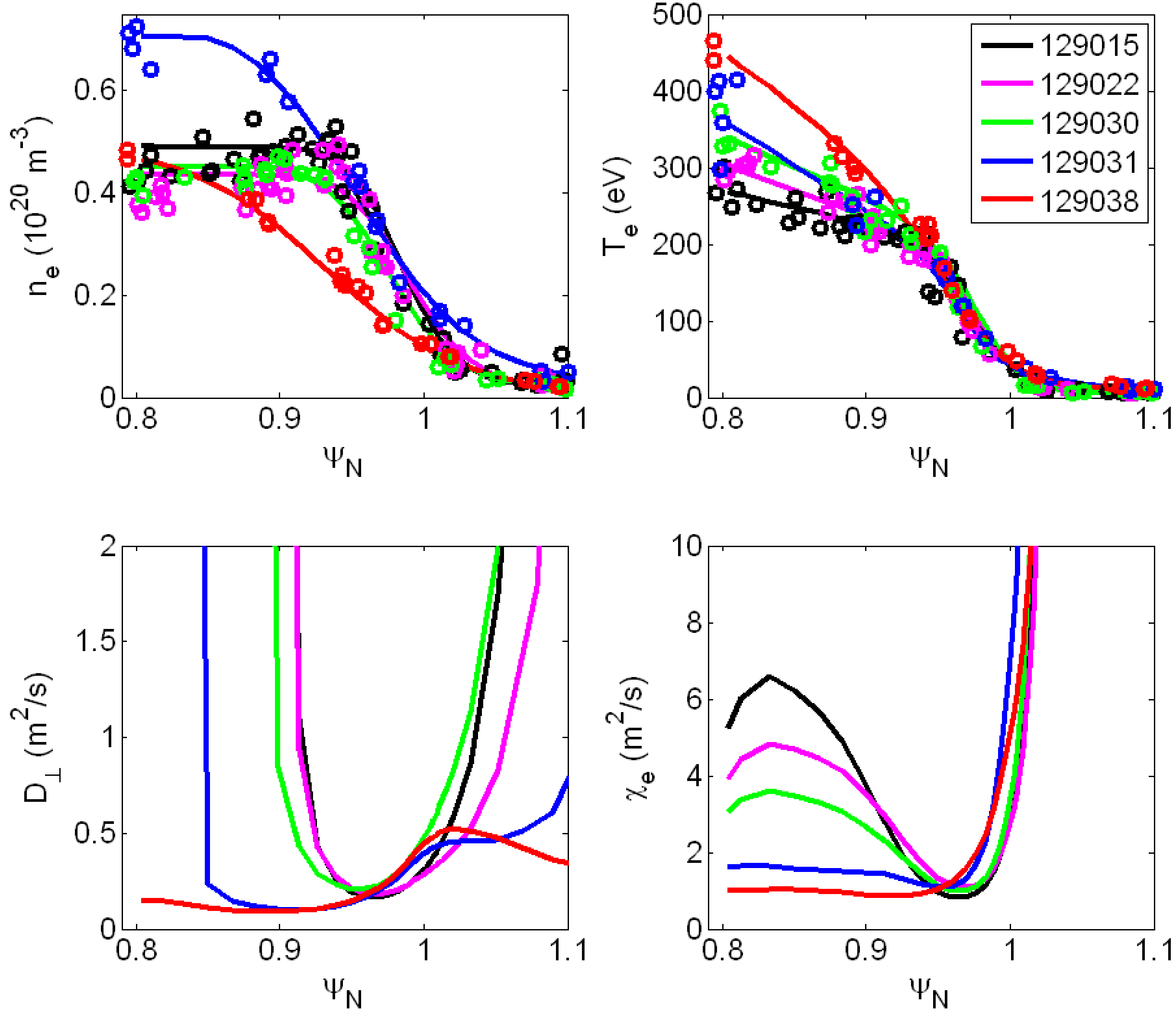






Inner region: as lithium coatings thicken, density barrier widens, pedestal-top χ_e reduced

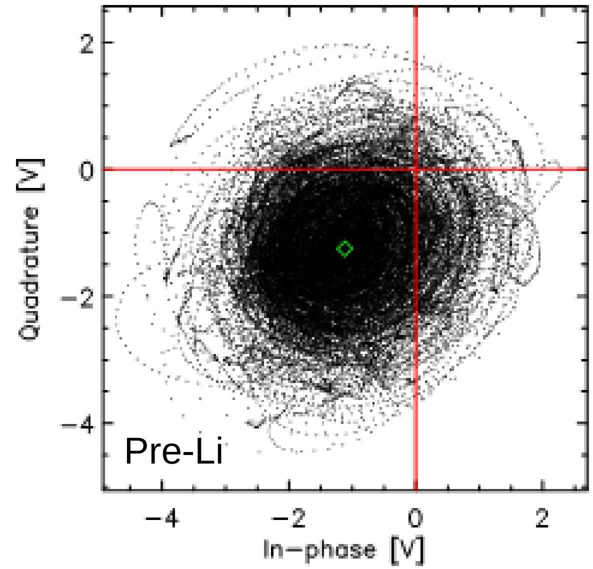
- Several shots analyzed with increasing lithium thickness
- ELMy to reduced frequency to ELM-free

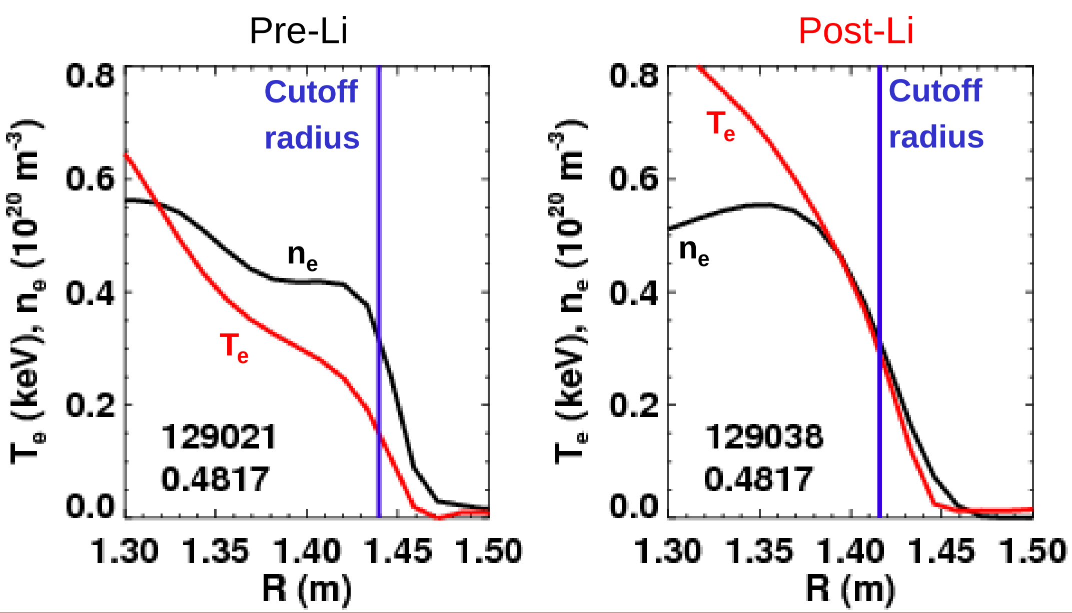


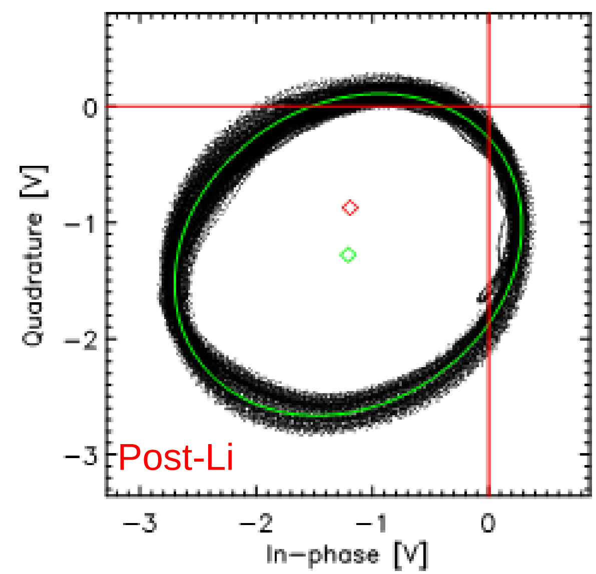
- Barrier in particle transport widens with lithium thickness
- χ_e inside Ψ_N~0.95 gradually reduced

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 and phase fluctuations
  - Post-lithium: little amplitude fluctuation
  - 3D simulations using Kirchoff integral indicate turbulence level reduced from ~10% to ~1% with lithium

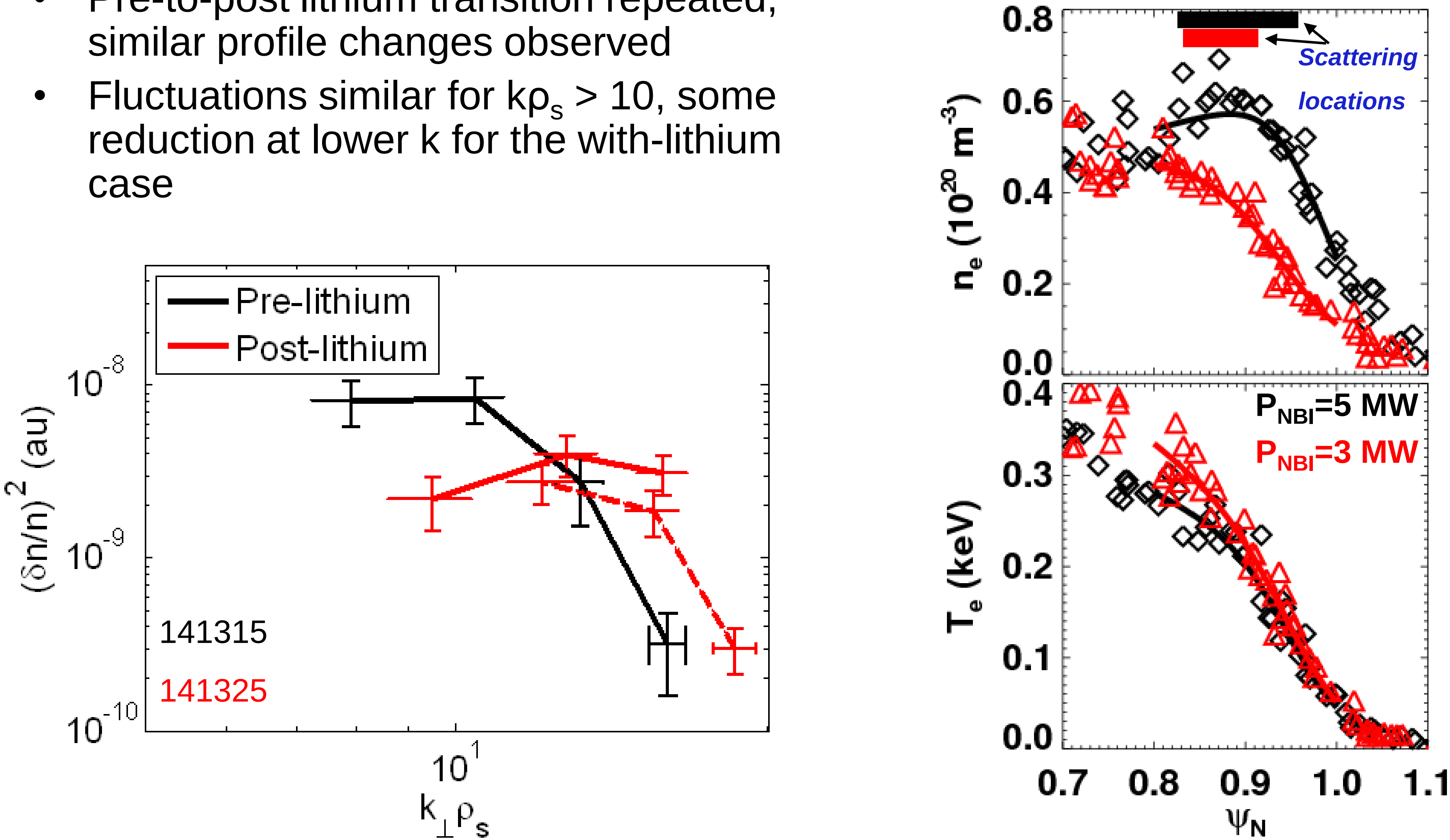






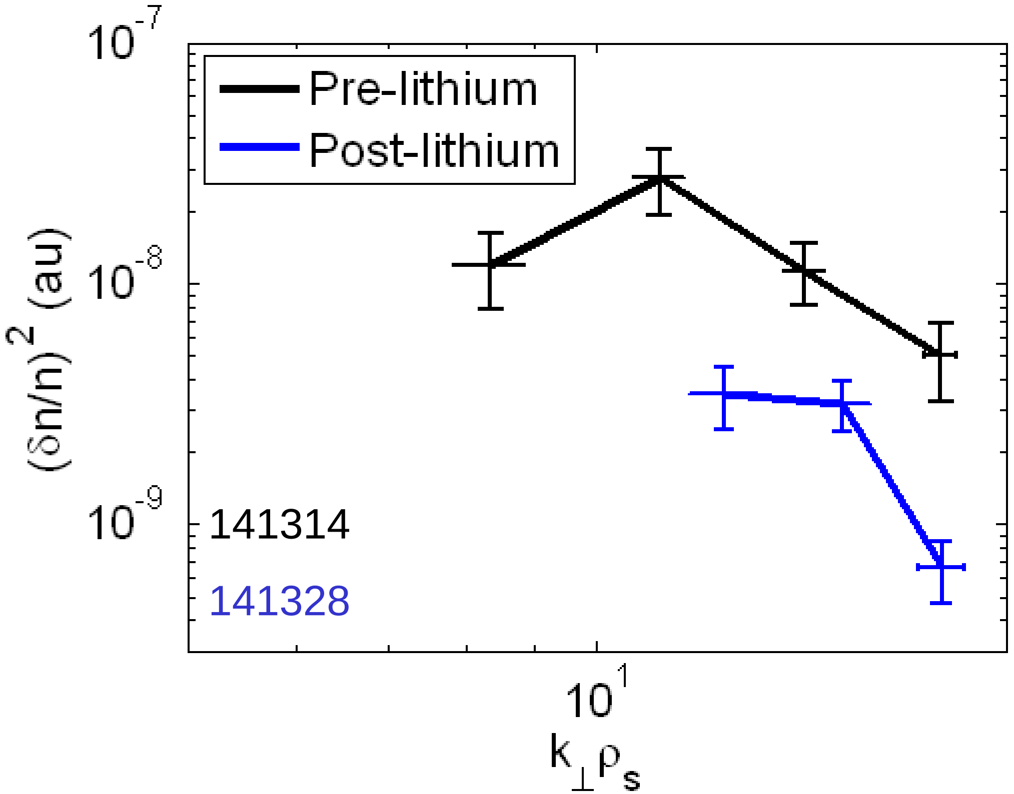
High-k scattering diagnostic shows little change in fluctuation amplitude at $k\rho_s > 10$

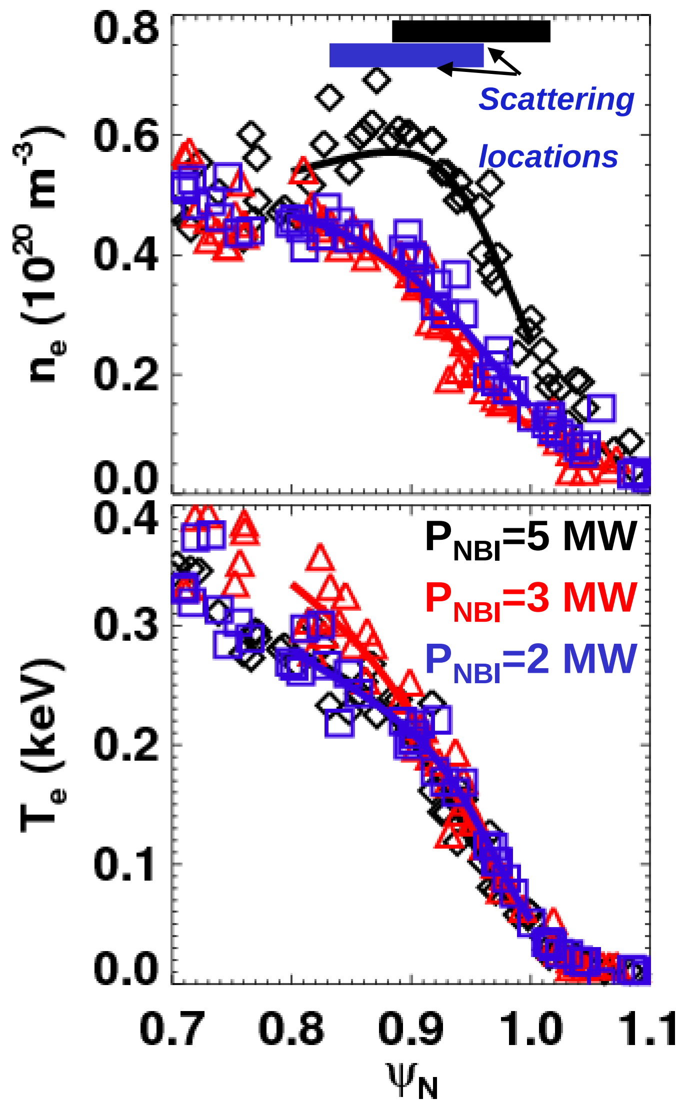
- Pre-to-post lithium transition repeated, similar profile changes observed
- Fluctuations similar for $k\rho_s > 10$, some reduction at lower k for the with-lithium case



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

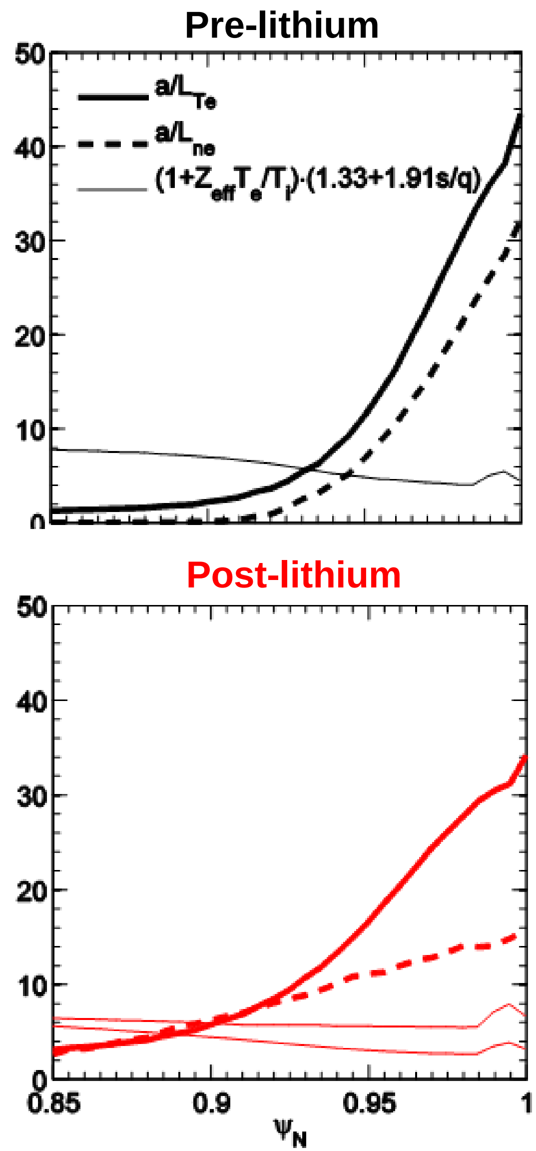
- Power reduced to 2 MW
- T_e profile similar to pre-lithium
- Fluctuation amplitude reduced across measured $k\rho_s$





ETG is unstable in steep gradient edge

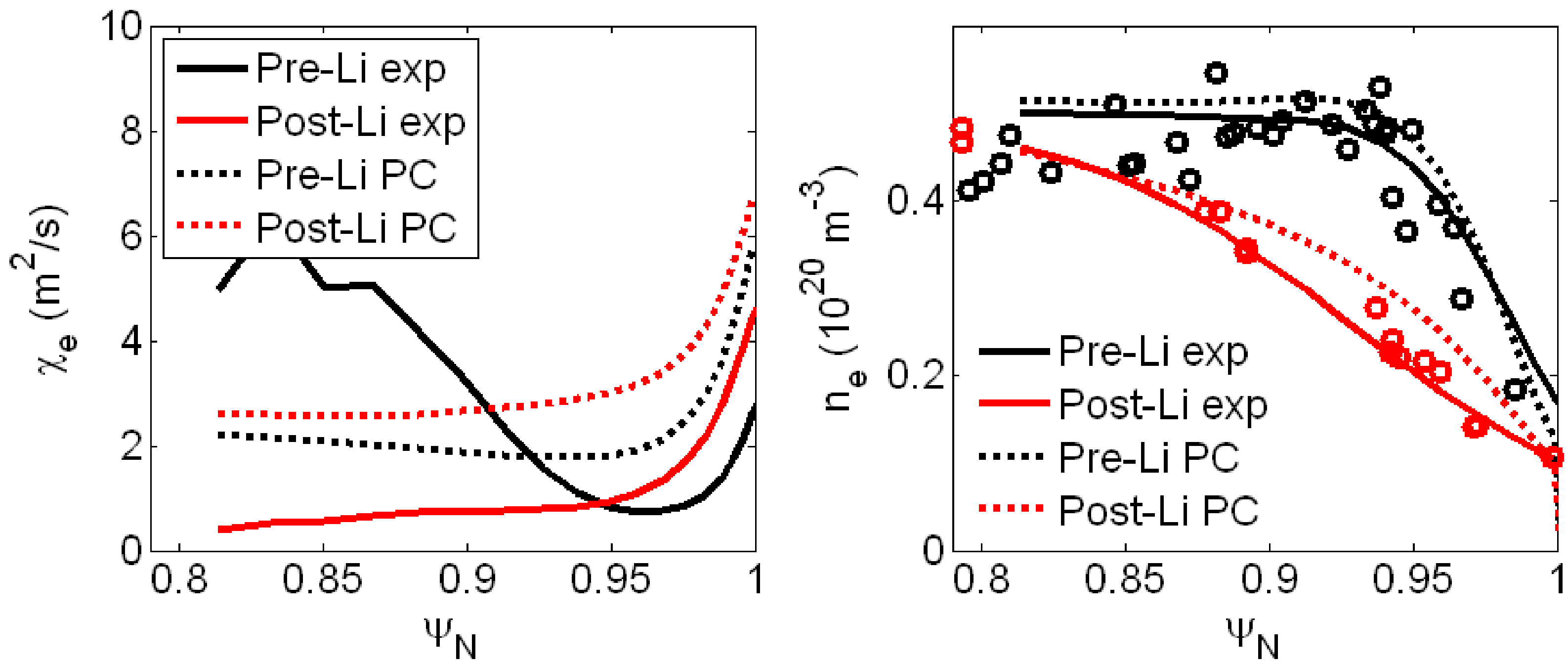
- Investigating ETG stability with GYRO [1]
  - $\chi_e \sim$ 2-5 ($\rho_e^2 v_{te}/L_{Te}$), within range of nonlinear expectations
  - Electrons satisfy gyrokinetic ordering ρ_e/L_{Te} < 1/400
- ETG unstable in steep gradient region (ψ_N > 0.92)
  - Threshold likely set by density gradient
  - $\eta_{e,crit}$ ~ 1-1.25 calculated in AUG edge [2], compared to core criteria $\eta_{e,crit}$ ~ 0.8 [3]
- ETG stable at top of pedestal (ψ_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



Edge transport is reduced, transport barrier widened with lithium coatings

- Measured pedestal profile changes with lithium are reproduced in 2-D edge modeling

- Matching midplane profiles requires change to transport coefficients in addition to recycling
  - Transport barrier widens with lithium, giving wider pedestal
  - T_e gradient relatively unchanged outside $\psi_N \sim 0.95$

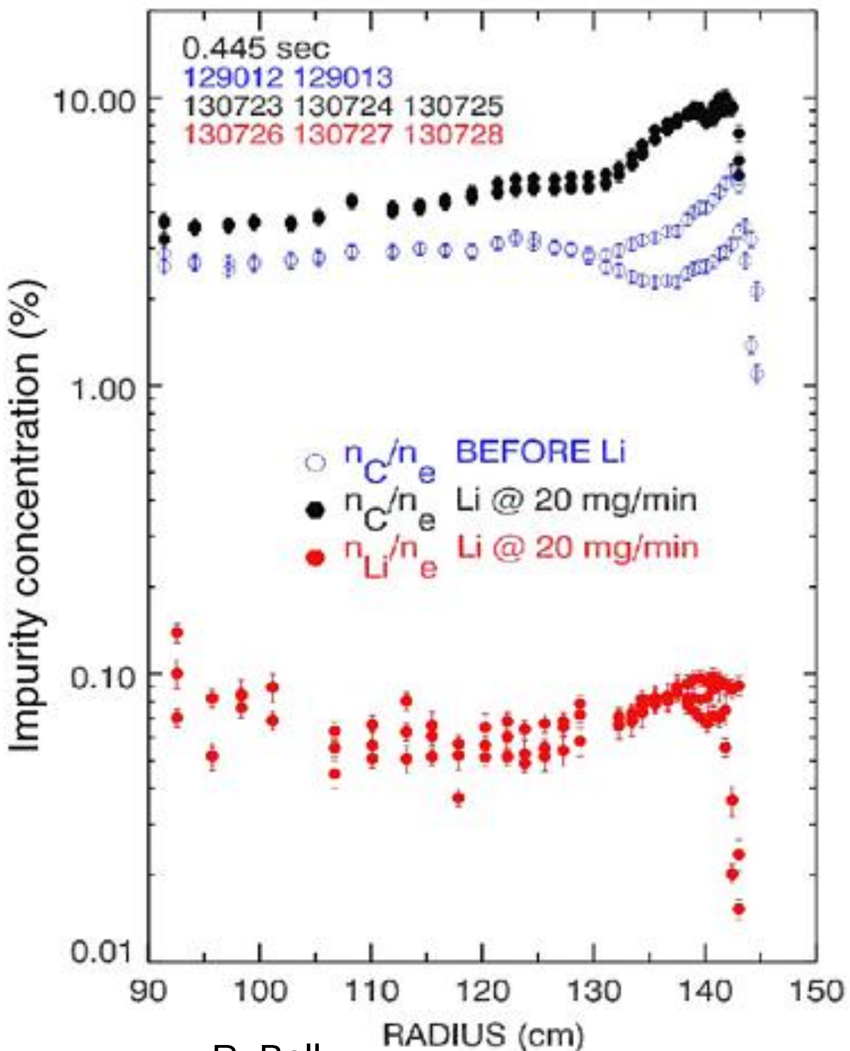
- Fluctuation measurements show reduced edge turbulence in inner pedestal region

- Future research will focus on possible transport mechanisms
  - ETG and paleoclassical possible mechanisms for edge transport

BACKUP

Carbon is the dominant impurity species with lithium coatings

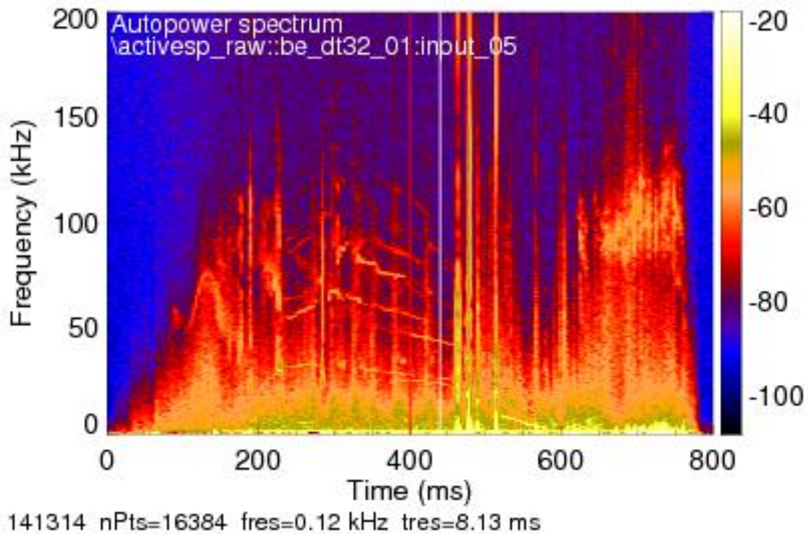
- Measured lithium concentration is much less than carbon
  - Carbon concentration ~100 times higher
  - Carbon increases when lithium coatings are applied
  - Neoclassical effect: higher Z accumulates, low Z screened out
- Increase in n_C due to lack of ELMs
  - Can be mitigated by triggering ELMs

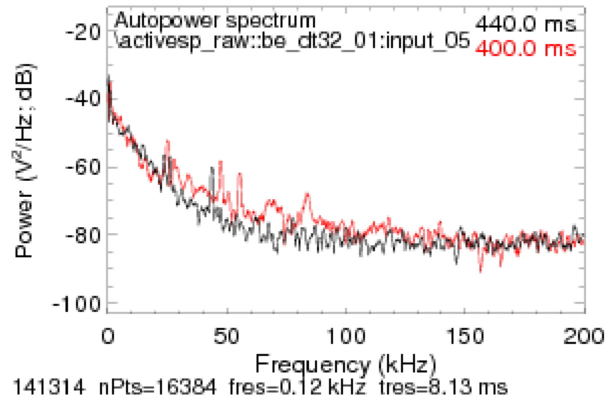


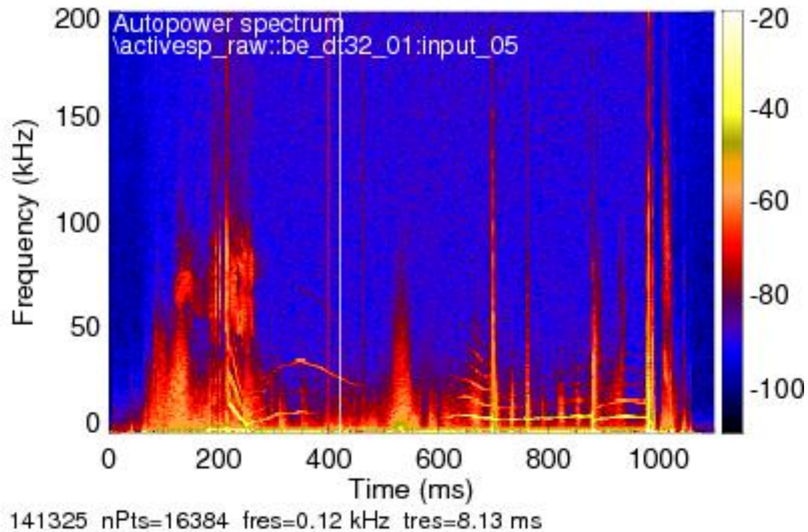
R. Bell

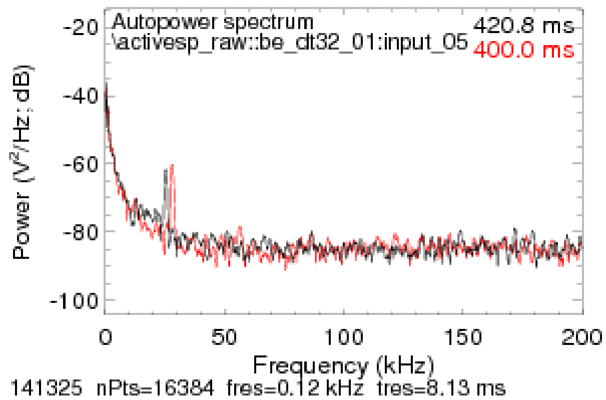
M. Bell, PPCF **51** (2009) 124054

BES also shows reduced turbulence levels in post-lithium discharges



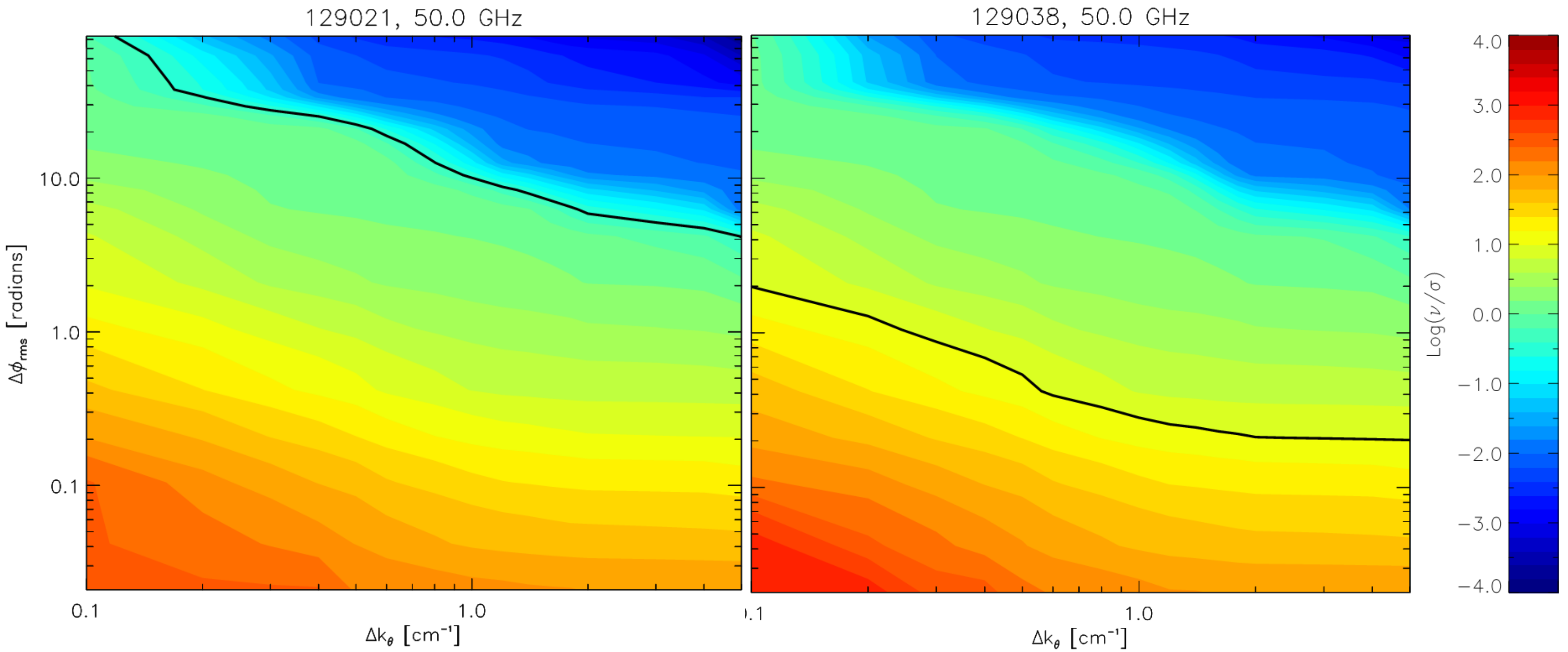






***Courtesy D.R. Smith, UW**

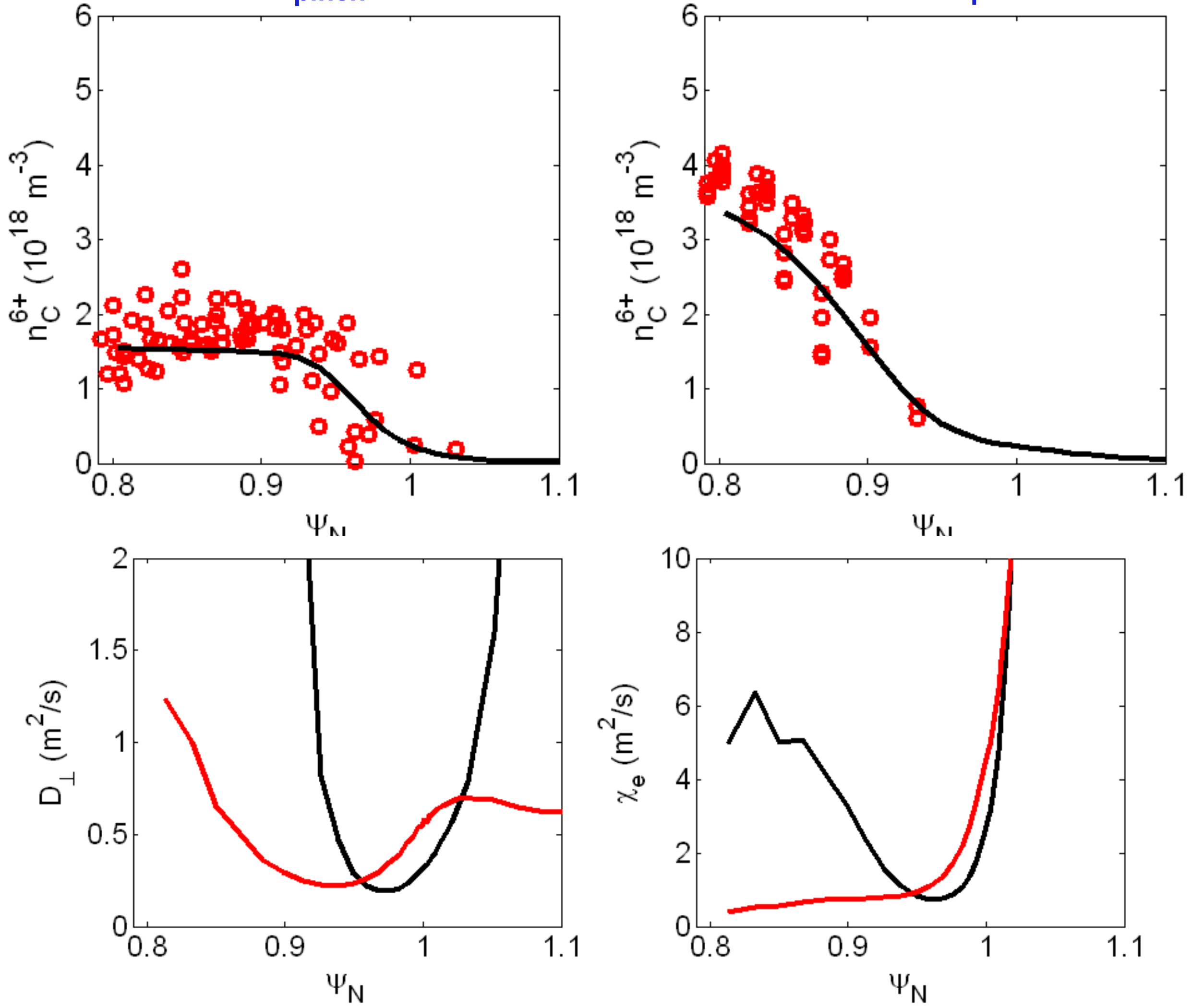
Reflectometer analysis



Carbon is included to model Z_{eff} profile

- Sputtering of carbon included, chemical sputtering yield of 2% assumed
- Same $D_\perp$ for all species; carbon species given spatially constant inward convective velocity, adjusted to match measured carbon content
- Charge state distribution calculated by SOLPS, yields an estimate of Z_{eff} for comparisons to theory
- Transport modification is qualitatively unchanged with carbon

Pre-lithium: V_{pinch} = 20 m/s **Post-lithium: V_{pinch} = 15 m/s**



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

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  - 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