NSTX-U

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The nearly continuous improvement of discharge characteristics and edge stability with increasing lithium coatings in NSTX

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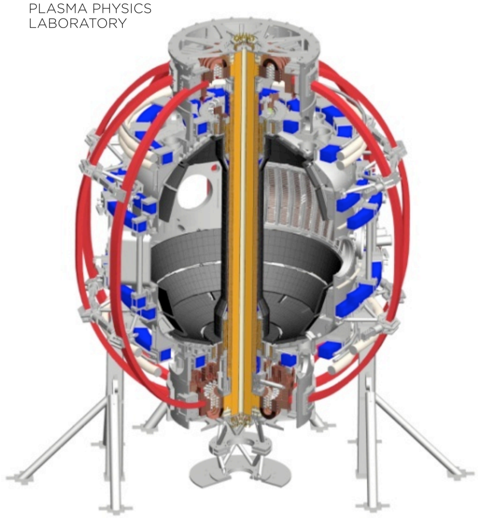
24th IAEA Fusion Energy Conference

8-13 October 2012, San Diego, CA

PPPL PRINCETON PLASMA PHYSICS LABORATORY



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Power and particle exhaust a key challenge for future devices

- Liquid metals are being studied at PPPL as an alternative to solid PFCs for future devices
- NSTX used lithium wall coatings (evaporative and liquid) to test the efficacy of lithium in particle and power exhaust
  - Lithium has effective deuterium retention -> low recycling
  - Lithium will be important research line in NSTX-Upgrade, which is scheduled to commence operation in 2014

Plasma characteristics and edge stability improved nearly continuously with increasing lithium coatings

- Lithium evaporated before discharge; amount scanned
- ELM frequency declined, and eventually went to 0

R. Maingi, PRL 2011
R. Maingi, NF 2012

- Global characteristics changed
  - Recycling: D_α declined in all measured views
  - Energy confinement (τ_E, H-factor) improved, consistent with reduced transport at lower ν^*
  - *When discharges were ELM-free, radiated power increased with time (we tested several techniques to ameliorate this problem)*

S. Kaye, EX/7-1
W. Guttenfelder, TH/6-1

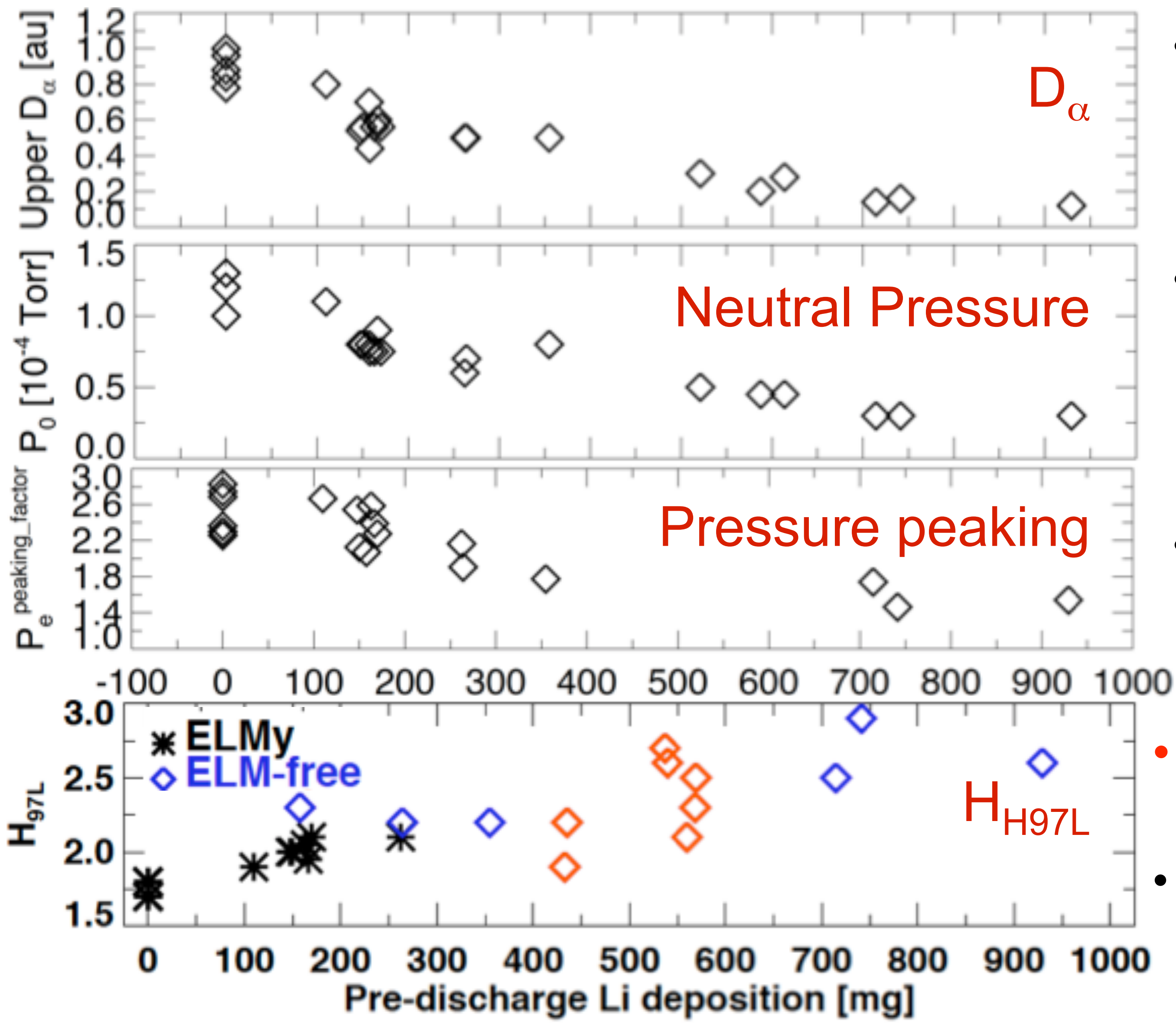
- Edge transport declined, stability improved
  - n_e, P_e and P_{tot} profile widths increased with lithium

J. Canik, EX/P7-16
J. Canik, PoP 2011
D. Boyle, PPCF 2011
C.S. Chang, TH/P4-12
A. Diallo, EX/P4-4

➢ *No liquid lithium divertor (LLD) in these experiments*

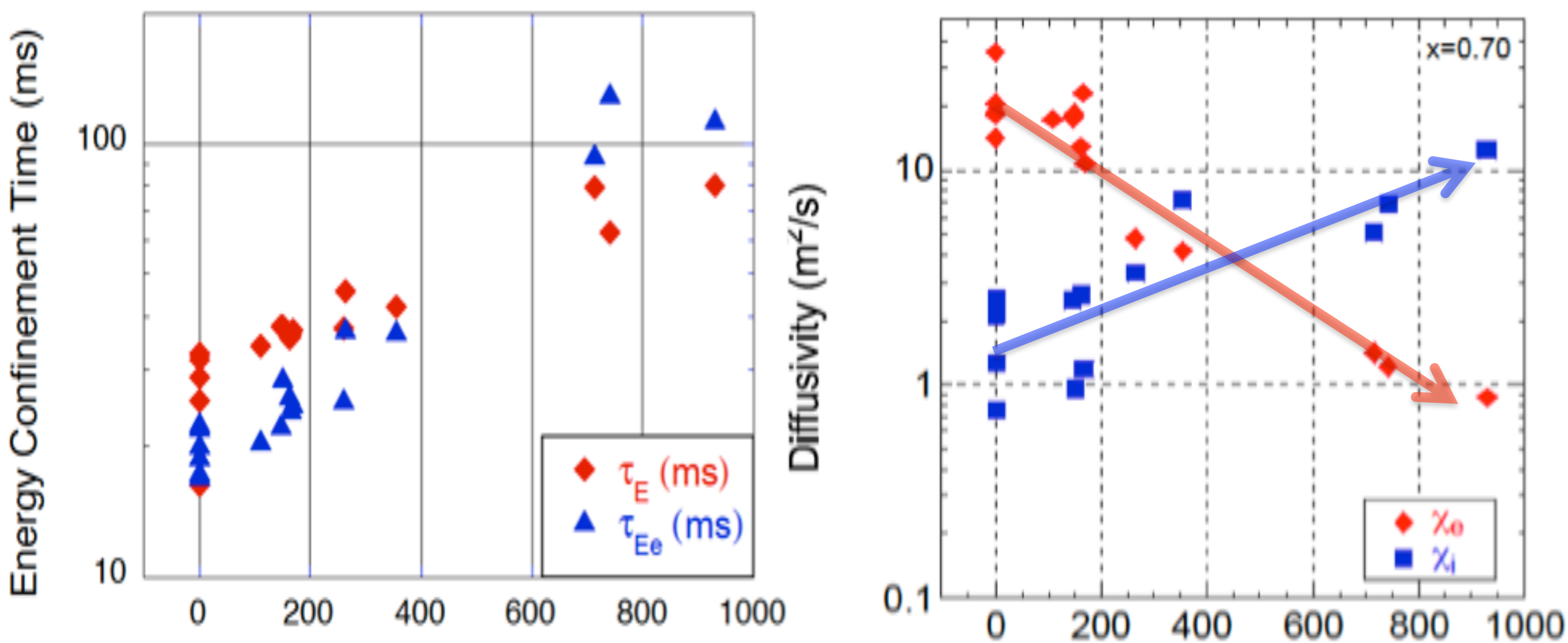
M. Jaworski, EX/P5-31

Recycling, neutral pressure, and pressure peaking decreased nearly continuously with increasing lithium; H_{H97L} increased



- R_p from SOLPS interpretive modeling went from 0.98 to 0.9
- Dropped by ~ 80%
- Dropped by ~ 50%
- **H_{H98y2} range from 0.8-1.4**
- Data in orange from other experiment

Energy confinement increased and edge electron transport decreased with pre-discharge lithium evaporation



Pre-discharge lithium deposition (mg)

- Edge ion transport increased

TRANSP

R. Maingi, PRL 2011, S. Kaye, IAEA 2012 EX 7/1

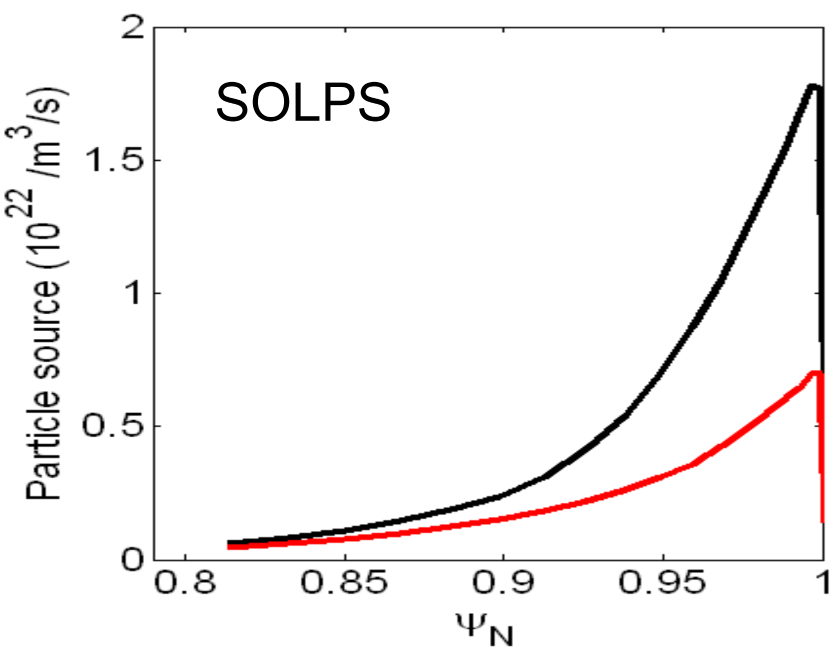
SOLPS interpretive simulations indicate particle fueling source from recycling was reduced with lithium

- Target recycling coefficient varied to match peak divertor D_{α}
- Separatrix position adjusted as needed to match divertor peak heat flux

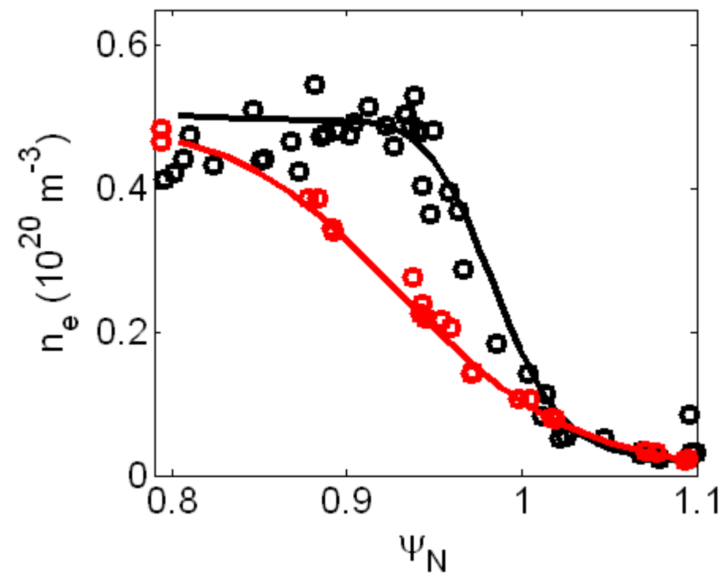
J. Canik PoP 2011

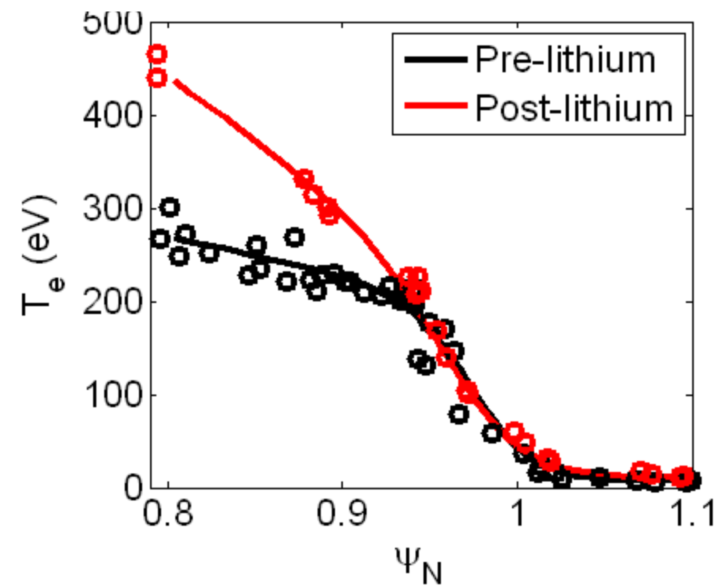
SOLPS interpretive simulations indicate particle fueling source from recycling was reduced with lithium

- Target recycling coefficient varied to match peak divertor D_α
- Separatrix position adjusted as needed to match divertor peak heat flux
- Radial profile of D_{eff}, χ_e^{eff}, χ_i^{eff} varied to match midplane n_e, T_e, T_i, for the computed recycling source profile



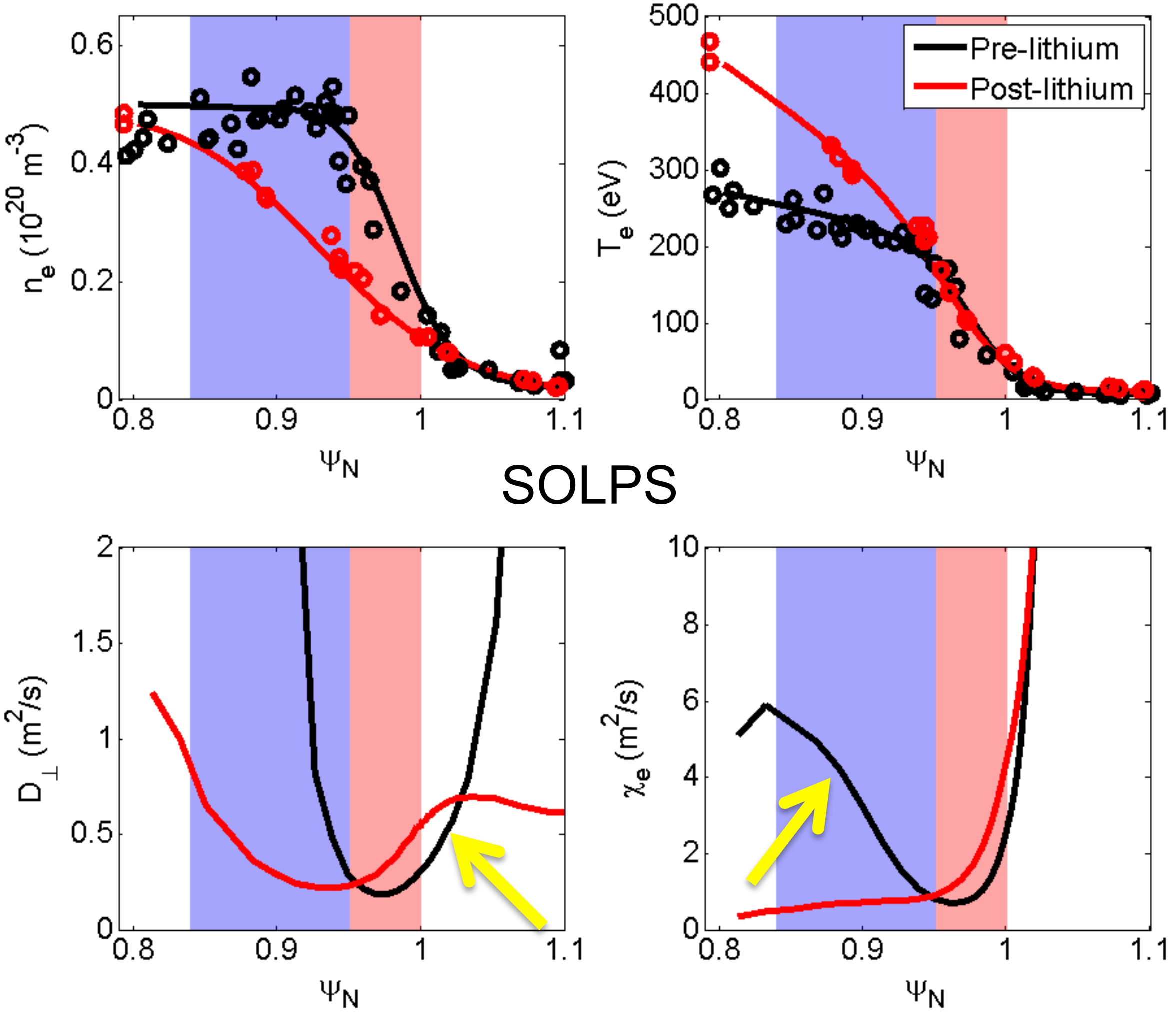
J. Canik PoP 2011





SOLPS interpretive simulations indicate transport barrier widens with lithium coatings, broadening pedestal

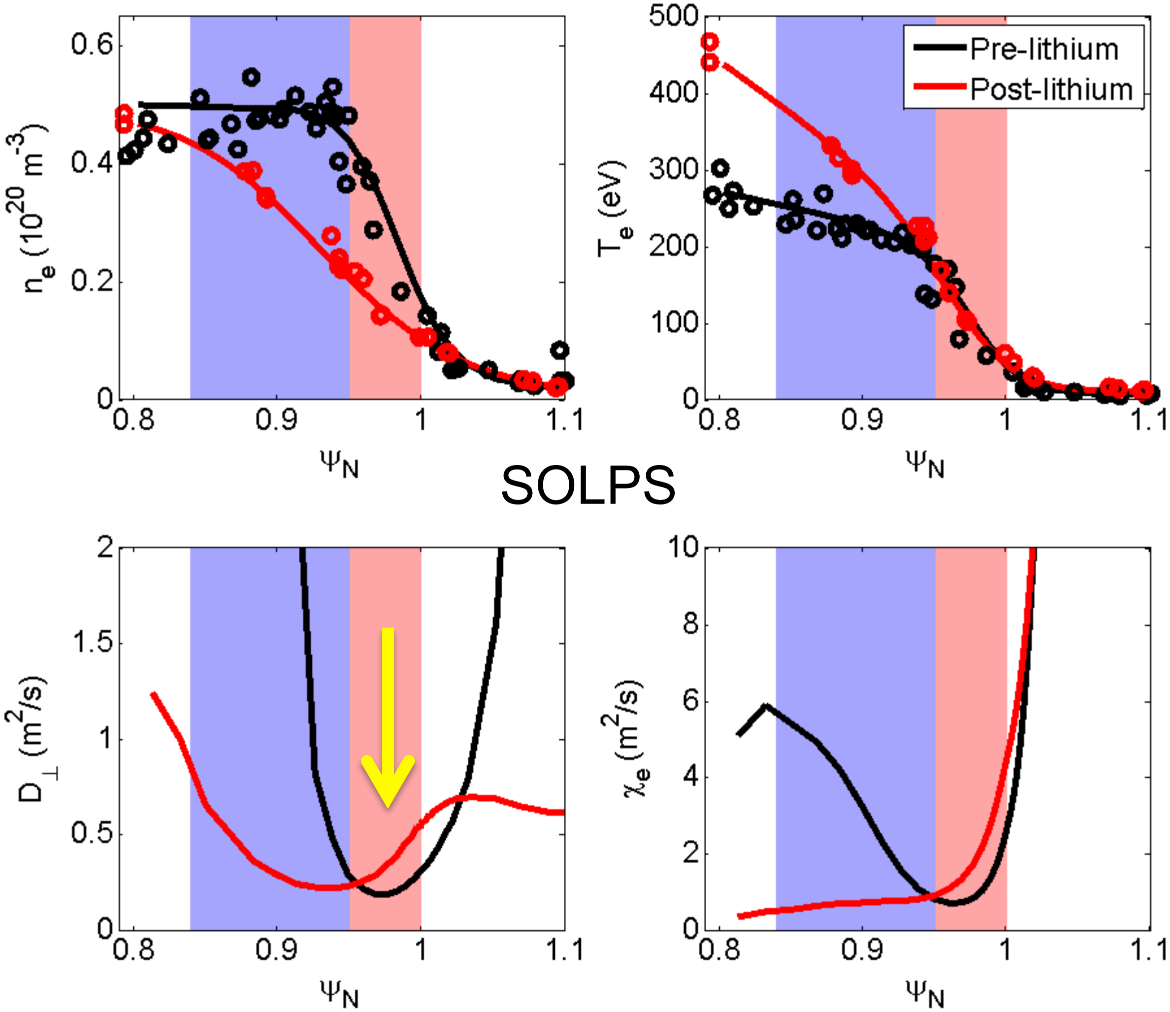
- Pre-lithium case shows typical barrier region inside separatrix



SOLPS interpretive simulations indicate transport barrier widens with lithium coatings, broadening pedestal

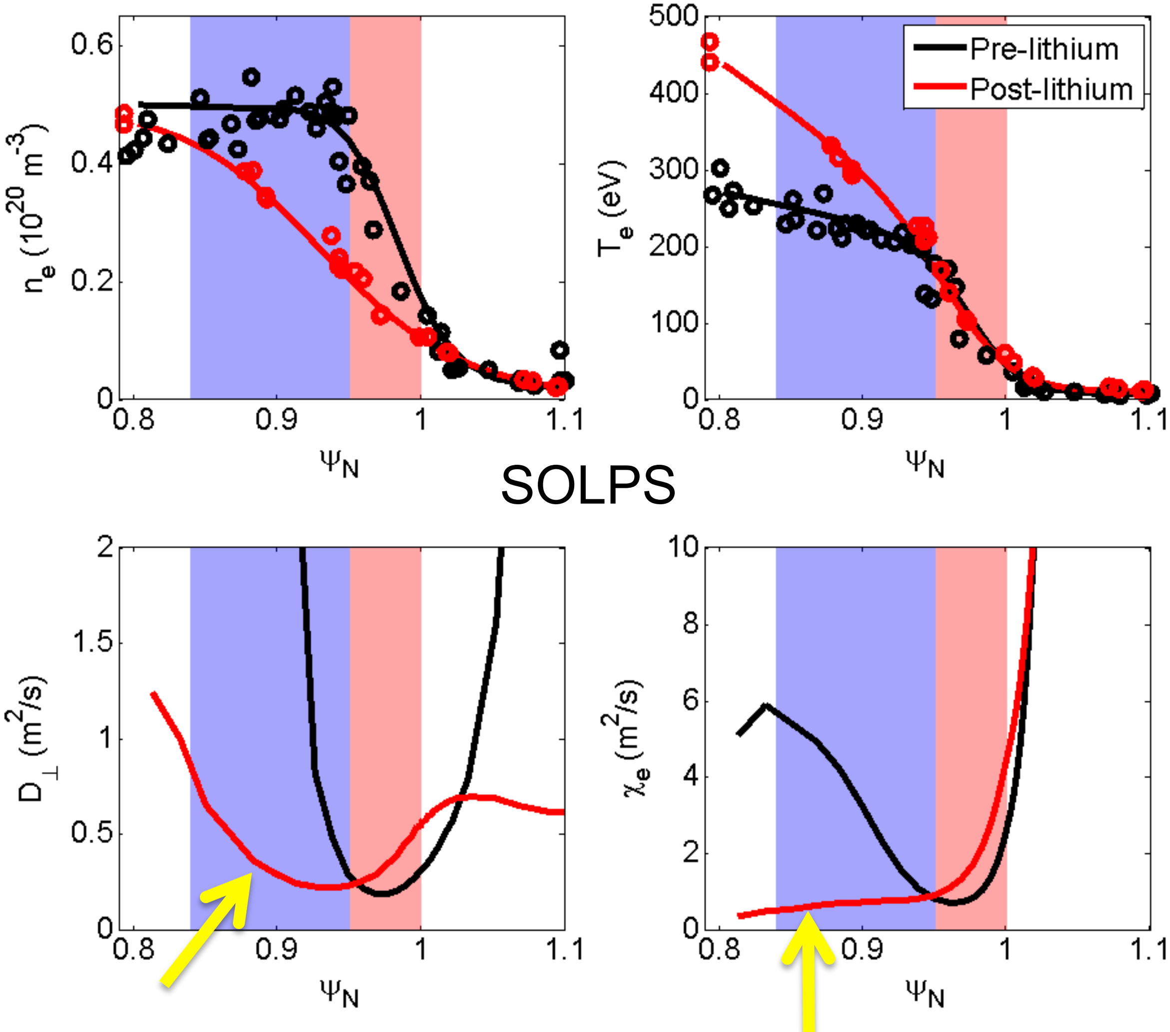
- Pre-lithium case shows typical barrier region inside separatrix
- Change in n_e profile with lithium from $0.95<\psi_N<1$ consistent with drop in fueling at ~ constant transport

(red shaded region)



SOLPS interpretive simulations indicate transport barrier widens with lithium coatings, broadening pedestal

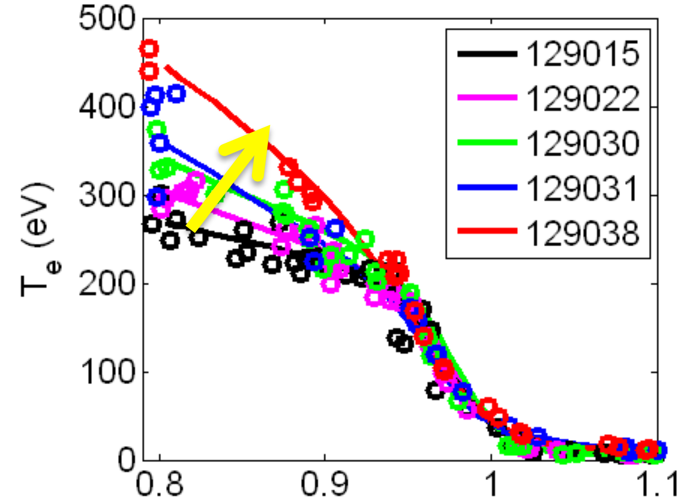
- Pre-lithium case shows typical barrier region inside separatrix
- Change in n_e profile with lithium from $0.95<\psi_N<1$ consistent with drop in fueling at ~ constant transport
- Pedestal is much wider with lithium
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)

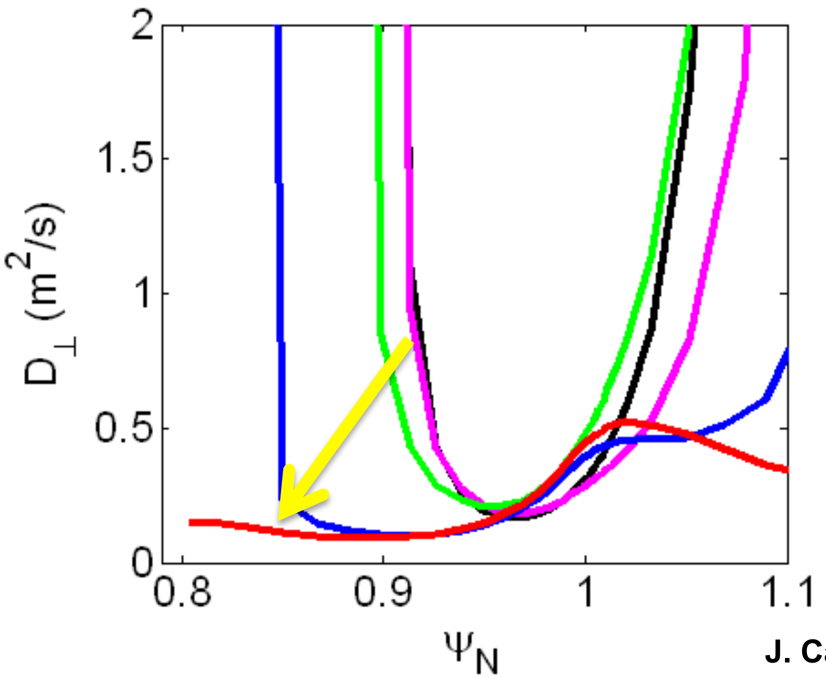


J. Canik PoP 2011

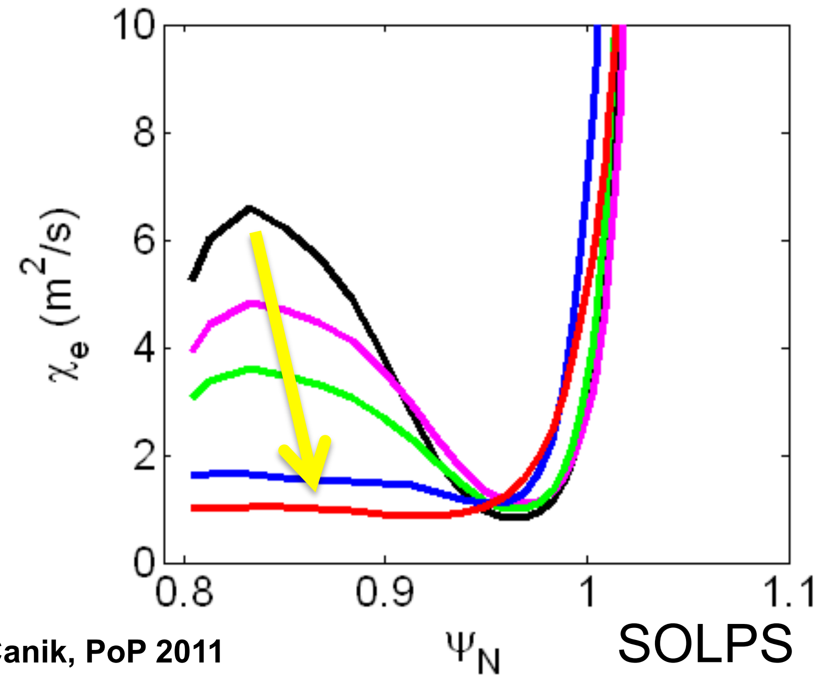
Transport barrier widens continuously with increasing pre-discharge lithium, i.e. pedestal-top D, χ_e reduced

- Several shots analyzed with SOLPS with increasing lithium (direction of arrow)
- First three discharges were ELMy, last two ELM-free
- T_e gradient clamped in last 5% of ψ_N, but increased from ψ_N=0.8-0.95



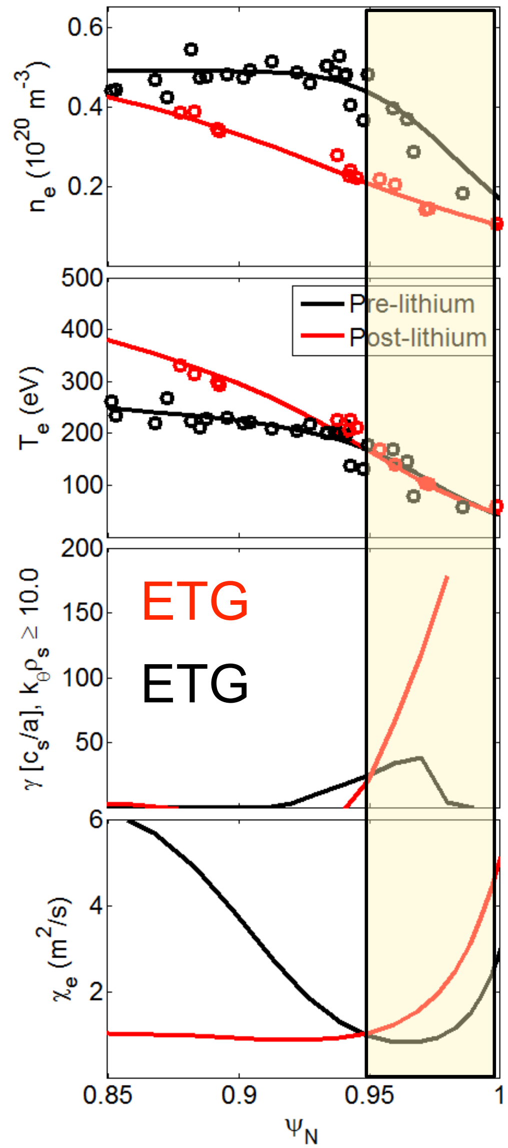


J. Canik, PoP 2011



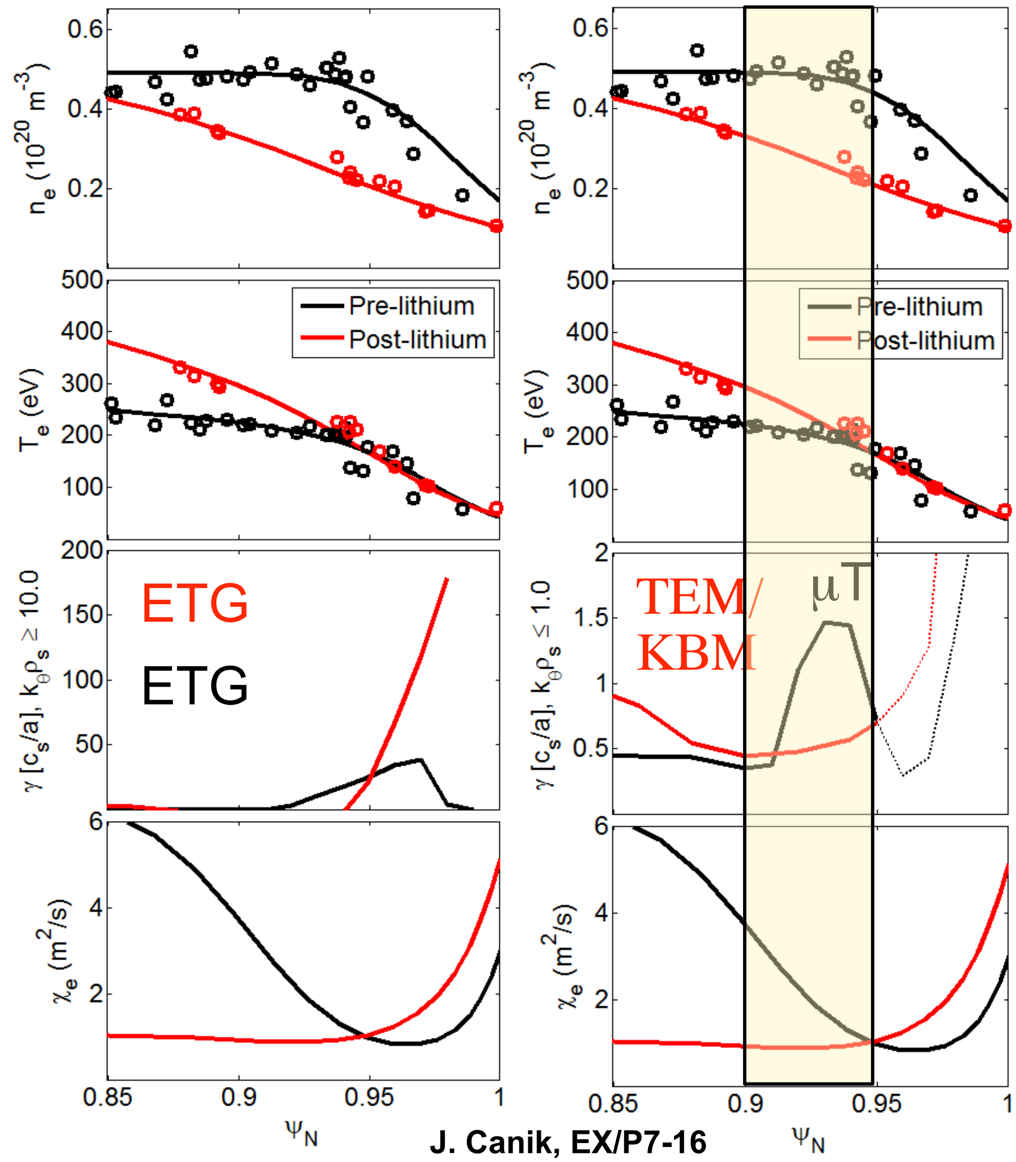
Work in progress: change in edge density gradient with lithium coatings alters the edge micro-stability properties

- From ψ_N = 0.95-1, n_e gradient reduced with lithium
  - ➢ ETG more unstable, correlates with higher χ_e



Work in progress: change in edge density gradient with lithium coatings alters the edge micro-stability properties

- From ψ_N = 0.95-1, n_e gradient reduced with lithium
  - ➢ ETG more unstable, correlates with higher χ_e
- From ψ_N = 0.8-0.95, n_e gradient increased with lithium
  - ➢ μT (micro-tearing modes) more stable over outer part of range, correlates with lower χ_e
- Similar to analysis by Dickinson on MAST (e.g. Roach, TH/5-1)



J. Canik, EX/P7-16

Work in progress: change in edge density gradient with lithium coatings alters the edge micro-stability properties

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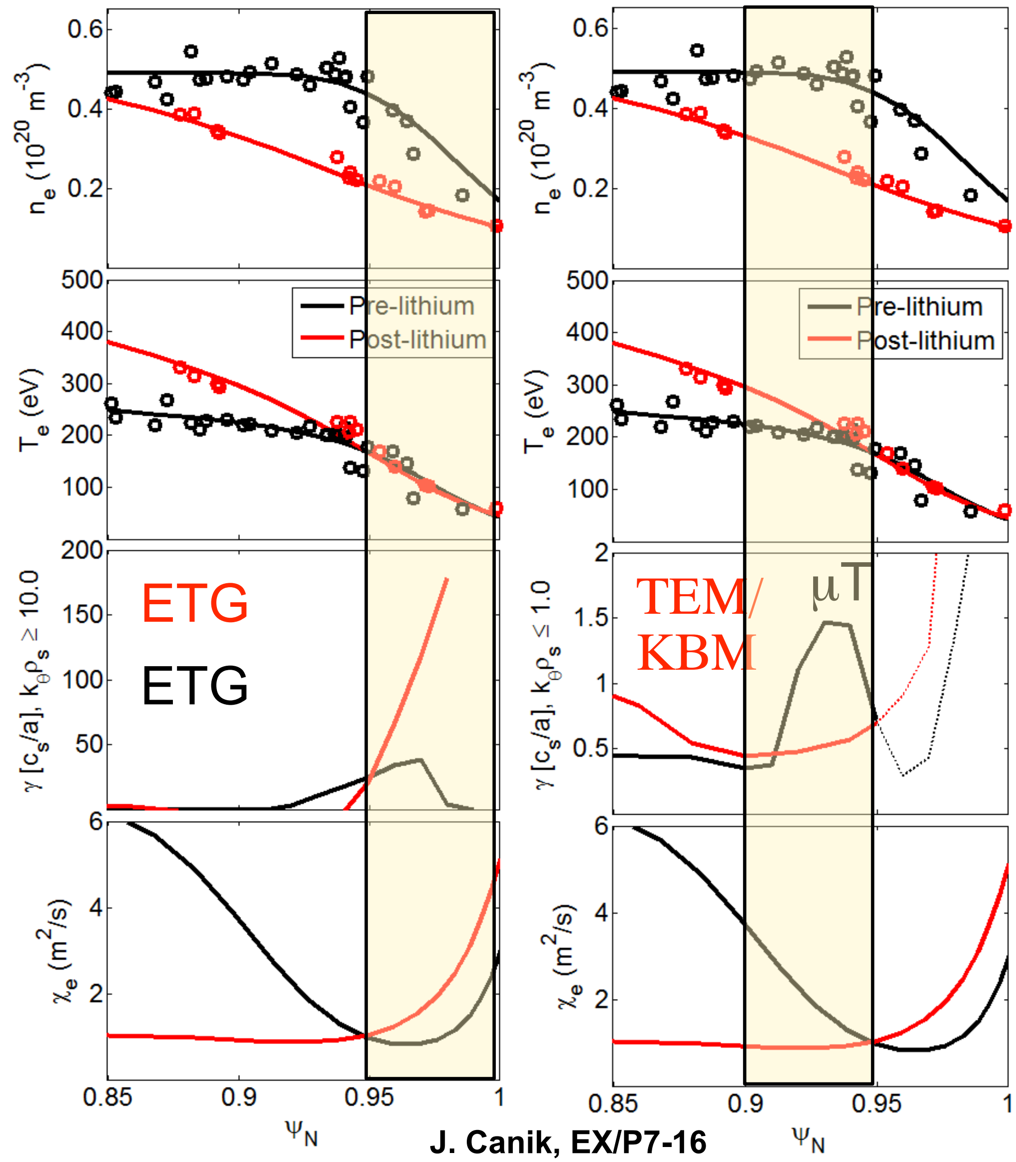
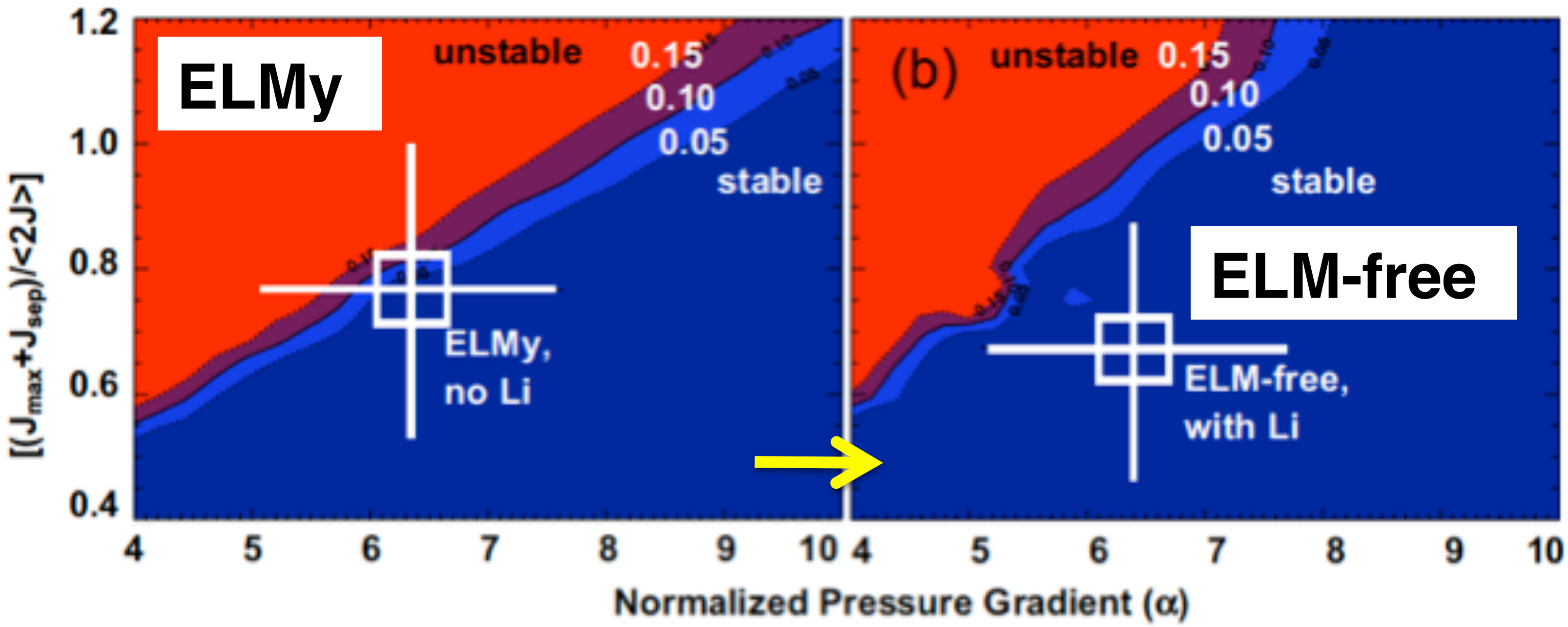
  - ➢ ETG more unstable, correlates with higher χ_e
- From ψ_N = 0.8-0.95, n_e gradient increased with lithium
  - ➢ μT more stable over outer part of range, correlates with lower χ_e
- Both μT and ETG are plausible candidates – drive transport in electron channel
- E x B shear rate higher w/Li
- These are linear GS2 calcs – need non-linear calcs for actual heat flux



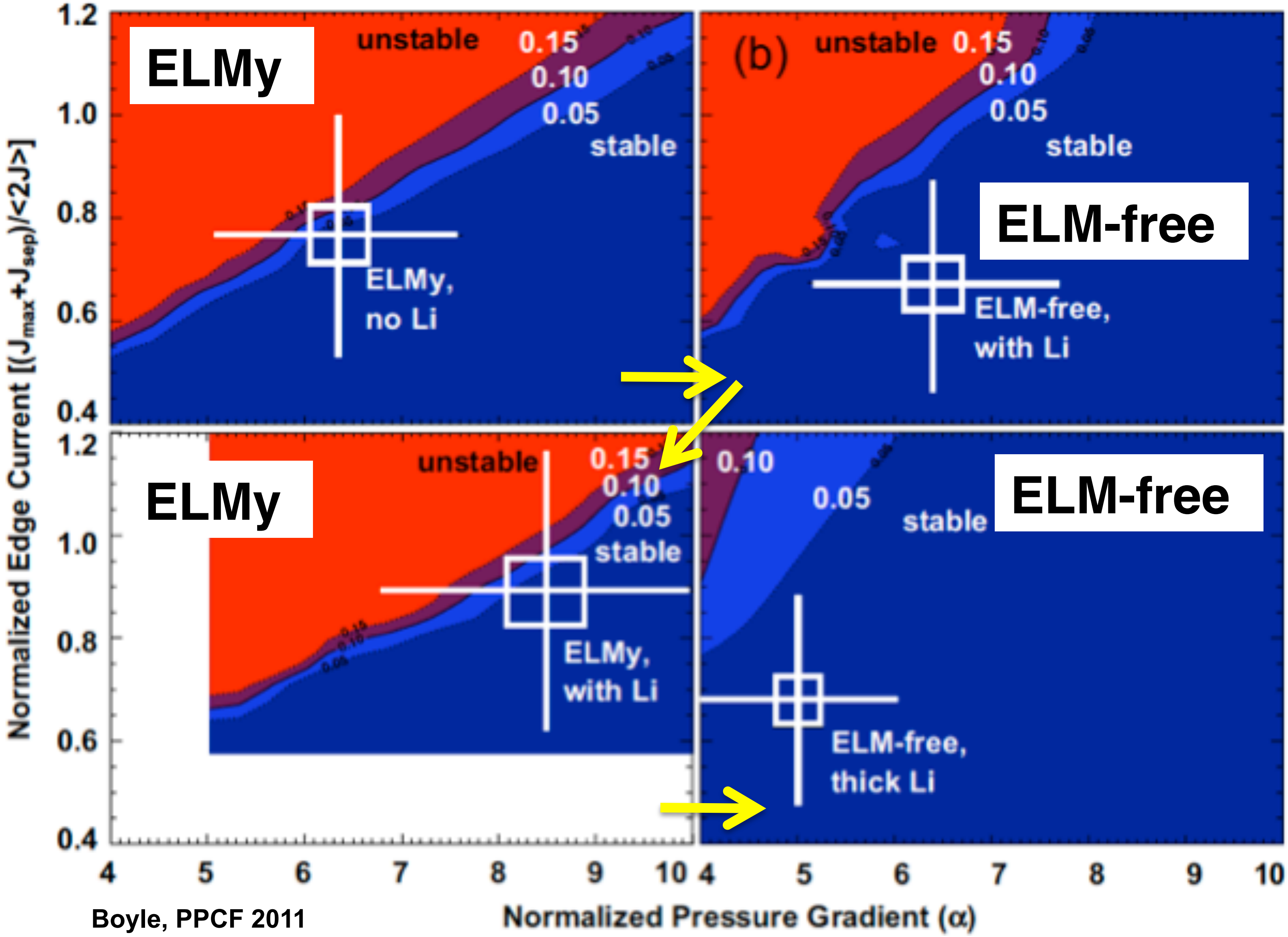
J. Canik, EX/P7-16

ELMy discharges closer to kink/peeling stability boundary than ELM-free ones



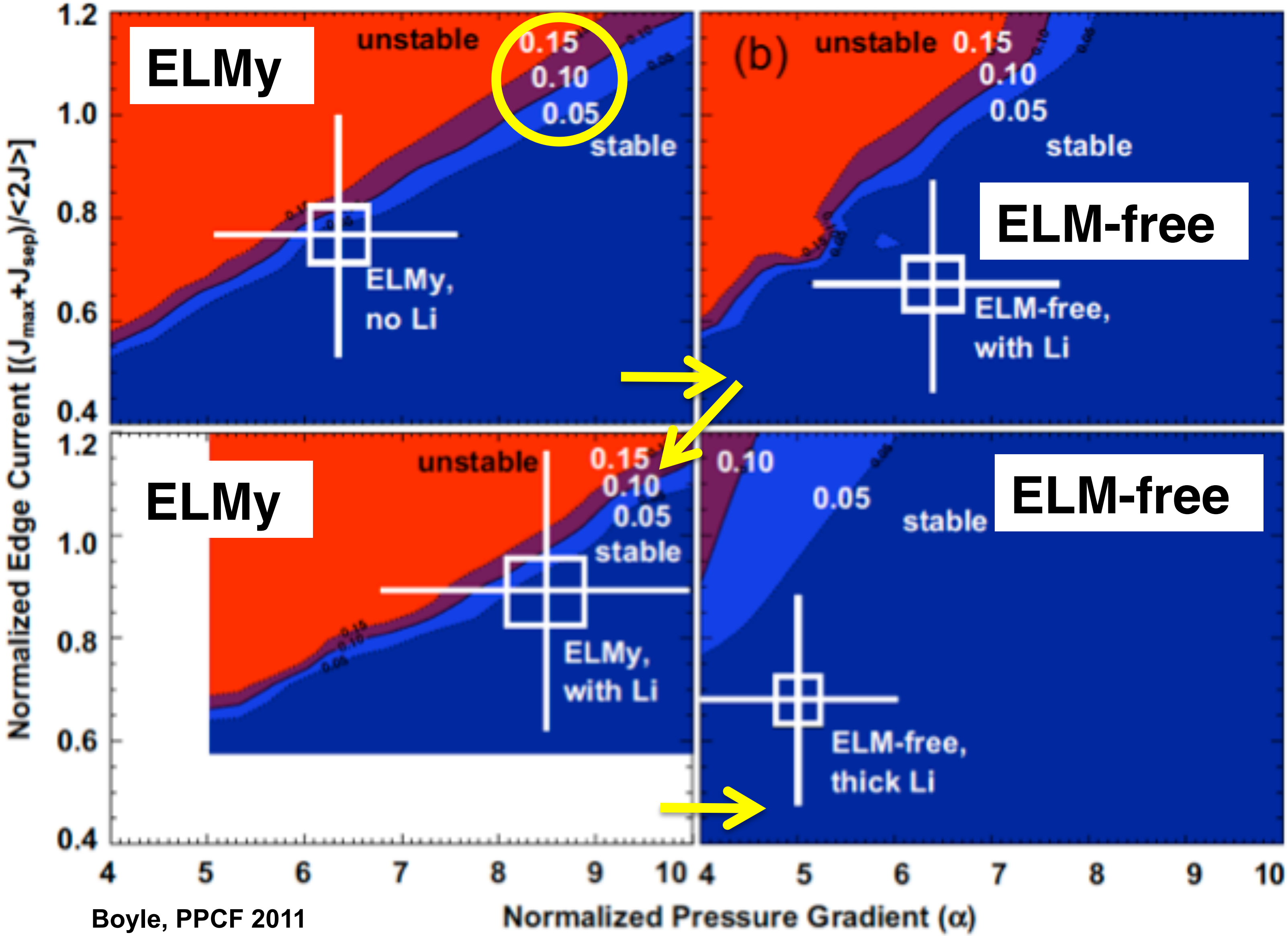
Boyle, PPCF 2011

ELMy discharges closer to kink/peeling stability boundary than ELM-free ones



Boyle, PPCF 2011

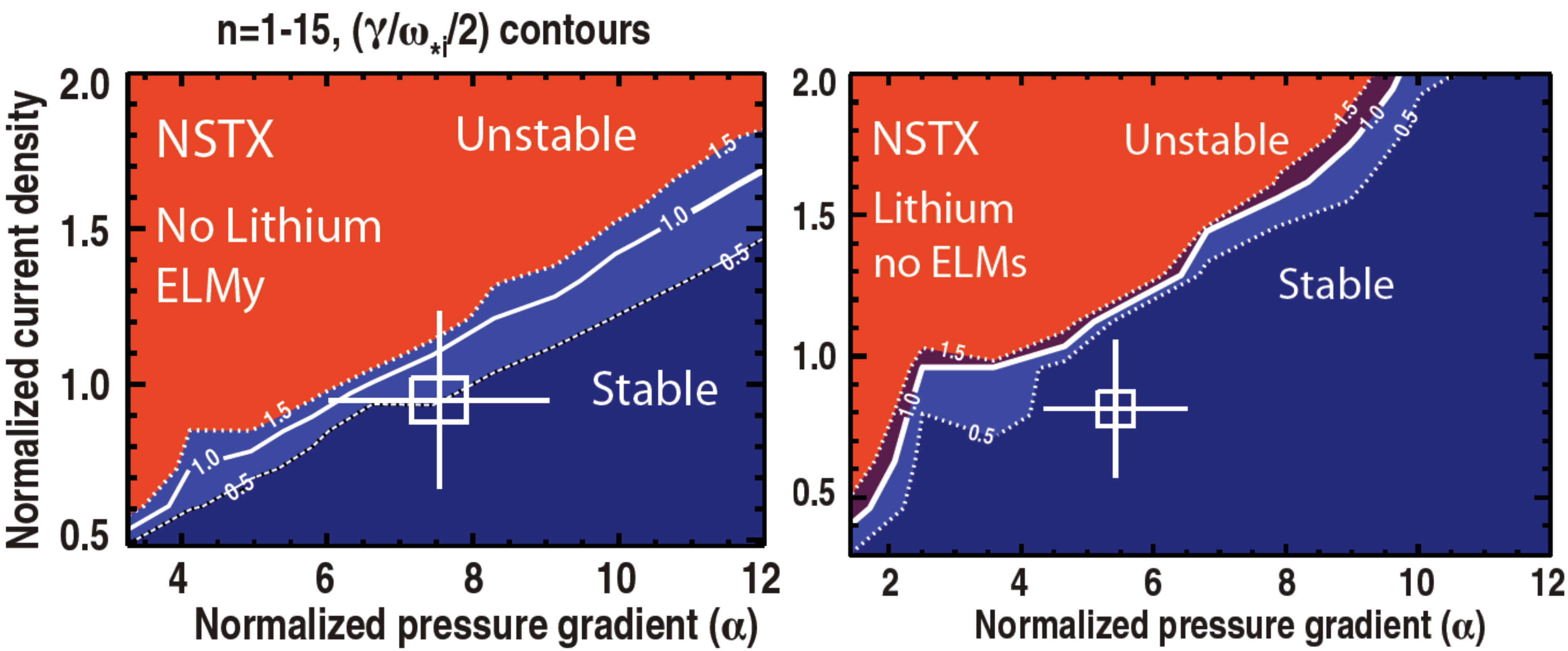
Ideal growth rates low: why instabilities not stabilized by diamagnetic flow?



Boyle, PPCF 2011

Revised bootstrap current calculation from XGC and extended ELITE calculation (n=1-15) increased growth rates

- ELMy discharges at the ideal instability boundary
- ELM-free discharges still in stable operating space



Groebner, EX/11-4

XGC: C.S. Chang, TH/P4-12

Flowchart broken up into outer (recycling) zone and inner zone

ψ_N from 0.95-1 (recycling region)

ψ_N from 0.8-0.94

What is the role of lithium? To reduce recycling and associated fueling

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

ψ_N from 0.8-0.94

Flowchart

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS) ⇨ n_e and ∇n_e reduced

∇T_e clamped – ETG? (GS2)

ψ_N from 0.8-0.94

Flowchart

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

→

n_e and ∇n_e reduced

∇T_e clamped – ETG? (GS2)

→

n_e, P_e gradient reduced

P_i gradient unchanged

ψ_N from 0.8-0.94

Flowchart

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

→

n_e and ∇n_e reduced

∇T_e clamped – ETG? (GS2)

→

n_e, P_e gradient reduced

P_i gradient unchanged

→

J_{bs}, $J_{||}$ reduced - stabilizing (ELITE)

ψ_N from 0.8-0.94

Flowchart

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)	n_e and ∇n_e reduced ∇T_e clamped – ETG? (GS2)	n_e, P_e gradient reduced P_i gradient unchanged	J_{bs}, $J_{\|\|}$ reduced - stabilizing (ELITE)

ψ_N from 0.8-0.94

D_{eff} reduced, most in ELM-free (SOLPS)

Flowchart

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

→

n_e and ∇n_e reduced

∇T_e clamped – ETG? (GS2)

→

n_e, P_e gradient reduced

P_i gradient unchanged

→

J_{bs}, $J_{||}$ reduced - stabilizing (ELITE)

ψ_N from 0.8-0.94

D_{eff} reduced, most in ELM-free (SOLPS)

→

n_e and ∇n_e T_e and ∇T_e increased

χ_e reduced strongly – μT stable? (GS2)

Flowchart

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

n_e and ∇n_e reduced

∇T_e clamped – ETG? (GS2)

n_e, P_e gradient reduced

P_i gradient unchanged

J_{bs}, $J_{||}$ reduced - stabilizing (ELITE)

ψ_N from 0.8-0.94

D_{eff} reduced, most in ELM-free (SOLPS)

n_e and ∇n_e T_e and ∇T_e increased

χ_e reduced strongly – μT stable? (GS2)

Edge P_e follows n_e and T_e; peak P' shifts farther from separatrix

First key step is recycling reduction with lithium

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

→

n_e and ∇n_e reduced

∇T_e clamped – ETG? (GS2)

→

n_e, P_e gradient reduced

P_i gradient unchanged

→

J_{bs}, $J_{||}$ reduced - stabilizing (ELITE)

ψ_N from 0.8-0.94

D_{eff} reduced, most in ELM-free (SOLPS)

→

n_e and ∇n_e T_e and ∇T_e increased

χ_e reduced strongly – μT stable? (GS2)

→

Edge P_e follows n_e and T_e; peak P' shifts farther from separatrix

→

J_{bs}, $J_{||}$ increased but far from separatrix; improves stability to kink/peeling modes (ELITE)

The observed 'continuous' dependence was surprising, because we expected only the top monolayers to play a role

- Result surprising because nominal divertor film thicknesses of 60-500 nm obtained during the lithium evaporation scan
- Calculations for NSTX divertor shows ion implantation depth < 5 nm, i.e. << 60 nm – 500 nm coating thickness
  - ➢ SO: the effect should was not expected to vary for nominal film thickness > 10 nm
- Possibility uncovered by lab measurements: more lithium results in Oxygen segregation to the surface, which increases the film capacity to retain deuterium

C.N. Taylor, JNM 2011
J.P. Allain, PoP 2012

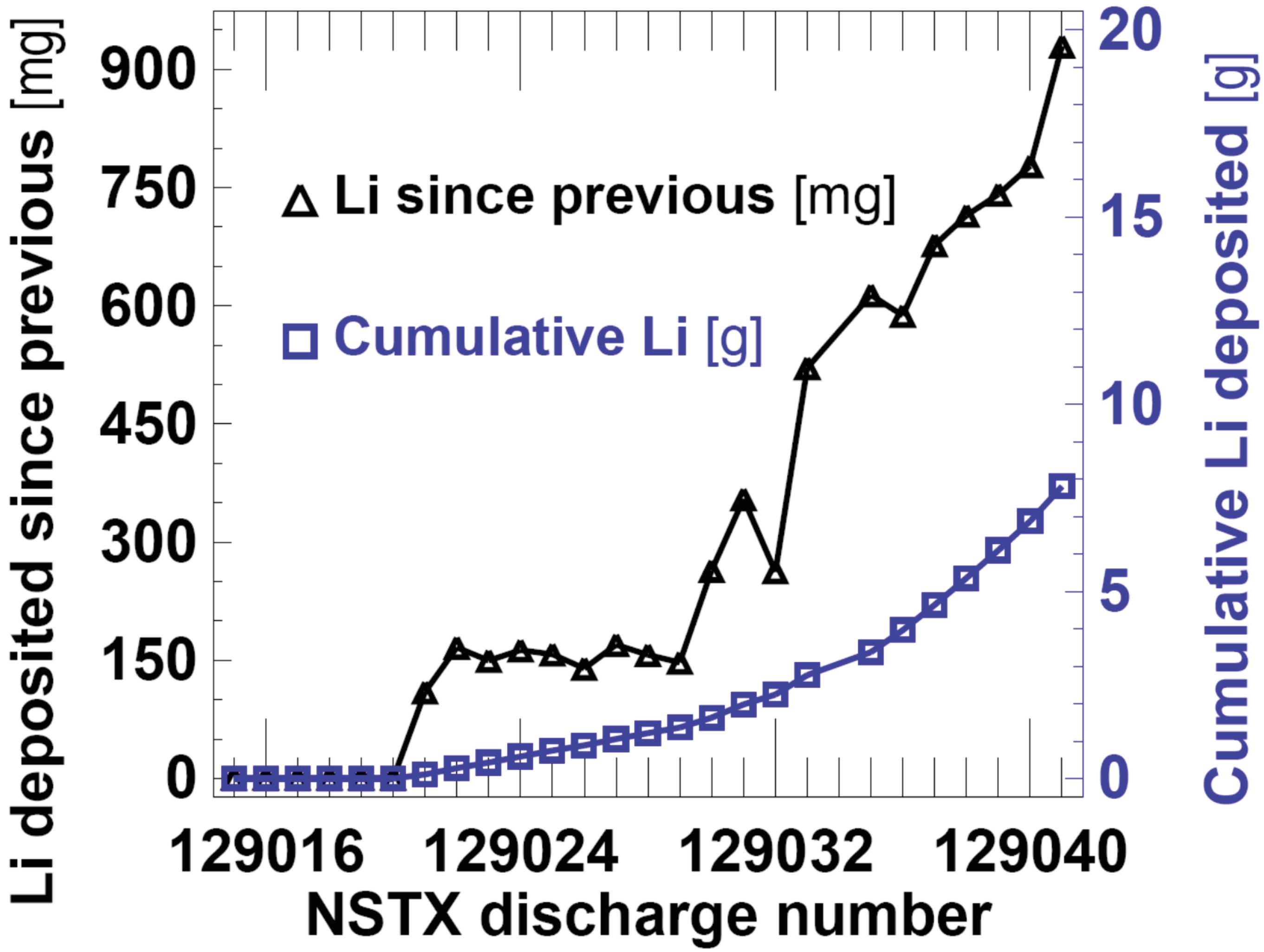
Global characteristics changed and edge electron transport declined with increasing Li deposition; ELMs eliminated

- Last 5% of ψ_N: recycling source drop leads to drop in density and pressure gradient
  - T_e gradient clamped, consistent with more unstable ETG
  - Drop in J_{BS}, Stabilizing to kink/peeling modes
- ψ_N from 0.8-0.95: particle transport drops
  - T_e gradient increased, consistent with more stable μT
  - Increased pressure and gradient, but current driven modes more stable
    - *Higher gradients allowed farther from separatrix*
- Density profile and particle transport change key first step
    - Underlying physics of particle transport change needs to be identified

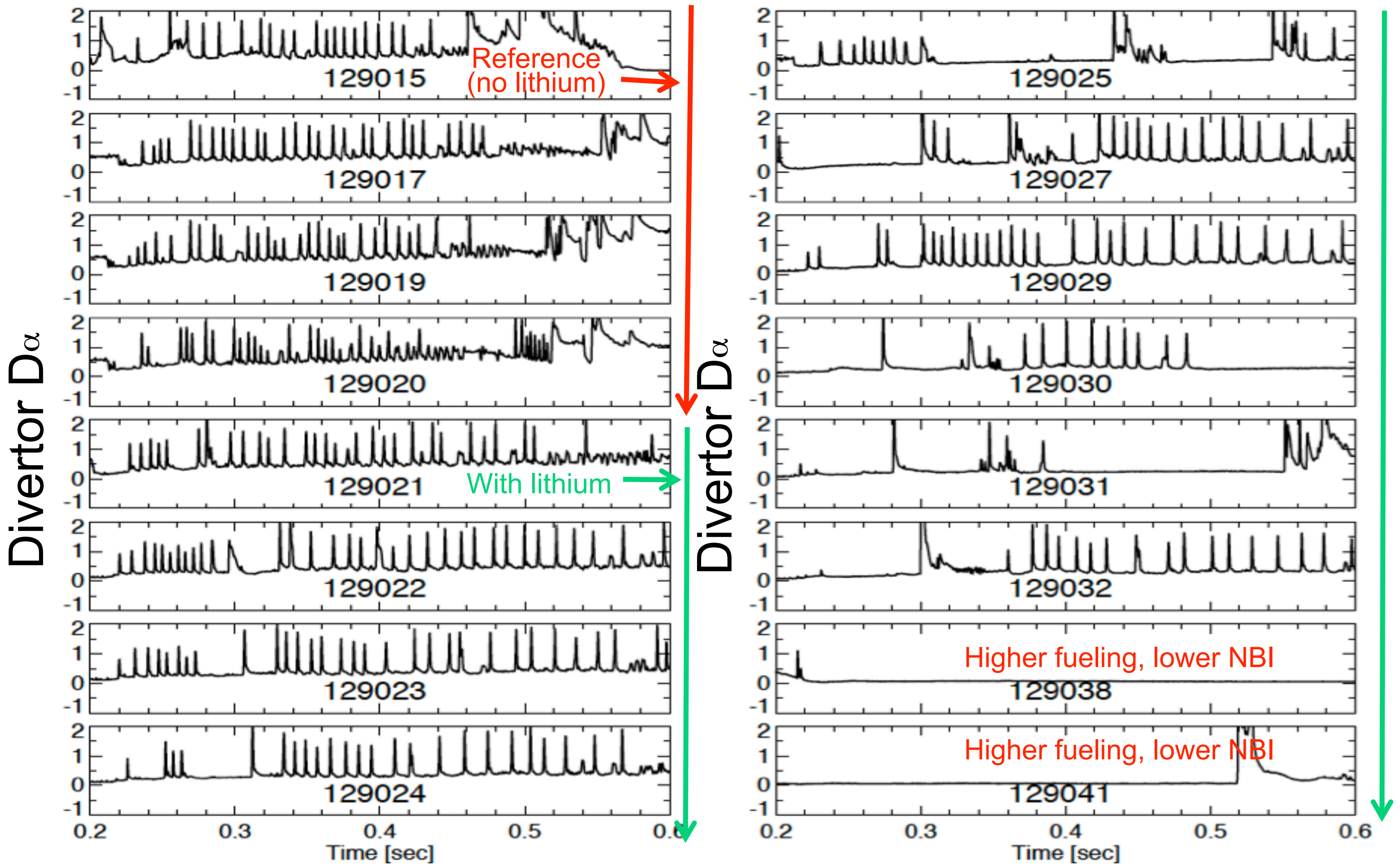
Backup

Pre-discharge lithium evaporation varied during experiment - first lithium usage in this particular run campaign

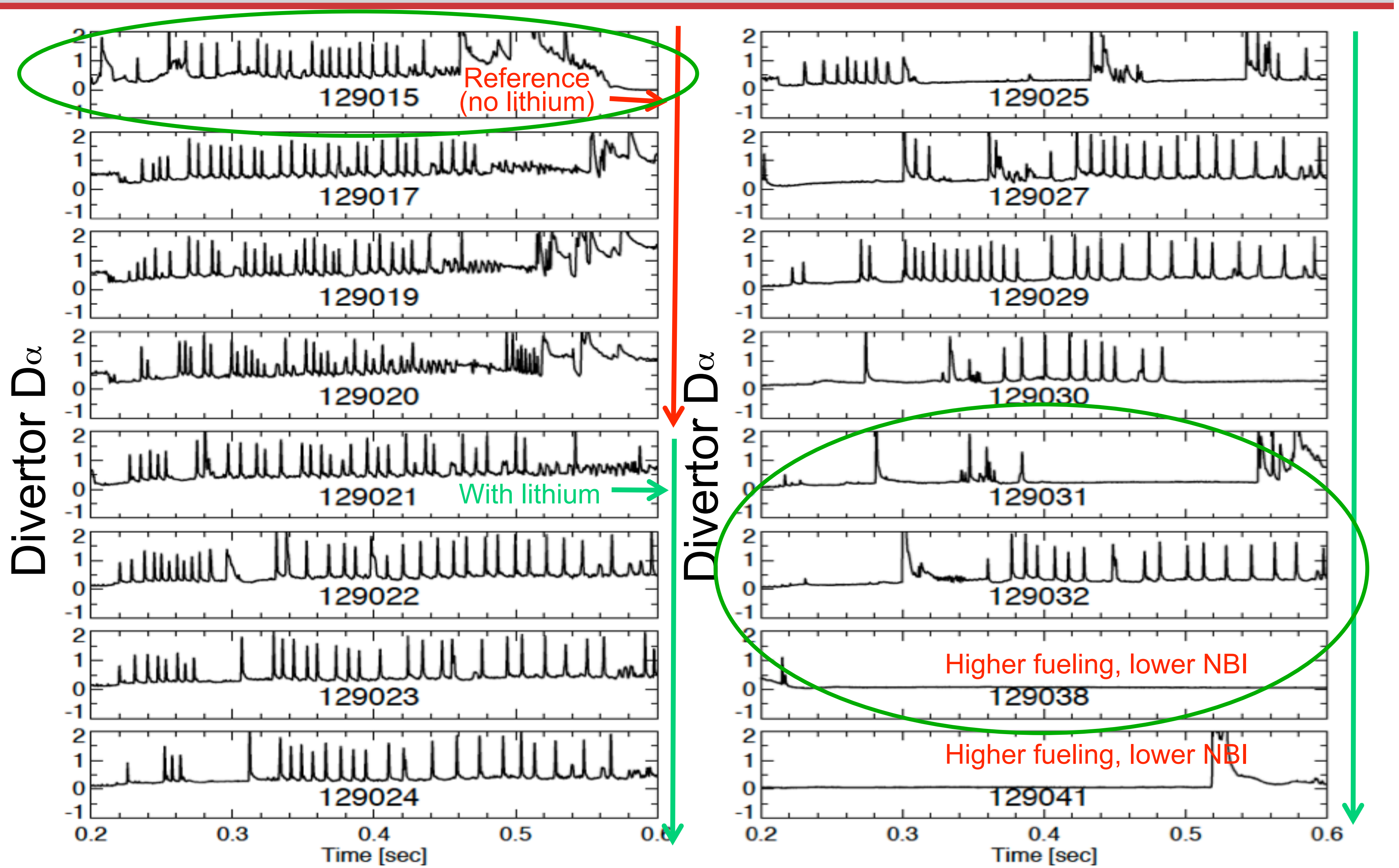
- Lithium evaporation before discharges with two overhead ovens



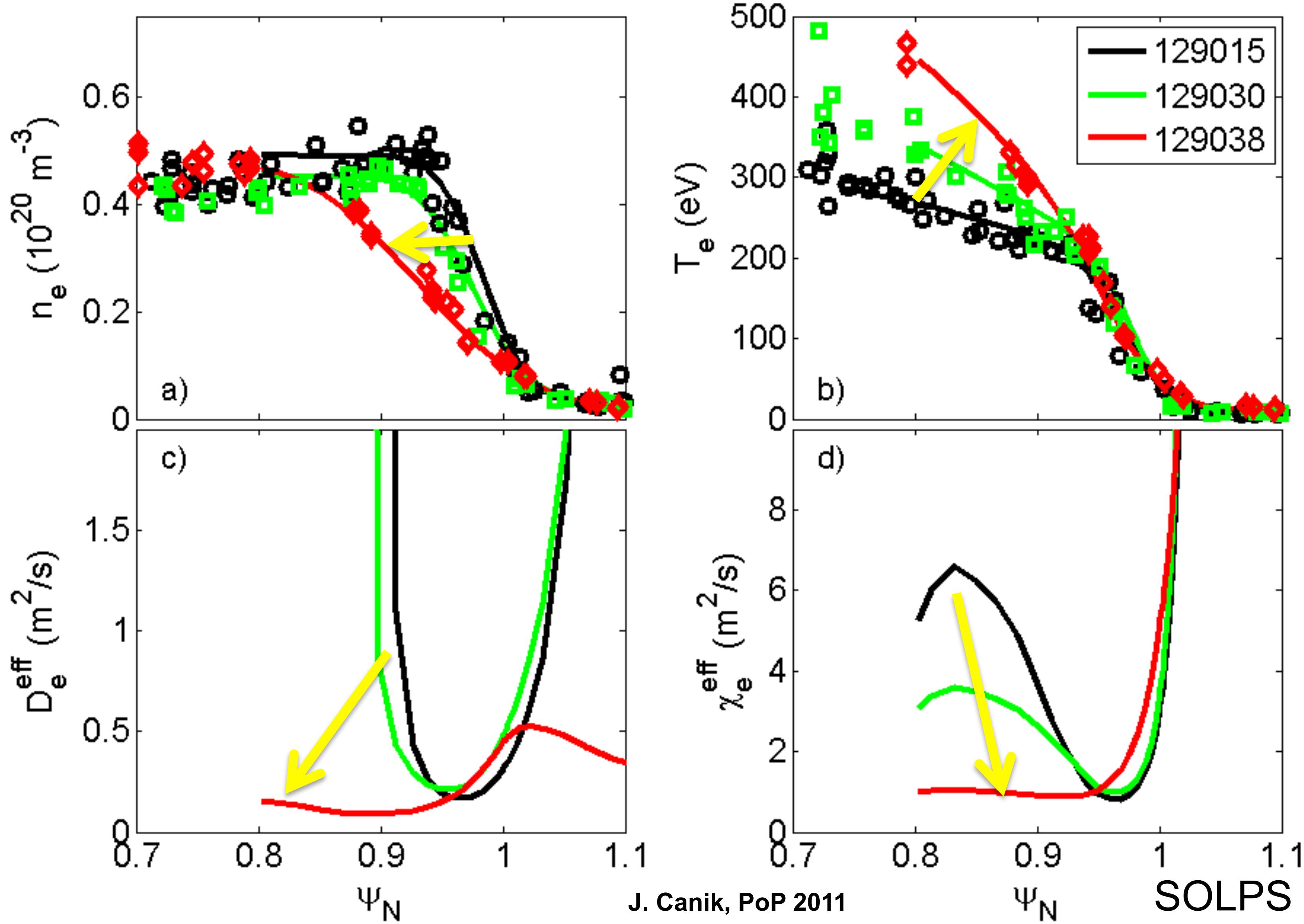
ELMs disappeared gradually during experiment



ELM elimination was not quite monotonic



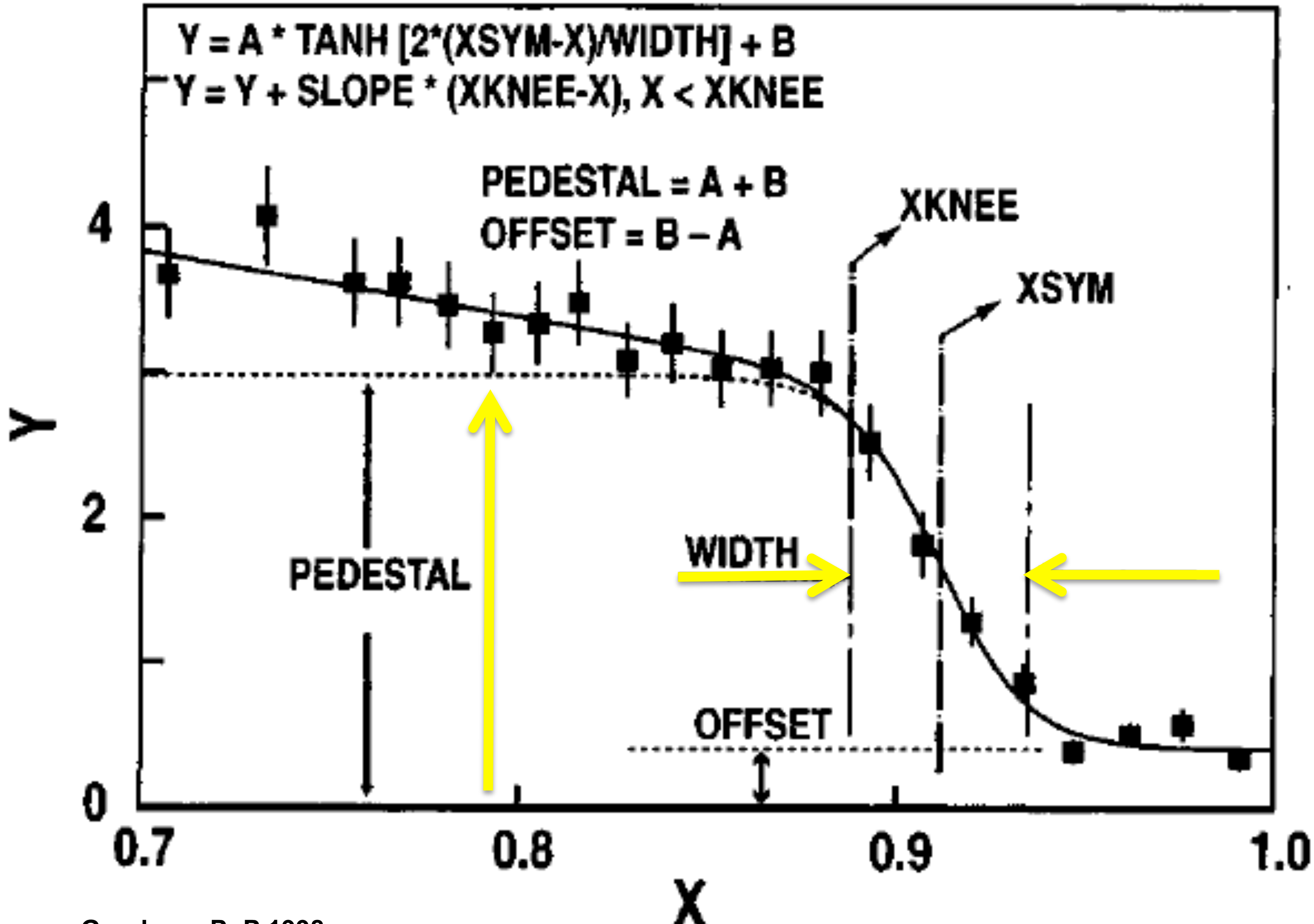
Transport barrier widens continuously with increasing pre-discharge lithium, i.e. pedestal-top D, χ_e reduced



J. Canik, PoP 2011

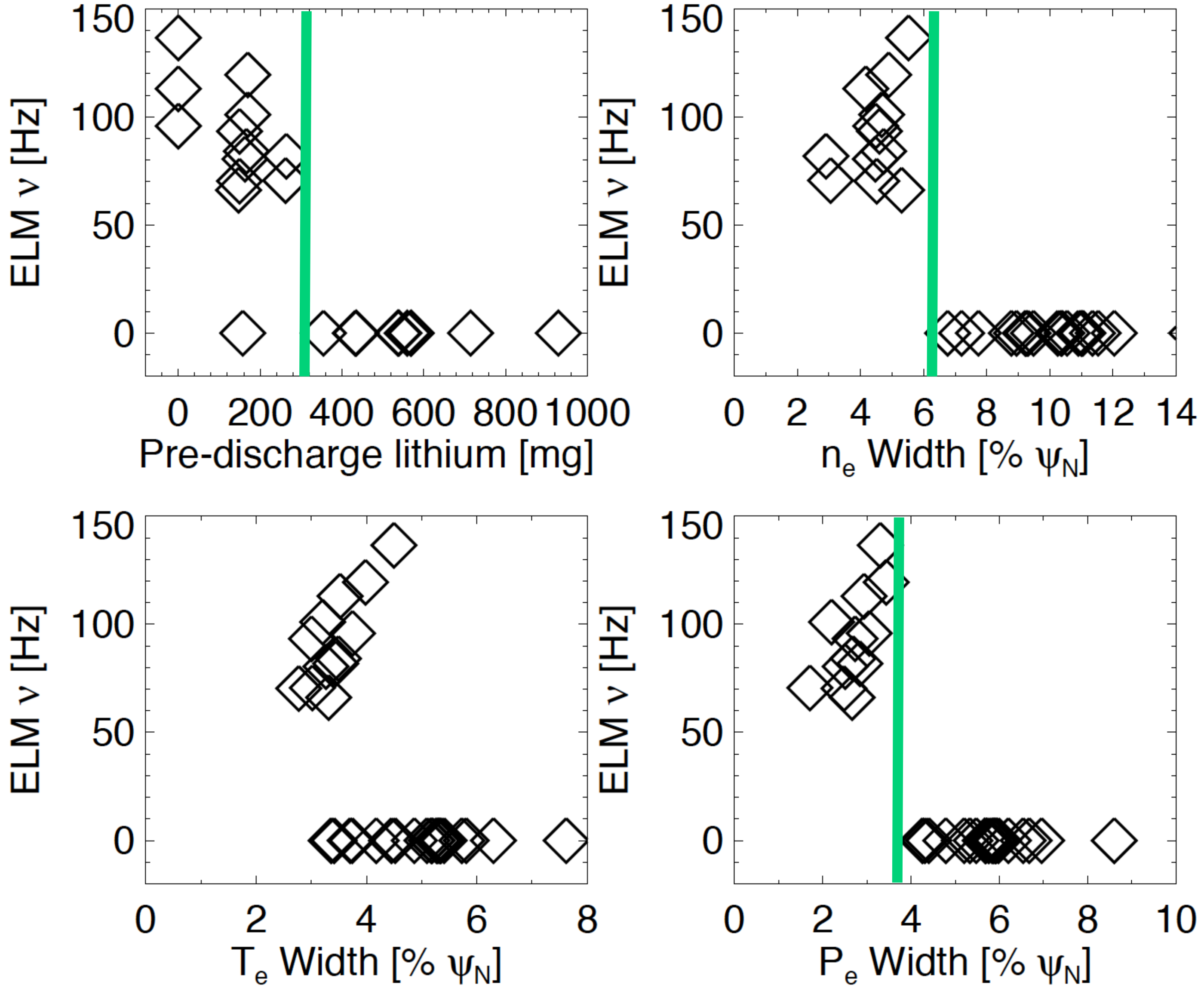
SOLPS

Edge density, temperature, and pressure profiles fitted to "standard" modified hyperbolic functional form

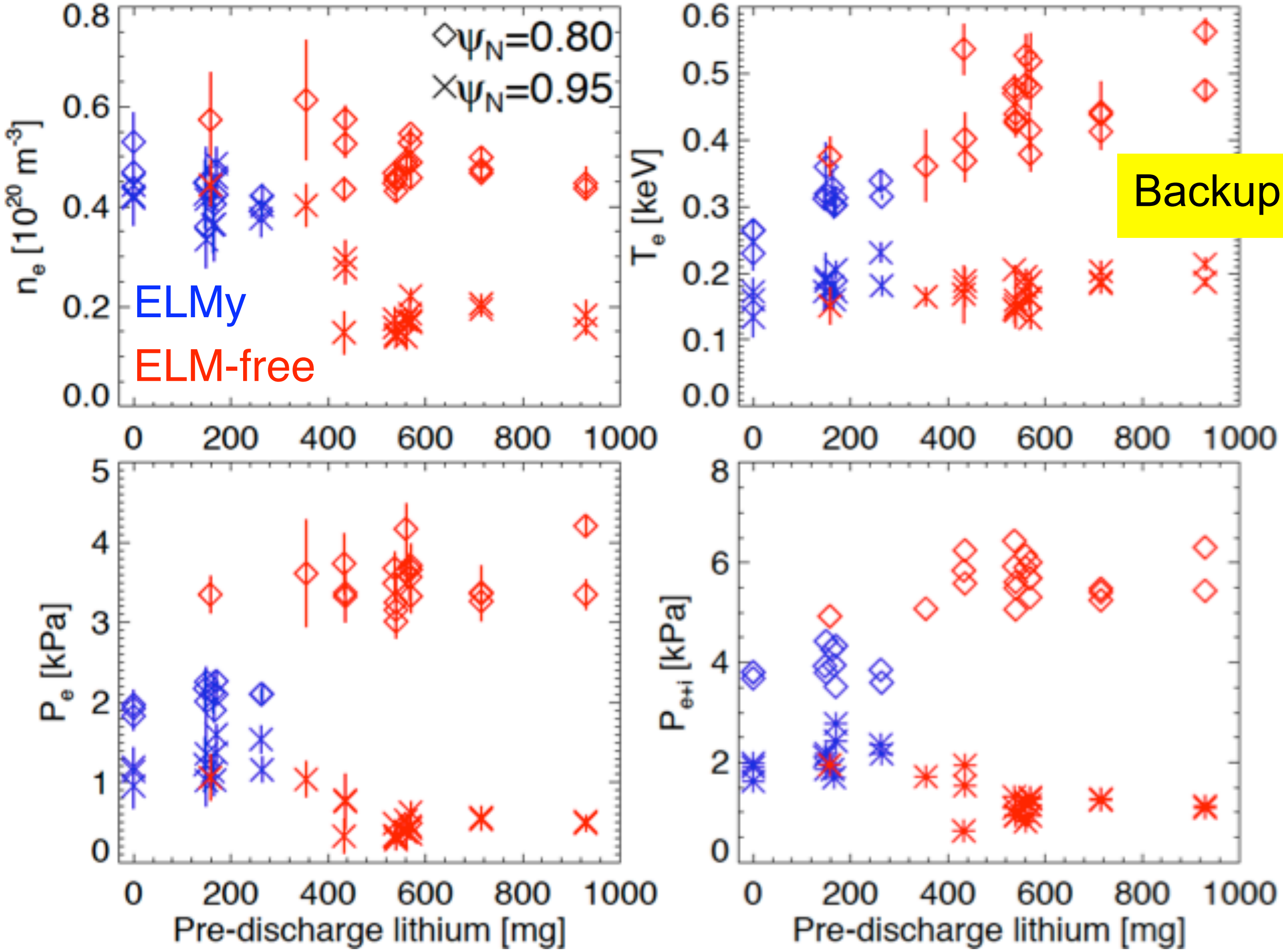


Groebner, PoP 1998

n_e and P_e "mtanh" profile widths separate ELMy and ELM-free data



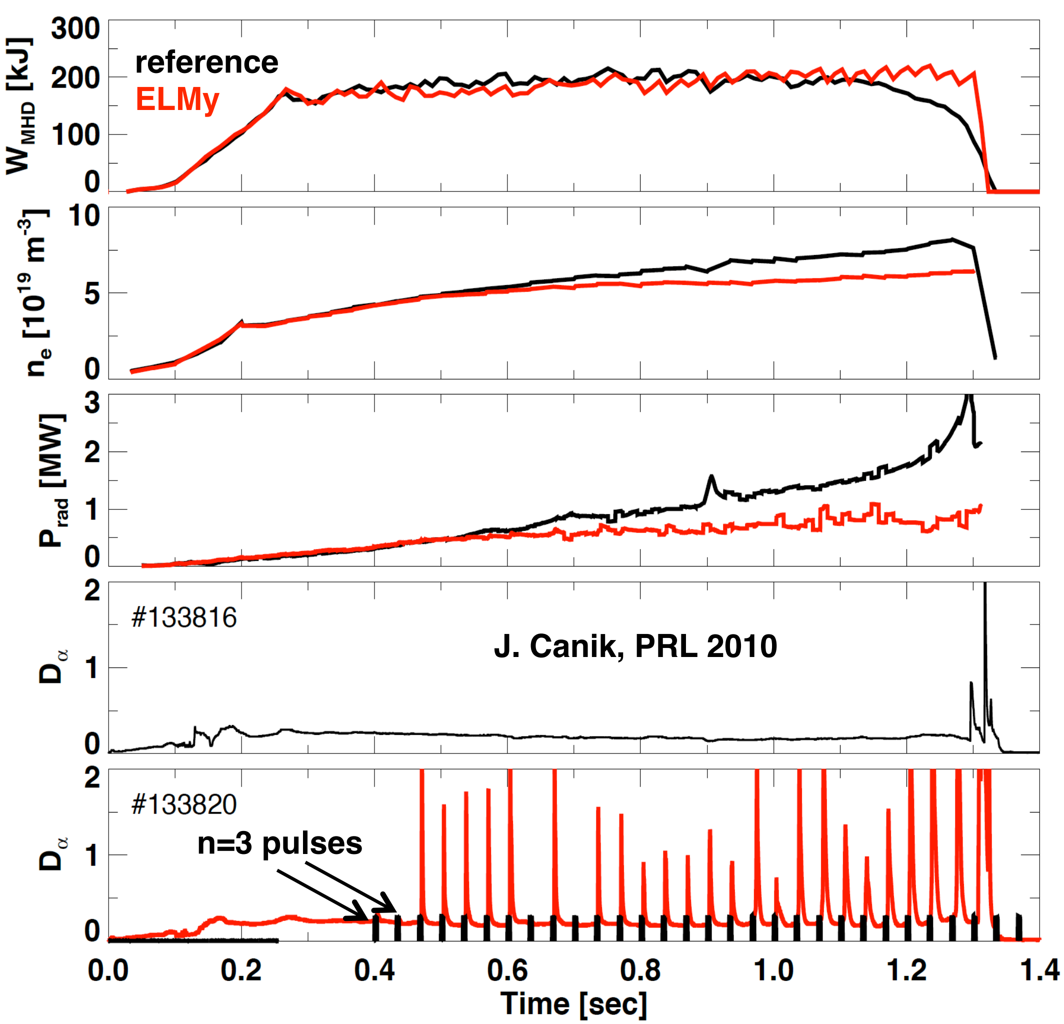
Density and pressure drop with lithium coatings at ψ_N=0.95, but increase at ψ_N=0.80 with increasing lithium



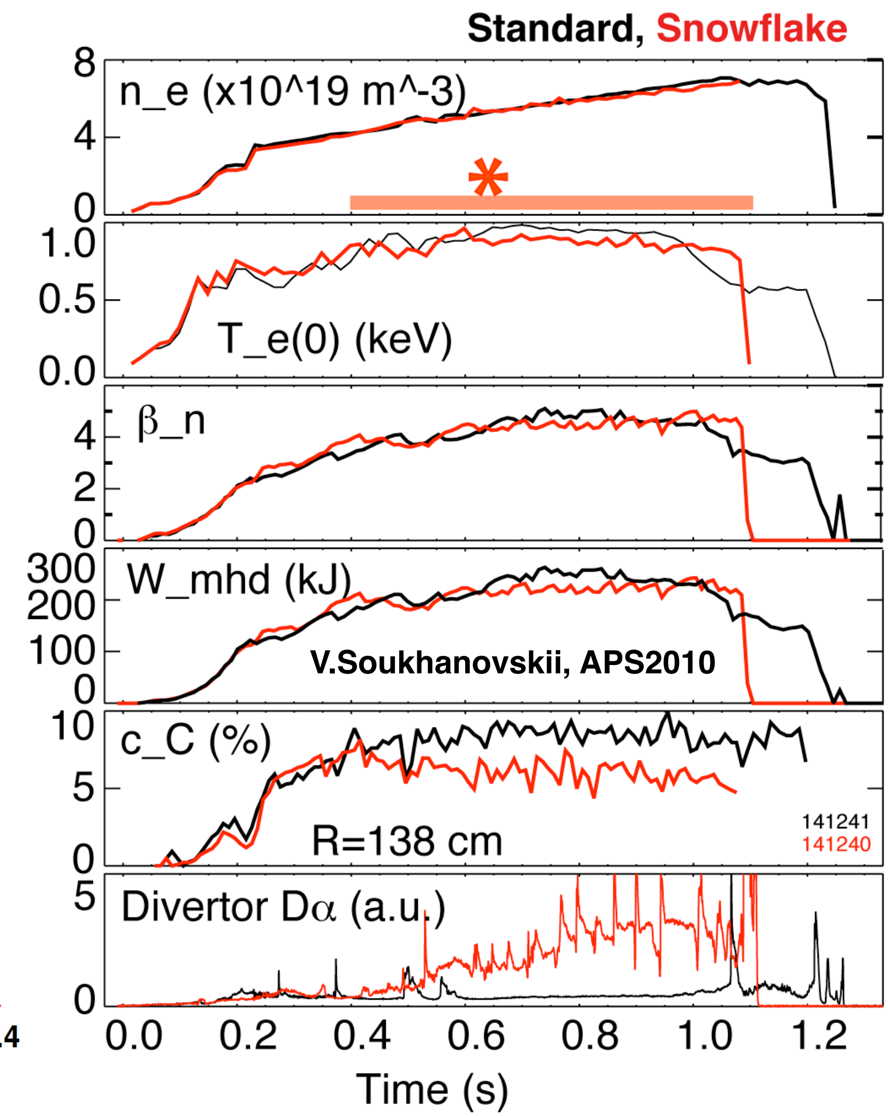
Backup?

3D external fields used to trigger ELMs, while "Snowflake Divertor" used to reduce edge impurity source

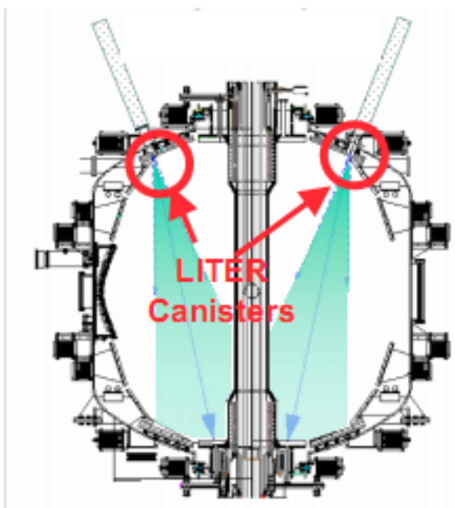
Type I ELMs triggered for impurity control (post-lithium, n=3)

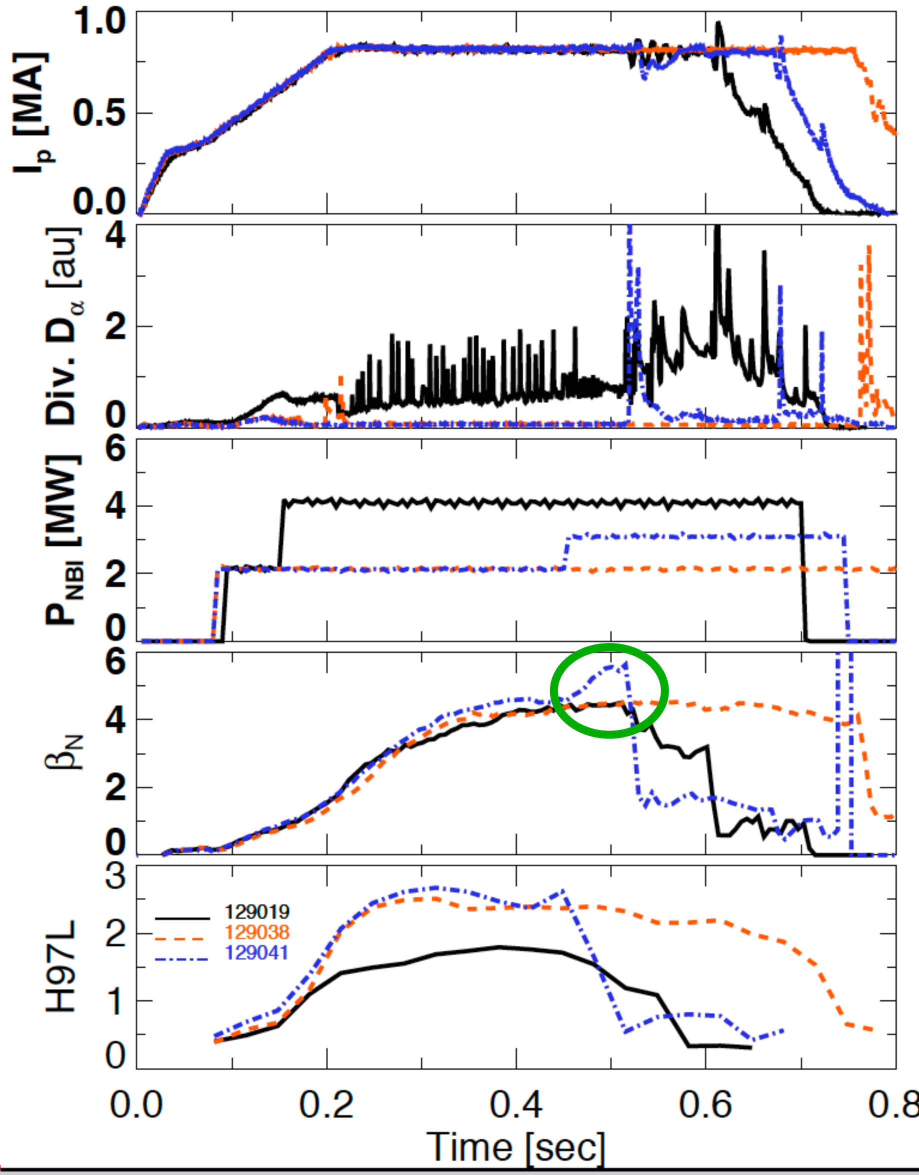


Snowflake Divertor



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

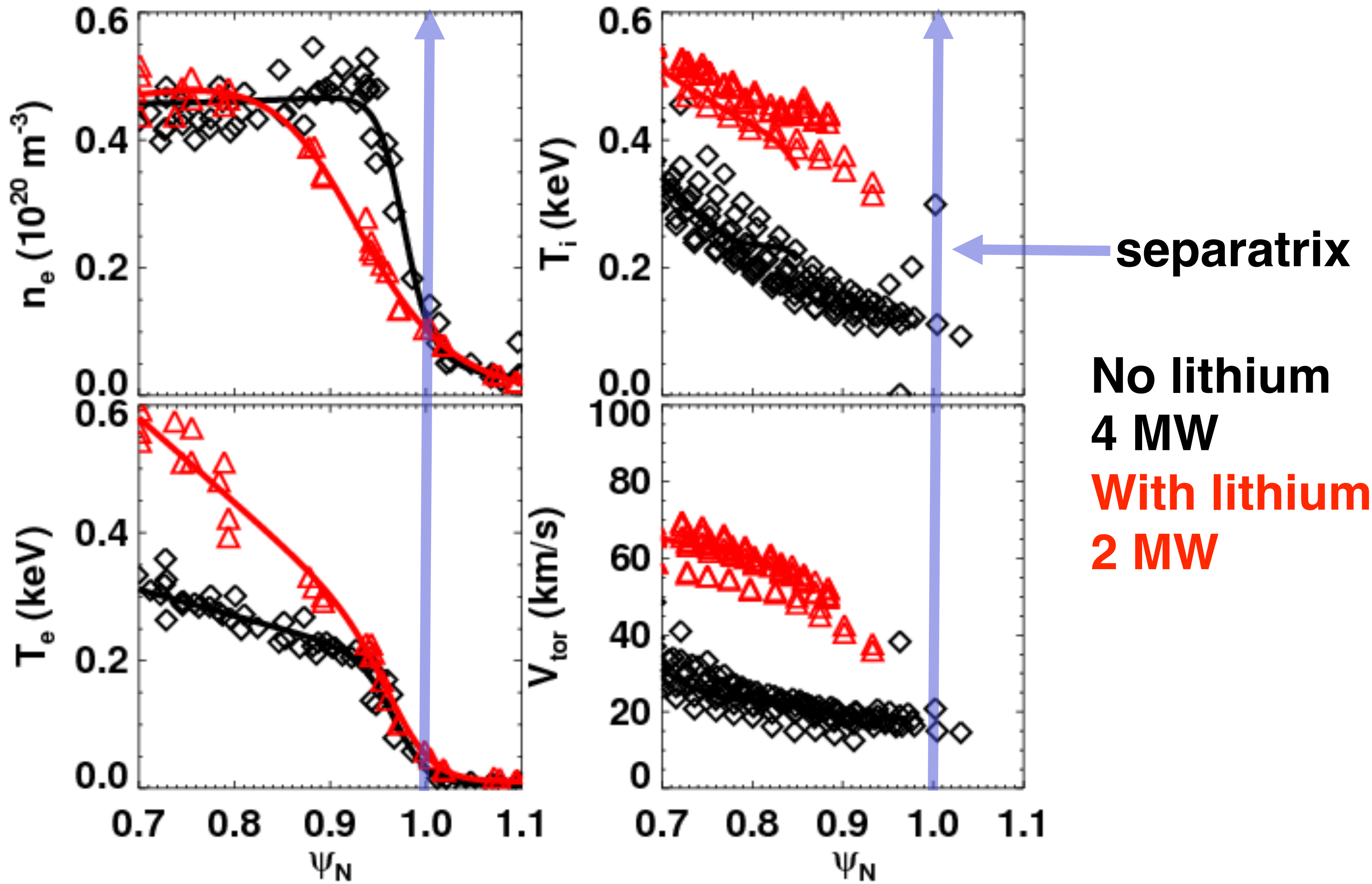




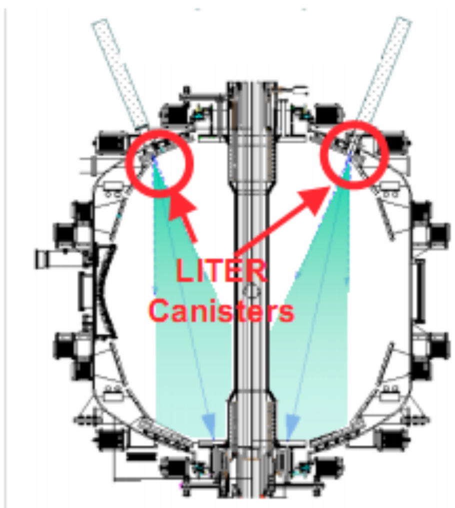
- Without Li, With Li, With Li
- ELM-free, reduced divertor recycling
- Power scan to identify β limit
- Core β limit observed, but no ELMs

D. Mansfield, JNM 2009
R. Maingi, PRL 2009

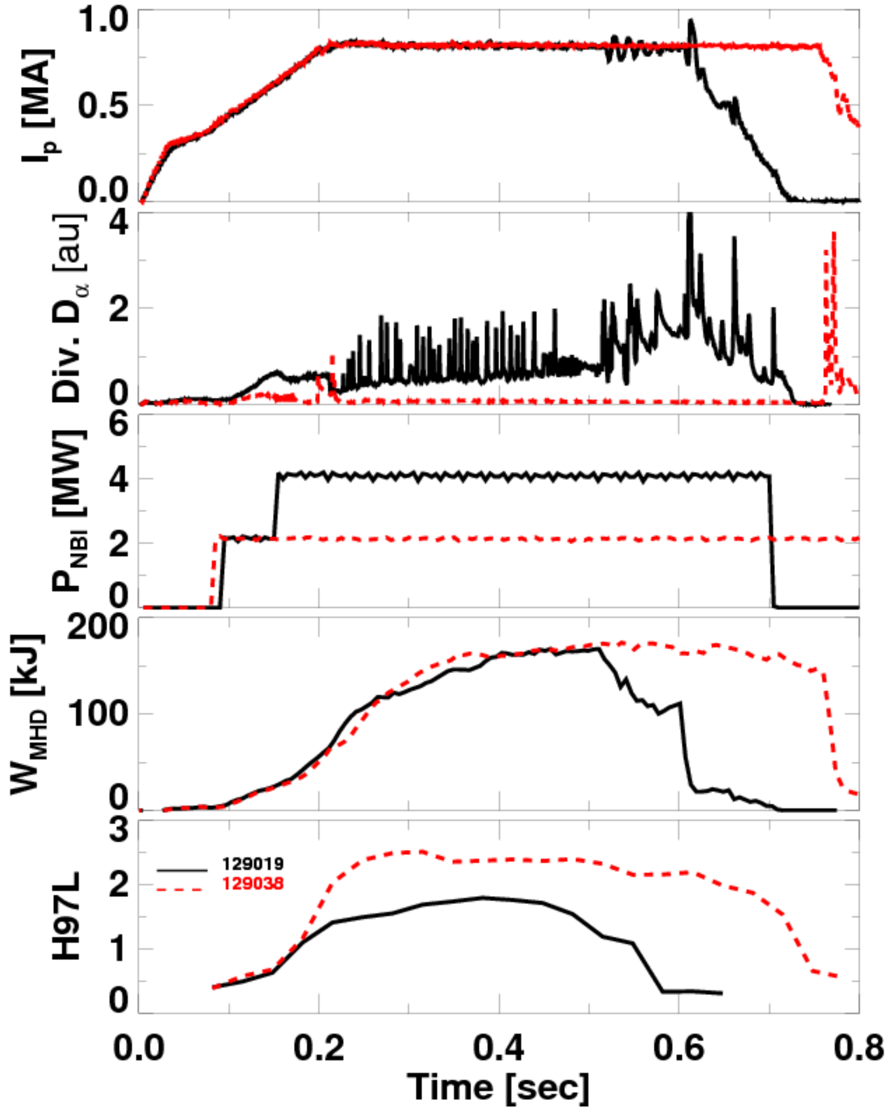
T_e, T_i increased and edge n_e decreased with lithium coatings



Type I ELMs eliminated, energy confinement improved with lithium wall coatings; (ELMs eliminated up to β_N limit)



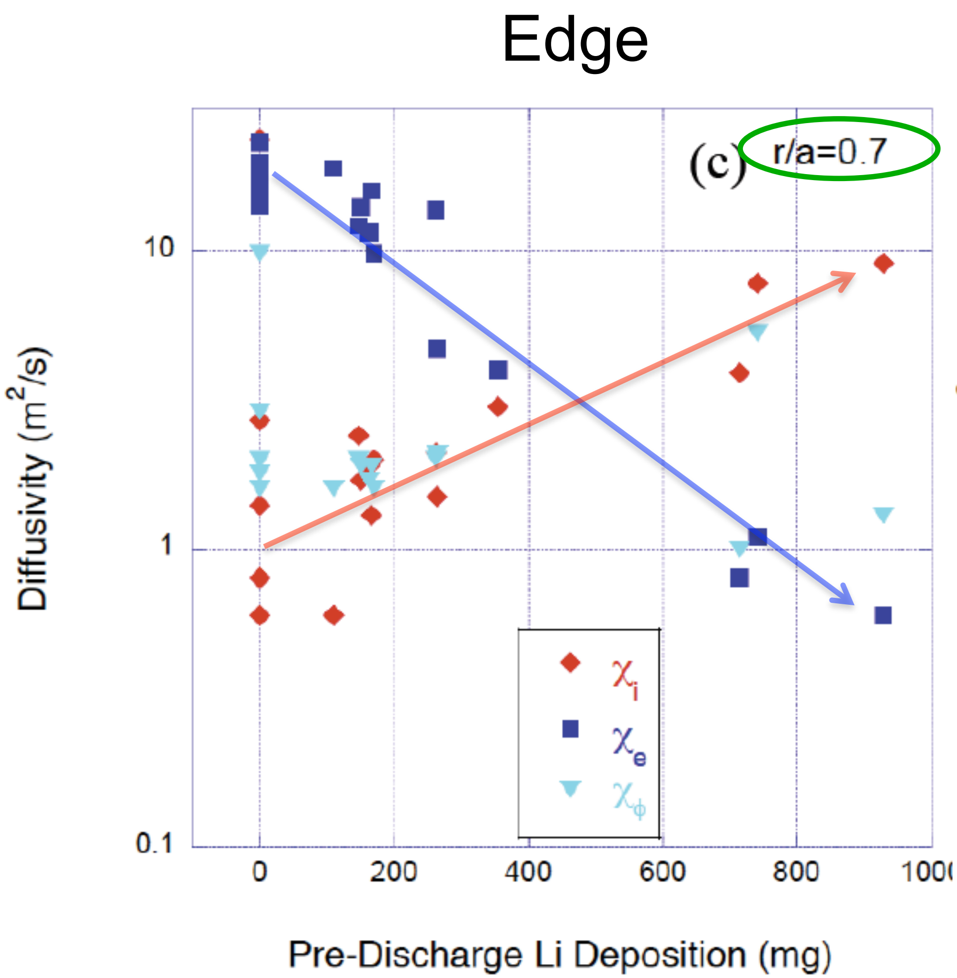
~ 700mg Li between 129037 and 129038

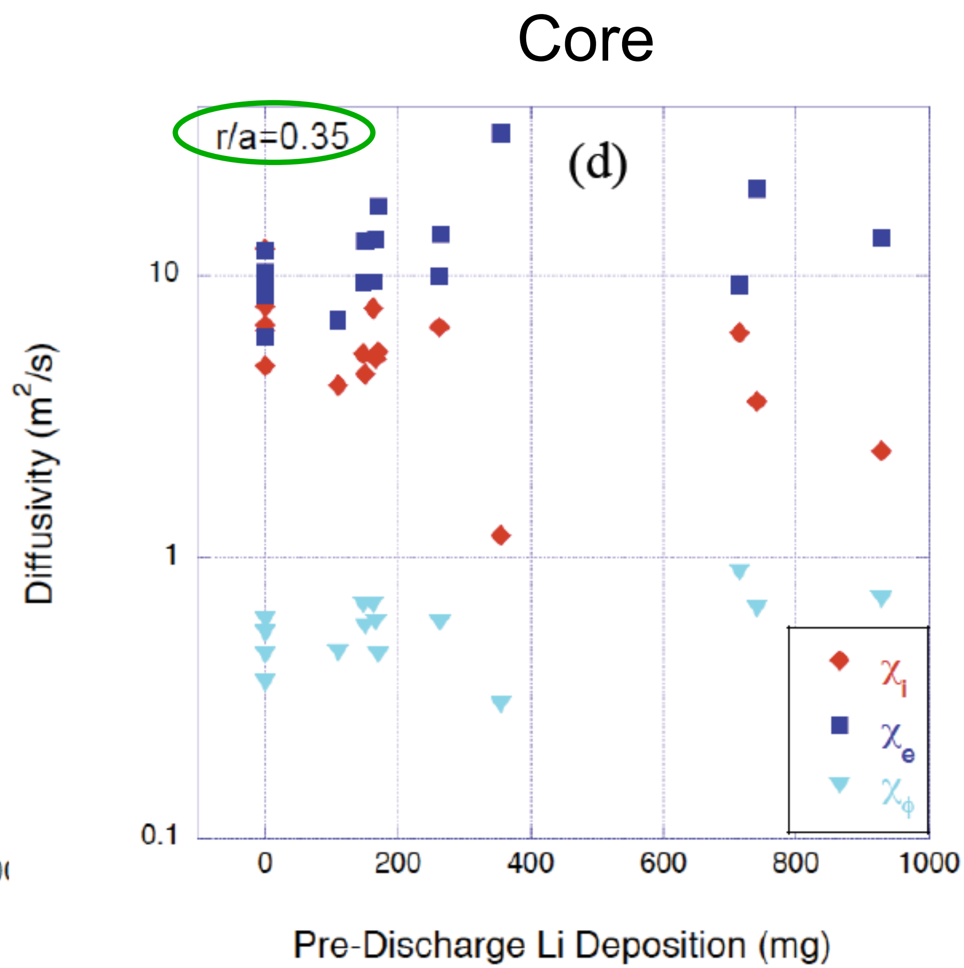


- Without Li, With Li *(pre-LLD)*
- ELM-free, reduced divertor recycling
- Lower NBI to avoid β limit
- Similar stored energy
- H-factor 40%↑

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

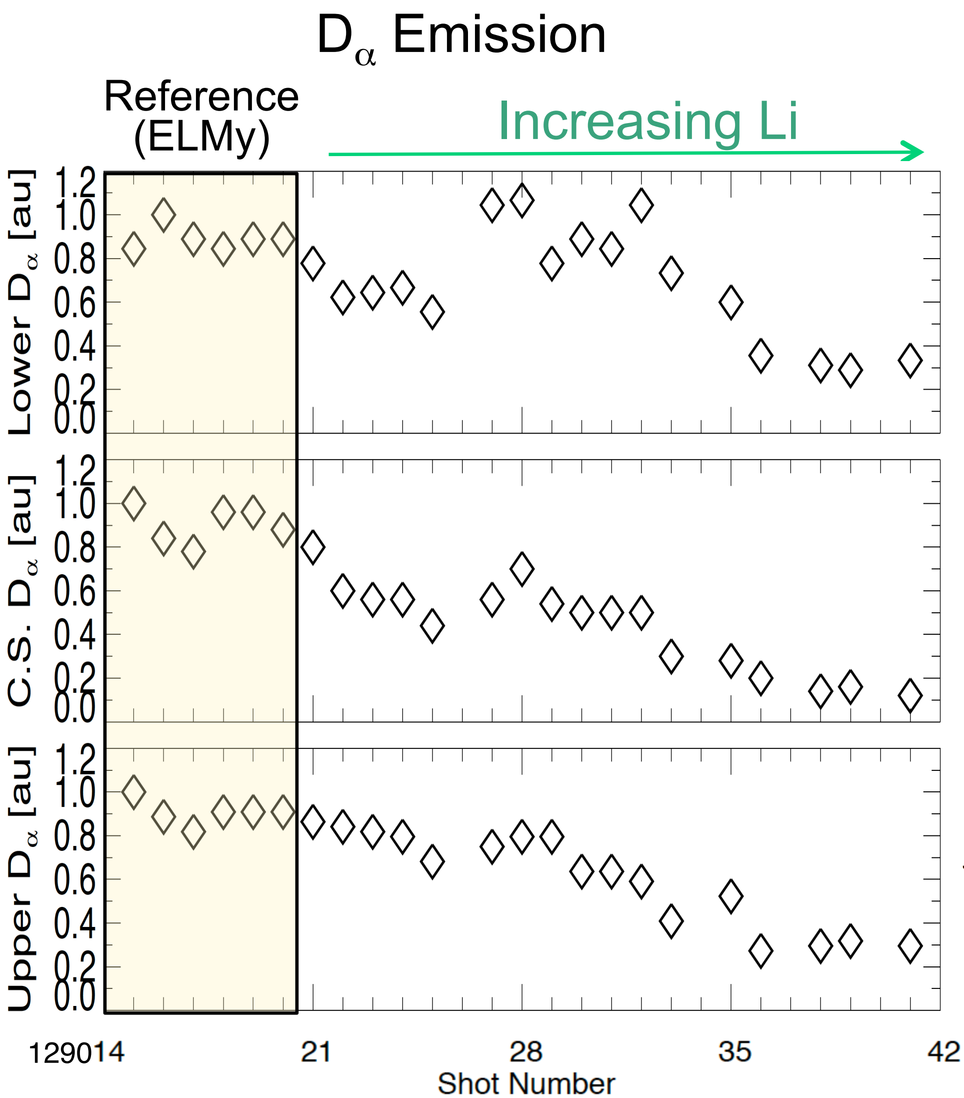
Edge χ_e goes down and χ_i goes up; core χ's unchanged

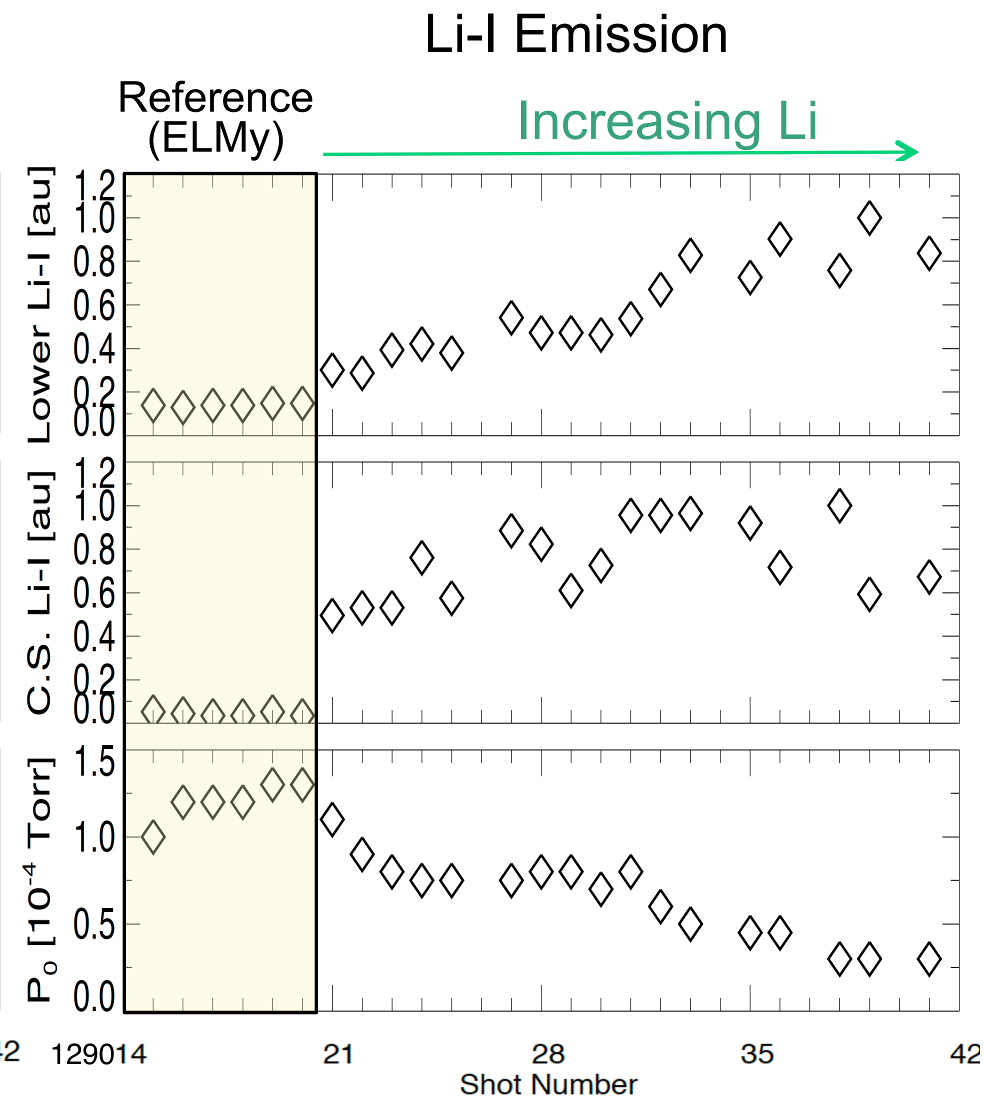




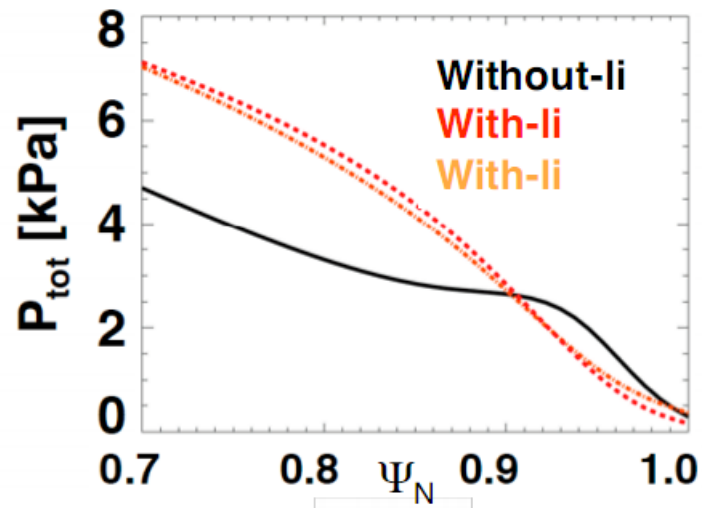
- Global increase in τ_E correlates with drop in edge χ_e
- Consistent with change in χ_e, D from SOLPS simulations

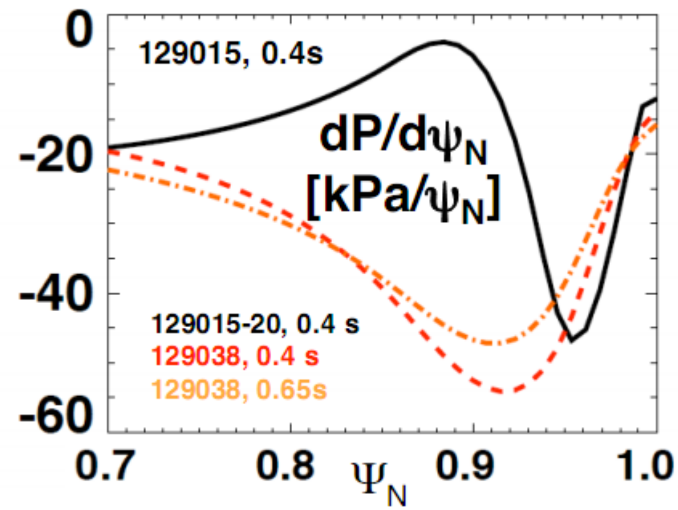
D_α decreases and lower divertor Li-I increases with increasing lithium evaporation

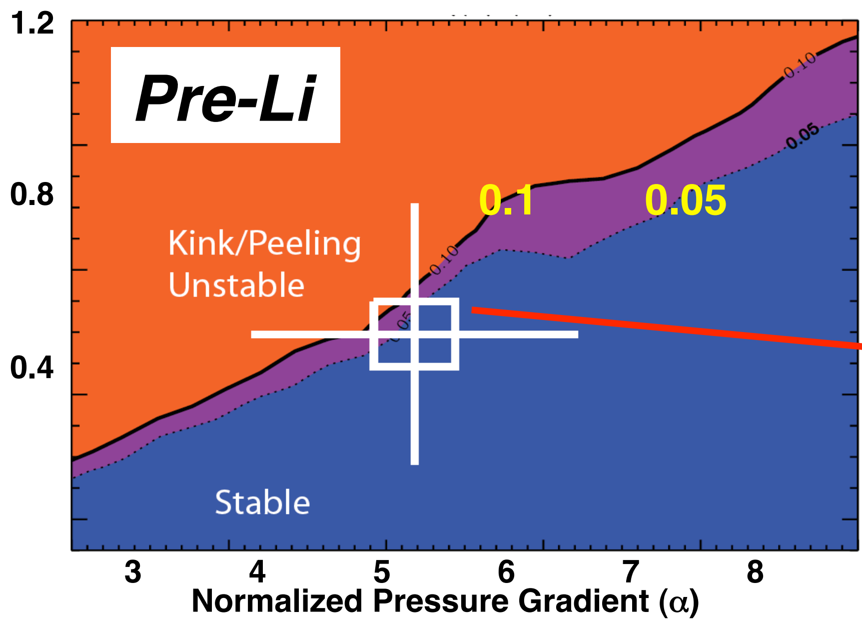




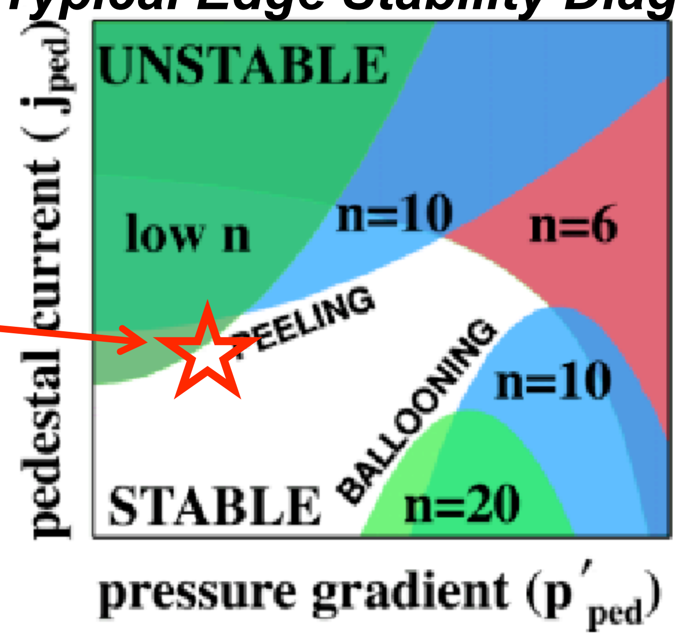
Pre-lithium discharge near the kink/peeling boundary (end points of lithium scan)



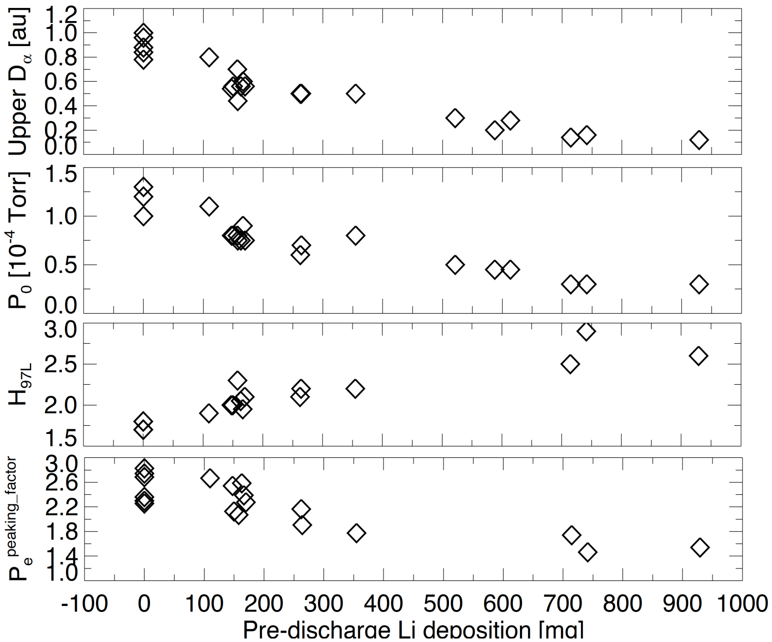


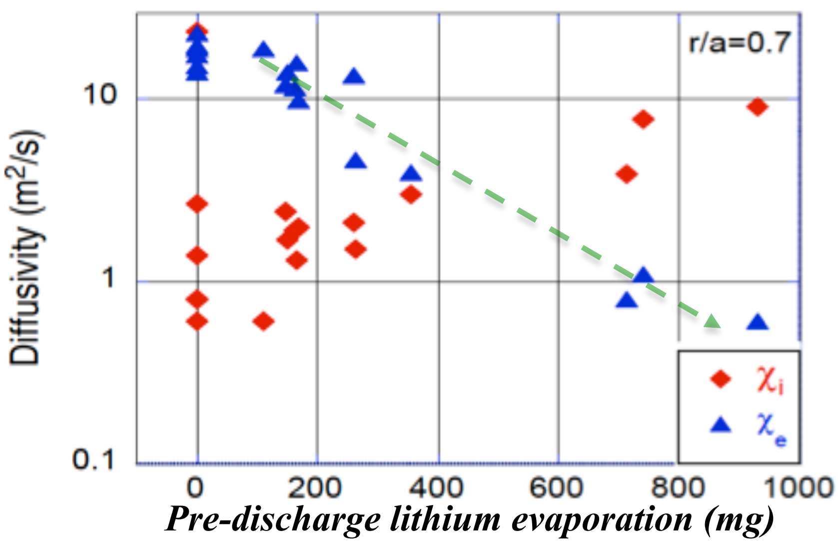


Typical Edge Stability Diagram



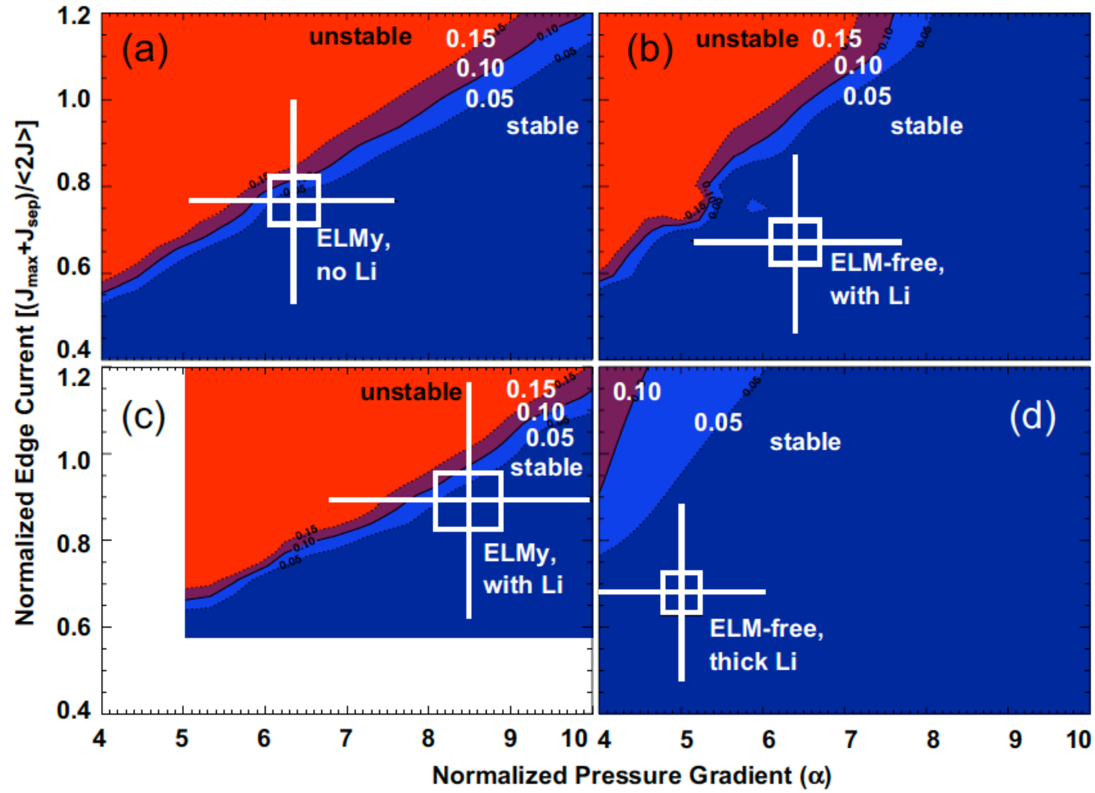
Edge recycling, neutral pressure, and pressure peaking decrease, while confinement and edge stability increase with increasing pre-discharge lithium in NSTX



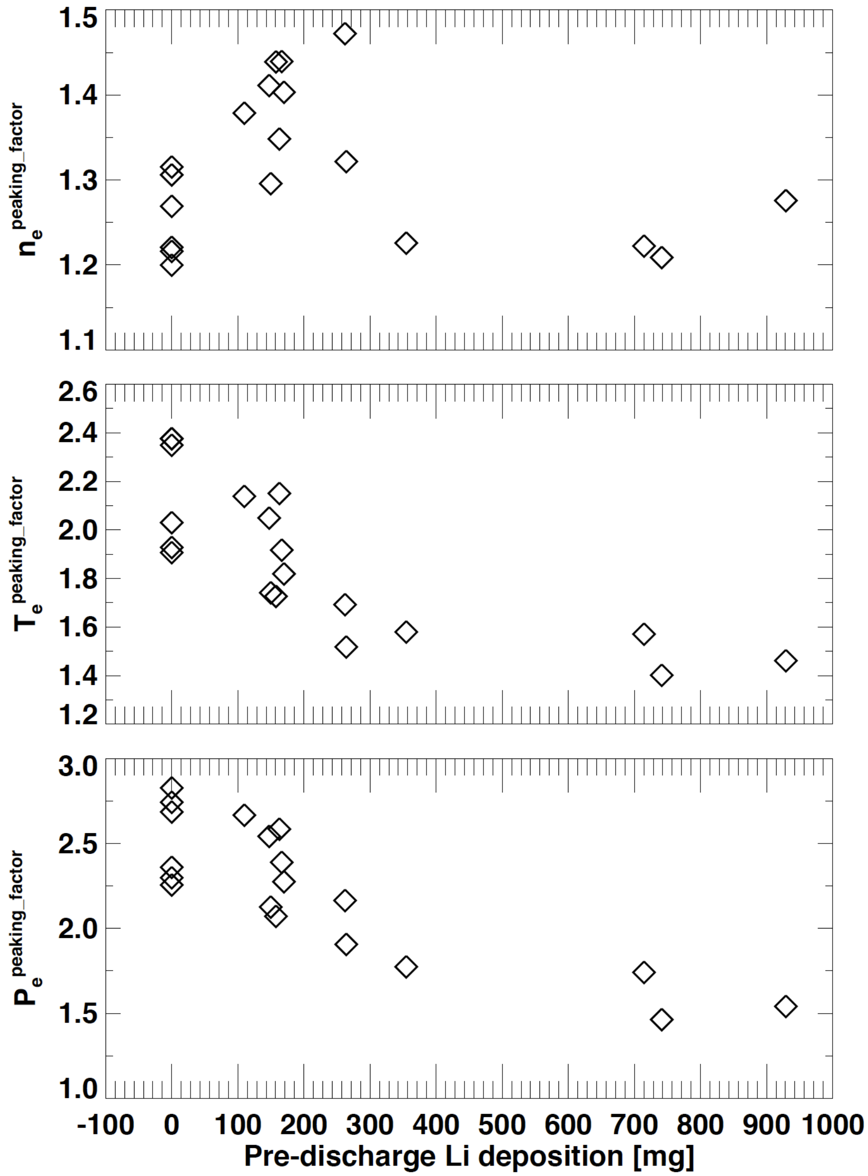


ELITE calculations

ELMy ELM-free



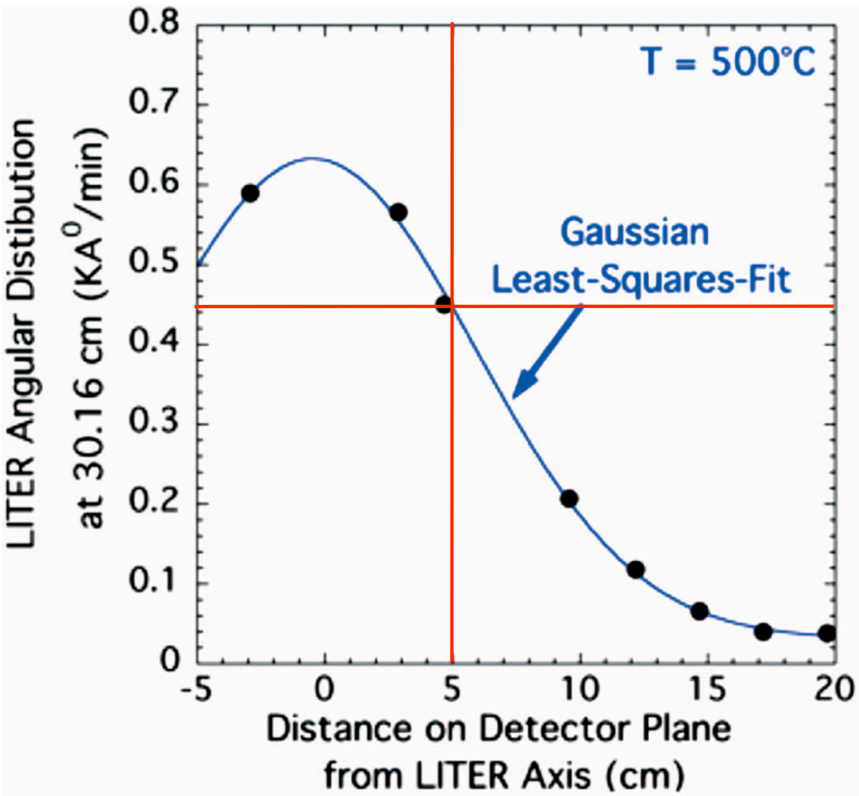
T_e and P_e profile peaking factors decrease with increasing lithium



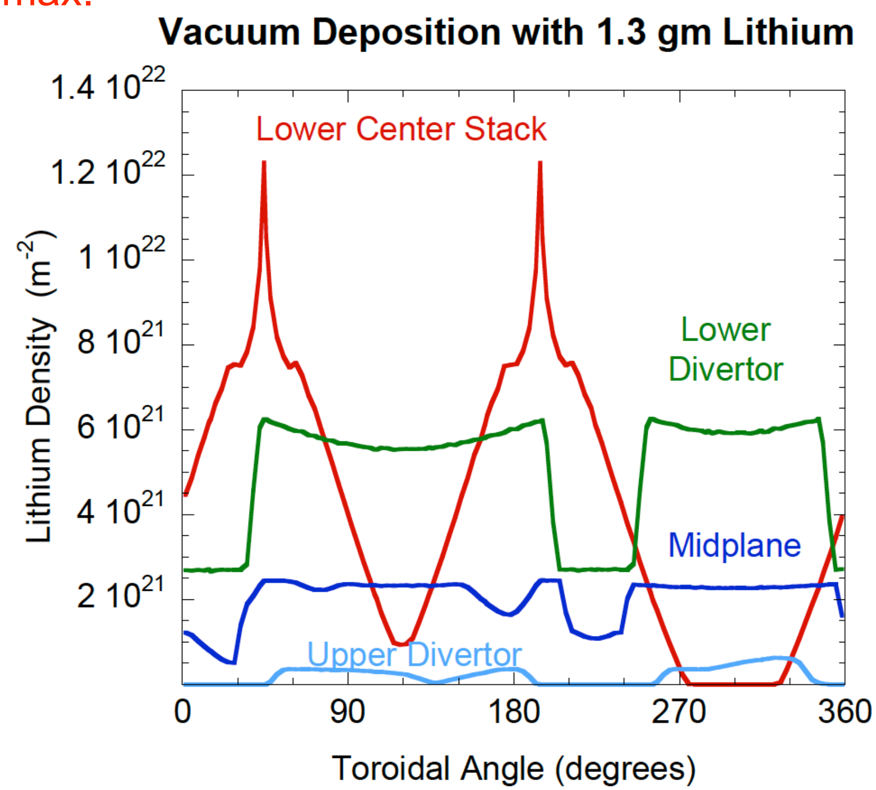
- n_e profile peaking factor first increases as ELM ν goes down, and then decreases as ELMs disappear and profile becomes hollow
- T_e and P_e profile peaking factors decrease ~ continuously, good for MHD stability

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.

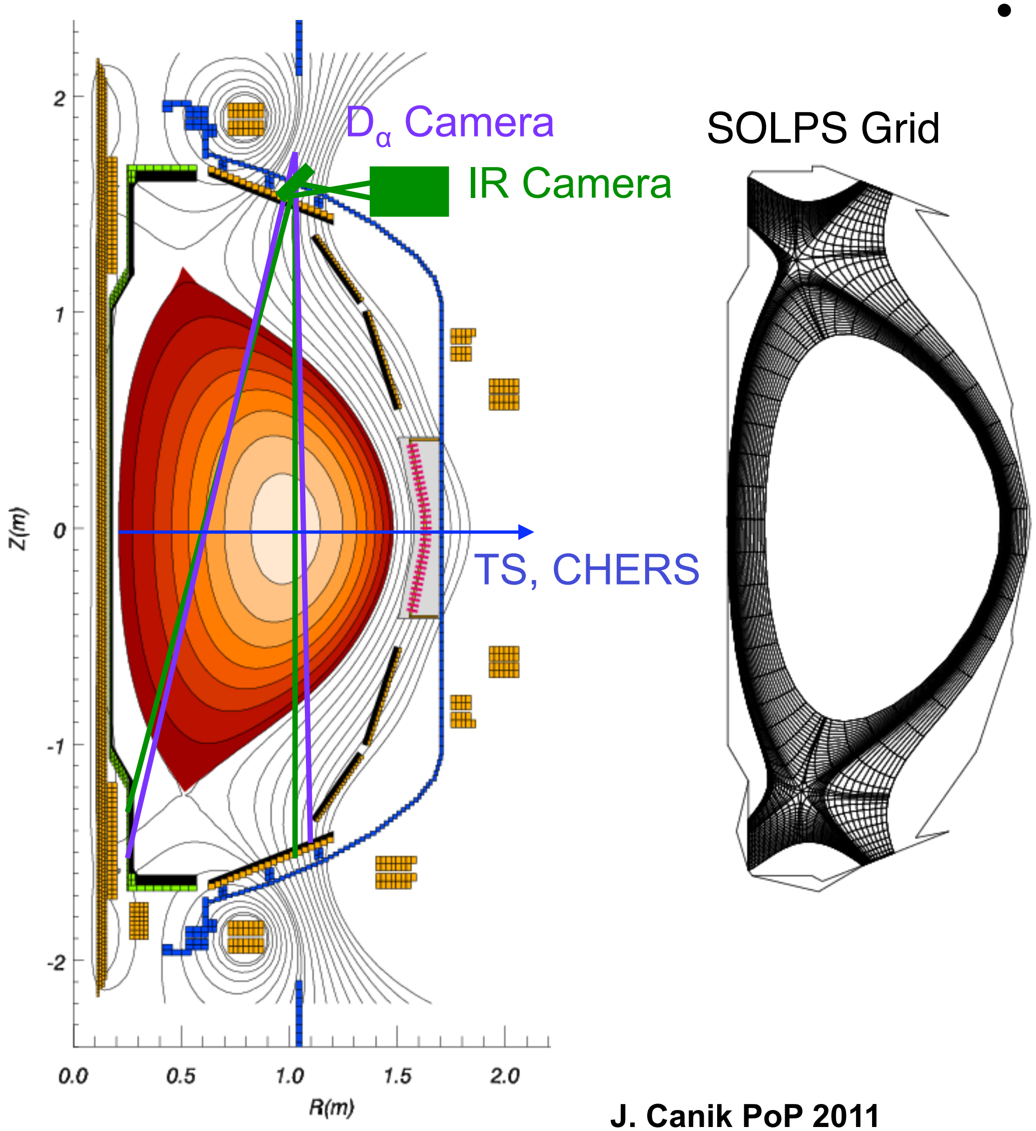


H. Kugel PoP 2008



* From H. Kugel, source?

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

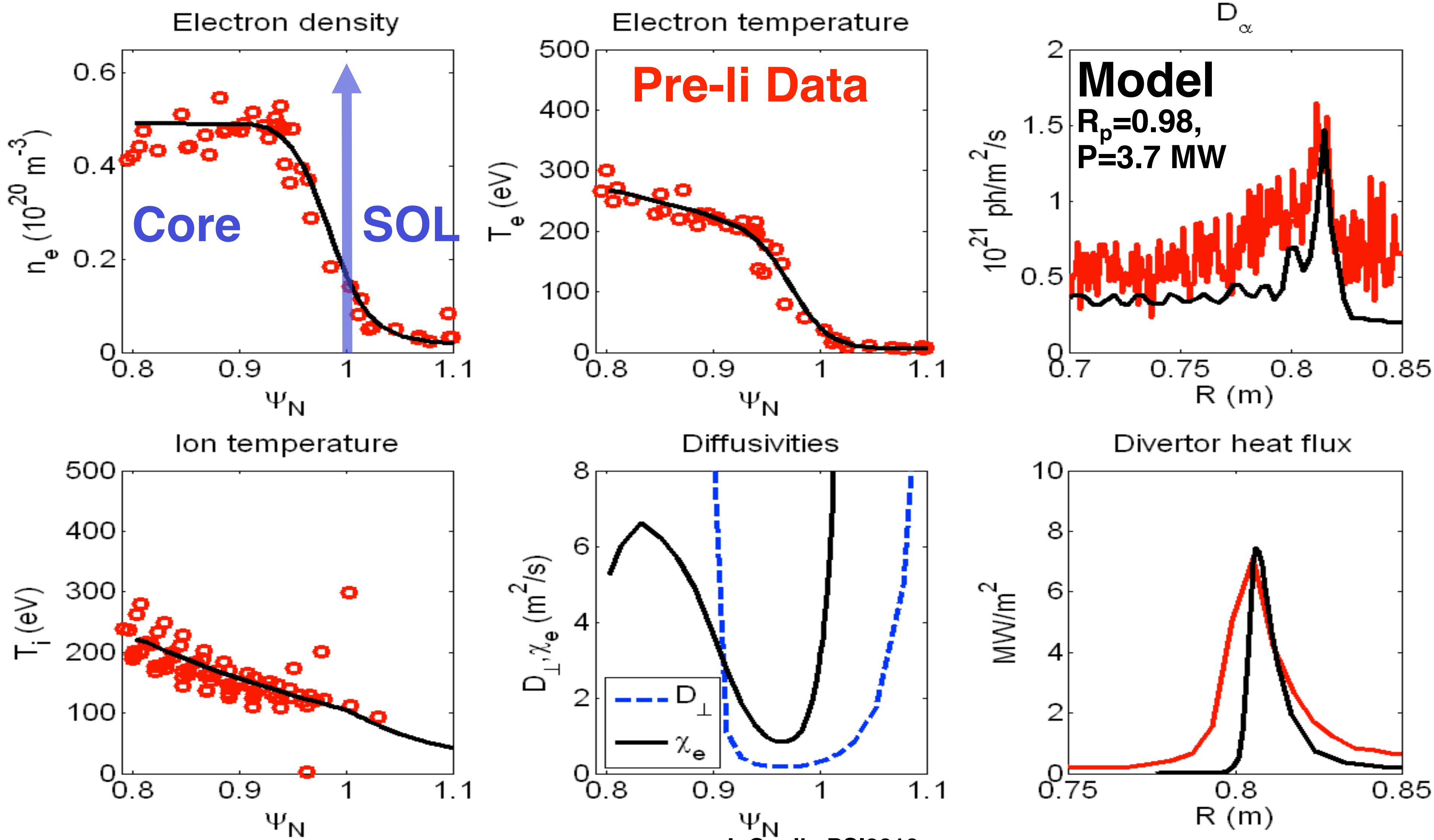


J. Canik PoP 2011

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

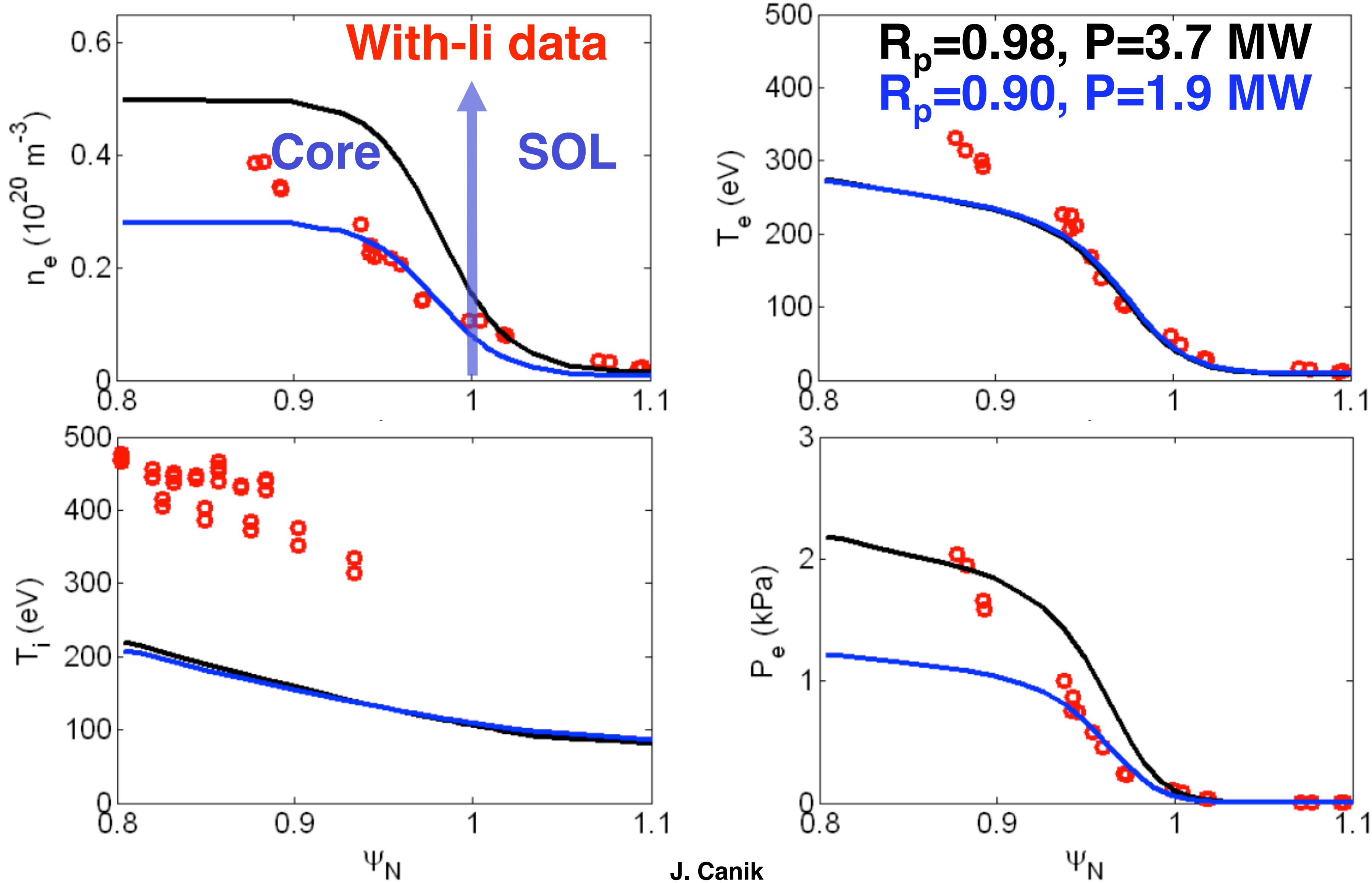
Parameters adjusted to fit data	**Measurements used to constrain code**
Radial transport coefficients $D_\perp$, χ_e, χ_i	Midplane n_e, T_e, T_i profiles
Divertor recycling coefficient	Calibrated D_α camera
Separatrix position/ T_e^{sep}	Peak divertor heat flux

2-D modeling used to model power and particle balance of baseline ELMy discharge



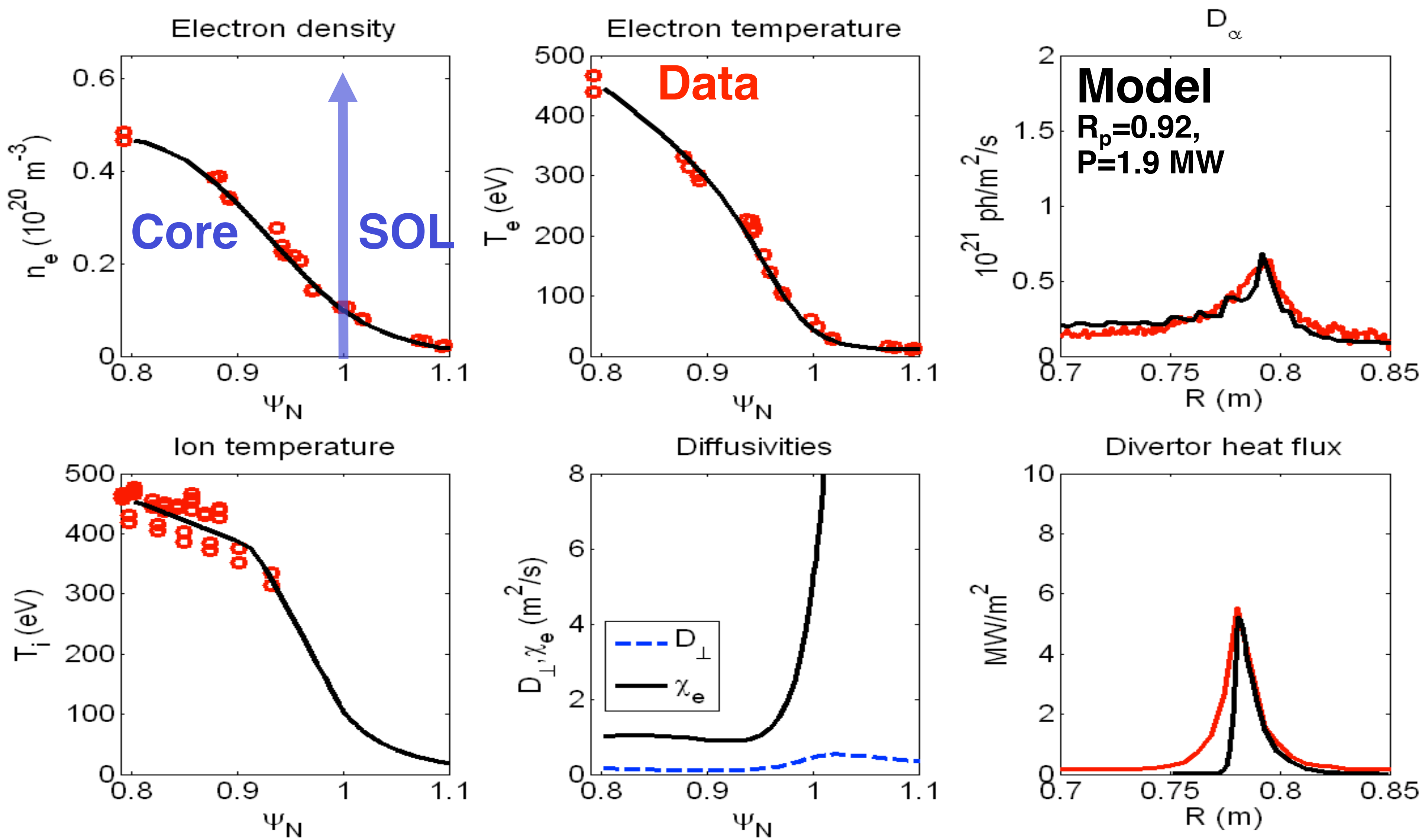
J. Canik, PSI2010

With-lithium discharge profiles not reproduced with simple recycling coefficient change



J. Canik

With-lithium discharge profiles better matched with transport and recycling coefficient change

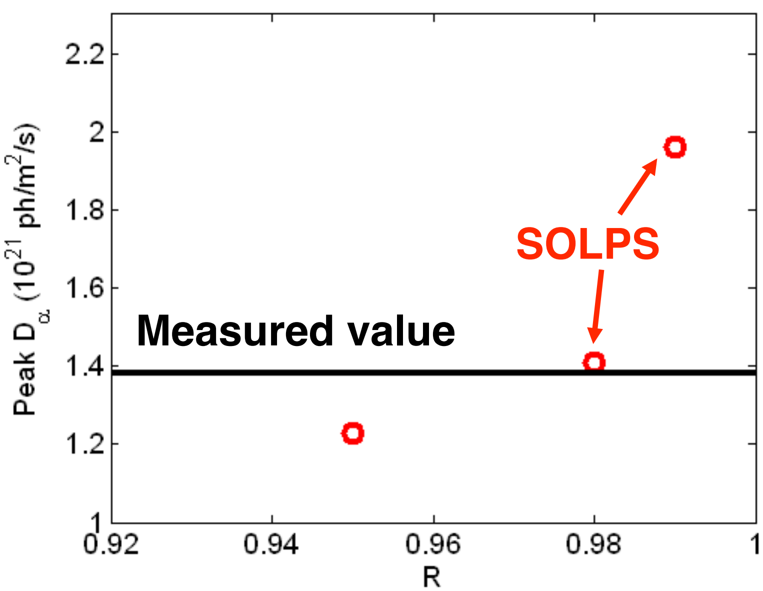


J. Canik

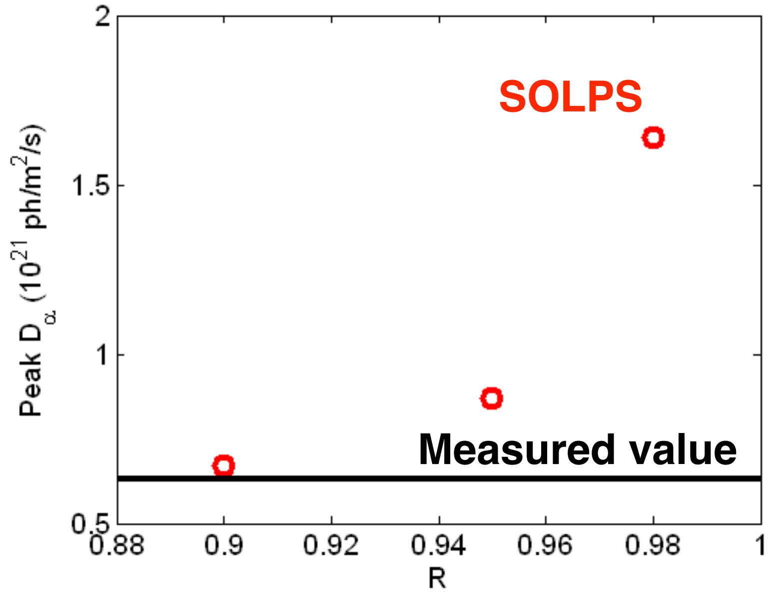
Peak D_α brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces R from ~.98 to ~.9

- 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

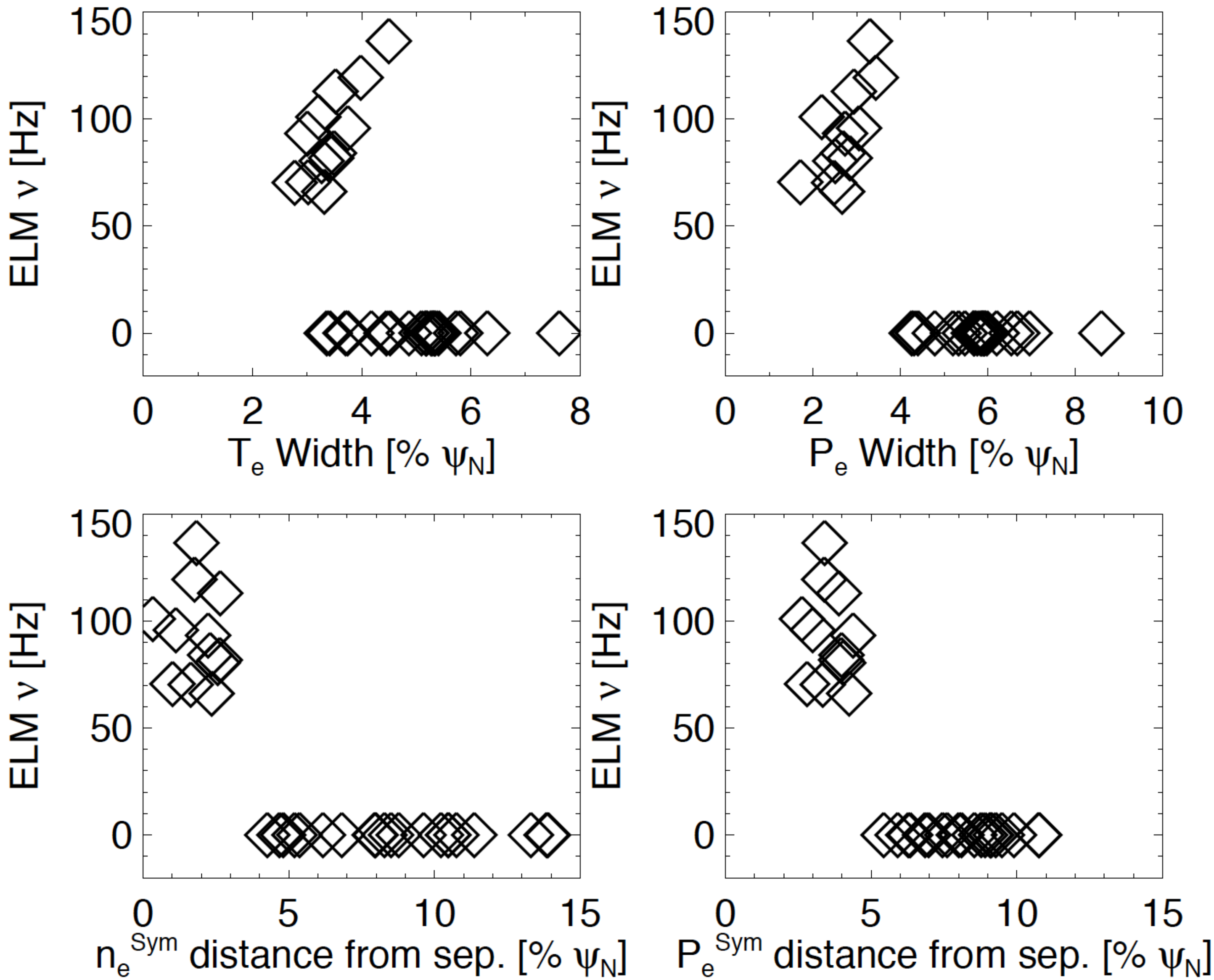
Pre-lithium



Post-lithium

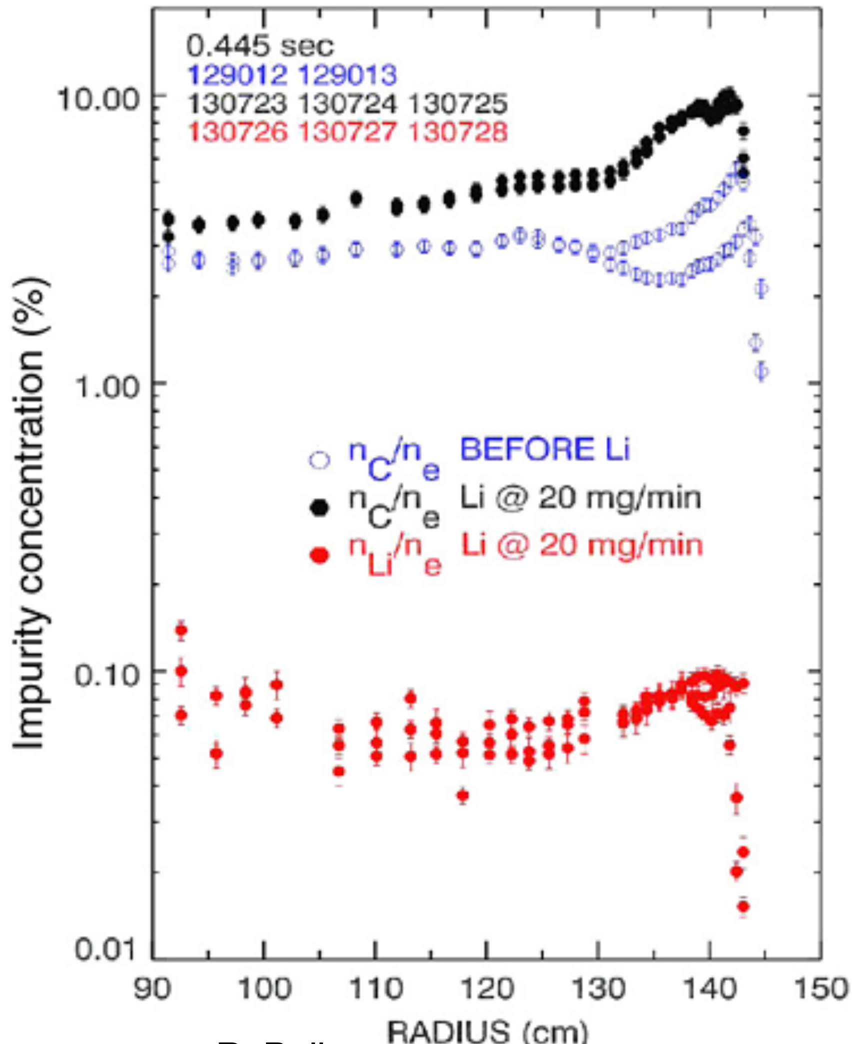


n_e and P_e "mtanh" symmetry points also separate ELMy and ELM-free data



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 may be due to lack of ELMs
  - Can be mitigated by triggering ELMs



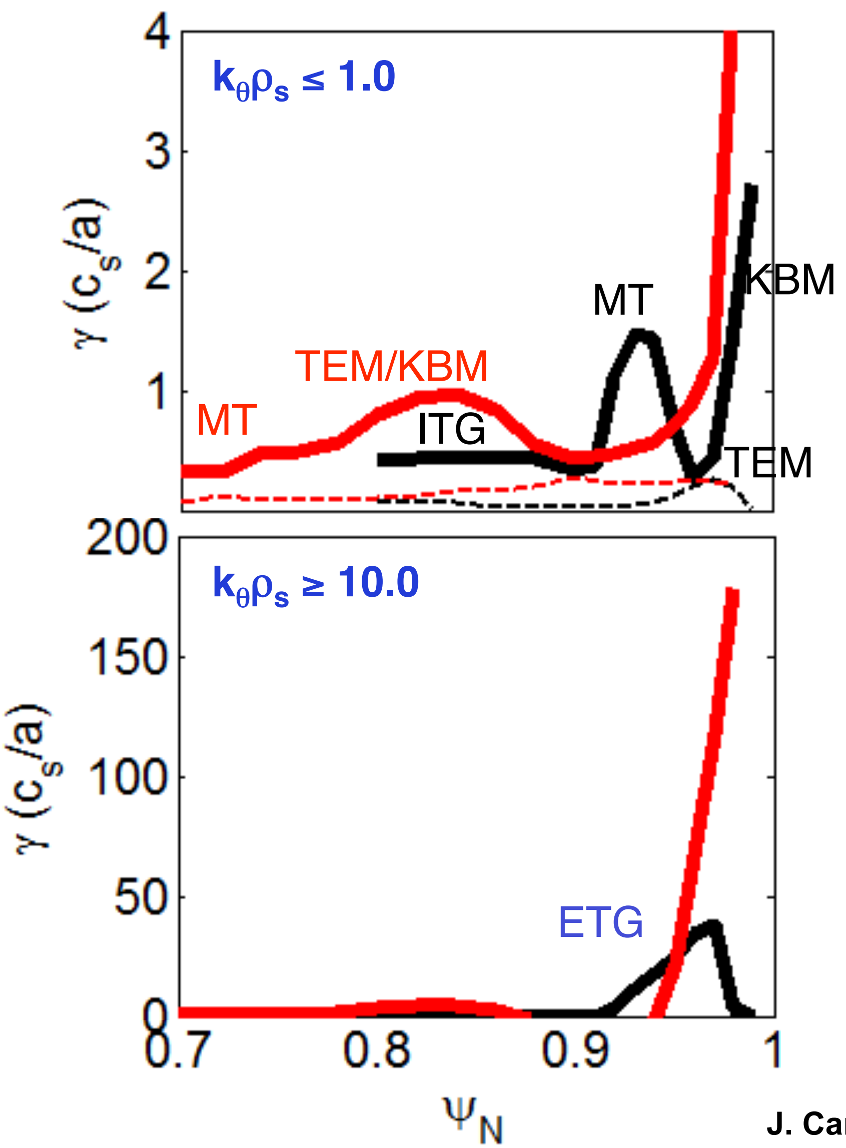
R. Bell

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

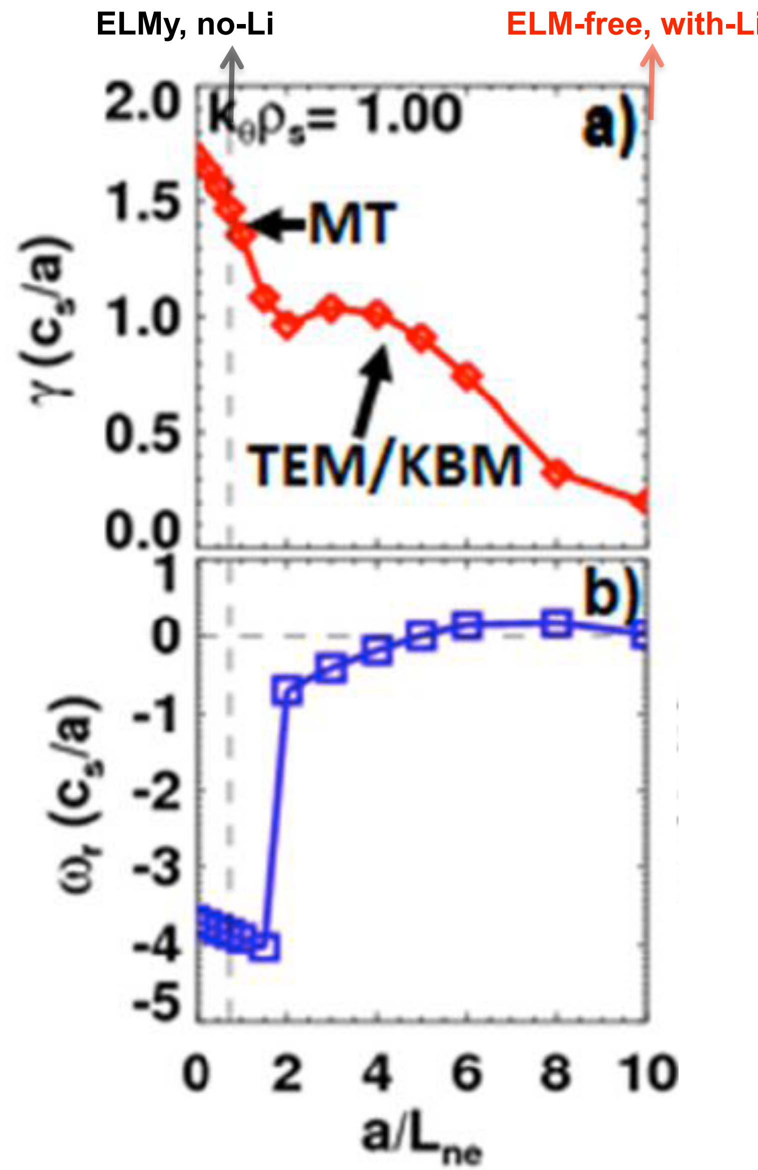
Power and particle exhaust a key challenge for future devices

- ITER is designed to operate in a “partially detached divertor” state, at the limits of heat removal capability for solid PFCs
  - “Attached divertor” states usually have 100% higher peak heat flux
  - There are challenges for tungsten in this environment
- DEMO designs have ~ 5x higher power density: if high core radiation unachievable, that heat exhaust problem may be impossible with solid surfaces
  - Liquid metals are an option, but need significant R &D
- NSTX used lithium wall coatings (evaporative and liquid) to test the efficacy of lithium in particle and power exhaust
  - Lithium has effective deuterium retention -> low recycling
  - Lithium will be important research line in NSTX-Upgrade, which comes online in 2014

Increased density gradient with lithium reduces micro-tearing drive; (ETG important in far edge in clamping T_e gradient)

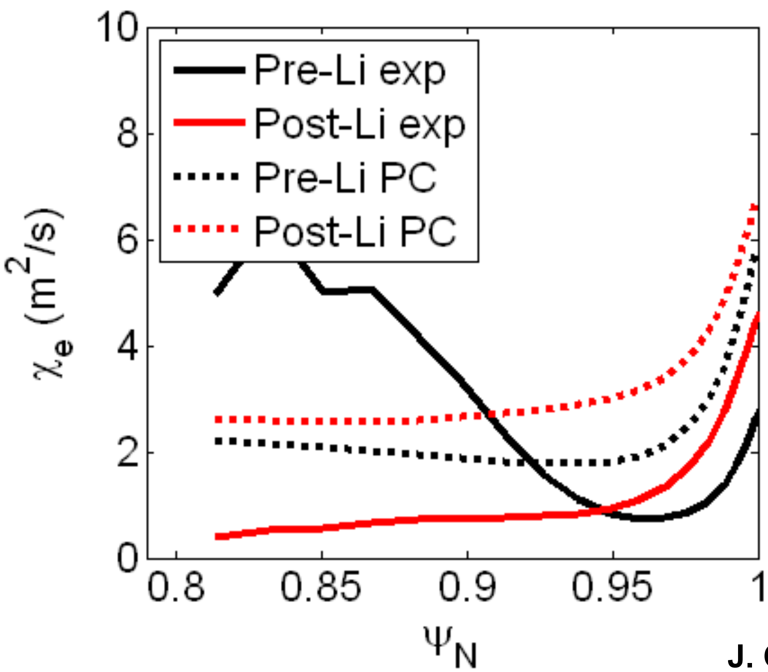


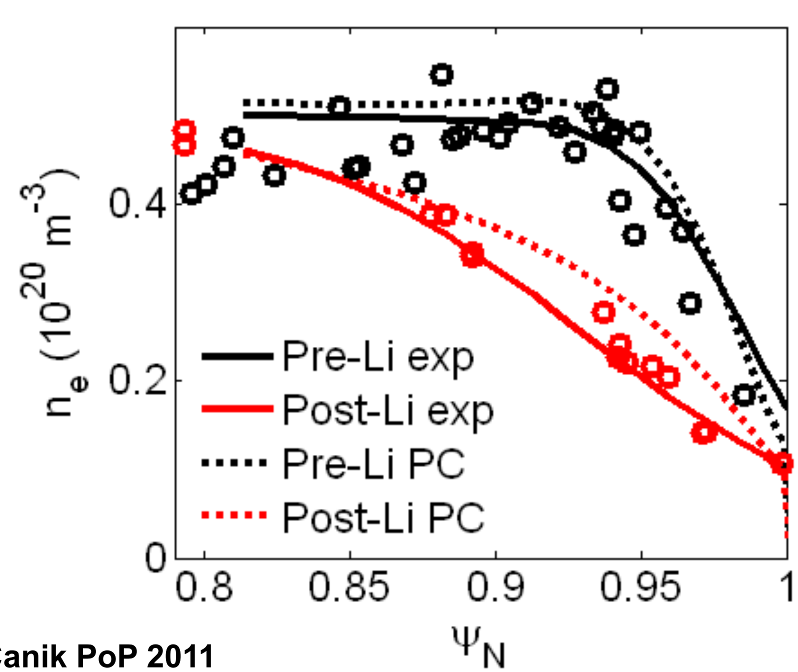
J. Canik, EX/P7-16



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





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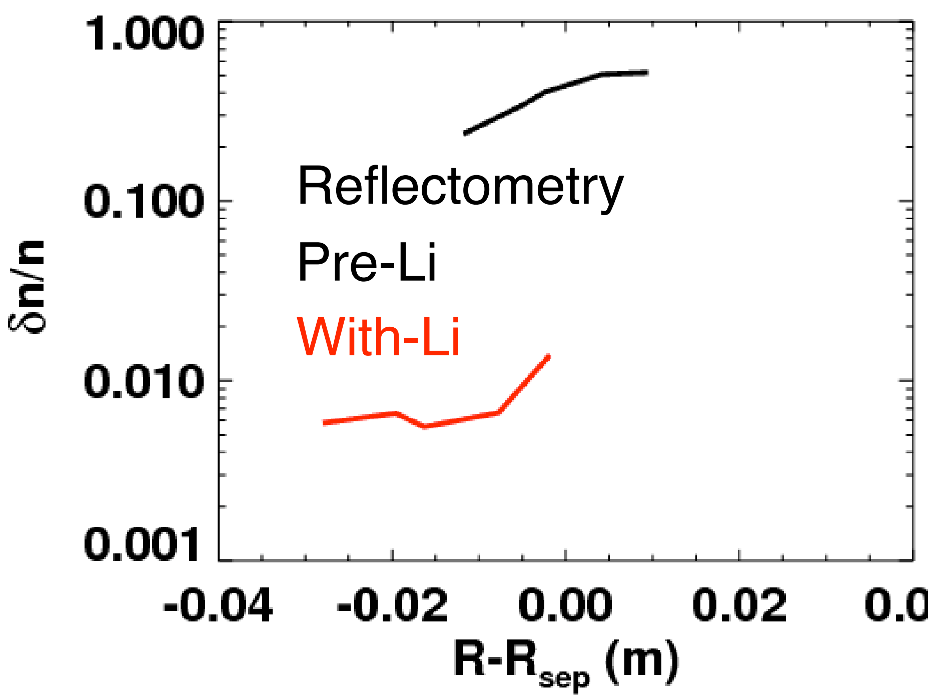
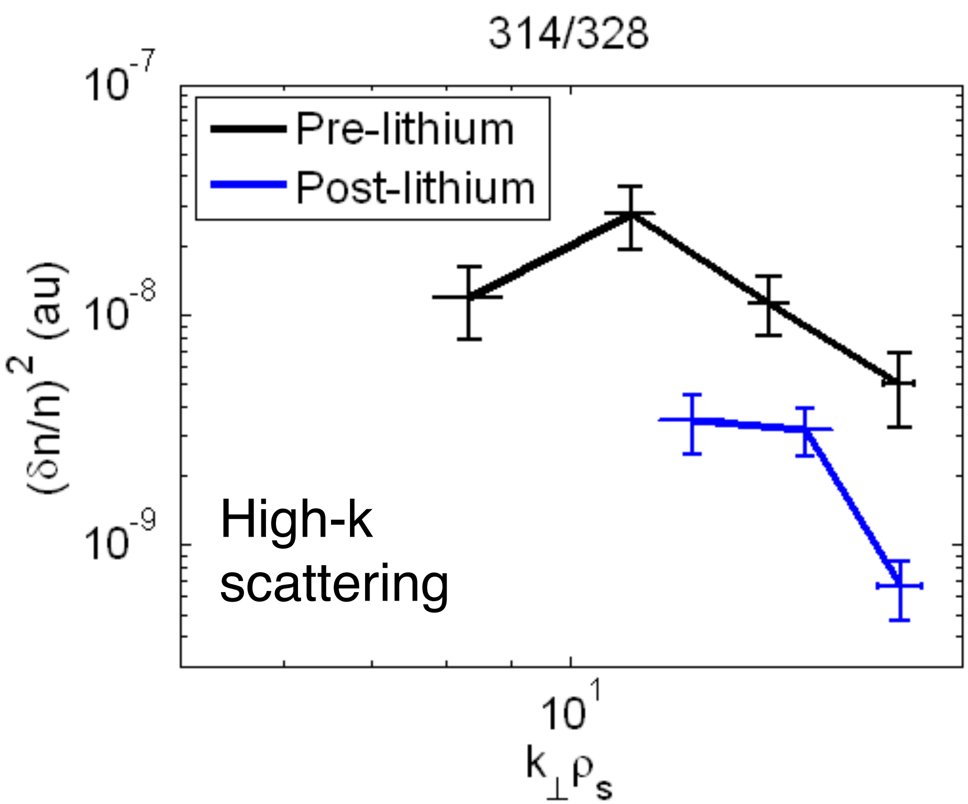
Edge fluctuations reduced with lithium coatings

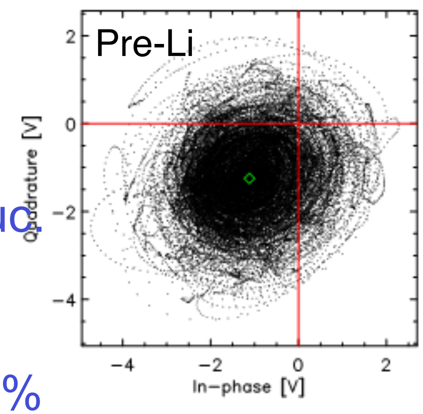


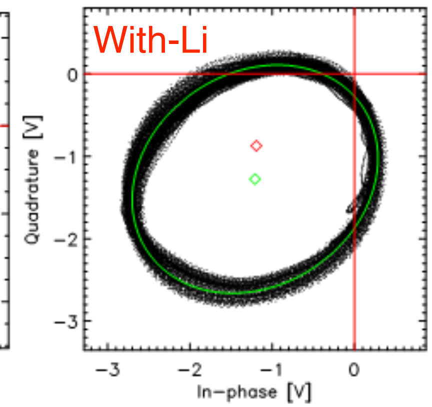


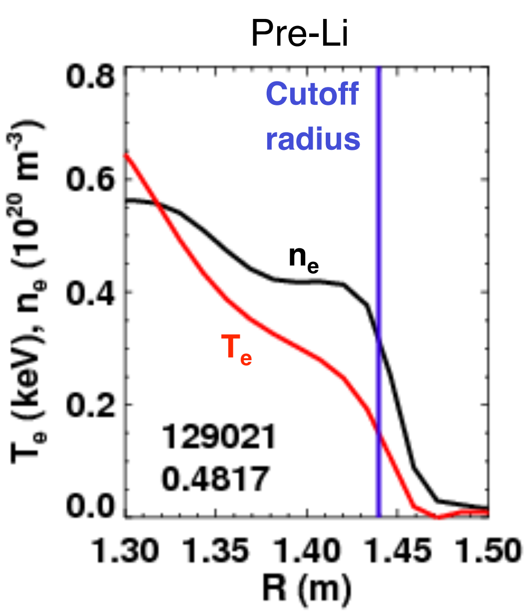
J. Canik PoP 2011

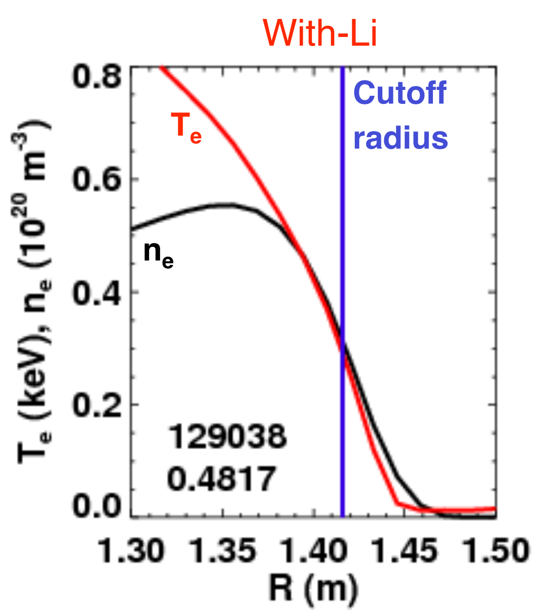
Edge reflectometry near pedestal top shows reduced density fluctuations with lithium

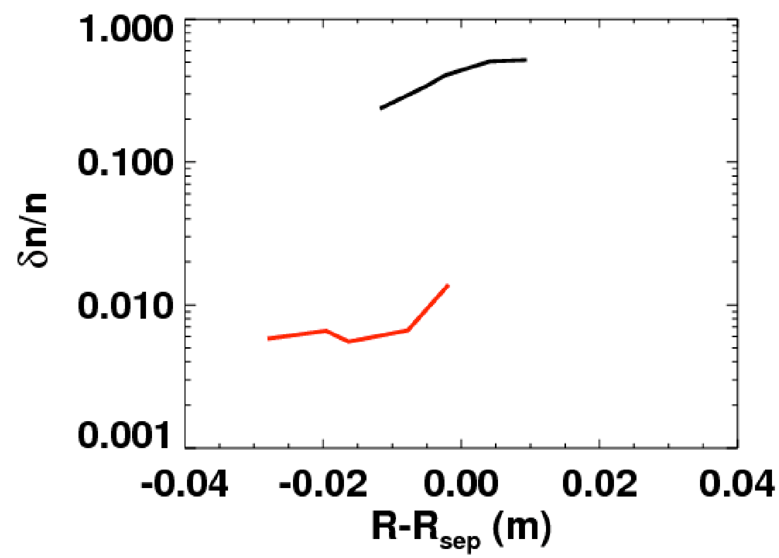
- Reduced transport in inner region->higher pedestal top pressure
- Reflectometer shows reduced fluctuation level
  - Pre-lithium: strong amplitude and phase fluc.
  - Post-lithium: little amplitude fluctuation
  - 3D simulations using Kirchoff integral indicate turbulence level reduced from ~10% to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







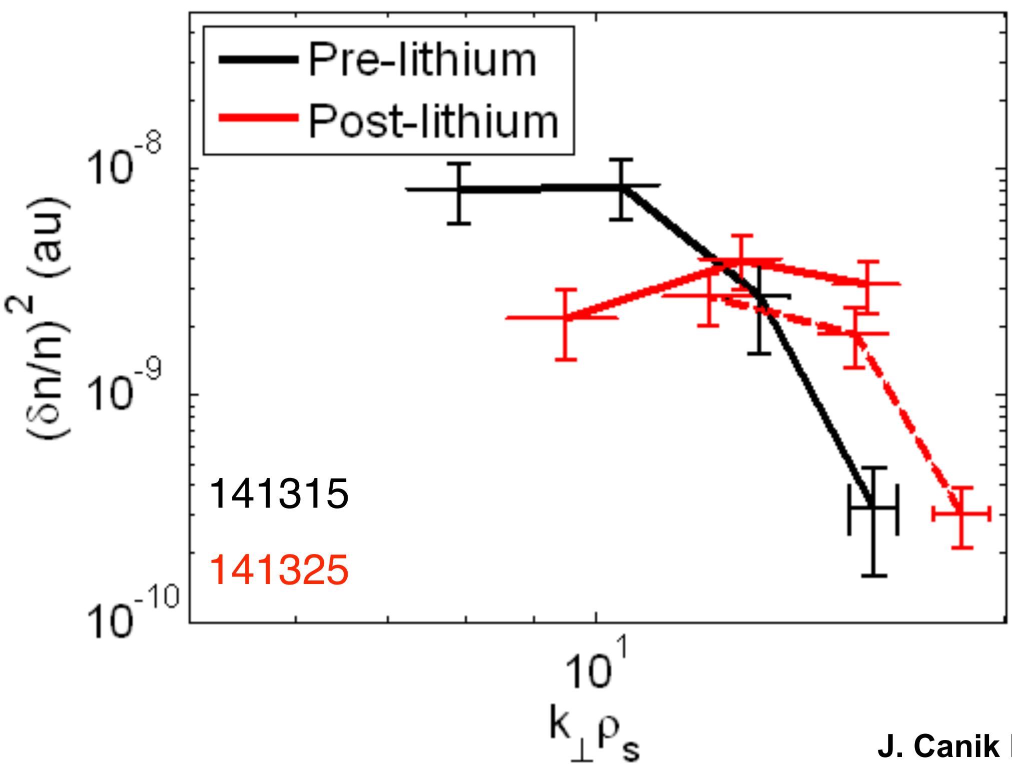


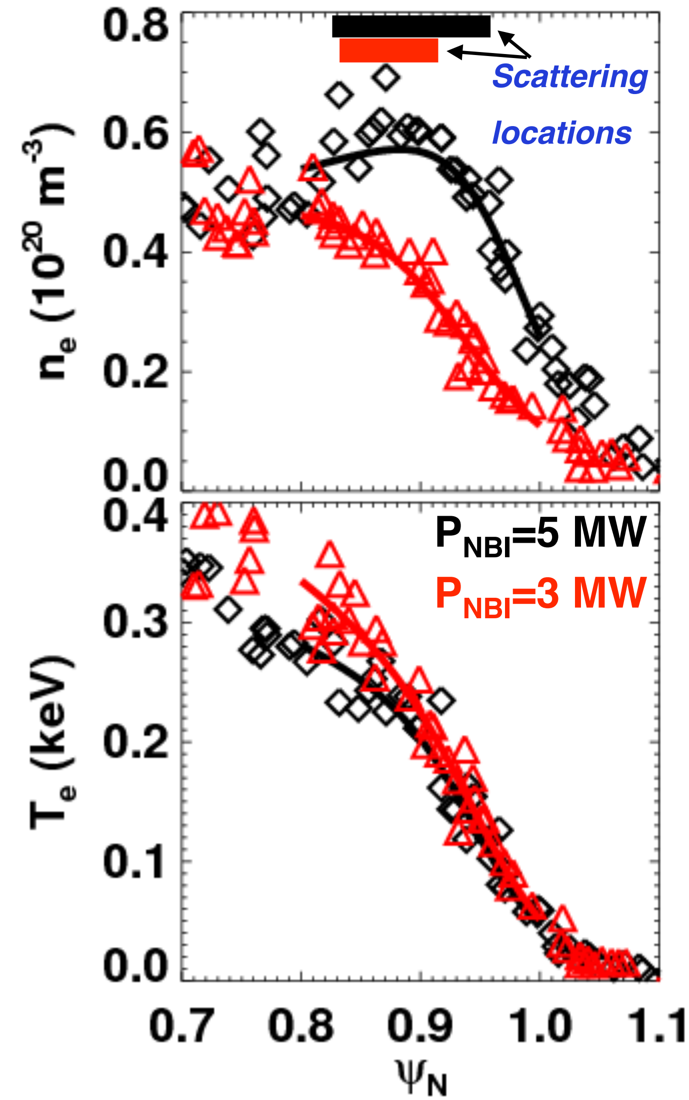


J. Canik PoP 2011

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

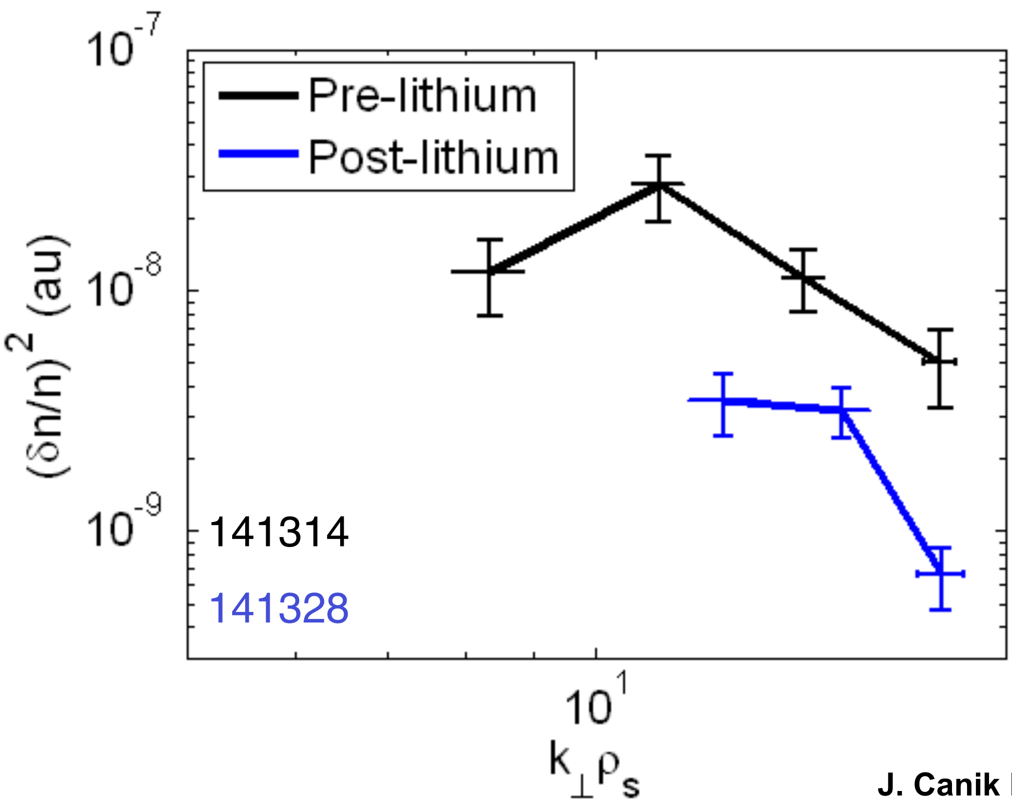


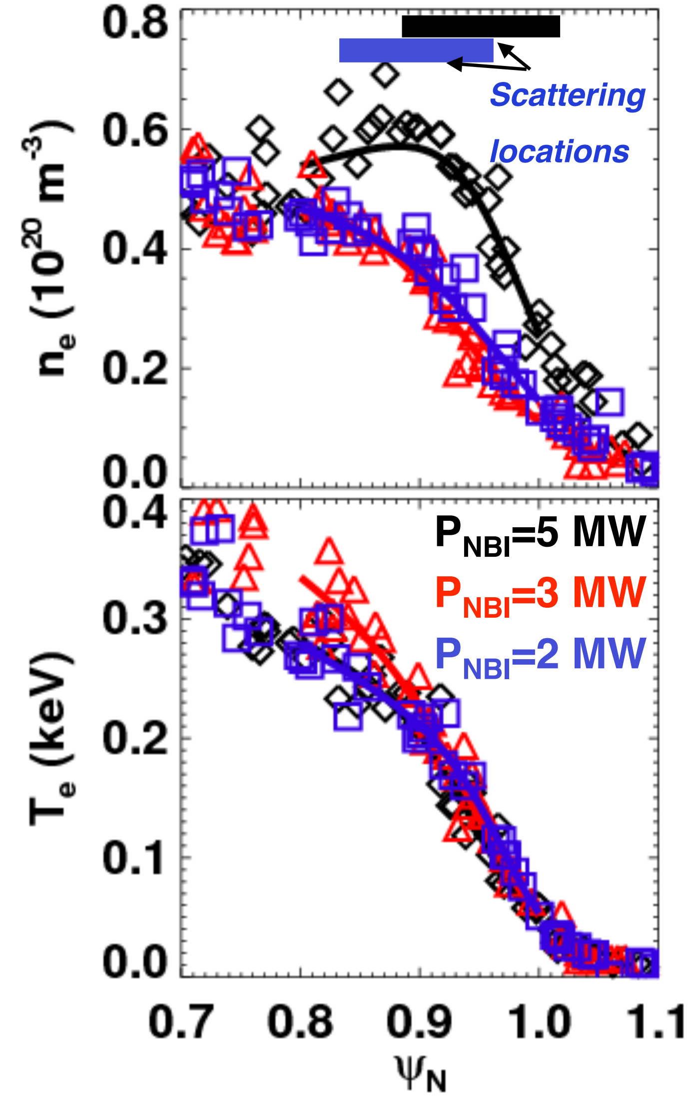


J. Canik PoP 2011

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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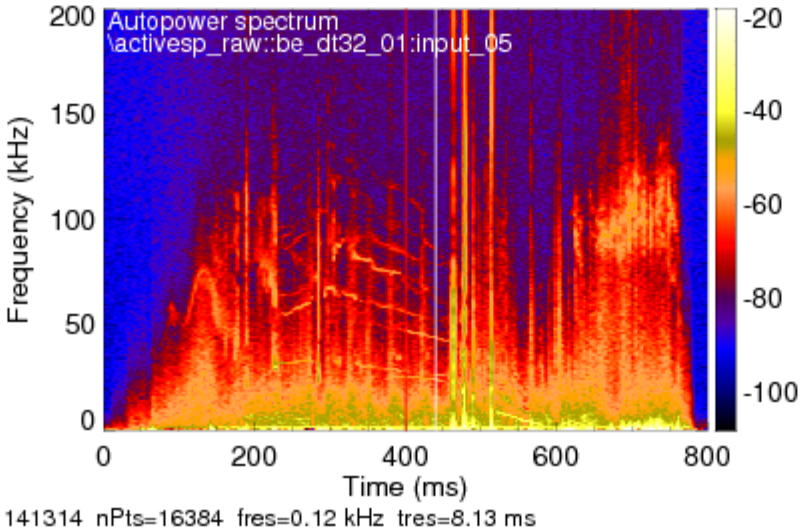
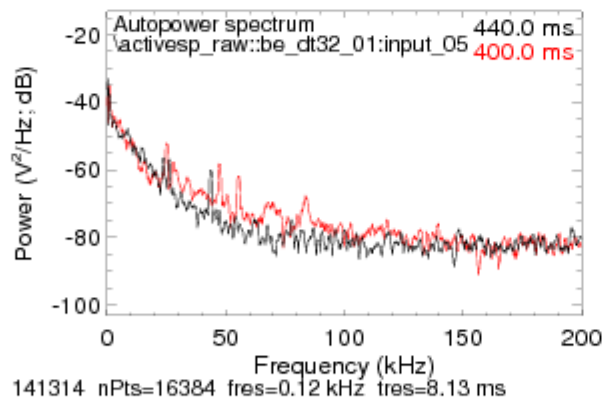
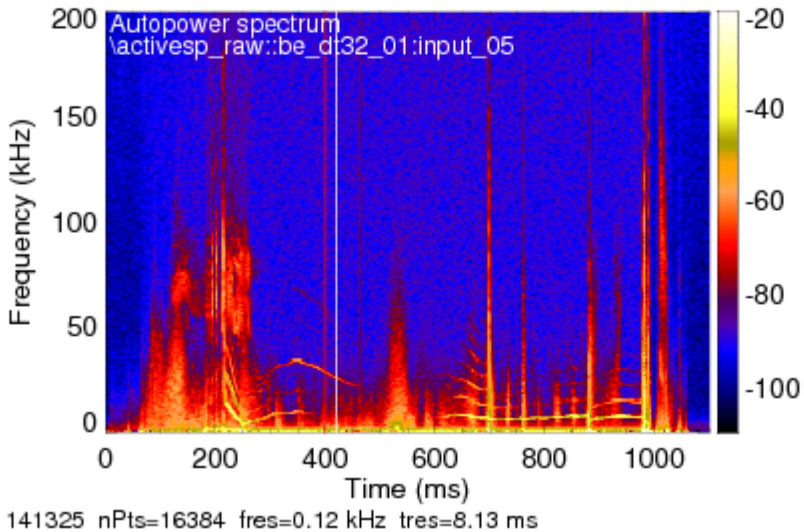
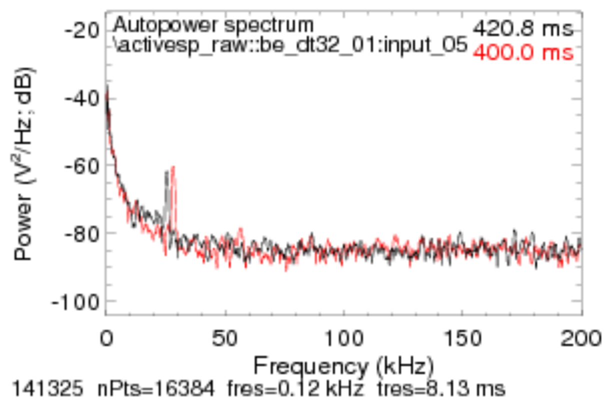
BES also shows reduced turbulence levels in post-lithium discharges









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