NSTX-U

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The effect of progressively increasing lithium coatings on plasma performance, and the underlying role on collisionality, in NSTX

R. Maingi Oak Ridge National Laboratory

S. Kaye, D. Boyle, J. Canik, T. Osborne, P. Snyder, M. Bell, R. Bell, C.S. Chang, A. Diallo, T.K. Gray, W. Guttenfelder, M. Jaworski, R. Kaita, H. Kugel, B. LeBlanc, J. Manickam, D. Mansfield, J. Menard, M. Ono, M. Podesta, R. Raman, Y. Ren, L. Roquemore, S. Sabbagh, C. Skinner, V. Soukhanovskii

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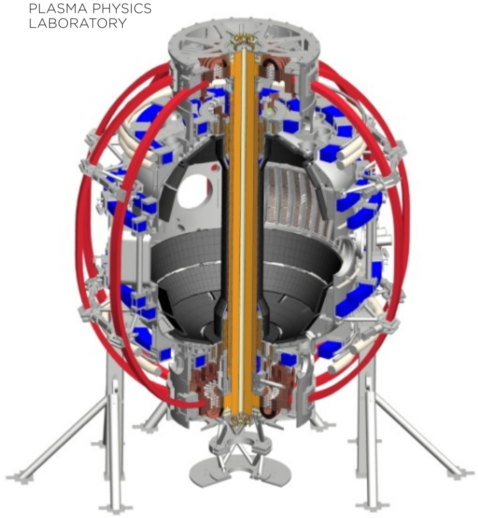
PPPL PRINCETON PLASMA PHYSICS LABORATORY



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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

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, IAEA 2012
W. Guttenfelder, IAEA 2012

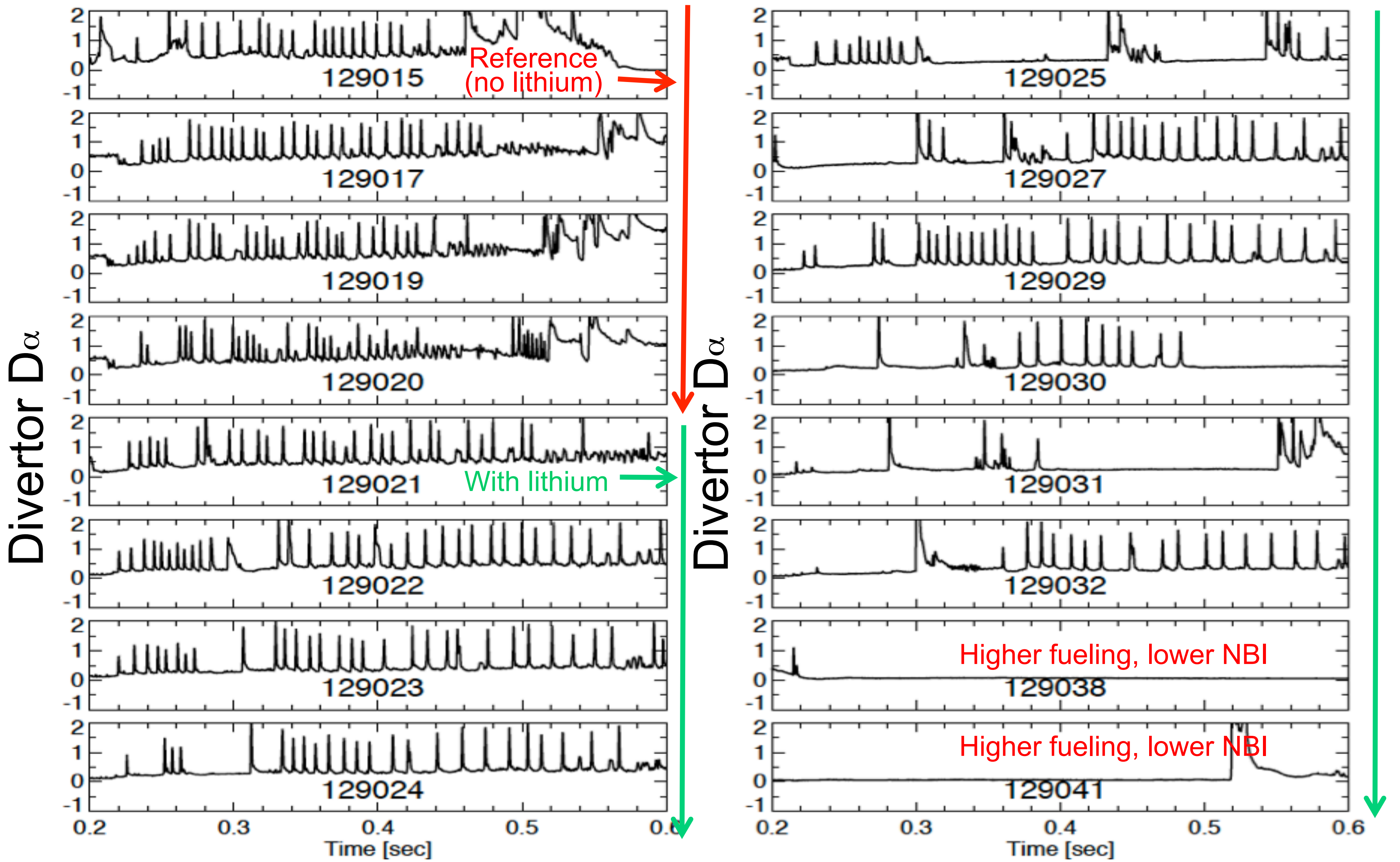
- Edge particle and thermal transport declined
- ELM frequency decreased before going to 0
  - Edge stability gradually improved

J. Canik, IAEA 2012
J. Canik, PoP 2011
D. Boyle, PPCF 2011
C.S. Chang, IAEA 2012
A. Diallo, IAEA 2012

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

M. Jaworski, IAEA 2012

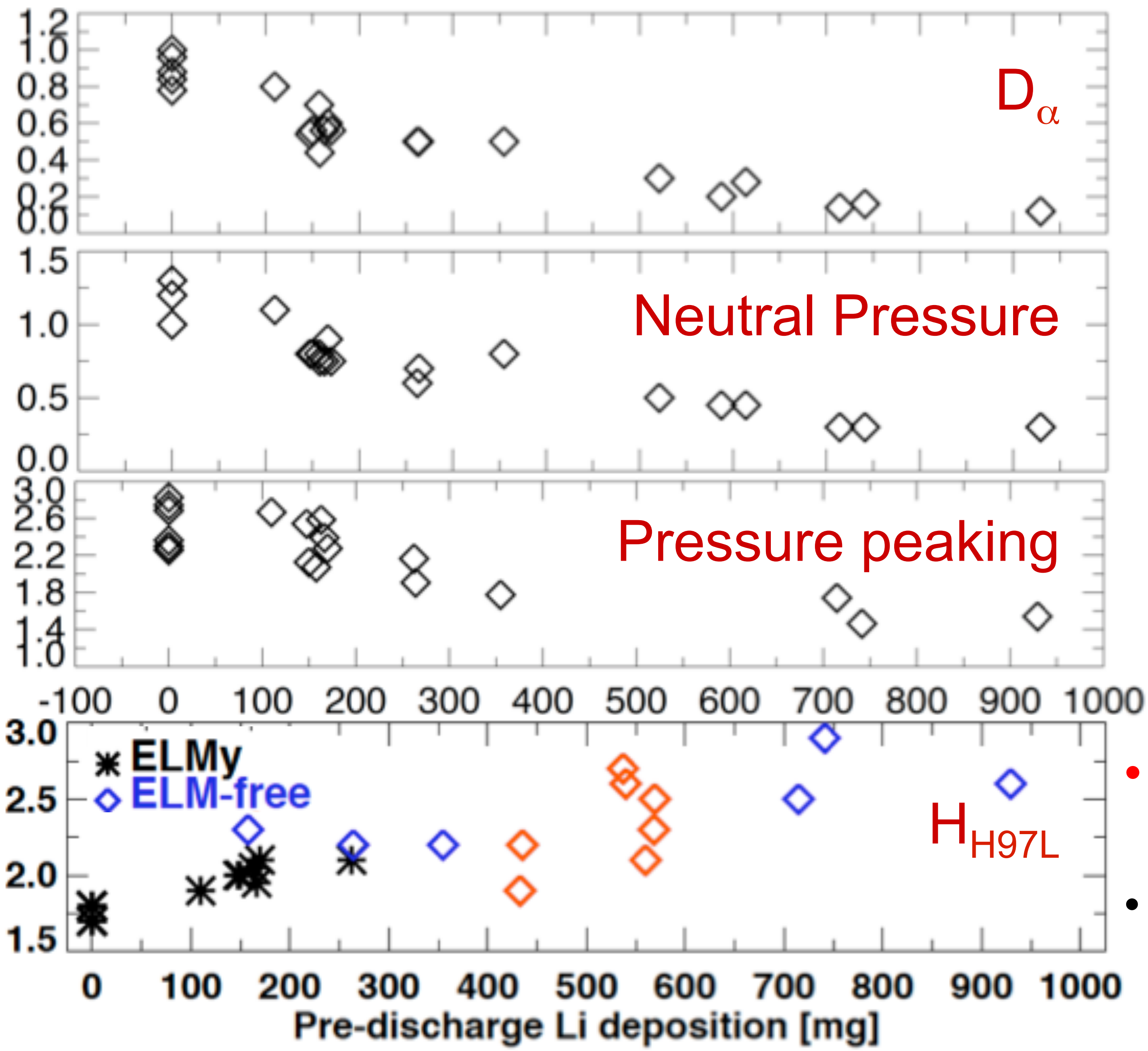
ELMs eliminated gradually during experiment



Outline

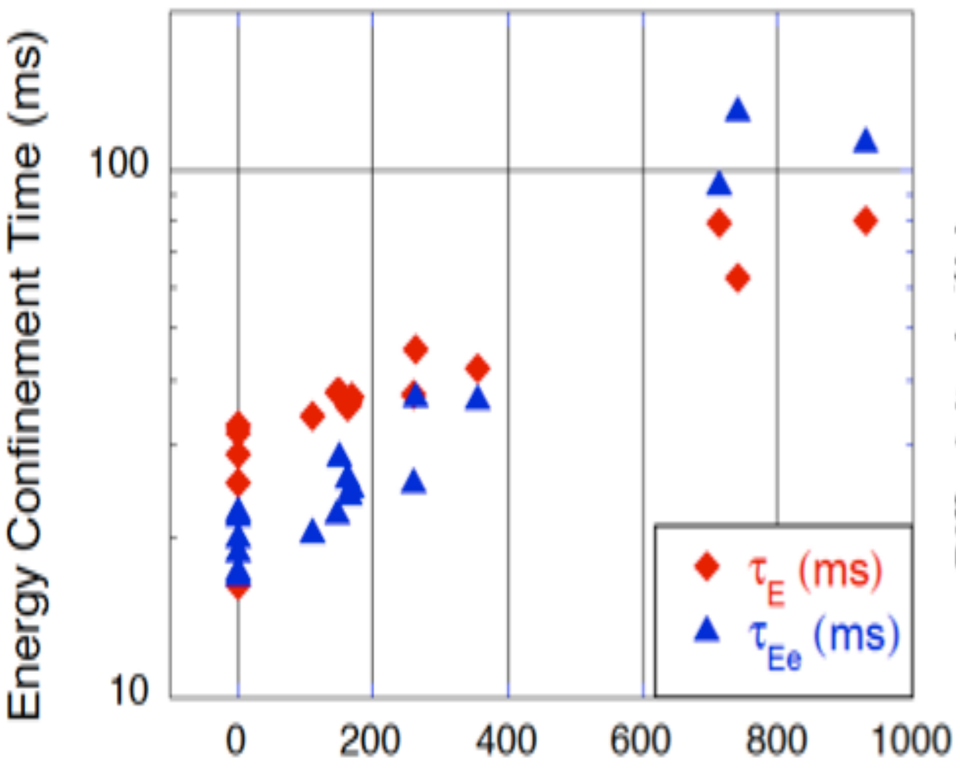
- Global changes, including collisionality and normalized gyro-radius, and SOLPS interpretive modeling
- Micro-stability and ELM stability calculations
- Flowchart describing role of lithium

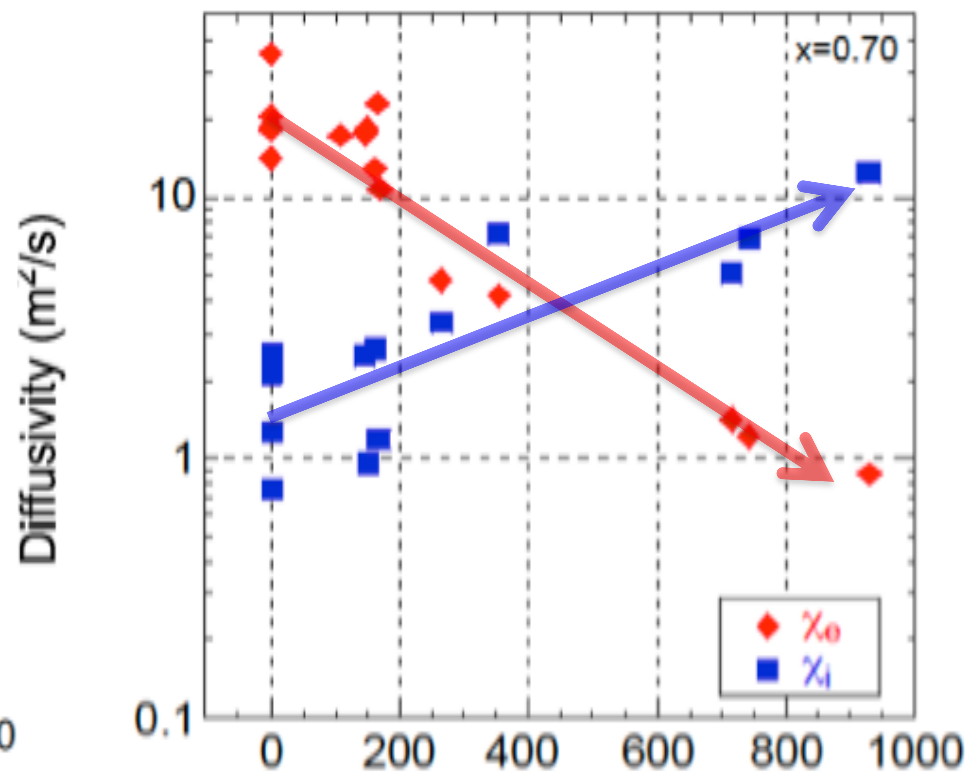
Recycling, neutral pressure, and pressure peaking decreased nearly continuously with increasing lithium; H_{H97L} increased



- **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)

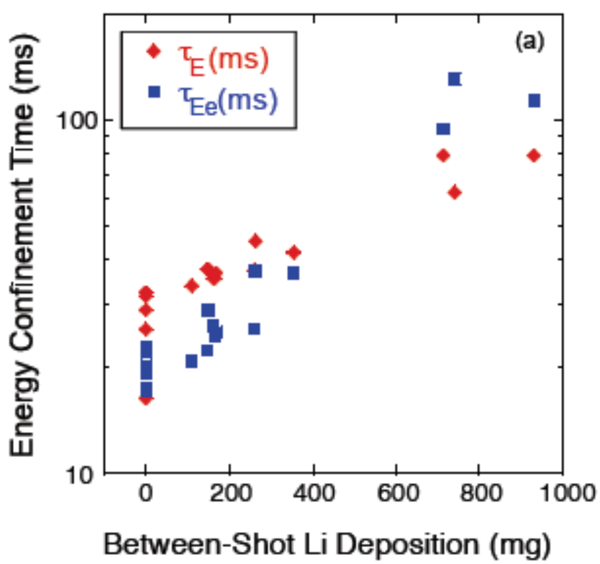
- Edge ion transport increased

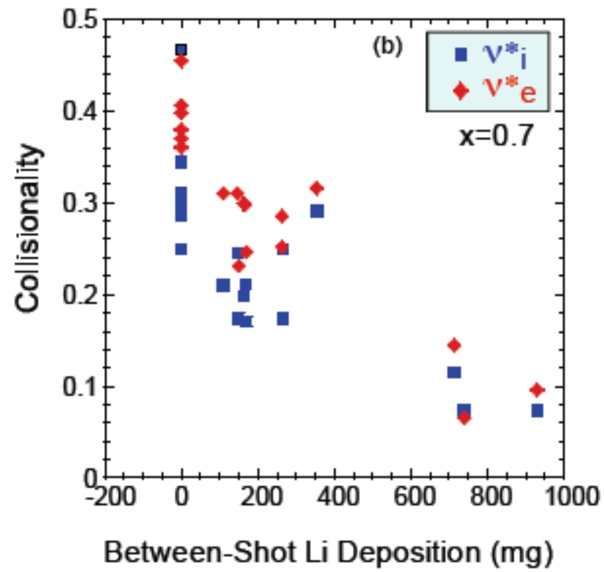
R. Maingi, PRL 2011, NF 2012; S. Kaye, IAEA 2012

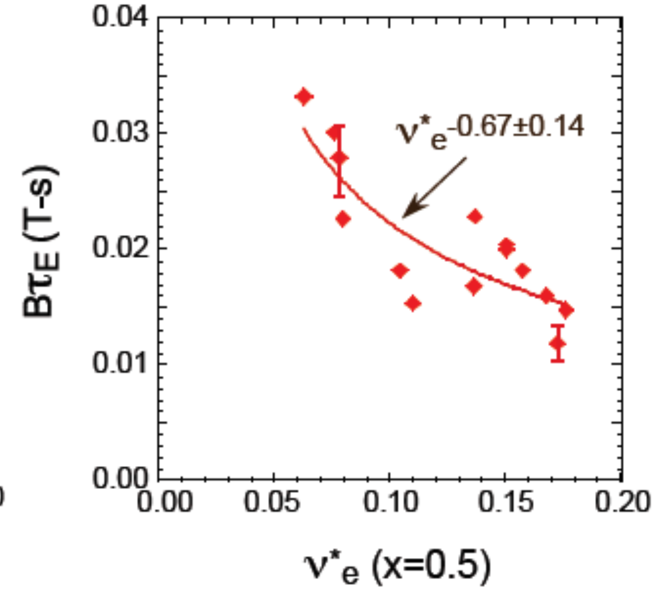
TRANSP

Confinement improvement also correlated with reduced collsionality

- Strong increase in total thermal and electron confinement
- Factor of five decrease in collisionality
- Strong and favorable dependence of τ_E with decreasing collisionality
  - Implications for FNSF (will operate at over one order of magnitude lower ν_ε*)







Maingi et al. PRL (2011), EX/11-2

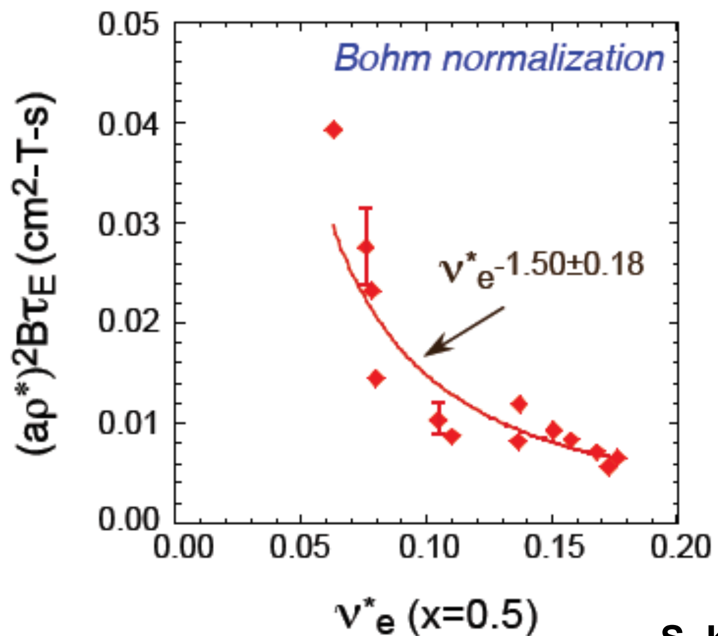
S. Kaye, IAEA 2012

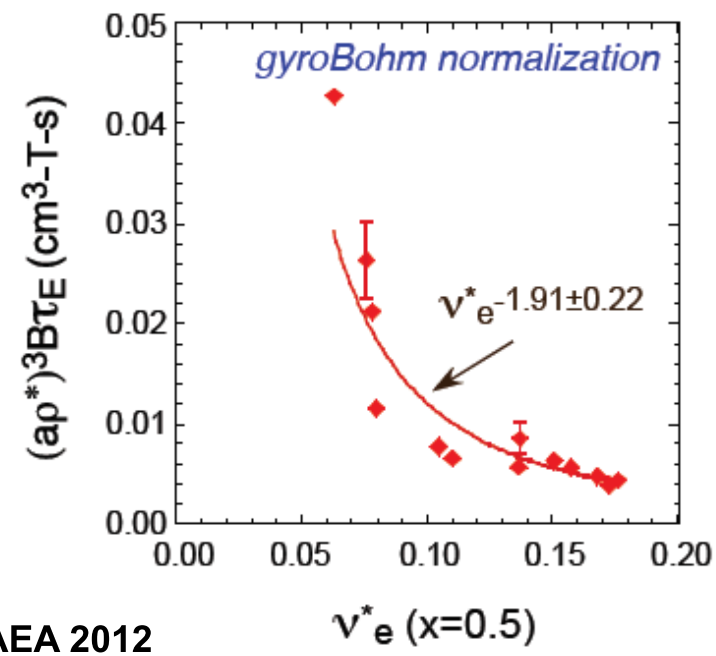
$x=[\Phi/\Phi_a]^{1/2}$

Dependence on ν^* even stronger when ρ^* variations considered

- *Express confinement scaling in terms of dimensionless parameters $\Omega\tau_E = B\tau_E = \rho^{*\alpha} f(\nu, \beta, T_e/T_i, \kappa, q, \ldots\ldots.)$ where $\alpha = -2$ for Bohm and $\alpha = -3$ for gyroBohm scaling*
  - *NSTX HeGDC+B discharges found to be consistent with gyroBohm (Kaye, 2006)*
- *For the Li scan, B, q, $\langle\beta\rangle$, κ, a … constant for all discharges*

Normalize τ_E further by $\rho^{*\alpha}$: test both Bohm and gyroBohm

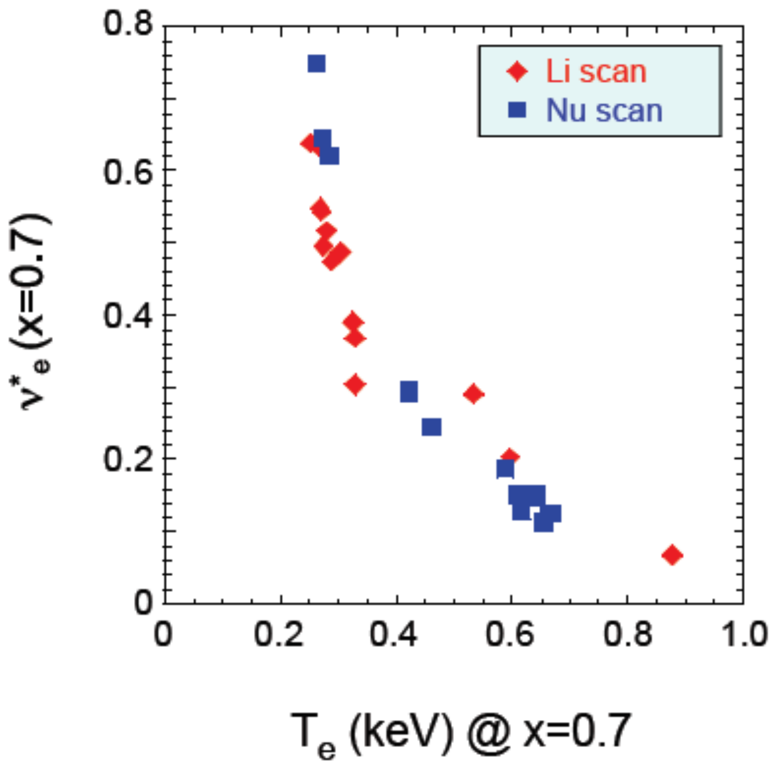


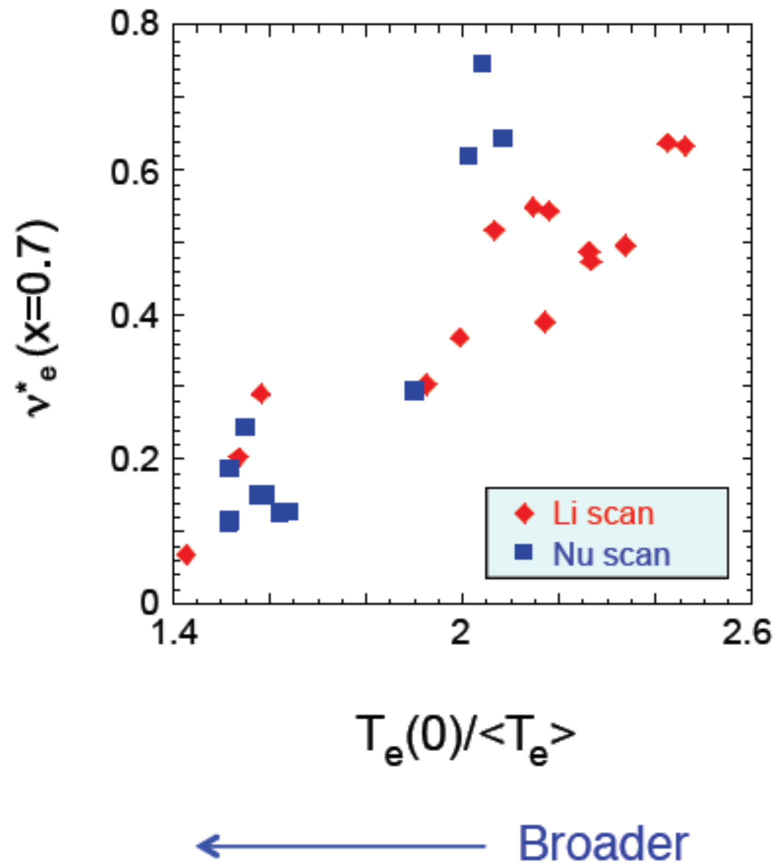


S. Kaye, IAEA 2012

Broadening of the T_e profile is main reason why ν^* and ρ^* vary with lithium conditioning and in other ν^* scans

$$\nu^* \sim 1/T_e^2$$

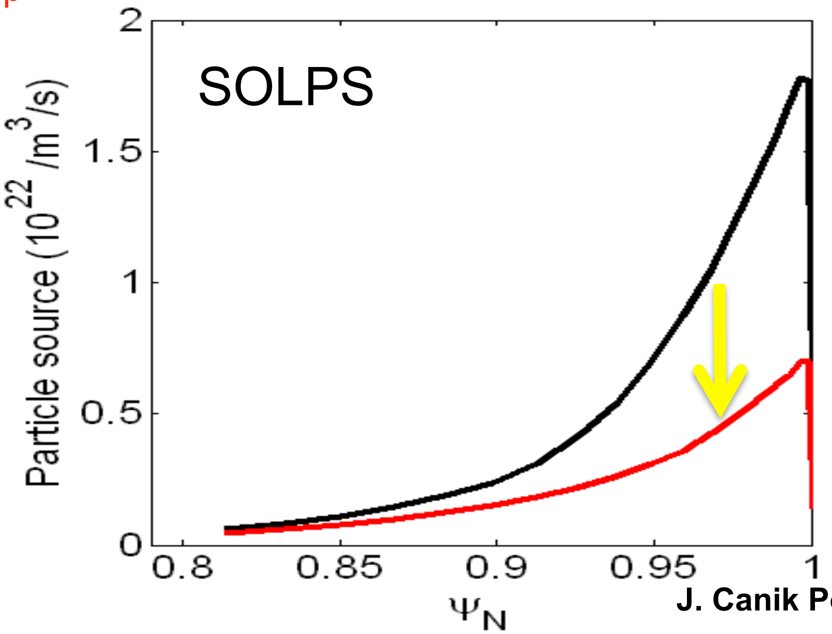




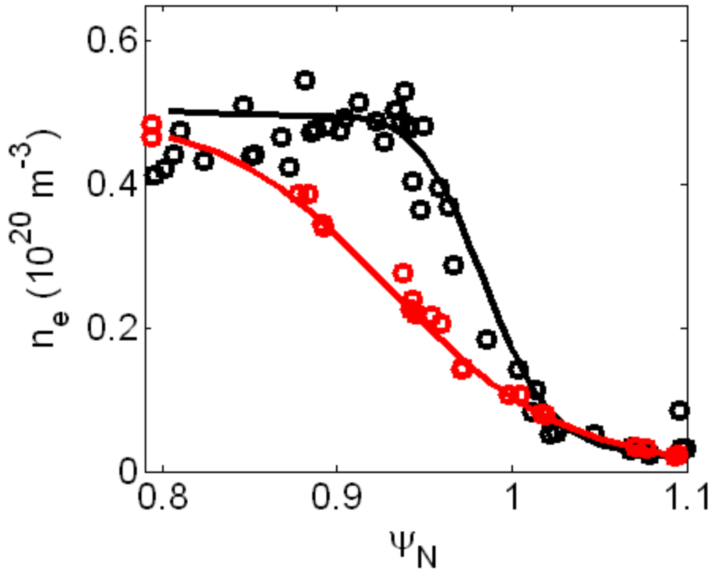
S. Kaye, IAEA 2012

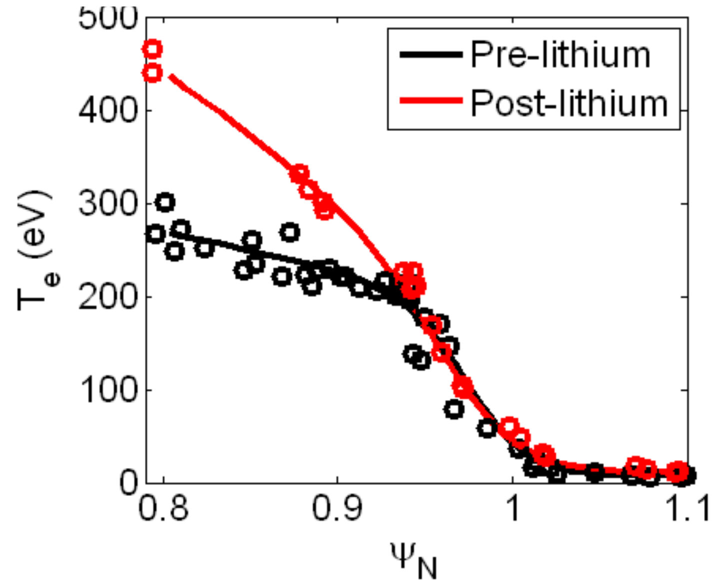
SOLPS interpretive simulations indicate particle fueling source from recycling was reduced with lithium

- 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
- R_p dropped from 0.98 to 0.9 with lithium



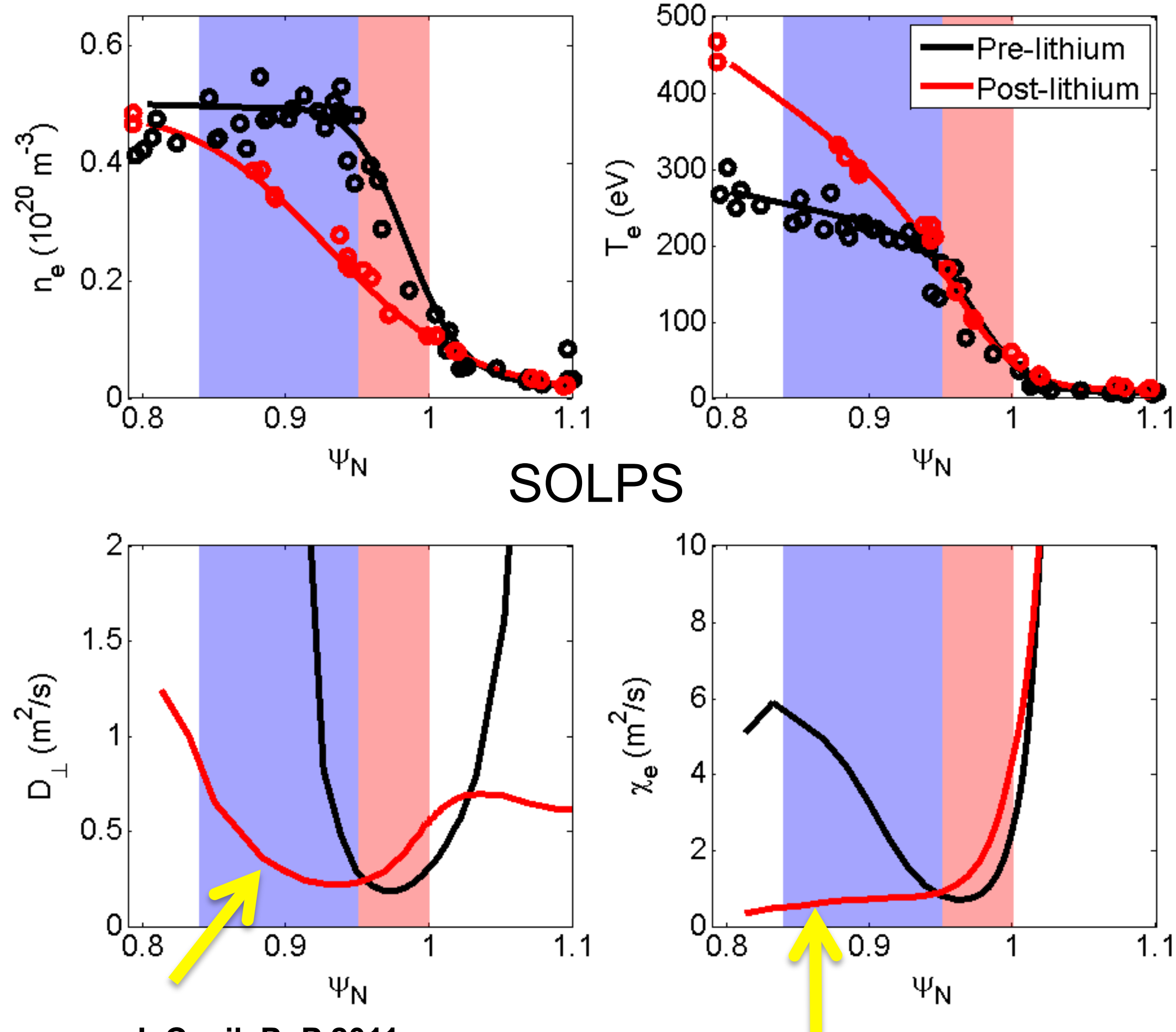
J. Canik PoP 2011





Recycling and edge transport changes interpreted with SOLPS simulations

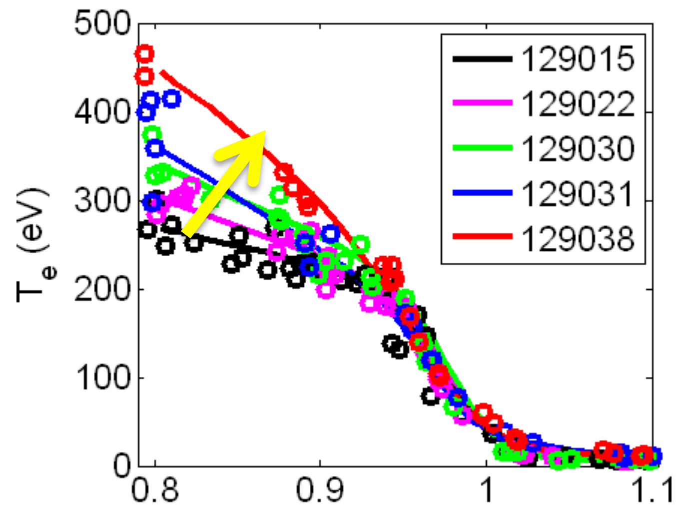
- Pre-lithium case shows typical barrier region inside separatrix
- Change in n_e profile with lithium from $0.95<\psi_N<1$ consistent with drop in fueling at ~ constant transport
- Spatial region of low transport expanded with lithium
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)

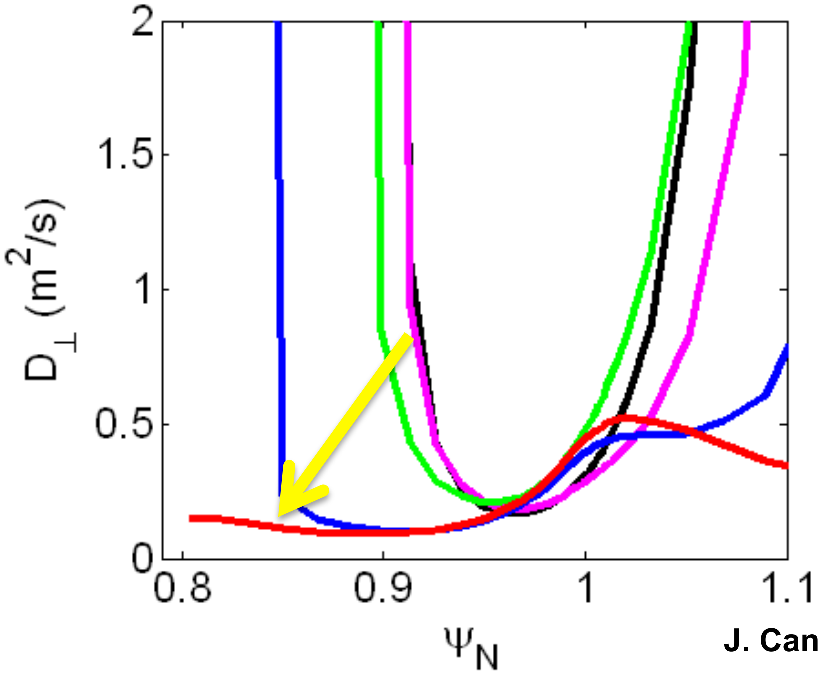


J. Canik PoP 2011

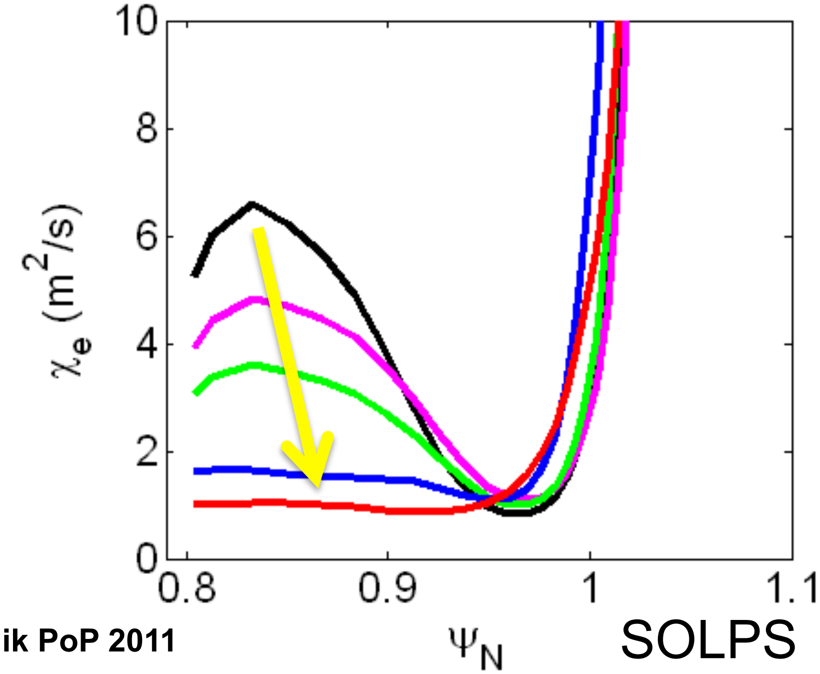
Spatial extent of low D, χ_e region expanded continuously with increasing pre-discharge lithium

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





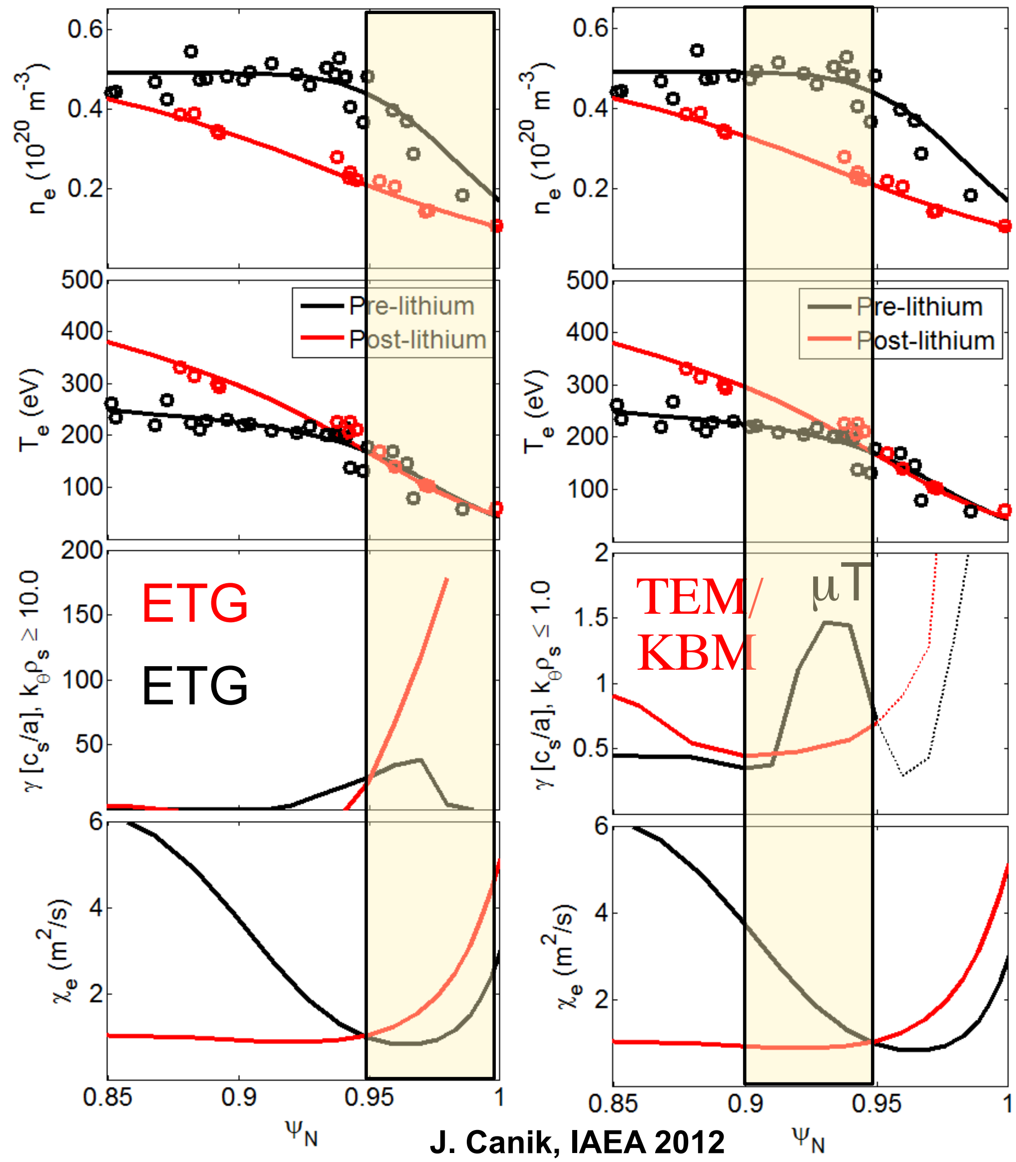
J. Canik PoP 2011



SOLPS

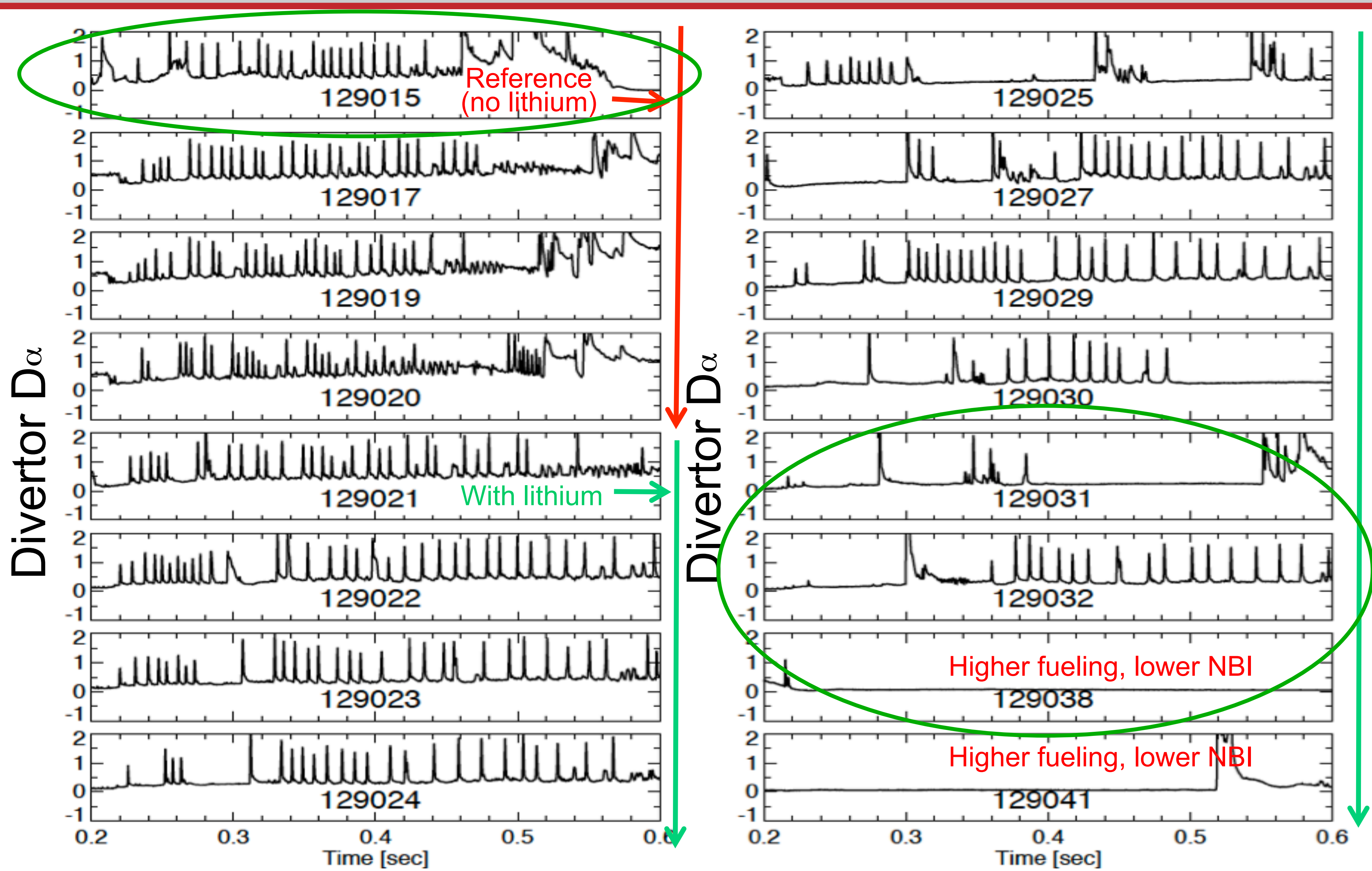
Work in progress: change in edge density gradient with lithium coatings alters the edge micro-stability properties

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

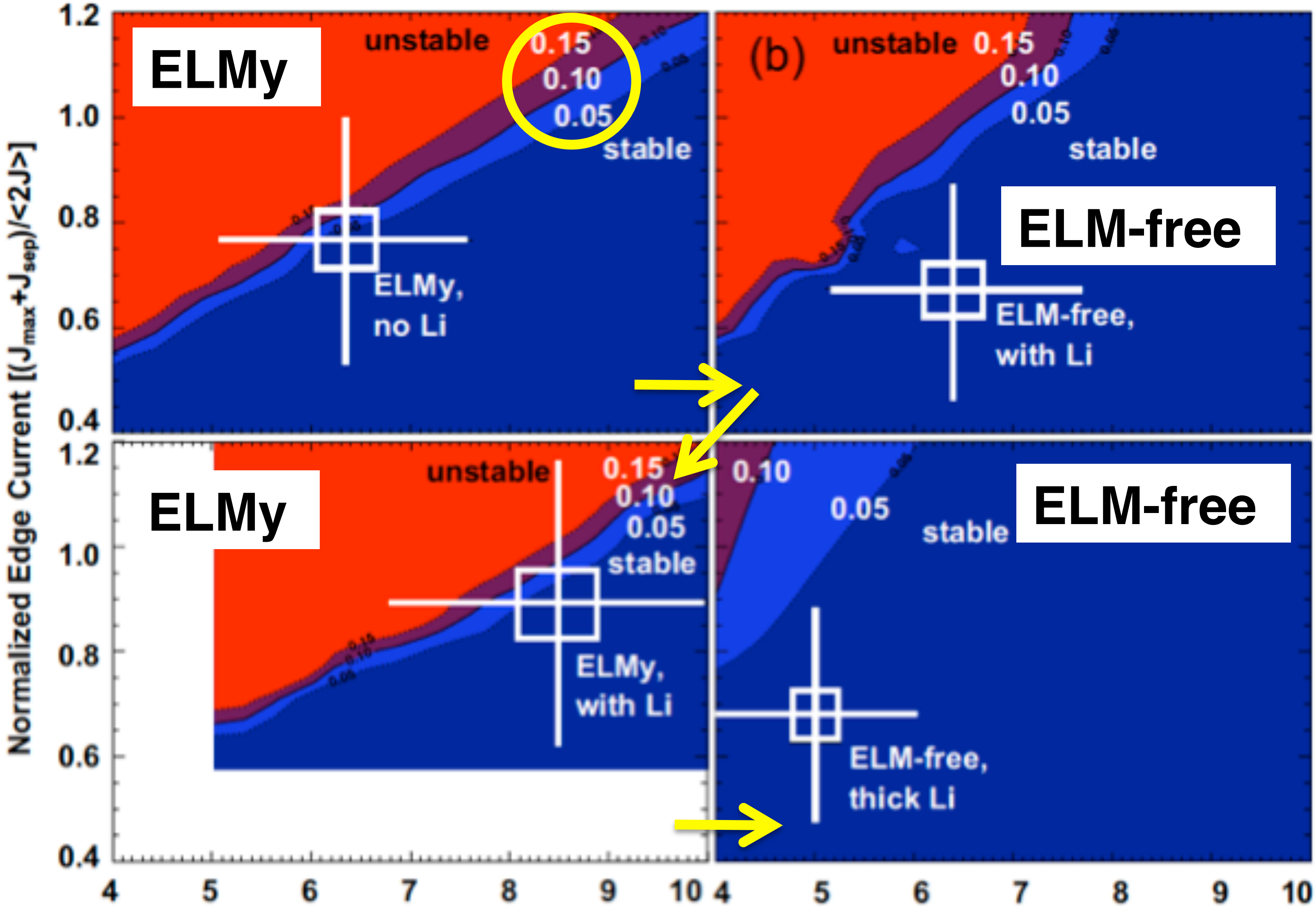


J. Canik, IAEA 2012

ELM elimination was not quite monotonic



ELMy discharges closer to kink/peeling stability boundary than ELM-free ones but ideal growth rates low: why instabilities not stabilized by diamagnetic flow?

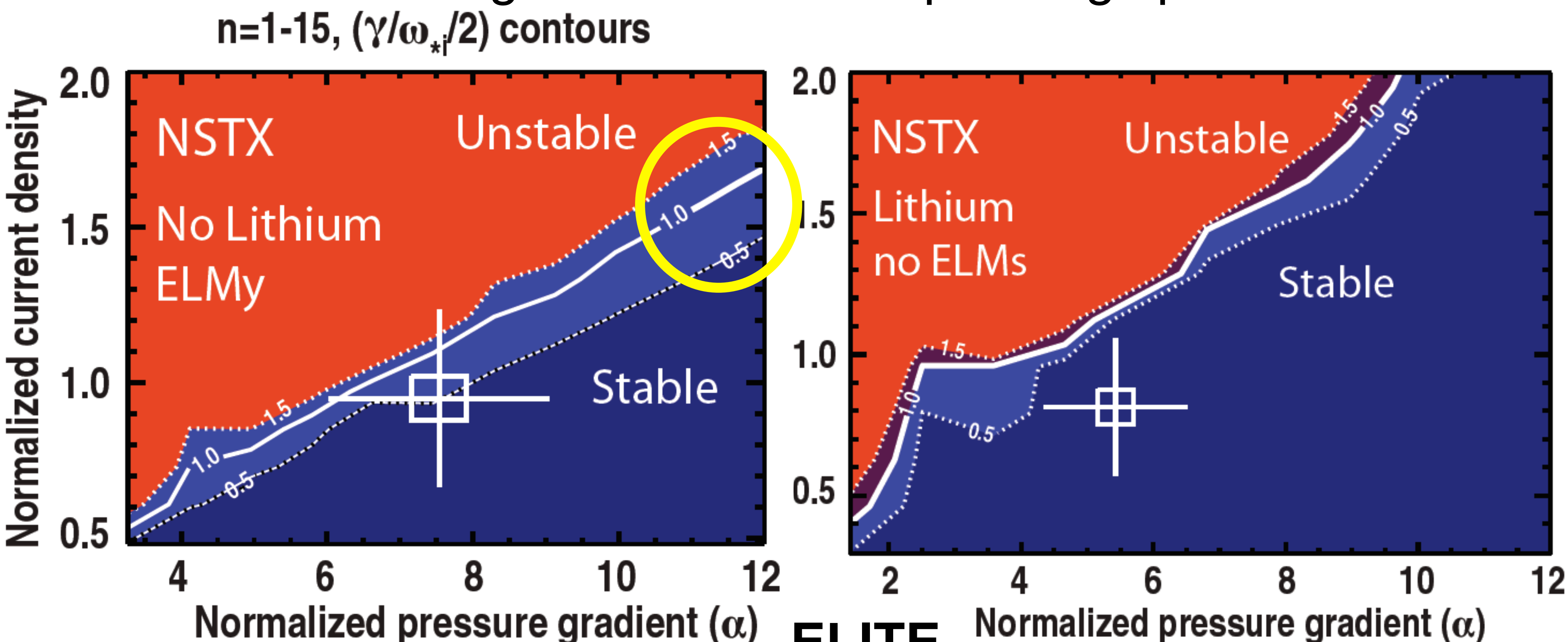


Boyle, PPCF 2011

ELITE

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

- Bootstrap current increased by 30%
- Growth rates for n=1, 2 were comparable than for n=3
- ELMy discharges at the ideal instability boundary
- ELM-free discharges still in stable operating space



ELITE

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)

→

n_e and ∇n_e **reduced**
∇T_e fixed

χ_e increased
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

- 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 was expected to saturate 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

- Correlates with reduced ν^* in outer half of plasma radius
- 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 still 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

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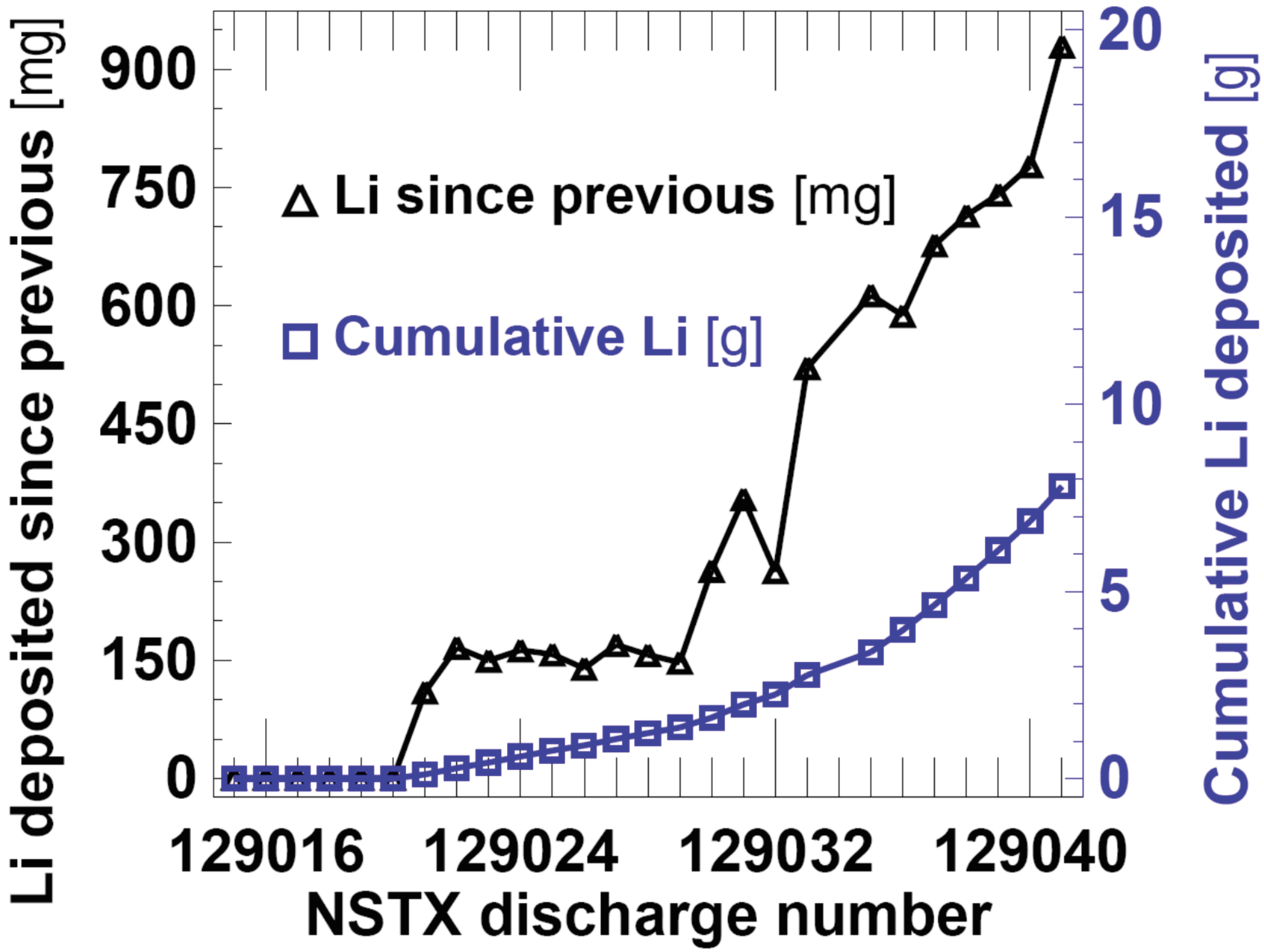
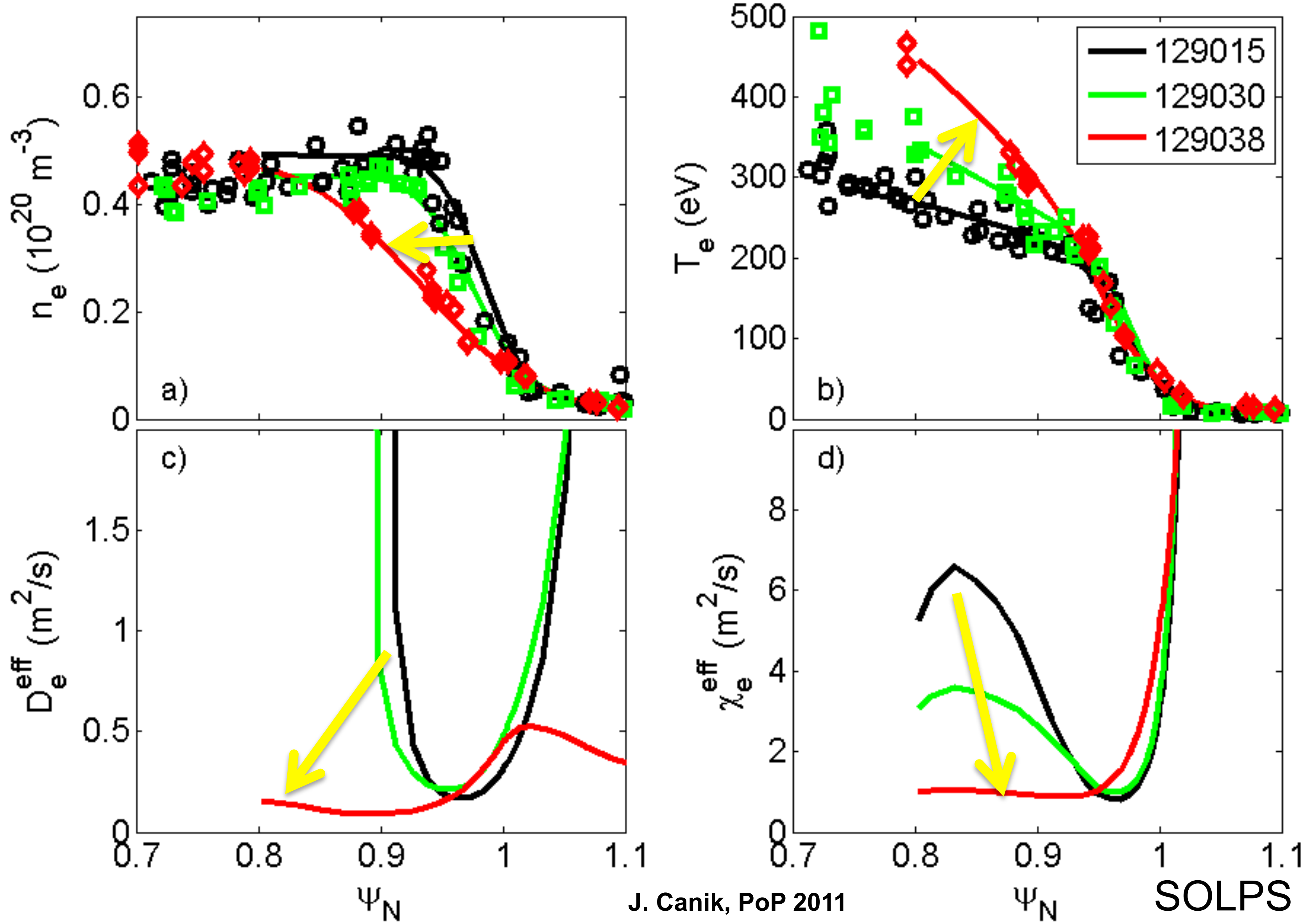
Pre-discharge lithium evaporation varied during experiment - first lithium usage in this particular run campaign

- Lithium evaporation before discharges with two overhead ovens



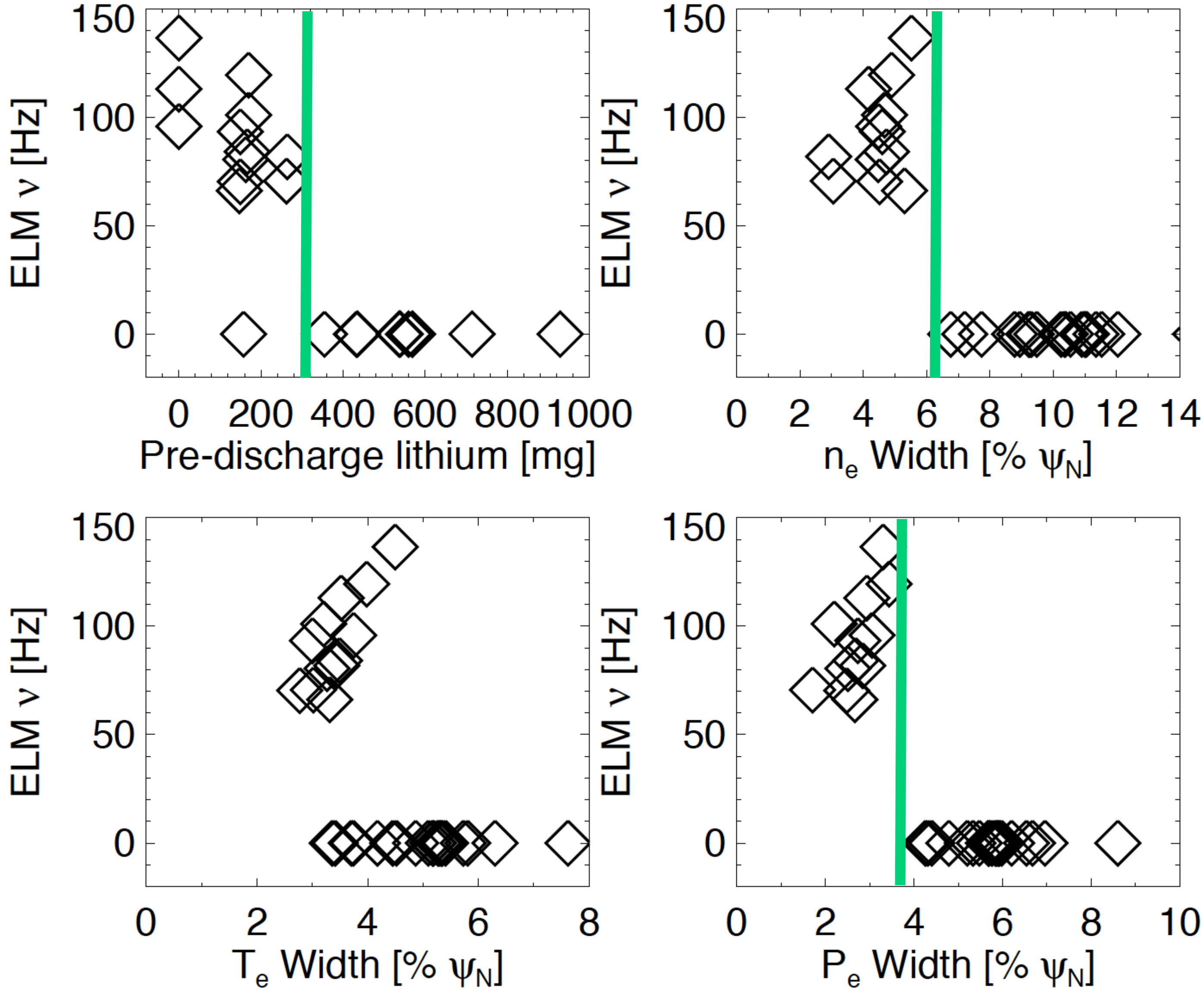
Transport barrier widens continuously with increasing pre-discharge lithium, i.e. pedestal-top D, χ_e reduced



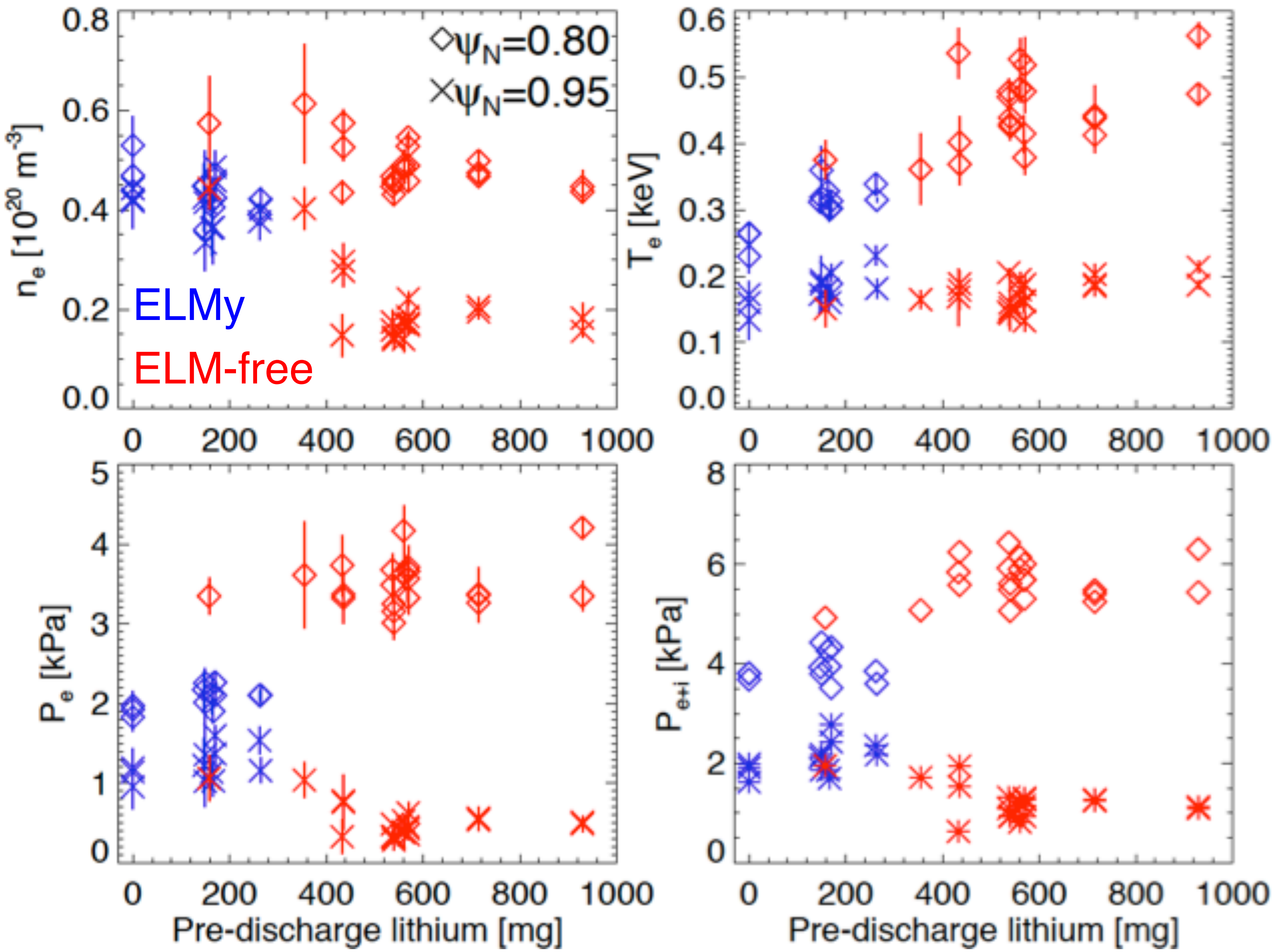
J. Canik, PoP 2011

SOLPS

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

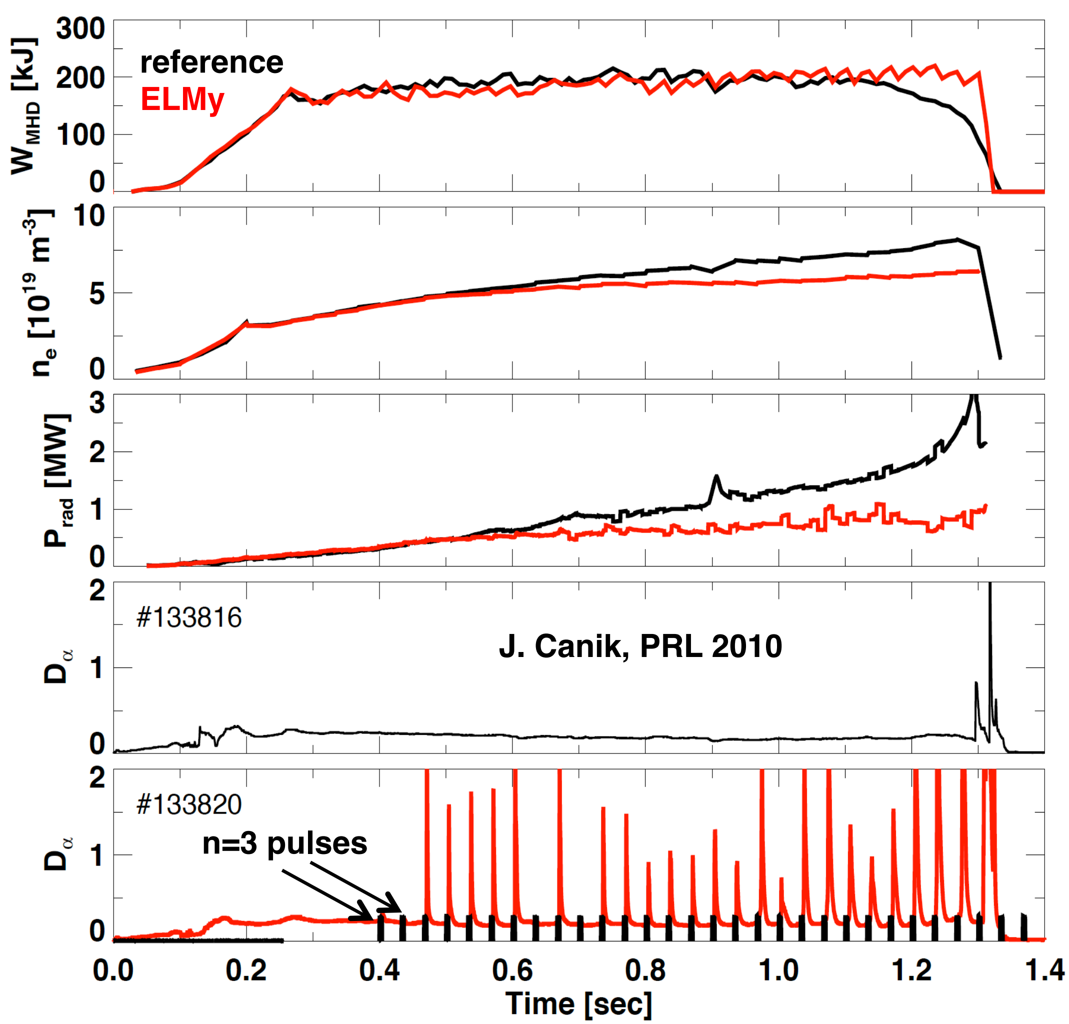


Density and pressure drop with lithium coatings at ψ_N=0.95, but increase at ψ_N=0.80 with increasing lithium

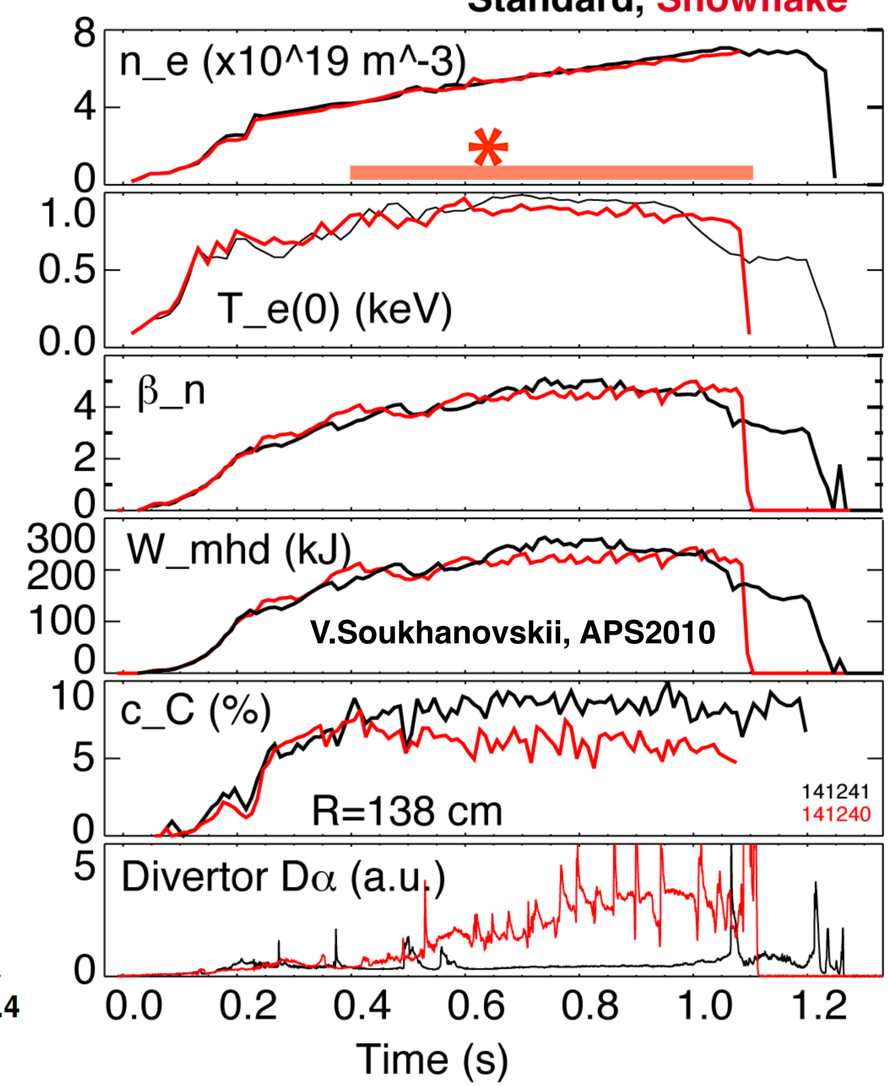


3D external fields used to trigger ELMs, while "Snowflake Divertor" used to reduce edge impurity source

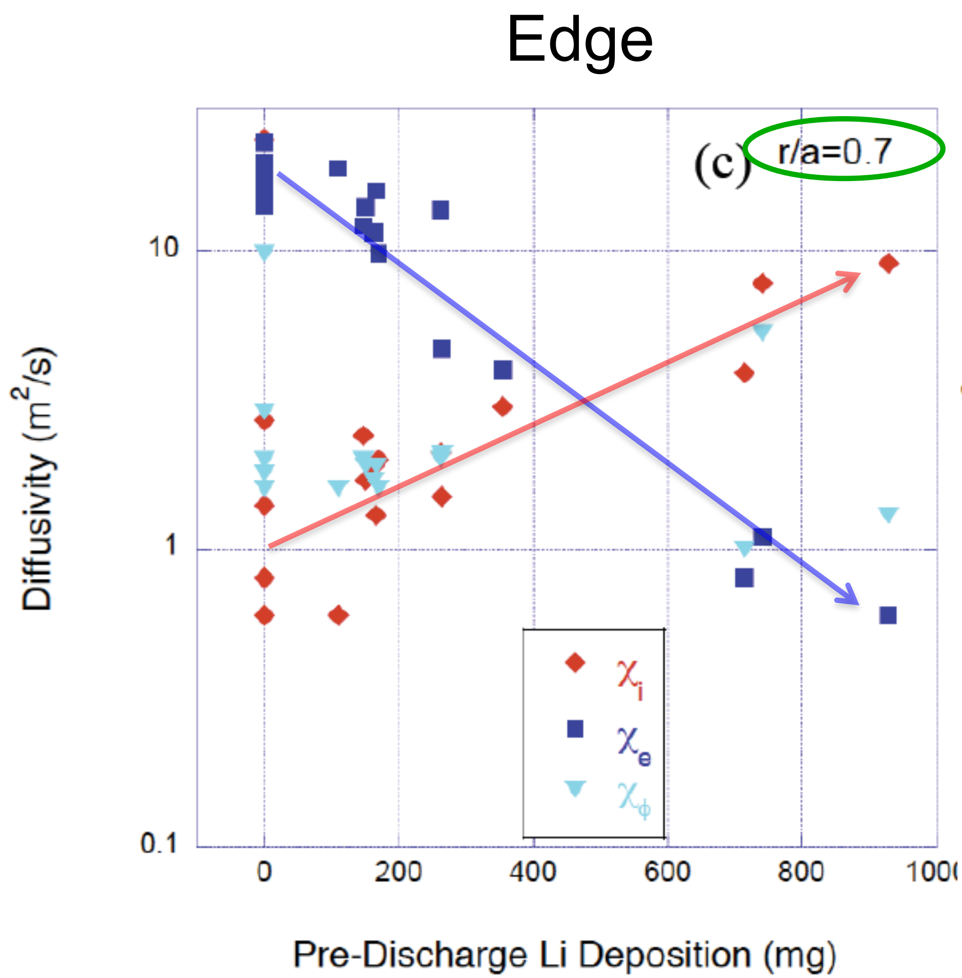
Type I ELMs triggered for impurity control (post-lithium, n=3)

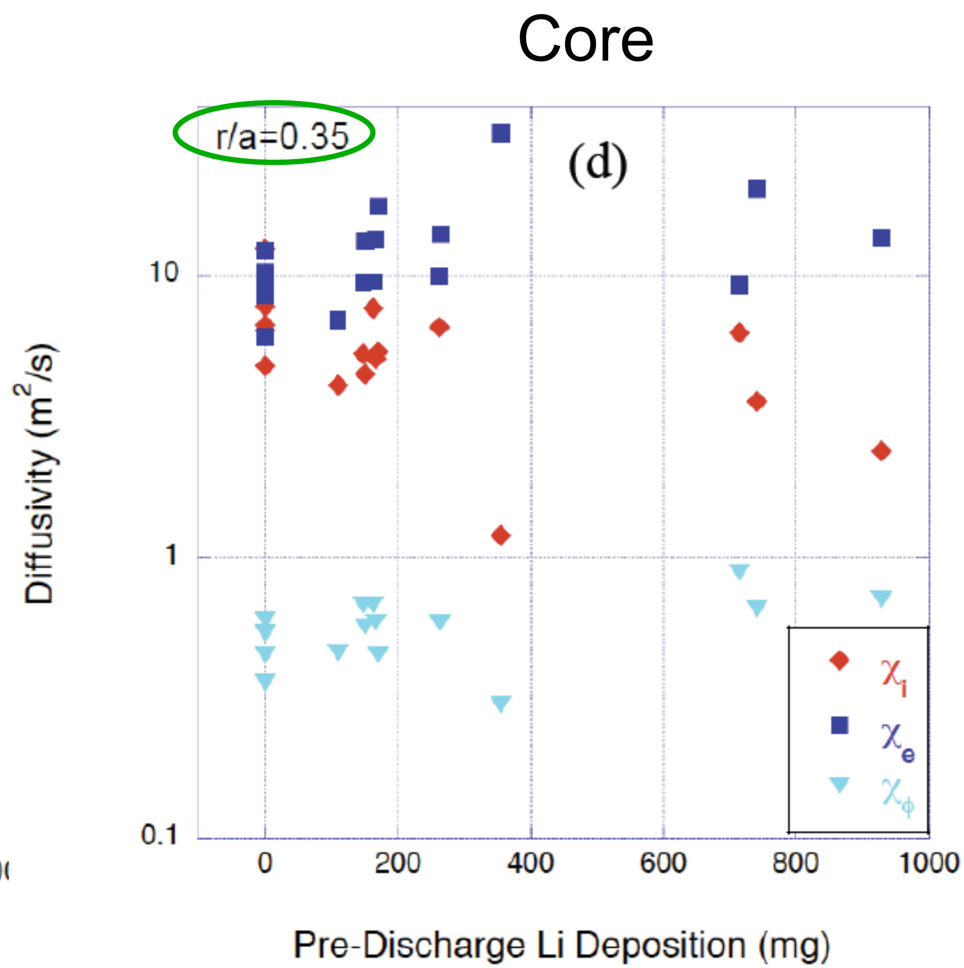


Snowflake Divertor



Edge 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