NSTX

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Varying the pre-discharge lithium wall coatings to alter the characteristics of the ELM-free H-mode pedestal in NSTX

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OAK RIDGE National Laboratory

GENERAL ATOMICS

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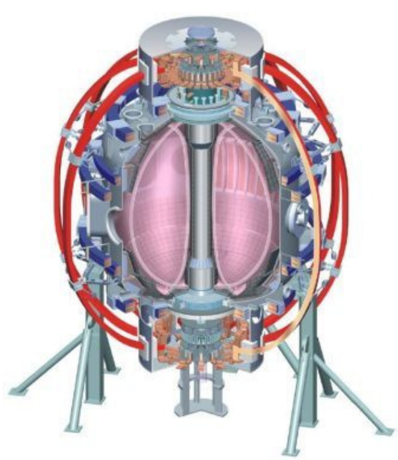

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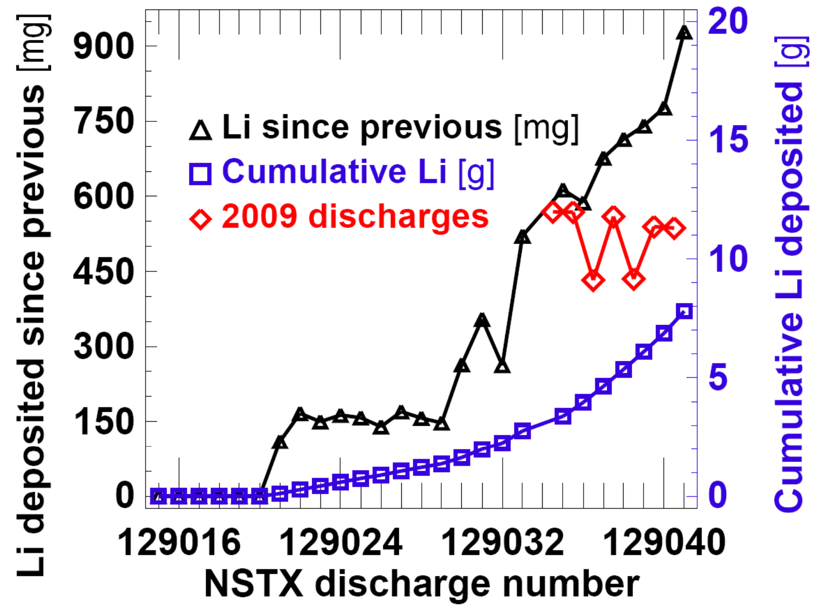
Evolution of ELM-free discharges with time & Li

- ELM-free discharges evolve with time
  - Impurities & density accumulate
  - How do surface conditions evolve?
- ELM-free discharges evolve with Li
  - 2008 Li scan + just analyzed 2009 data to fill in gaps
- Evolution of many different characteristics
  - Recyling: D_{α}, edge neutral pressure
  - Global: average density, stored energy, normalized beta
  - Transport and confinement
  - Pedestal structure



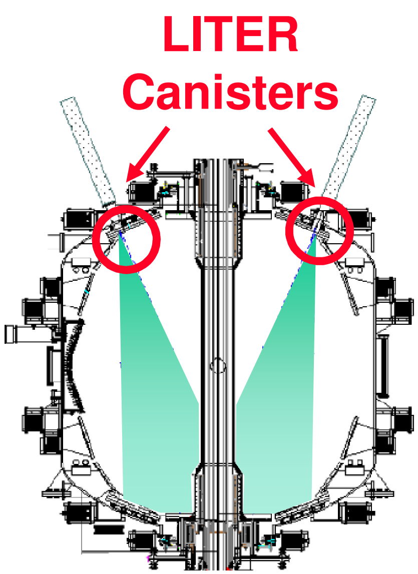
Experiment:	**2009 JNM**	**Kugel et al**
ELM observations:	**2009 JNM**	**Mansfield et al**
Profile/stability:	**2009 PRL**	**Maingi et al**
Full Scan Profile/stability:	**2011 PPCF**	**Boyle et al**
Full Scan Global/TRANSP:	**2011 PRL**	**Maingi et al**
Full Scan SOLPS:	**2011 PoP**	**Canik et al**

ELM-free H-mode discharges evolve with time

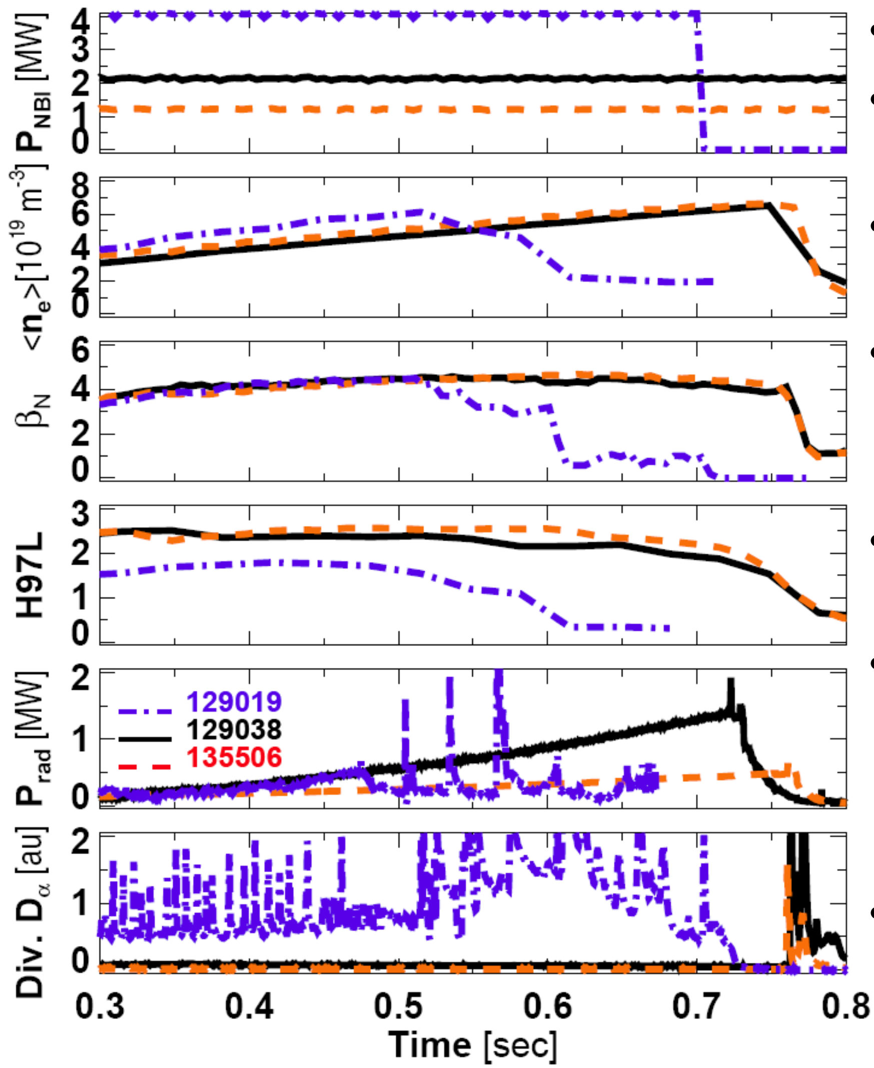
Pre-Li

With-Li

With-Li

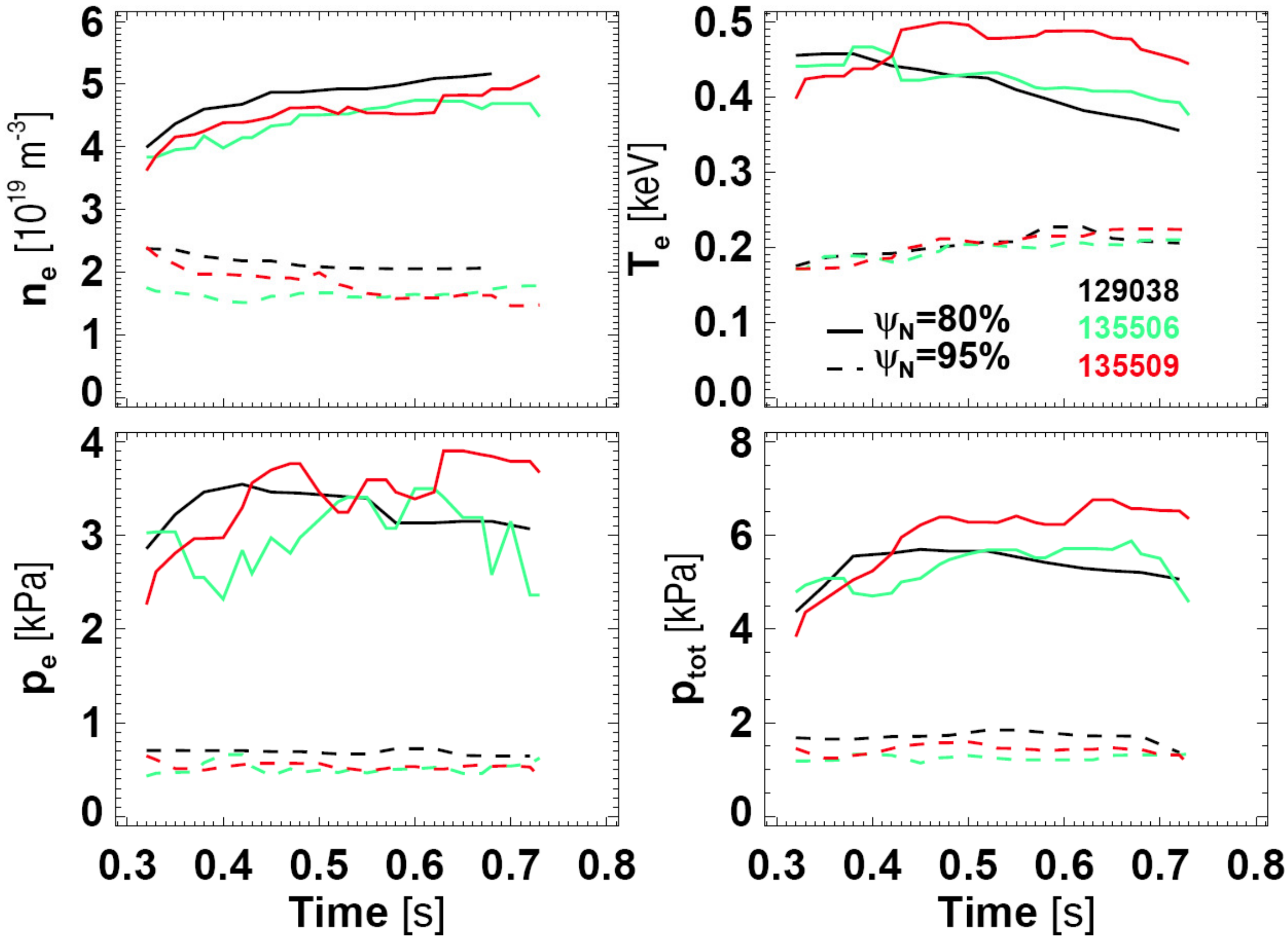


~ 700 mg Li before 129038



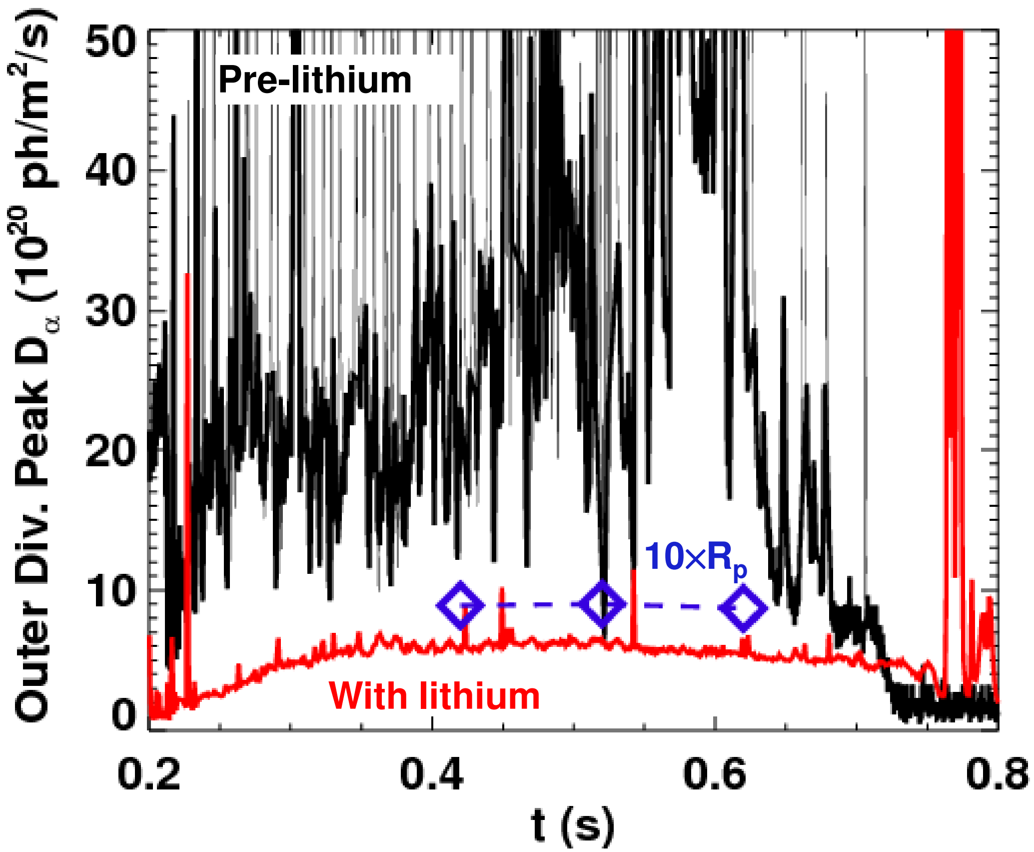
- Longer discharges
- Lower NBI to avoid β stability limit
- Slower **growth of electron density**
- Same stored energy w/ less heating
  - Improved confinement
- H-factor 40% higher
- Same P_{rad} but keeps growing after 0.5 s
  - **Impurity buildup w/o ELMs**
- ELM-free, reduced divertor recycling

Pedestal variations small despite global temporal evolution



Low-recycling conditions with lithium coatings last throughout NSTX discharges

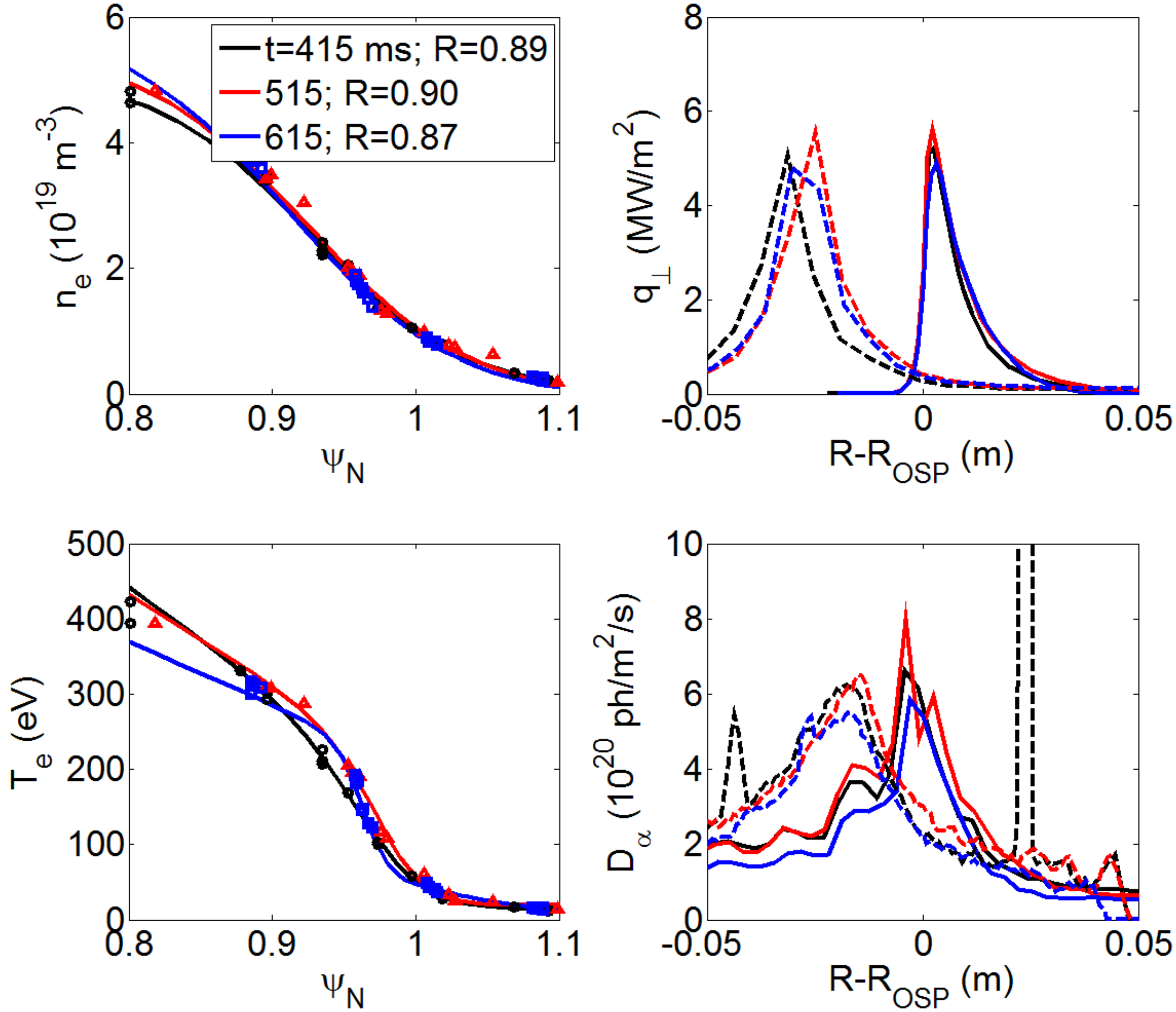
- Peak D_α emission at outer divertor does not increase toward the end of the discharge
  - And in fact often decreases
  - Without lithium, recycling increases throughout shot
  - Inferred PFC particle recycling coefficient (R_p) is ~ constant



SOLPS modeling indicates recycling coefficient remains low throughout low-δ discharge

- Measurements show little change during shot
  - Points/dashed lines are measurements
  - SOL n_e, T_e, Peak heat flux, D_α all ~constant
- Constraints in modeling*:
  - Fitted n, T profiles
  - Peak q_{div} (T_e^{sep})
  - Peak D_α (R_p)
- **Inferred R_p remains low**
  - **0.89, 0.90, 0.87**
  - **Without Li: R_p=0.98**

⇒ Li pumping appears to persist over these pulse lengths (~ 1s)

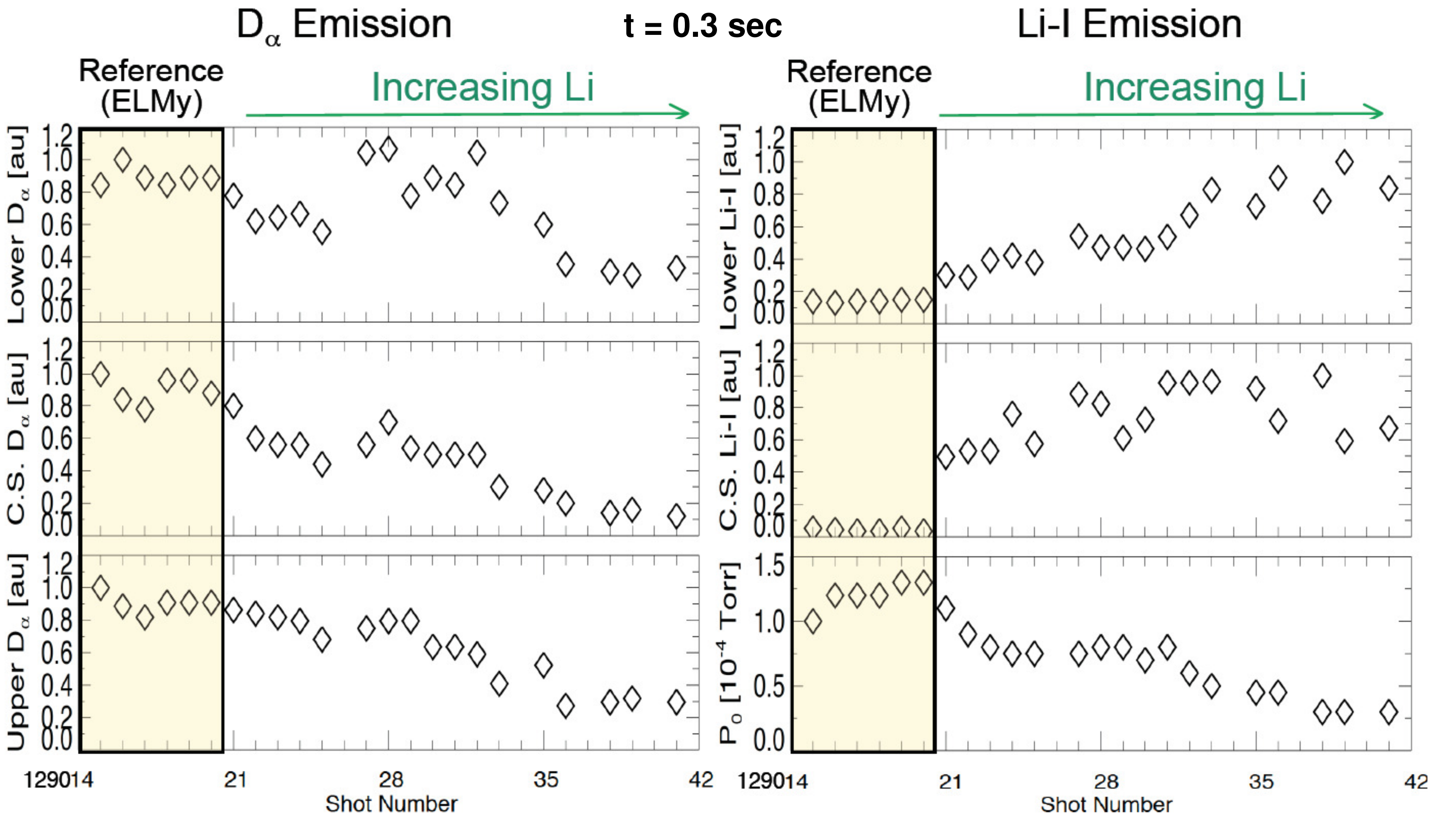


J Canik, JNM 415, S409 (2011)

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

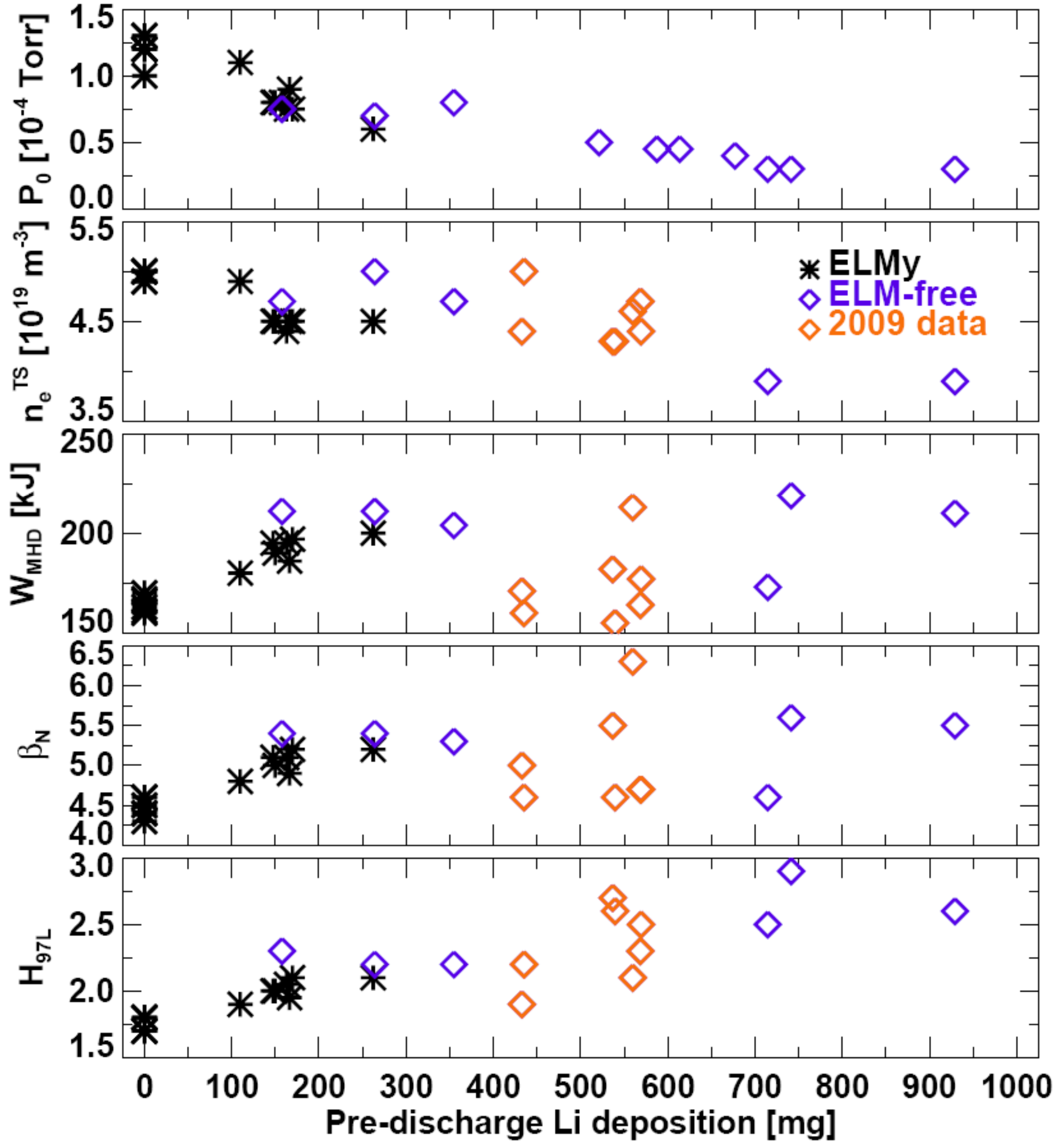
- Global characteristics change
  - Recycling: D_α emission declines
  - Edge neutral pressure decreases
  - Line average density at fixed time declines
  - Peak W_{MHD}, β_N increase at constant P_{NBI}
  - Confinement (H-factor) increases
- Pedestal characteristics change
  - Density & pressure pedestals get wider and shift away from separatrix
  - Peak density gradient reduced
  - Temperature and pressure increase at pedestal top
  - Density and pressure decrease at edge
  - Ion temperature and rotation increase
- **Evolution with lithium continues after ELM suppression**

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



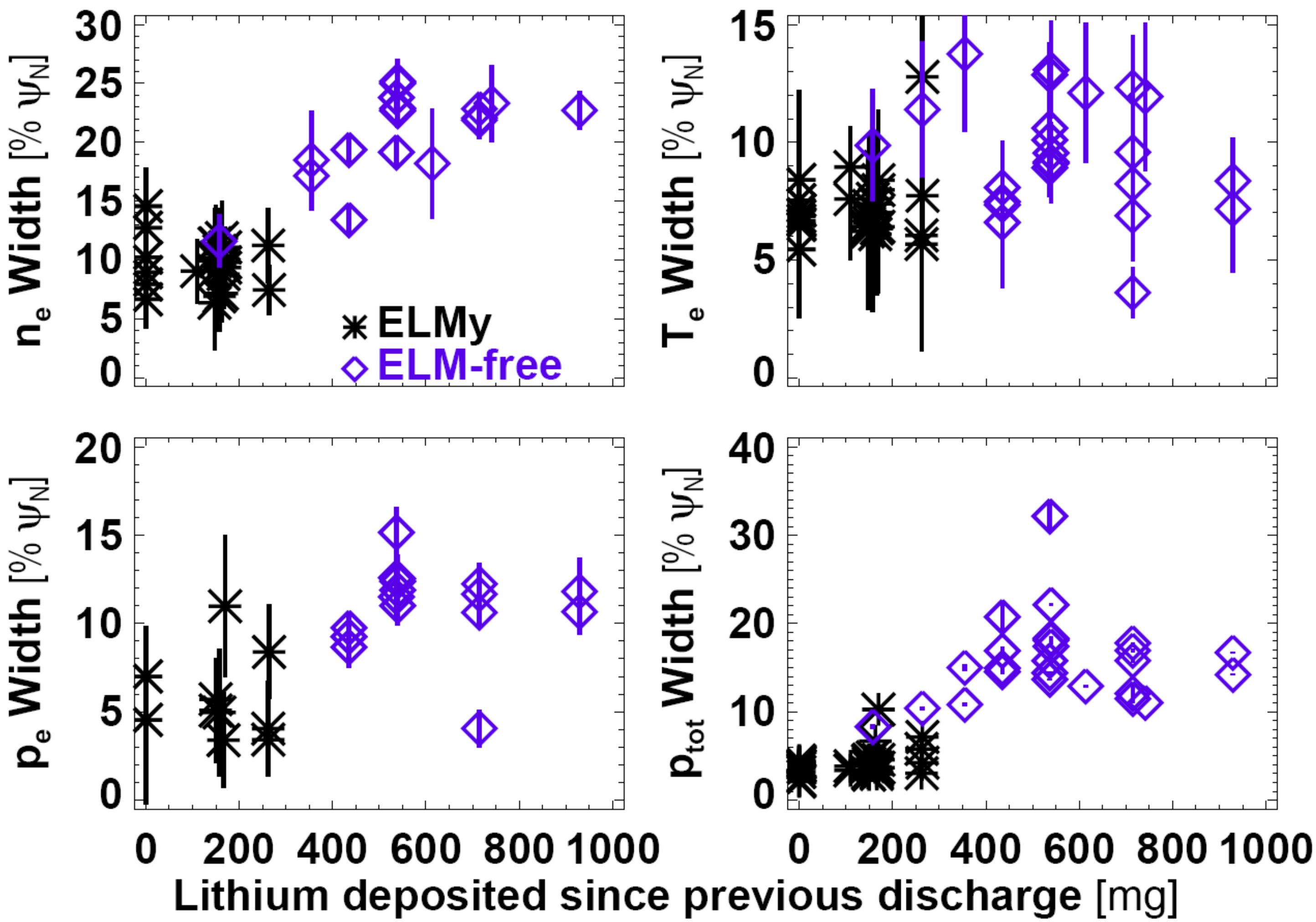
Maingi NF 2012

Global plasma performance improves nearly continuously with increasing lithium

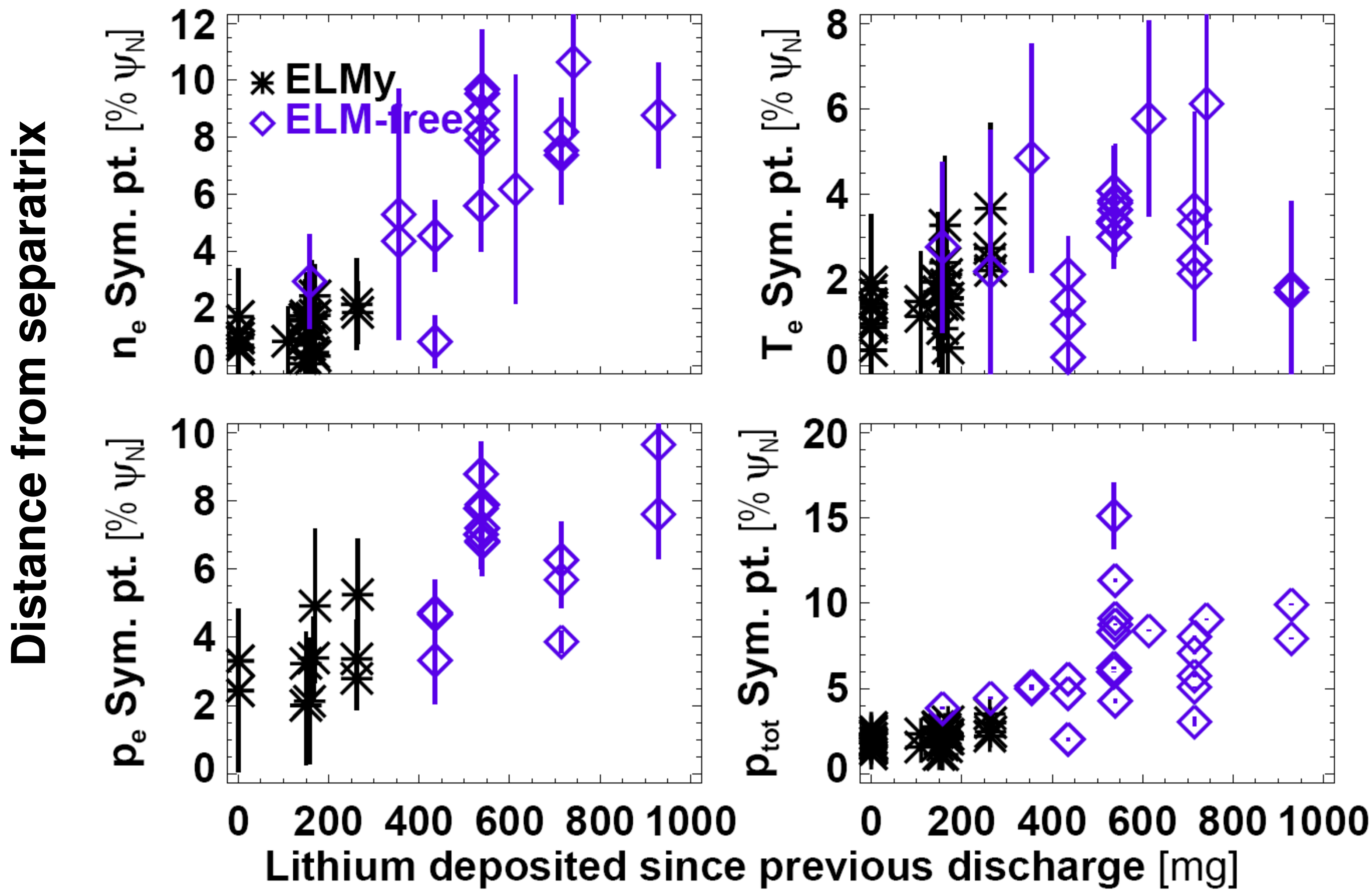


- Neutral pressure from fast ion gauge evaluated at fixed time (t=0.3 sec)
- Line-average density from Thomson n_e^{TS} evaluated at fixed time (t=0.4 sec)
- W_{MHD}, β_N, and H_{97L} (global τ_E, not thermal) evaluated at time of peak W_{MHD}
  - P_{NBI} varies: 4 MW for ELMy, 1.2-3 MW ELM-free
- 2009 data fills gap nicely

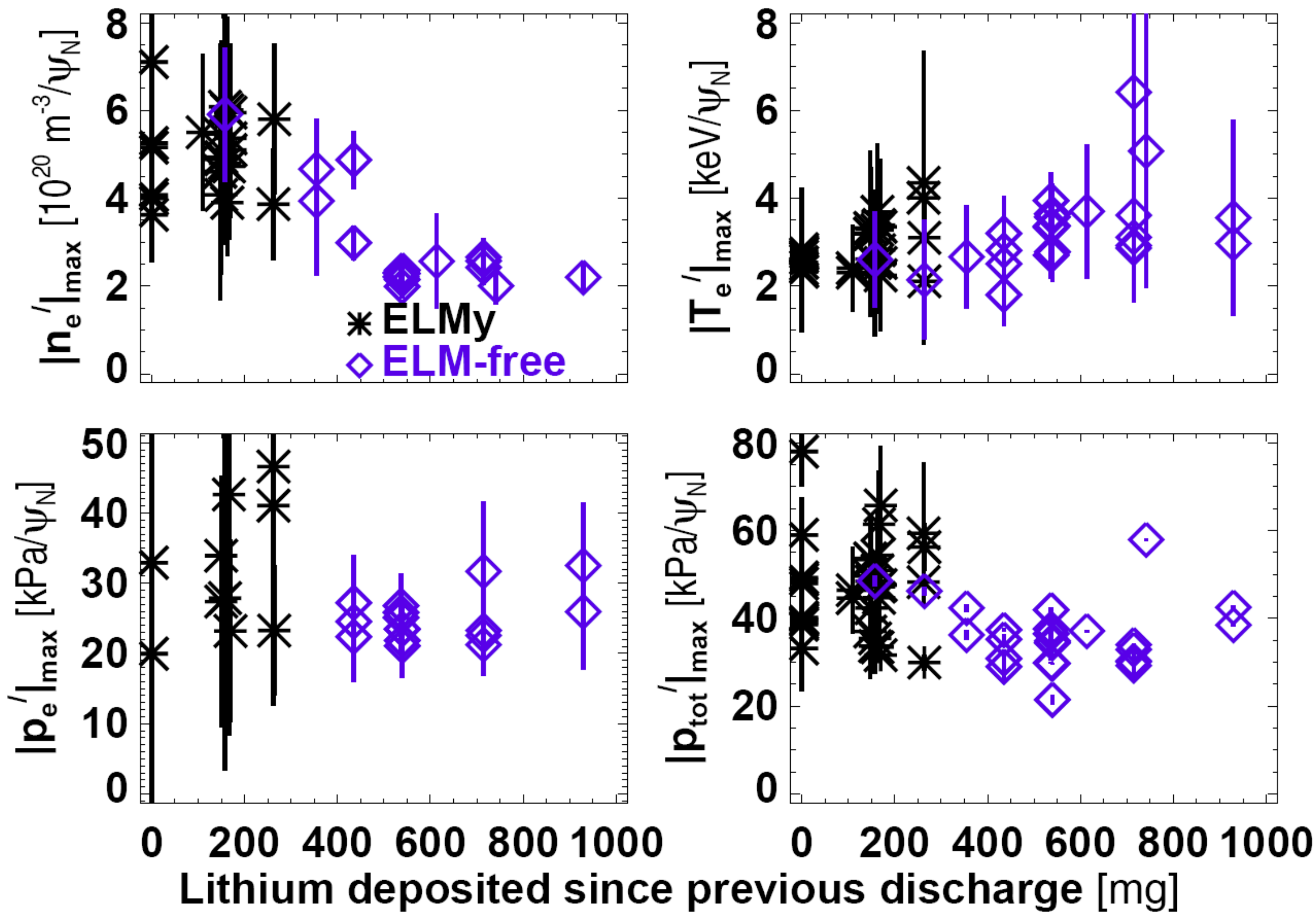
Density & pressure widths increase with lithium



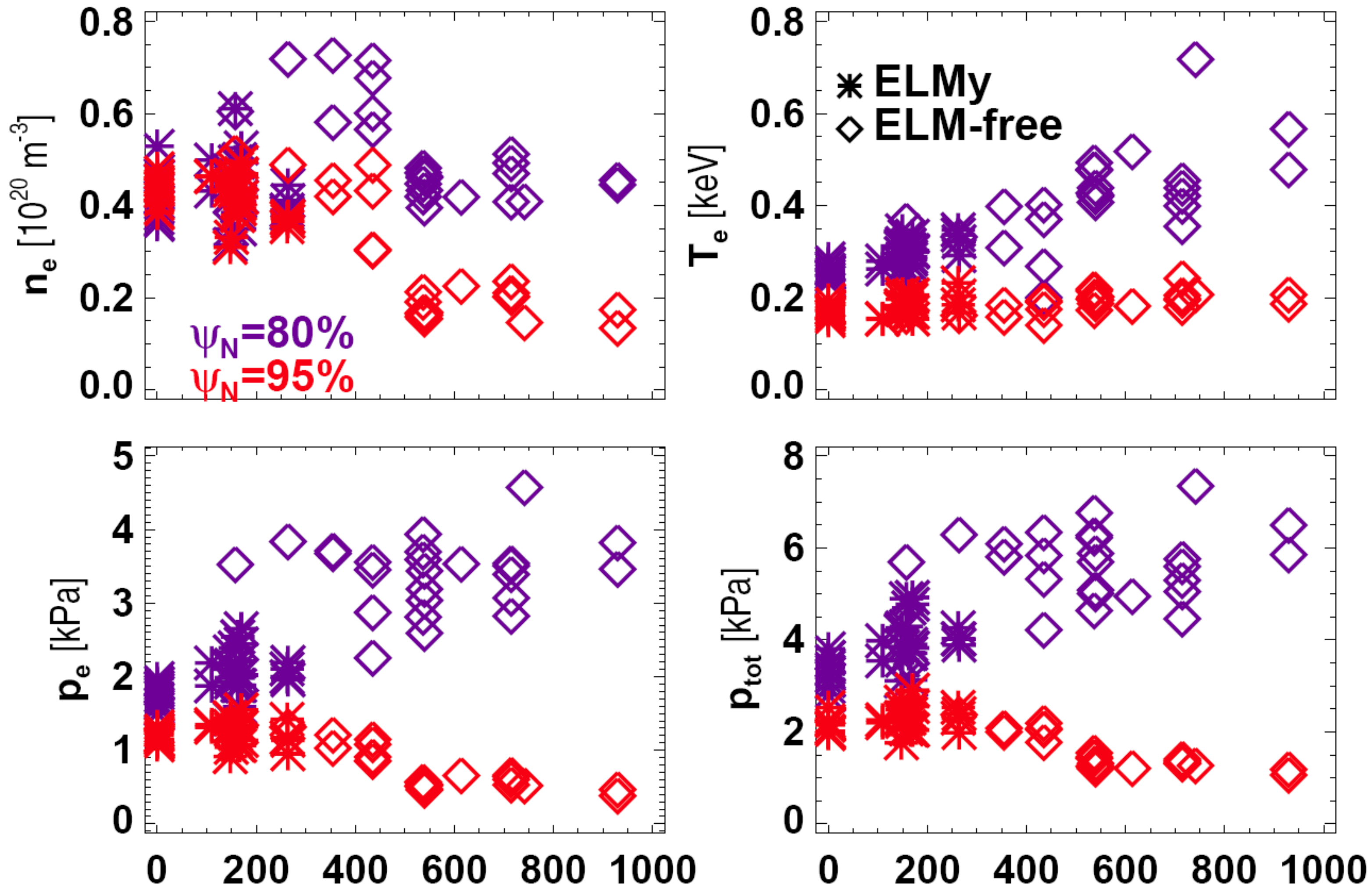
Density & pressure gradient peaks move farther from separatrix with lithium



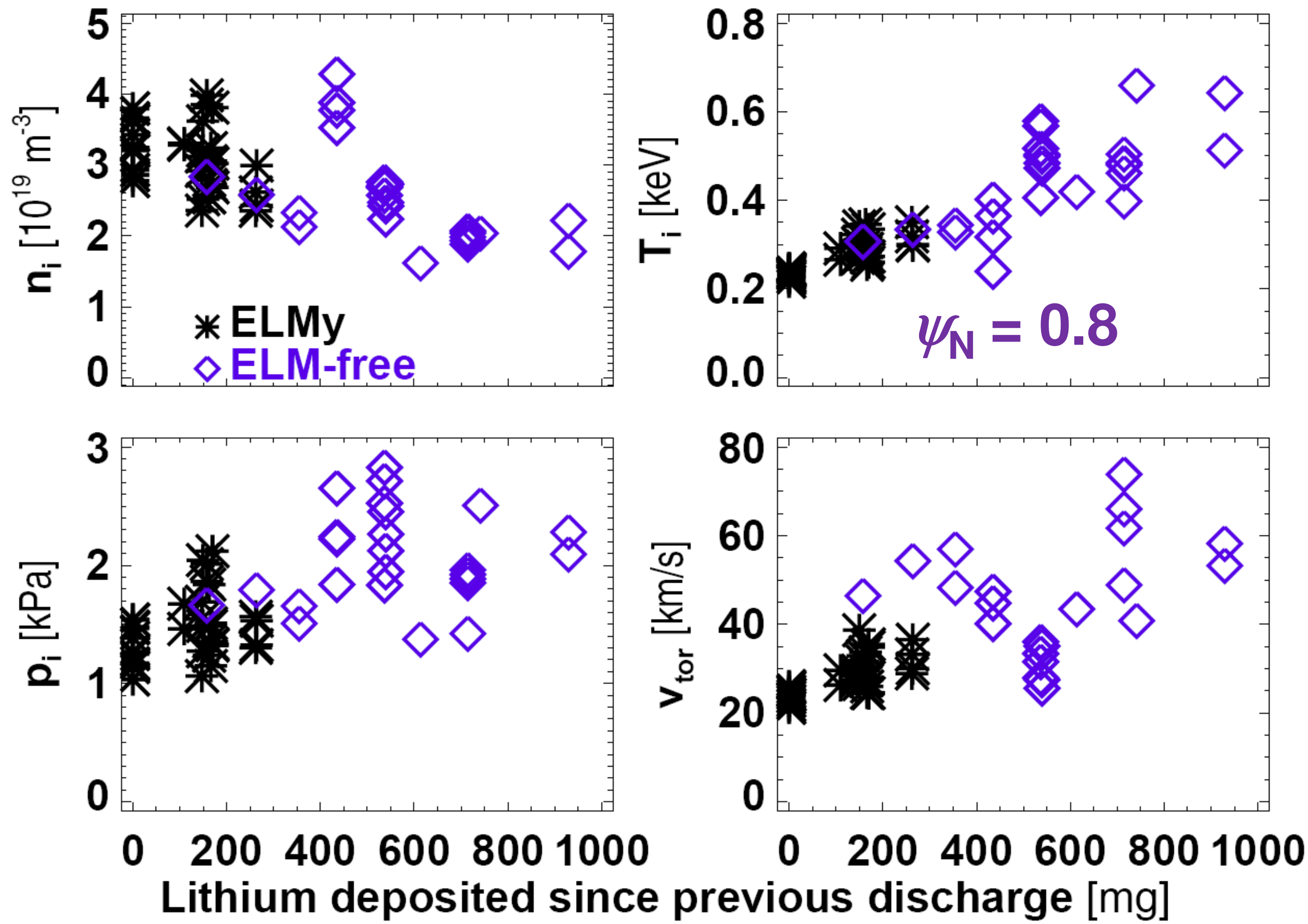
Density gradient peak gets smaller with lithium



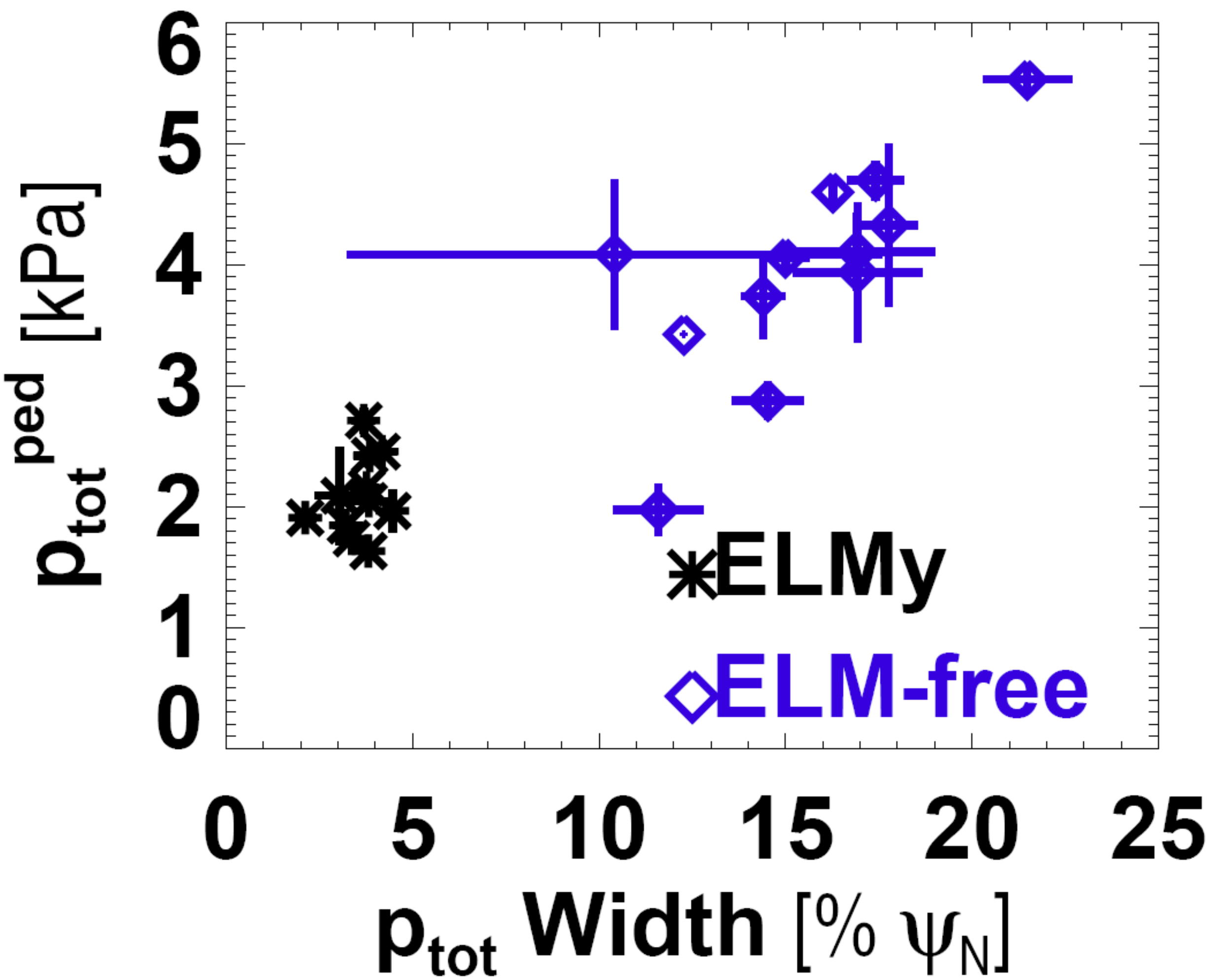
Temperature and pressure increase with lithium at pedestal top,
Density and pressure decrease with lithium at edge



Ion temperature and rotation increase with lithium



What limits pedestal growth & sets relationship between width and height ?



ELM-free pedestal evolves with Li, ~steady w/ time

- ELM-free discharges evolve w/ time
  - Impurities, Average density increasing
  - Might expect pedestal to evolve with time because of above, plus:
    - Fluence on Li degrading surface
      - No significant saturation observed in these discharges
    - Natural growth of transport barrier with time
      - Normally limited by peeling-ballooning limit (ELMs), none here
  - *Pedestal relatively steady with time*
- ELM-free discharges evolve w/ increasing Li
  - Indicators of recycling decrease continuously with Li
  - Confinement increases
  - Pedestal structure evolves w/ Li
- What limits pedestal evolution?
  - Not sure, but it seems to be controlled by the quantity of Li!

Thank you

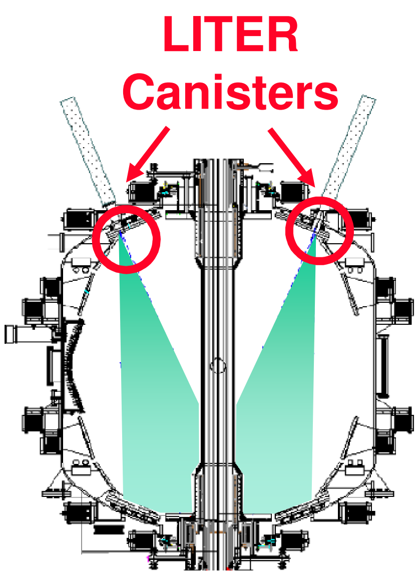
NSTX lithium wall coatings induce ELM-free H-mode

Pre-Li

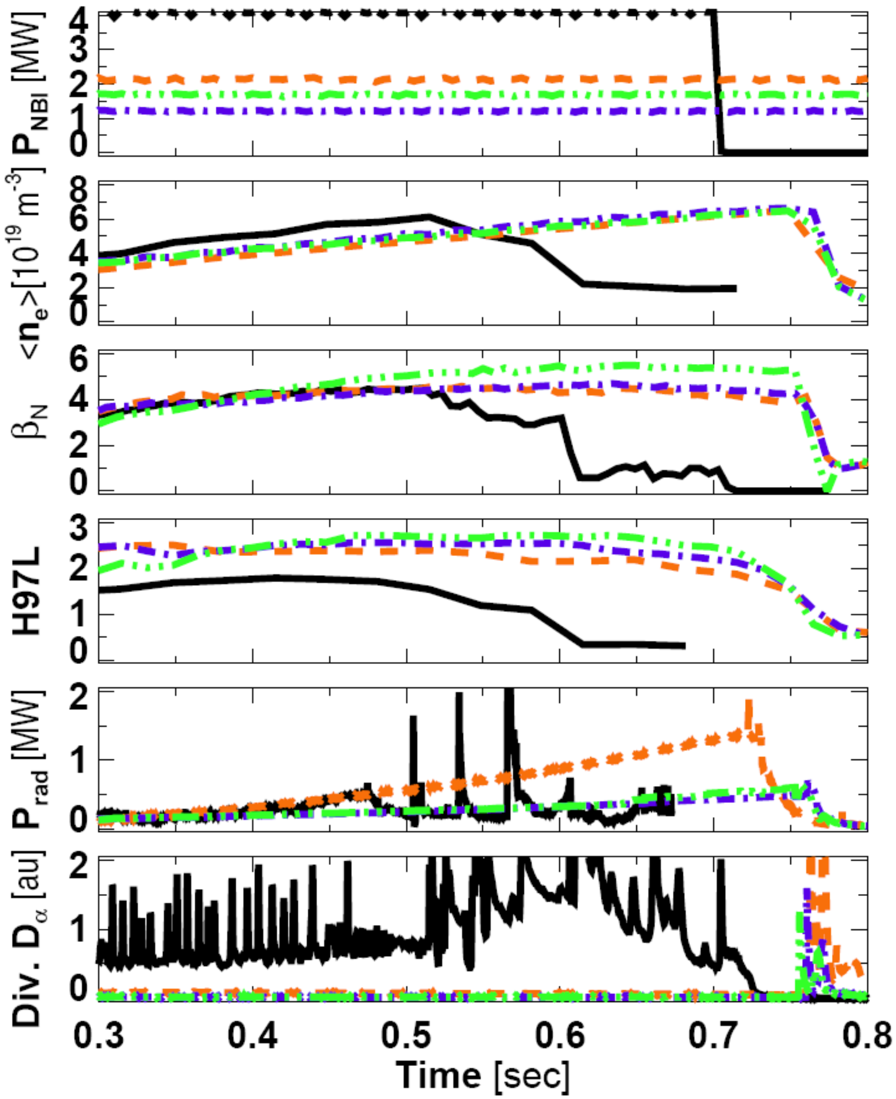
With-Li

With-Li

With-Li



~ 700 mg Li before 129038



- Longer discharges
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- Slower **growth of electron density**
- Same stored energy w/ less heating
  - Improved confinement
- H-factor 40% higher
- Same P_{rad} but keeps growing after 0.5 s
  - Higher P_{rad} /P_{heat}
  - **Impurity buildup** w/o ELMs
- ELM-free, reduced divertor recycling

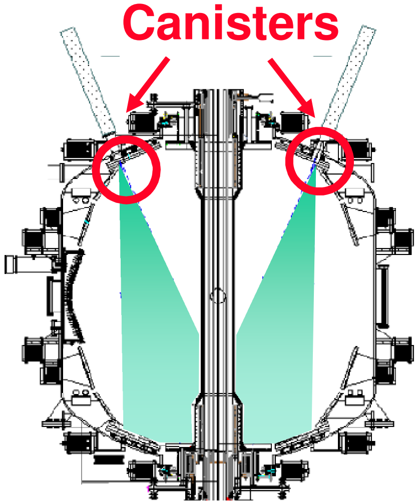
NSTX lithium wall coatings induce ELM-free H-mode

Pre-Li

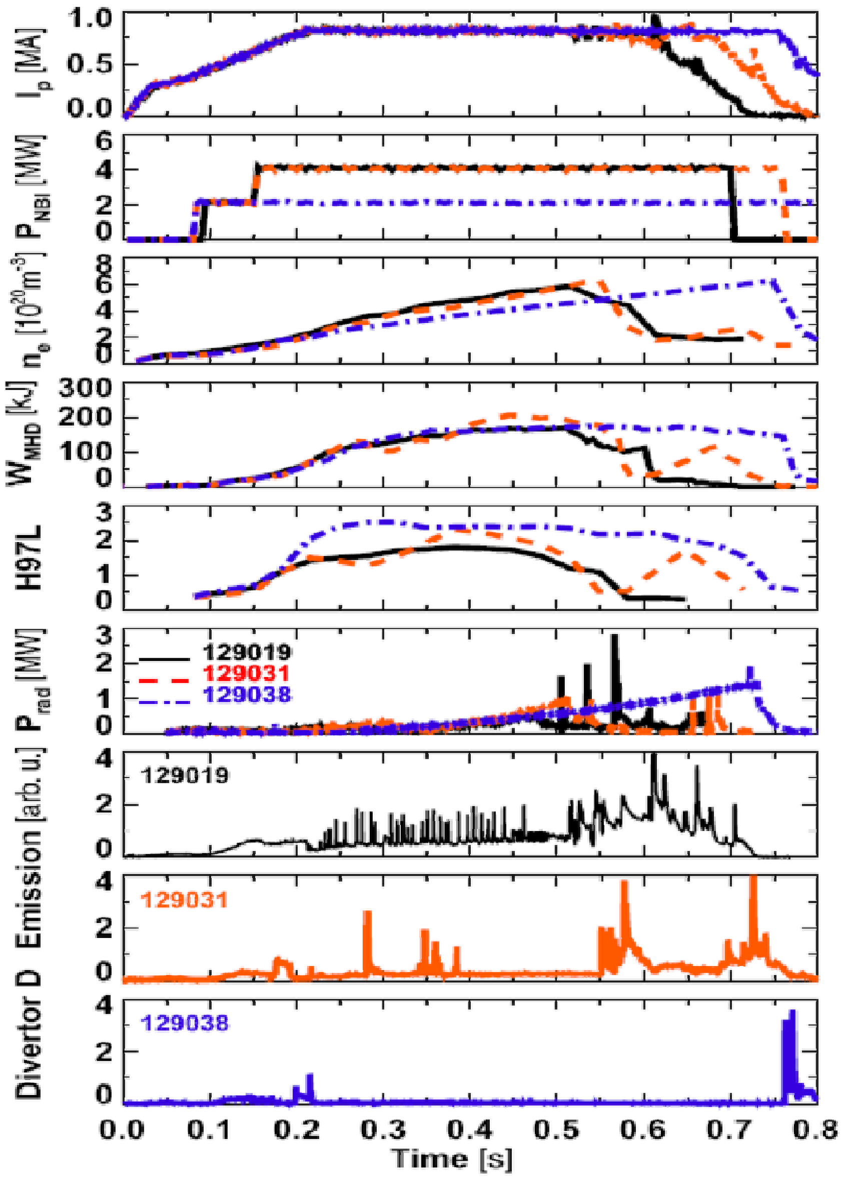
Intermediate-Li

Thick-Li

LITER Canisters



~ 700 mg Li before 129038



- Longer discharges
- Lower NBI to avoid β stability limit
- Slower **growth of electron density**
- Same stored energy w/ less heating
  - Improved confinement
- H-factor 40% higher
- Same P_{rad} but keeps growing after 0.5 s
  - Higher P_{rad} /P_{heat}
  - **Impurity buildup** w/o ELMs
- Partly ELM-free, reduced recycling
- ELM-free, reduced divertor recycling

Boyle PPCF 2011

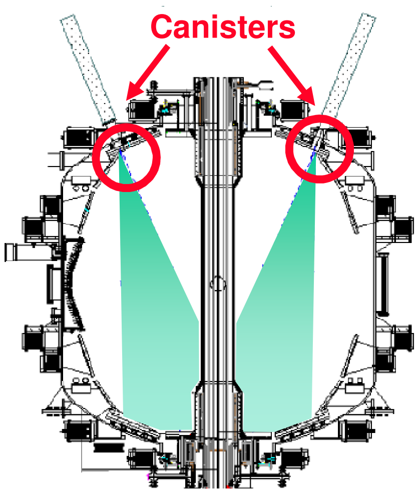
NSTX lithium wall coatings induce ELM-free H-mode

Pre-Li

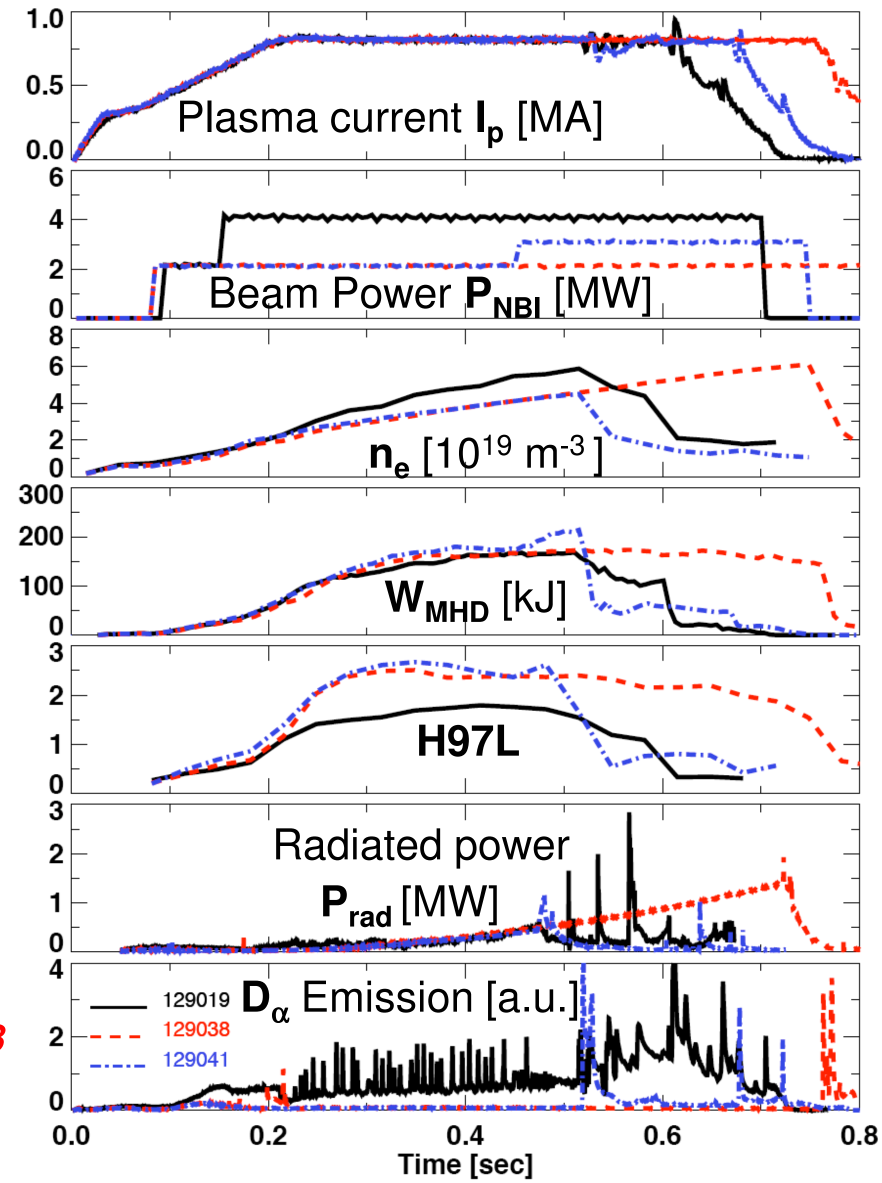
Post-Li

Post-Li

@ β limit



~ 700mg Li before 129038



- Longer discharges
- Lower NBI to avoid β stability limit
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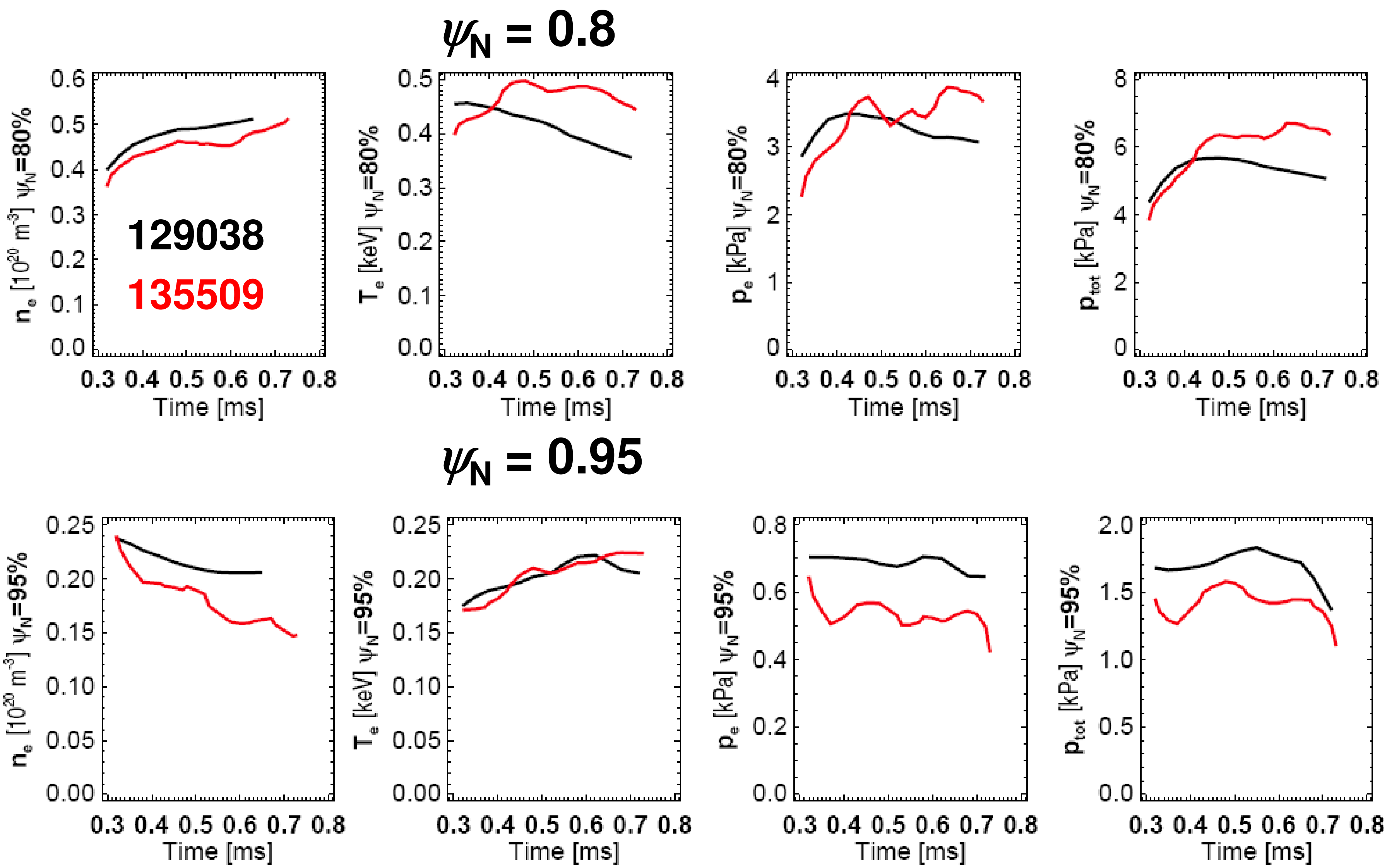
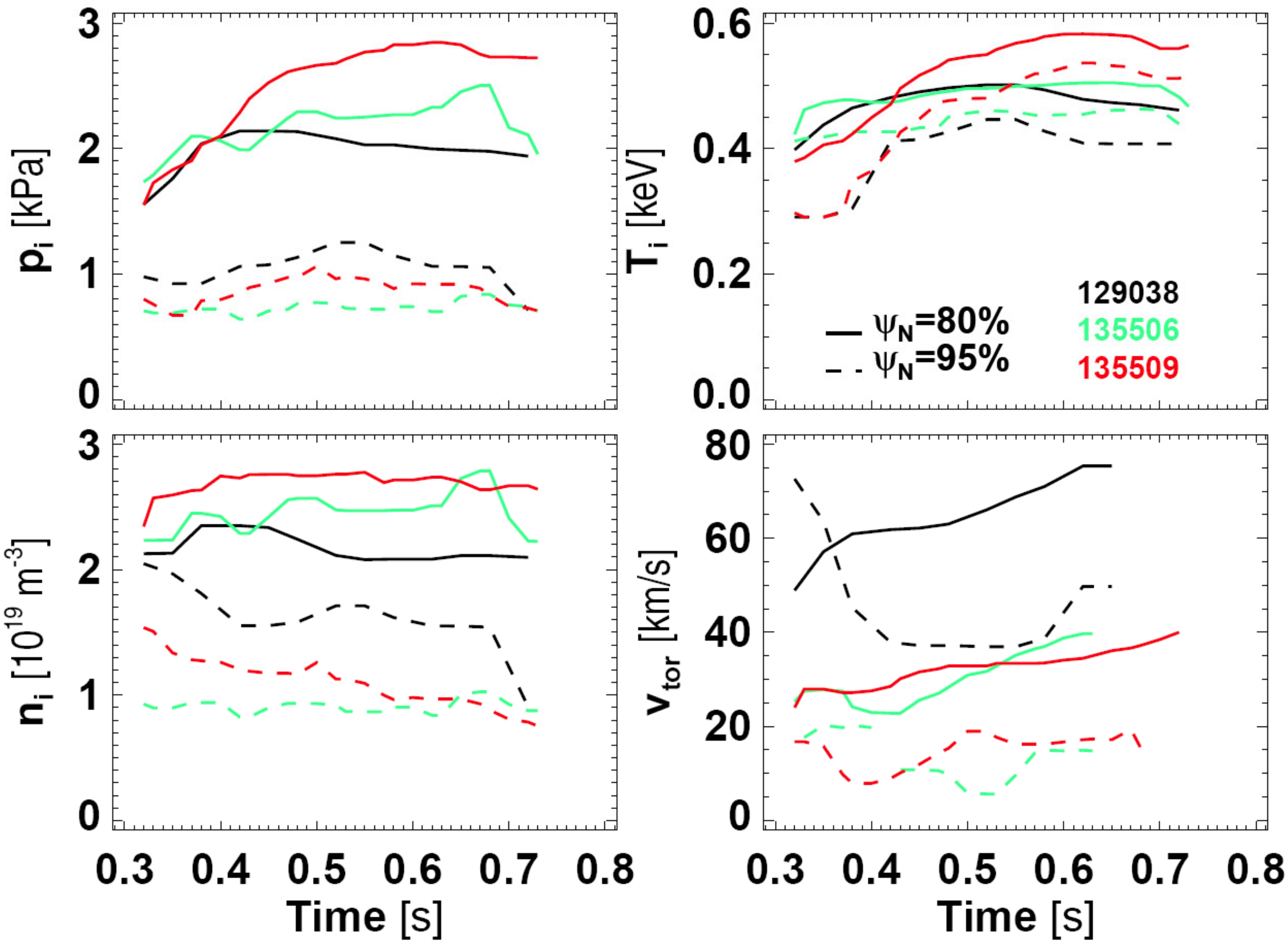
Maingi PRL 2009

Pedestal variations small despite global temporal evolution

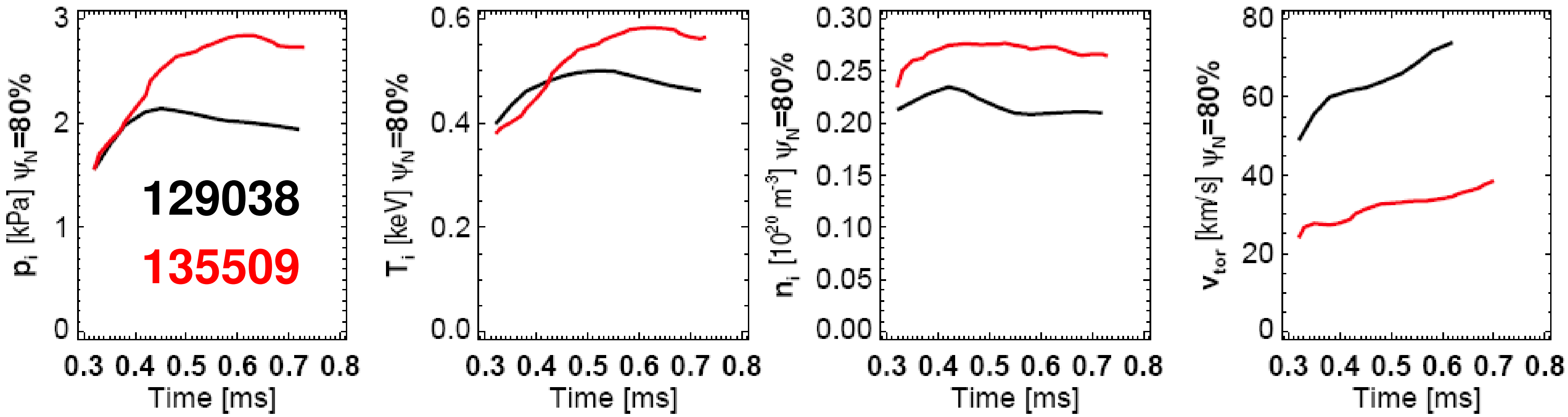


Ion profiles change more

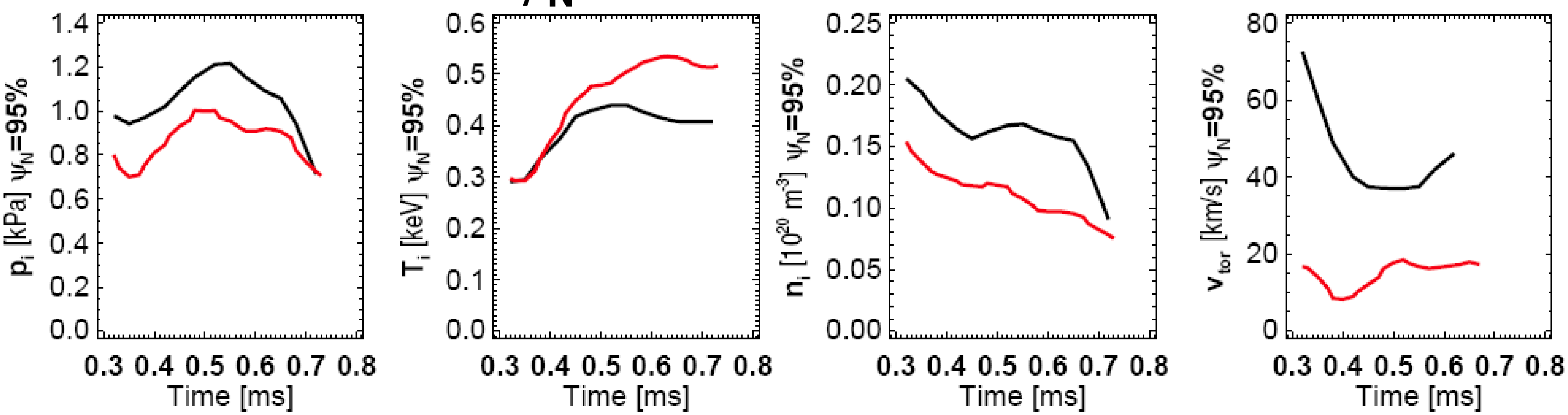


Ion profiles change more

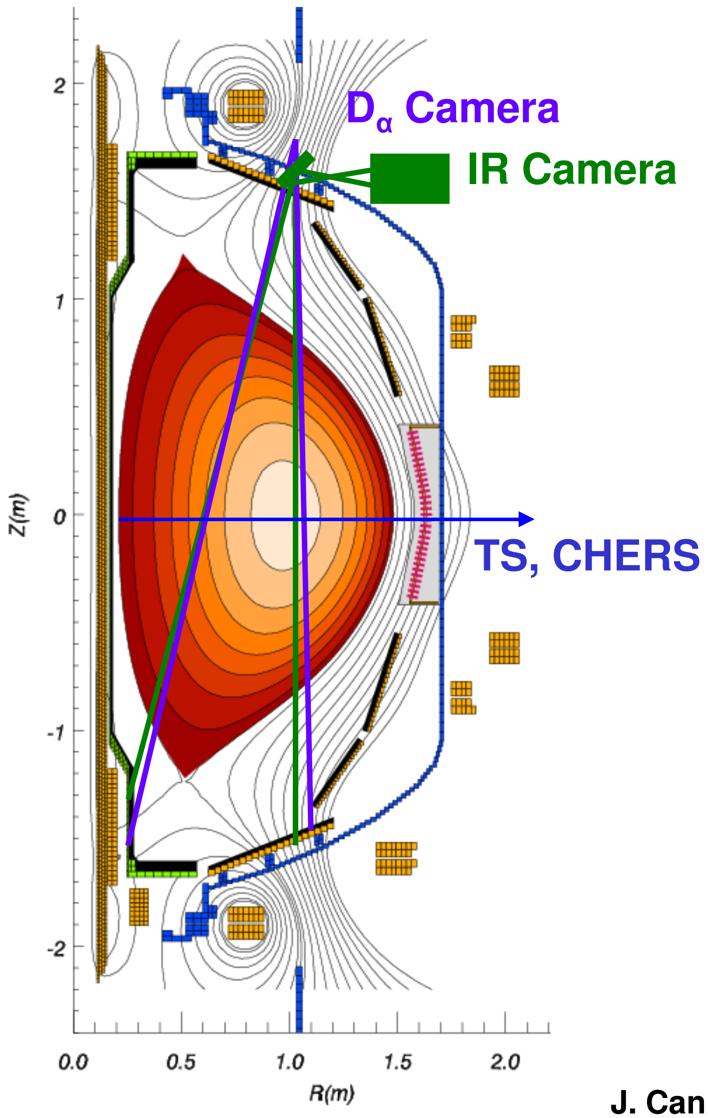
$\psi_N = 0.8$

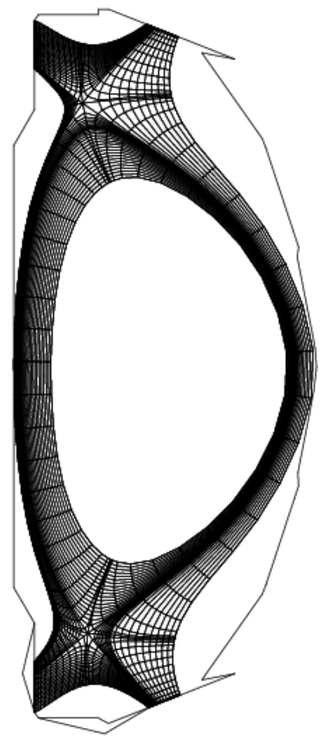


$\psi_N = 0.95$



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



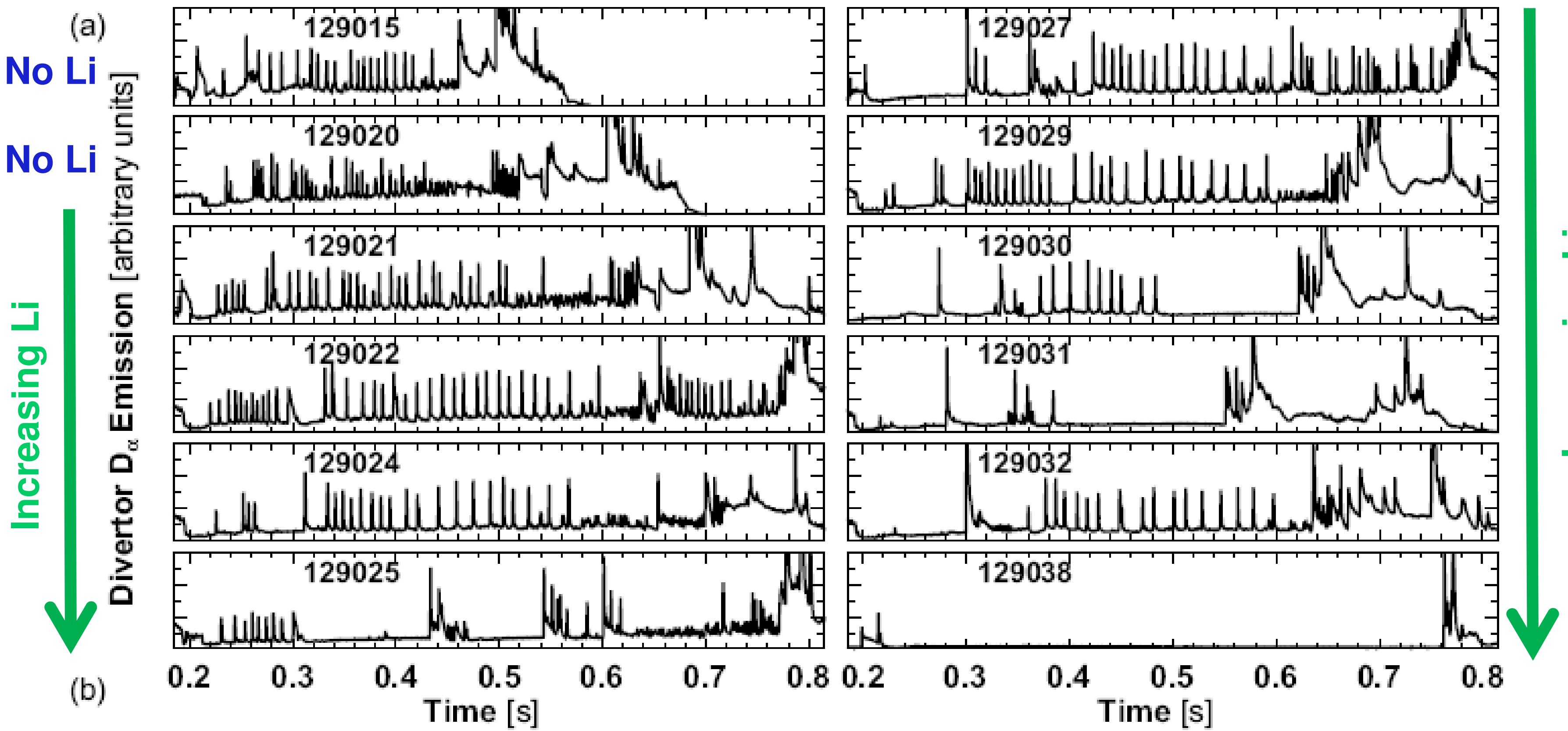


J. Canik PoP 2011

- 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

Increasing lithium gradually suppresses ELMs

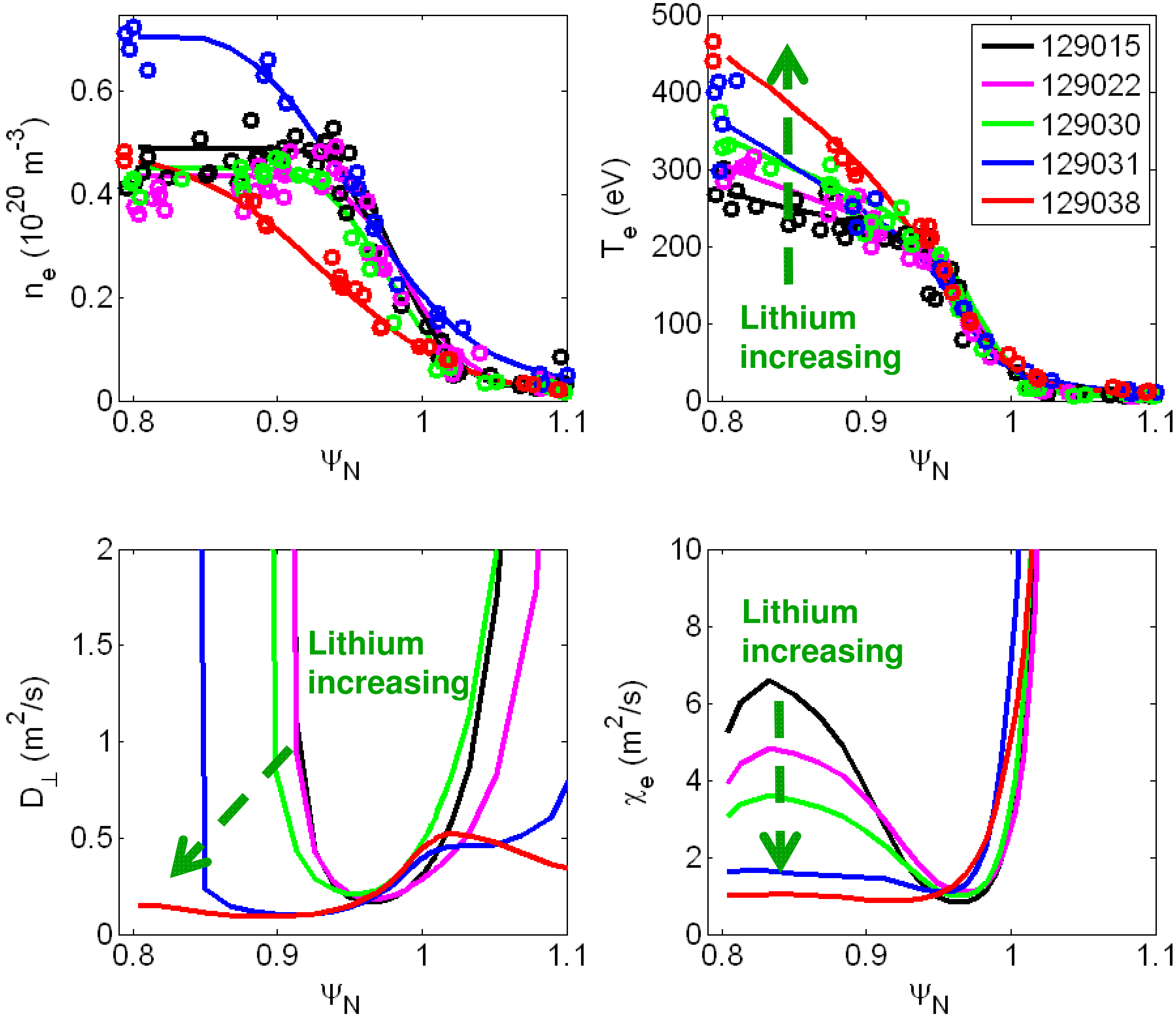


- Not quite monotonic – ELMs returned after off-normal events
- All discharges in 2009 scans were ELM free with ~500 mg Li

Boyle PPCF 2011

As lithium evaporation increases, transport barrier widens, pedestal-top χ_e reduced

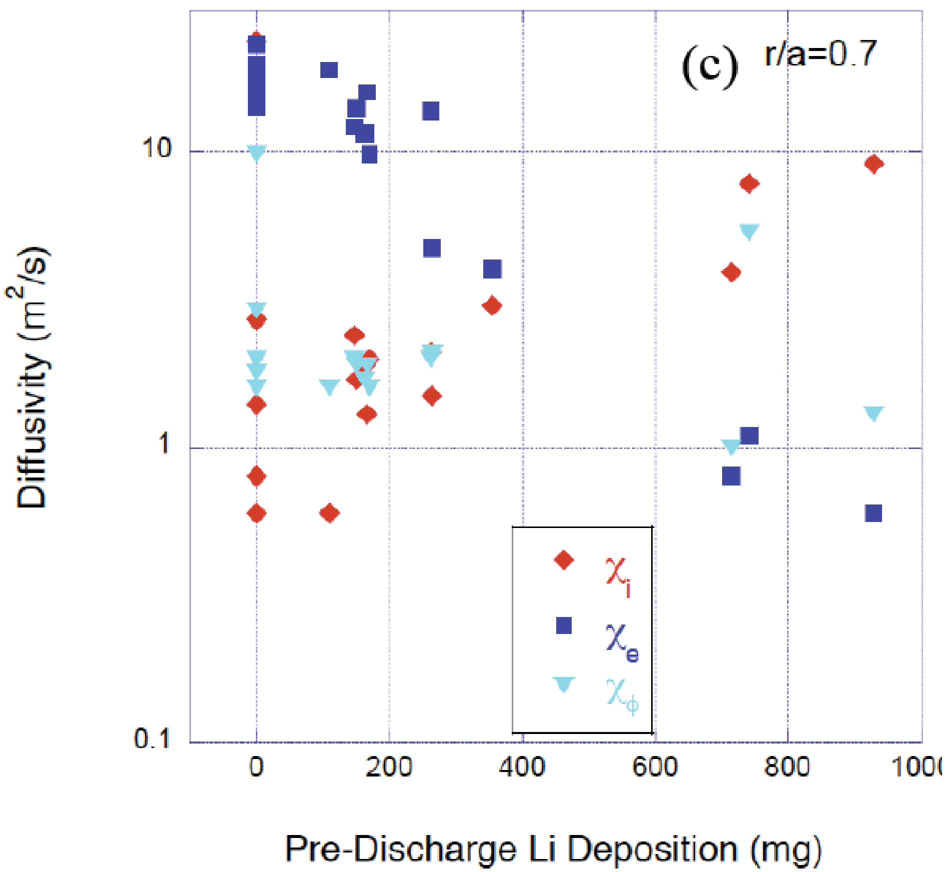
- Several shots with increasing lithium thickness analyzed with SOLPS
- ELMy to reduced frequency to ELM-free
- T_e gradient, χ_e clamped beyond $\psi_N = 0.95$

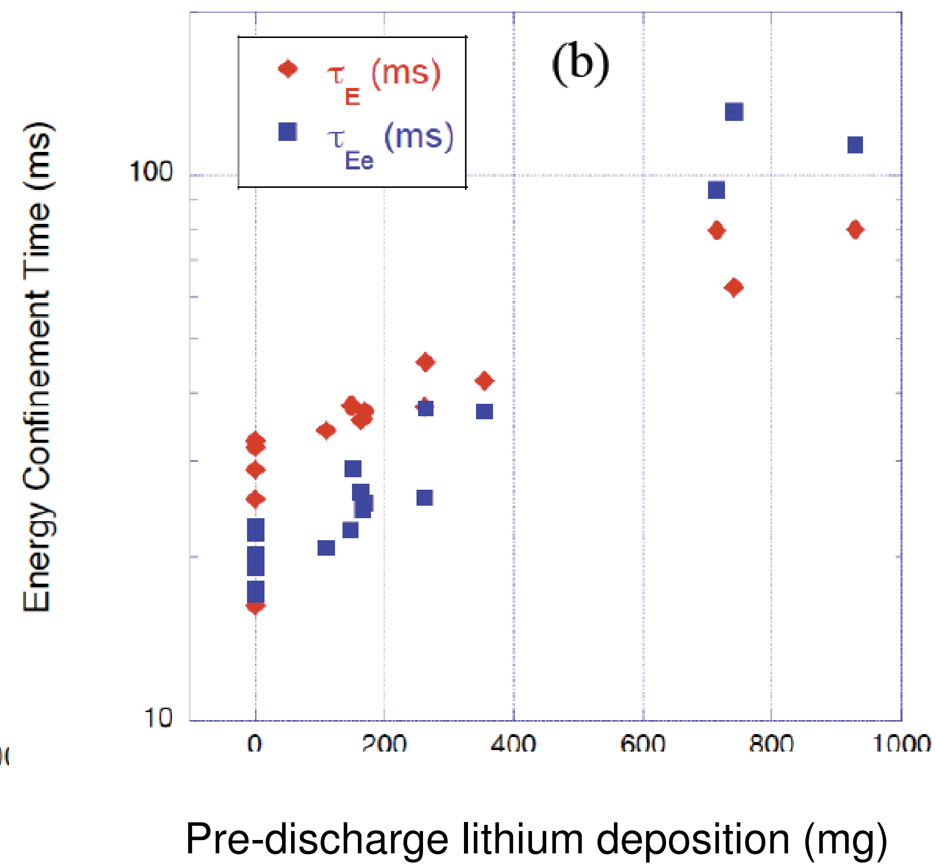


J. Canik PoP 2011

Global and electron confinement, τ_E and τ_{Ee}, increase with lithium evaporation, due mainly to reduction of χ_e at edge

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

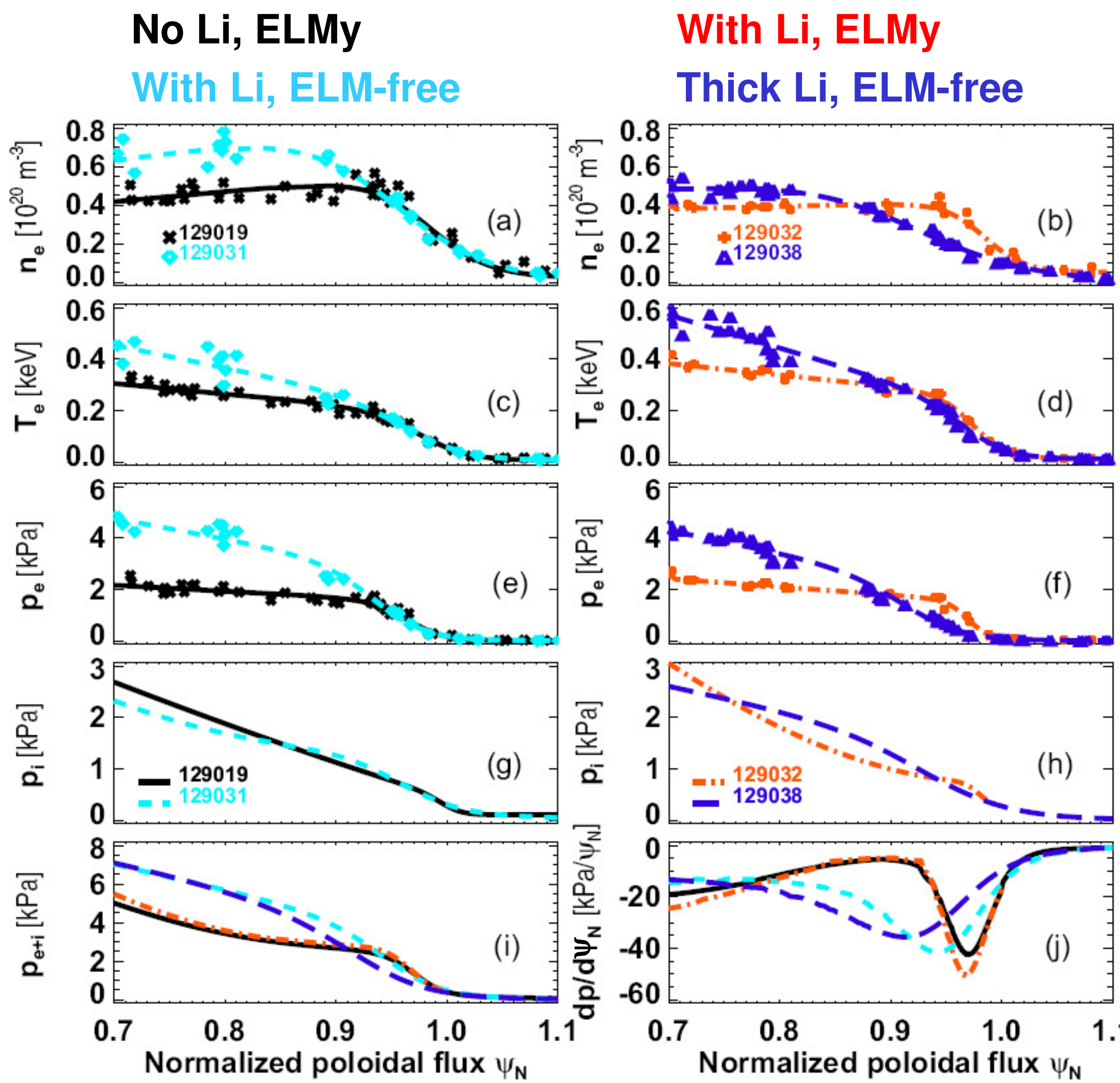




Maingi PRL 2011

In ELM-free discharges, Li has modified edge density profile

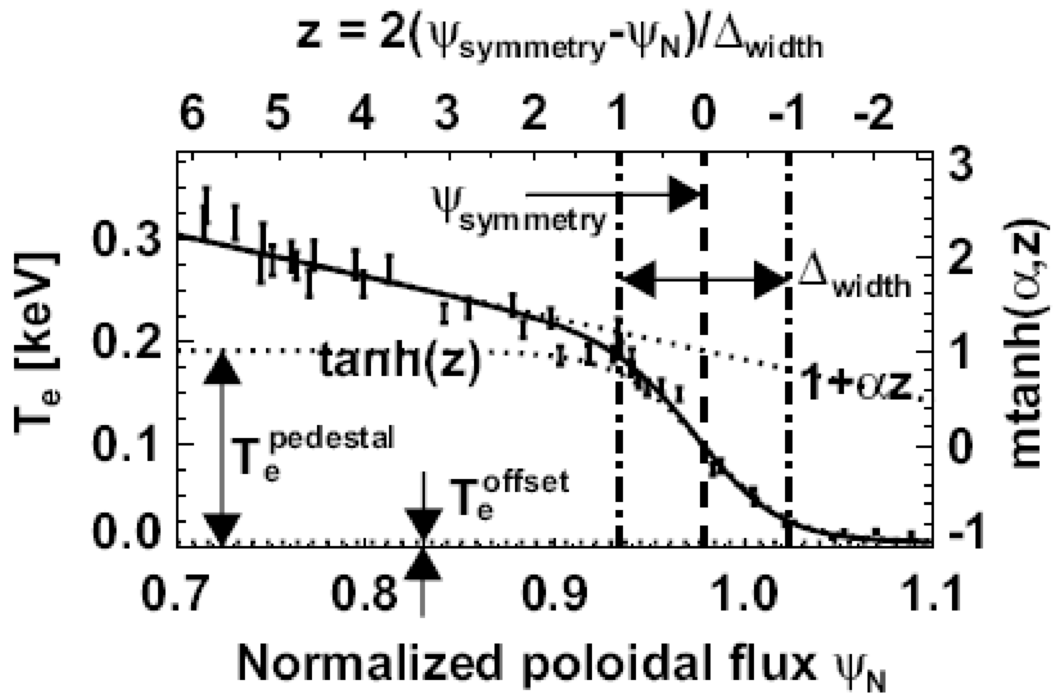
- ELM-free n_e and p_e pedestals are wider, p_e pedestals higher
- ELMy profiles similar w/ or w/o Li
- T_e clamped for $\psi_N > 0.95$
- P_i shows less change
- ELMy and ELM-free pressure gradient peaks same size, but ELM-free wider and shifted inward



Boyle PPCF 2011

Modified Tanh fits used to characterize pedestal structure

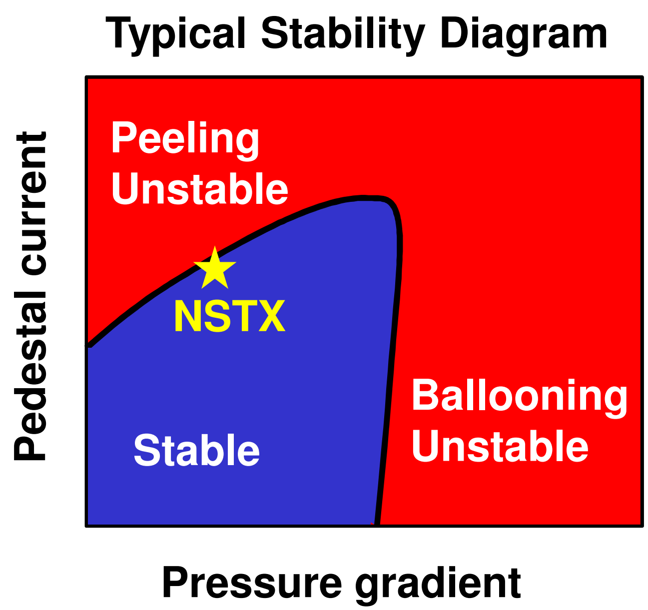
- Compare pedestal parameters from all the discharges in the scan
- TS and CHERS data from varying windows within 320-620 ms
- Larger dataset than in 2011 PPCF paper
  - Includes 2009 data
  - Fit more 2008 profiles using upgraded pyTools
  - Now with error bars



Boyle PPCF 2011

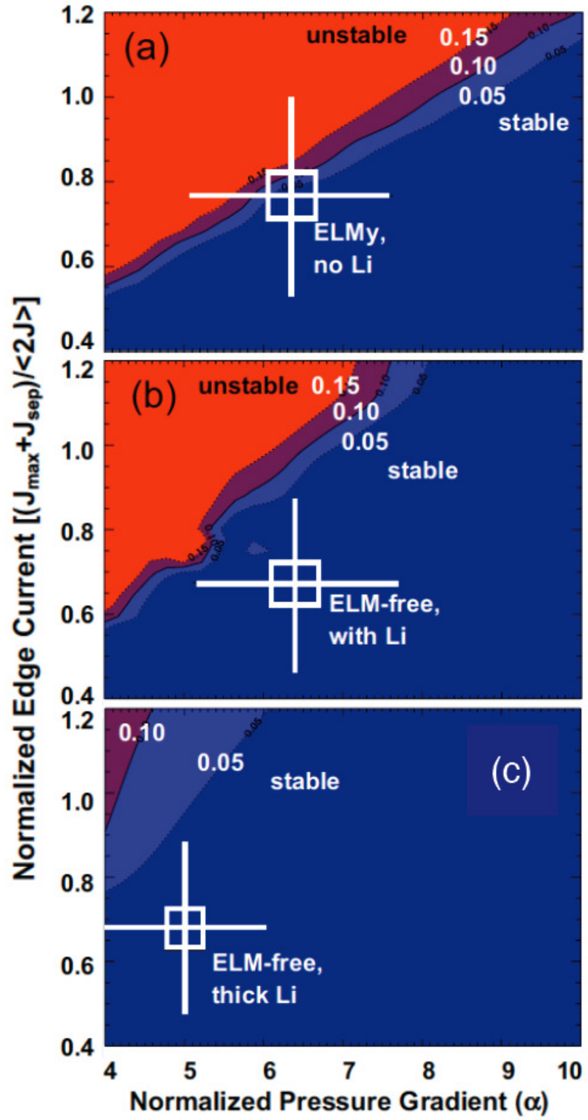
Peeling-ballooning modes believed to cause ELMs

- Stability determined by edge current and pressure gradient
- Crossing stability boundary causes current driven peeling modes or pressure driven ballooning modes.
- In this experiment, peak gradient magnitudes are **not** key parameter for ELM stability
- Location of the stability boundary depends on location of peak gradients
  - Farther from separatrix is stabilizing



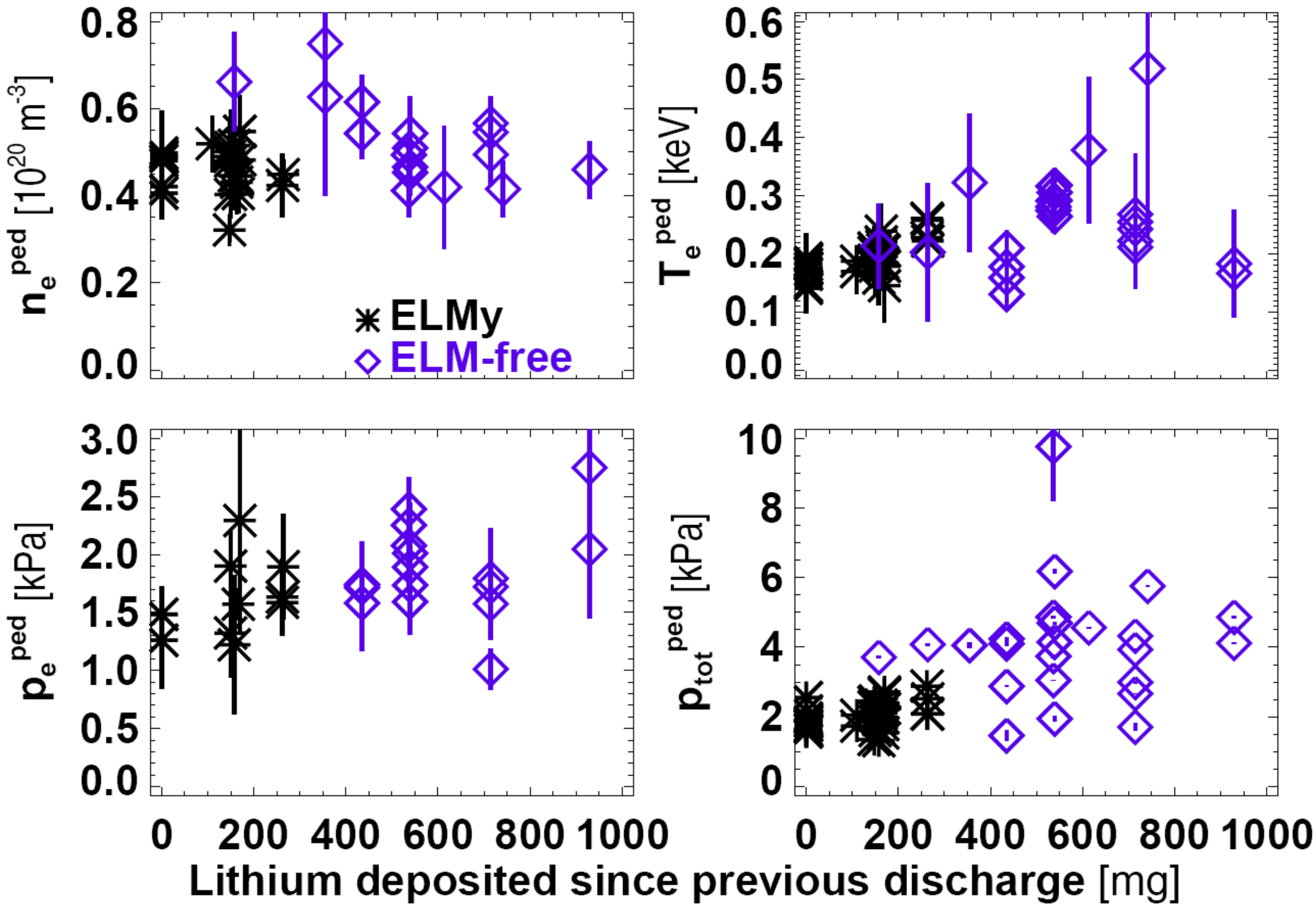
Distance from peeling stability boundary increases with Li

- ELITE calculations show NSTX discharges are closest to peeling stability boundary
- ELMy discharges are right at boundary
- Stabilization occurs when boundary moves up and left
- Reduced gradients from 95-100% -> reduced current -> reduced instability drive

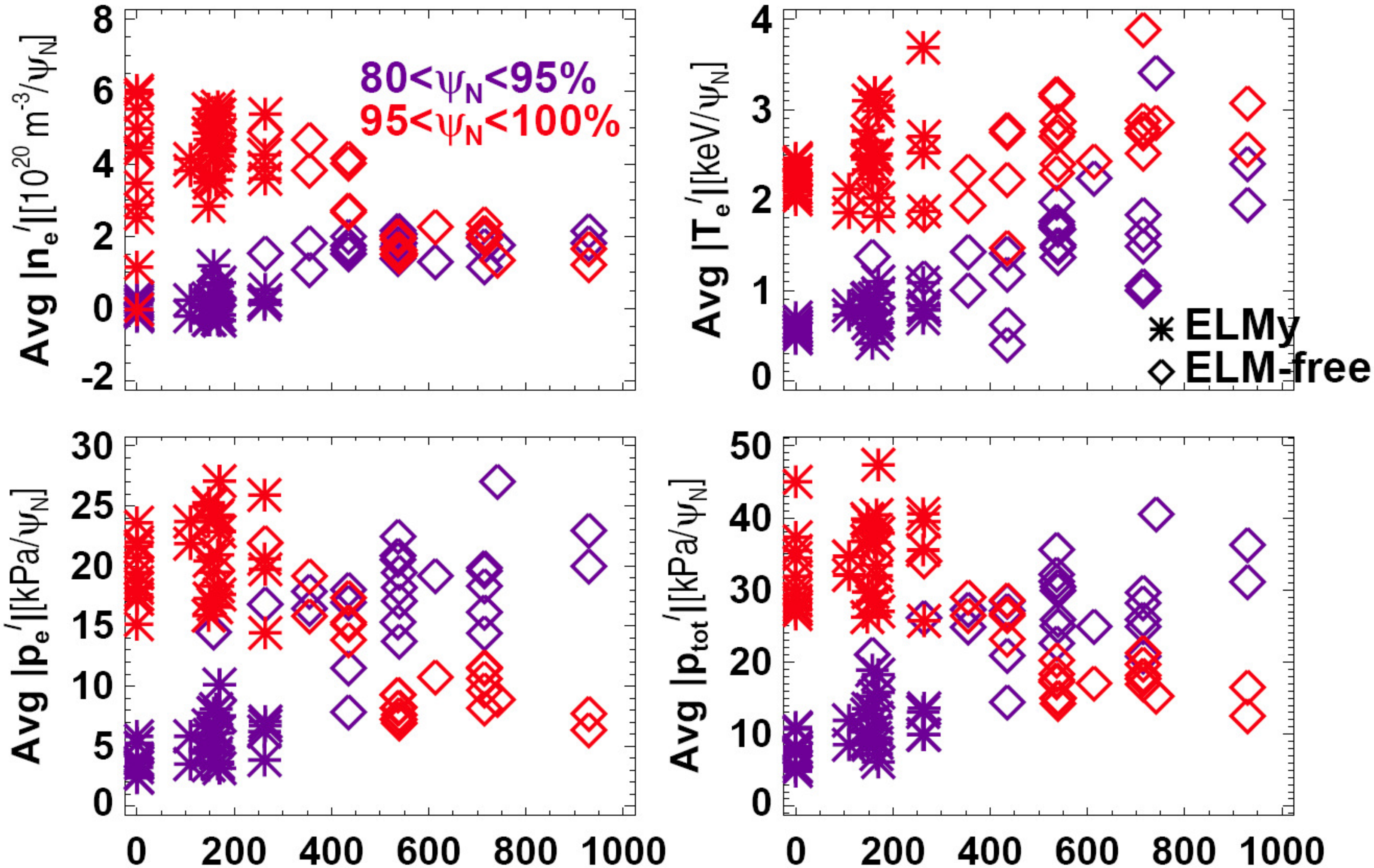


Boyle PPCF 2011

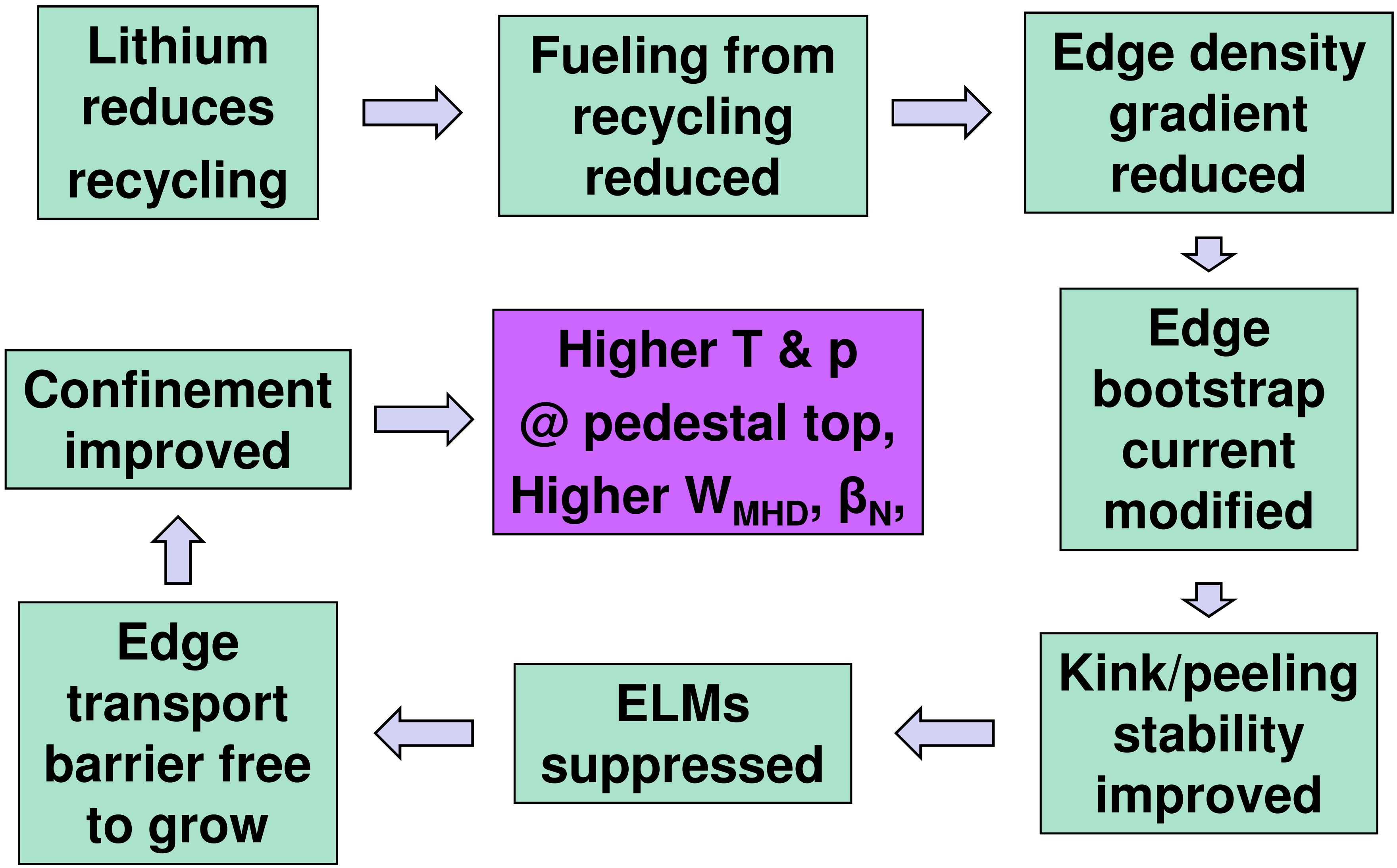
Pressure pedestal increases with lithium



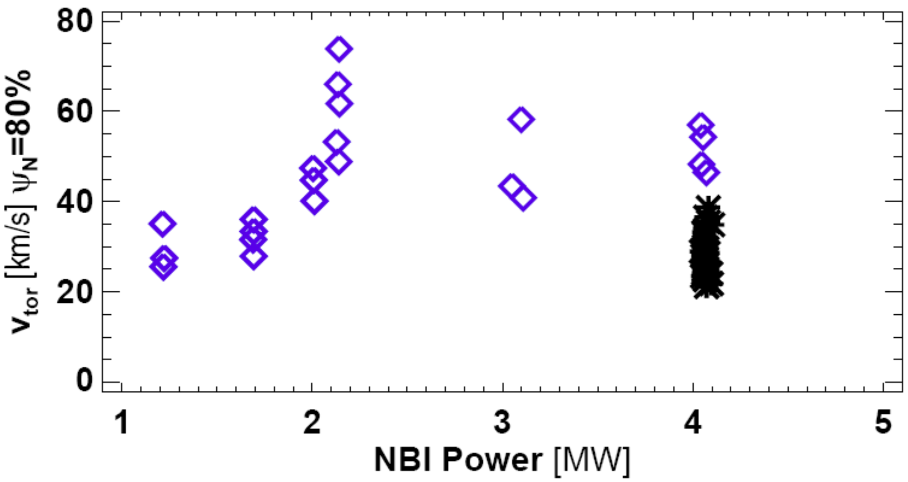
Gradients increase with lithium at pedestal top, n_e, p_e, p_{tot} gradients decrease with lithium at edge

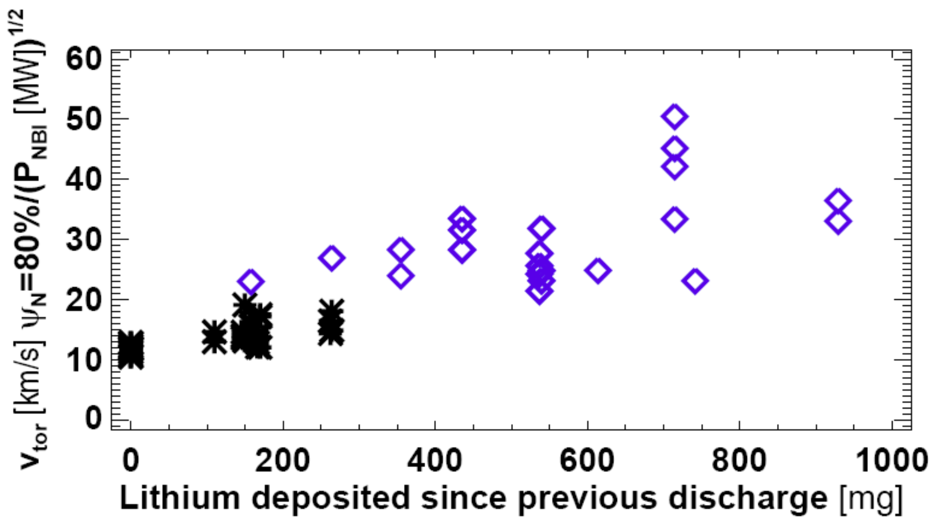


Density profile modification due to lithium pumping is the key in changing edge stability



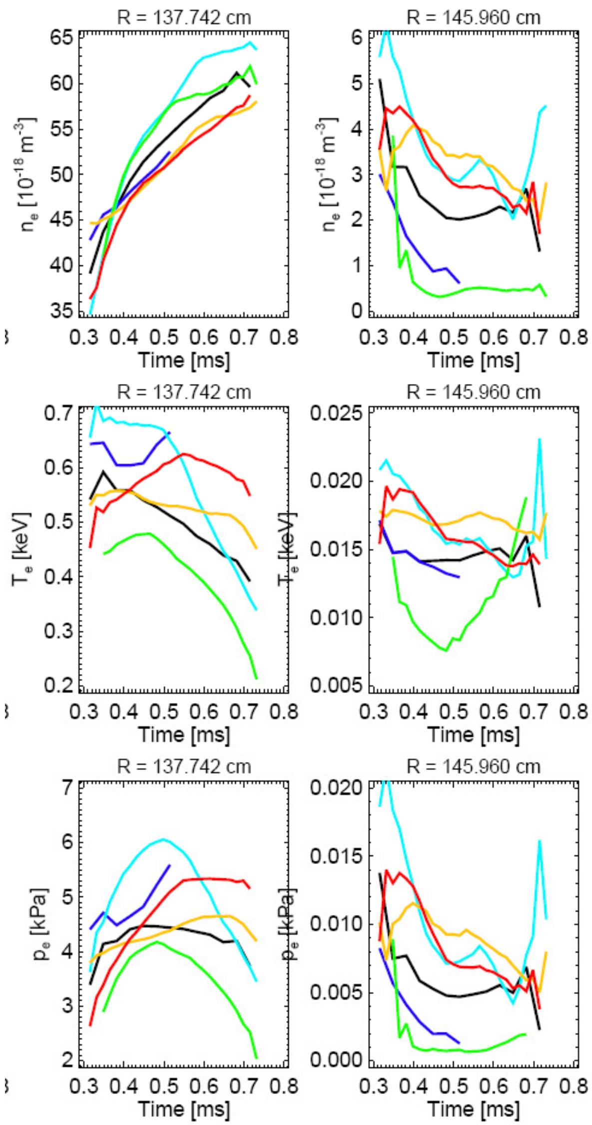
Rotation in ELM-free discharges dependent on beam power

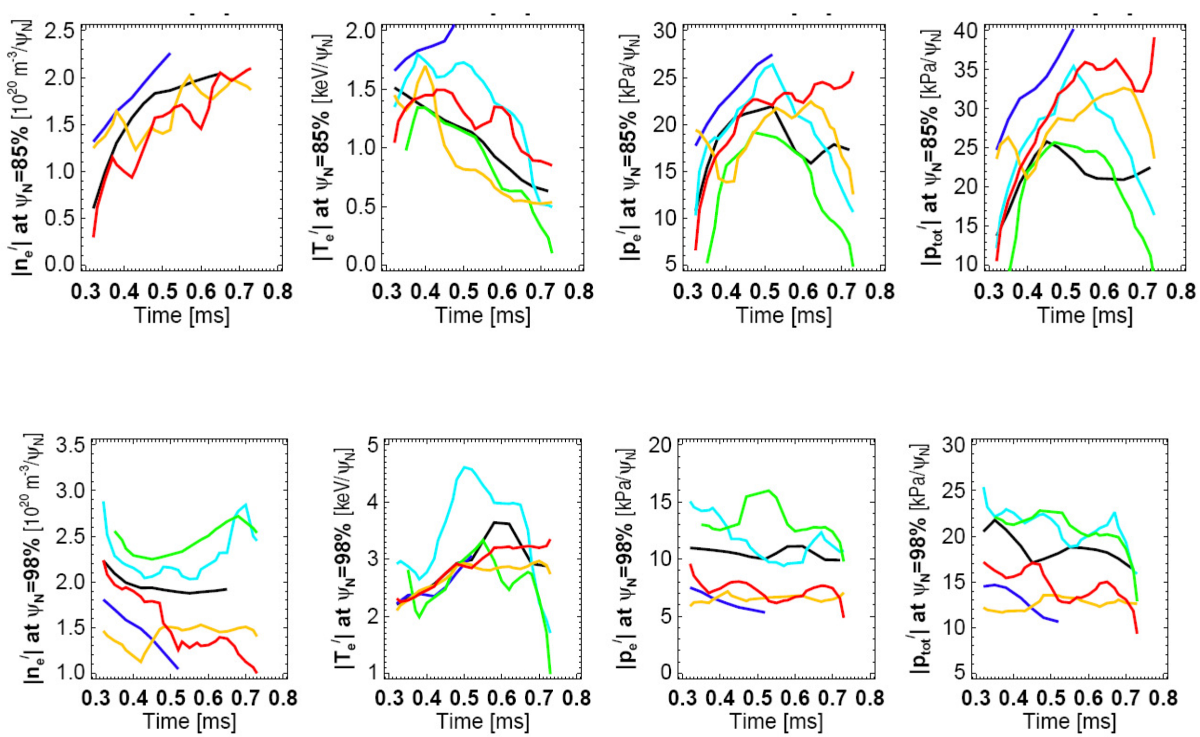




Backup Backups

Discharge evolutions?

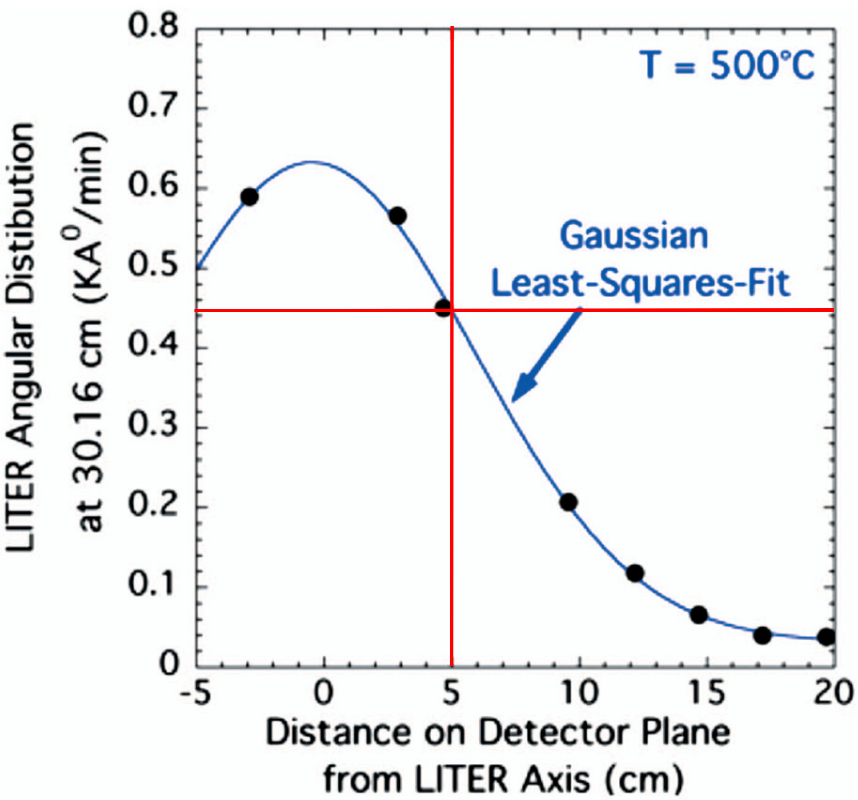




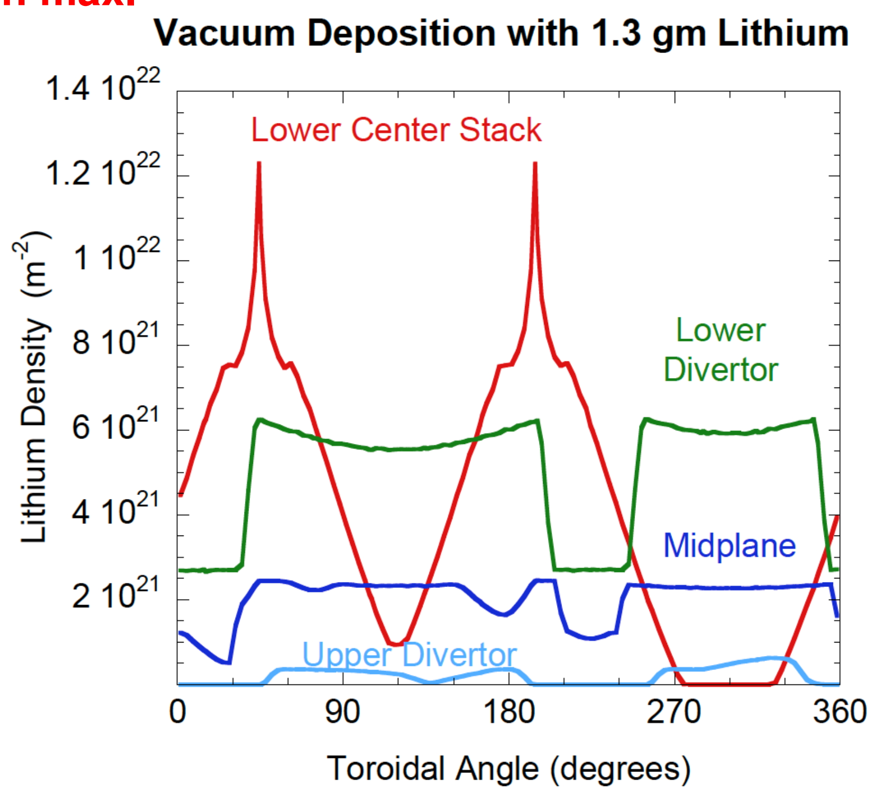
- **Quantities and Avg gradients 80-95% evolve differently than 95-100%**
- **Different lines are different shots**

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?

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

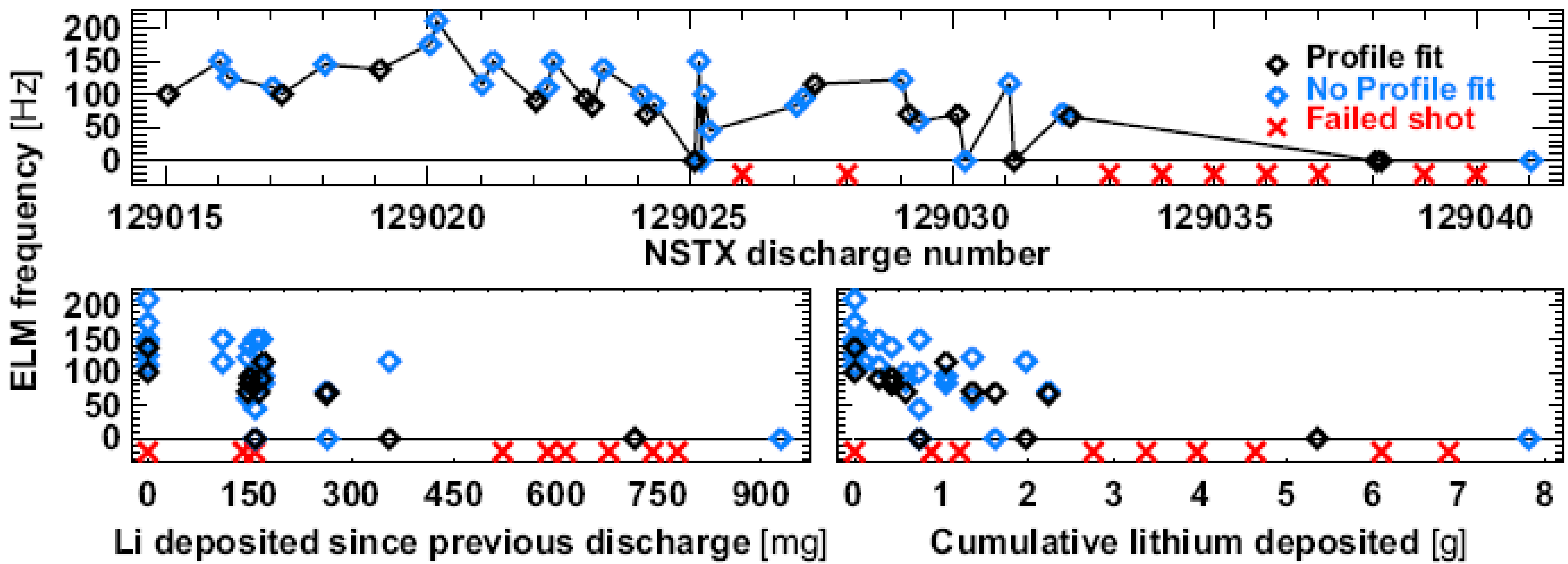
- **Nominal evaporation was ~ 150nm at the outer strike point at ~0.8m at the lowest 110mg rate**
  - **Toroidal variation gives ~ 60nm minimum deposition**
  - **Maximum deposition ~ 9x higher, or 500-1400nm! (900 mg)**
- **Surprising because implantation (pumping) depth expected to be < 10 nm**
  - **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 Zakharov: 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?

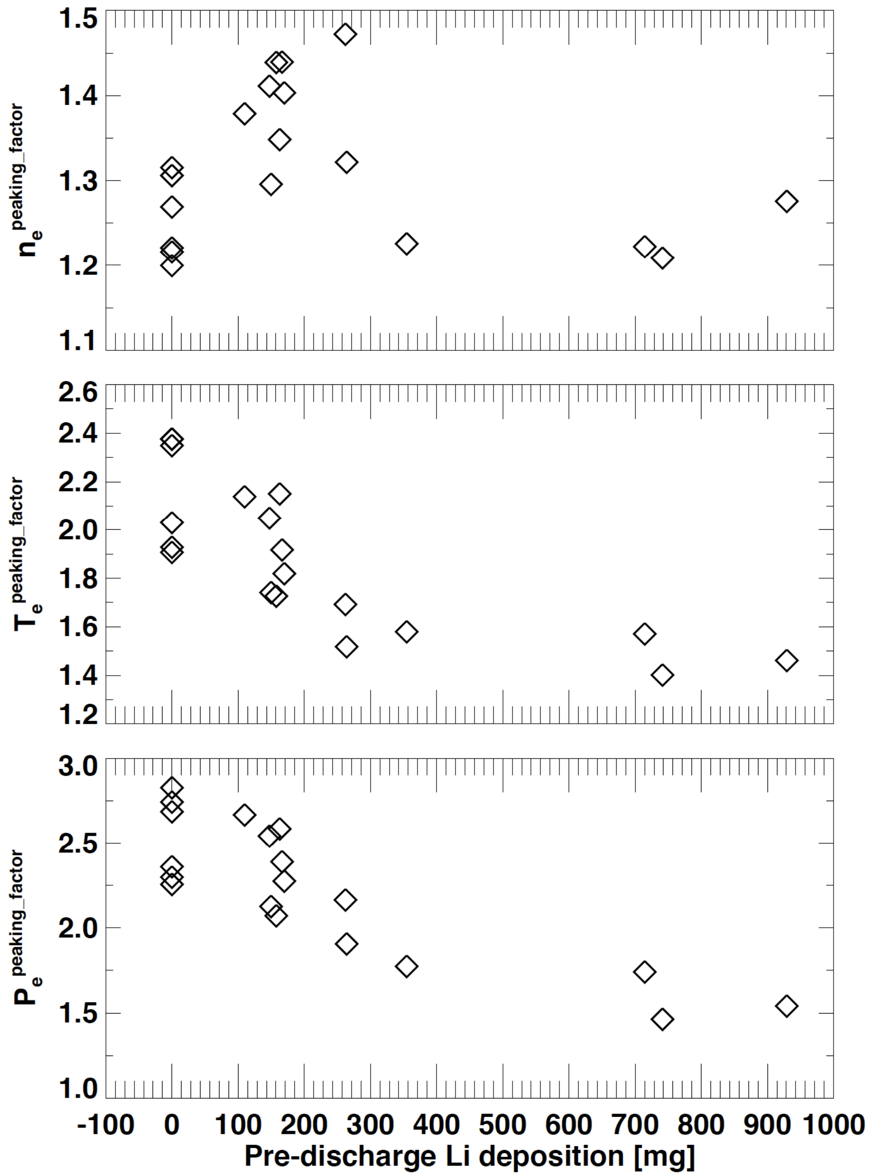
What causes this nearly continuous dependence of recycling, transport, and stability on increasing lithium?

- Deuteron implantation depth < 10 nm from simple calcs.
  - $T_e^{div} < 30$ eV, $E_i < 5\ T_e^{div}$, used PC version of TRIM
  - Stopping distance computed for Li compounds on graphite
- Minimum evaporation (~100 mg): nominal film thickness ~ 30nm at the outer strike point at the lowest rate, i.e. at least 3x higher than the implantation depth
  - Toroidal average actually ~ 80 nm minimum, i.e. > 8x higher
- Maximum evaporation (~900mg): nominal film thickness ~ 9x higher than minimum, i.e. 27x greater than implantation depth!
- *These are all 'ideal' calculations - surface chemistry of reactive lithium could alter these results*



Boyle PPCF 2011

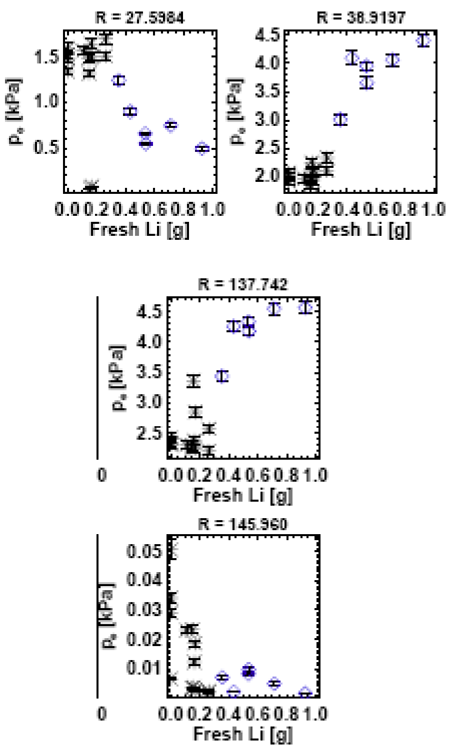
T_e and P_e profile peaking factors decrease with increasing lithium

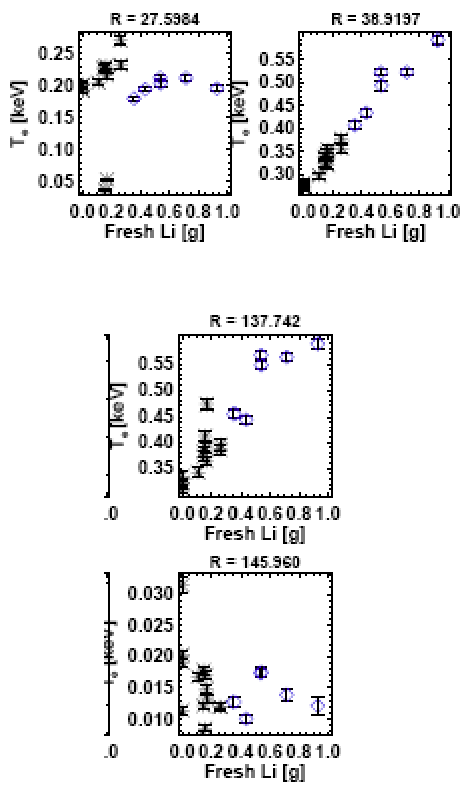


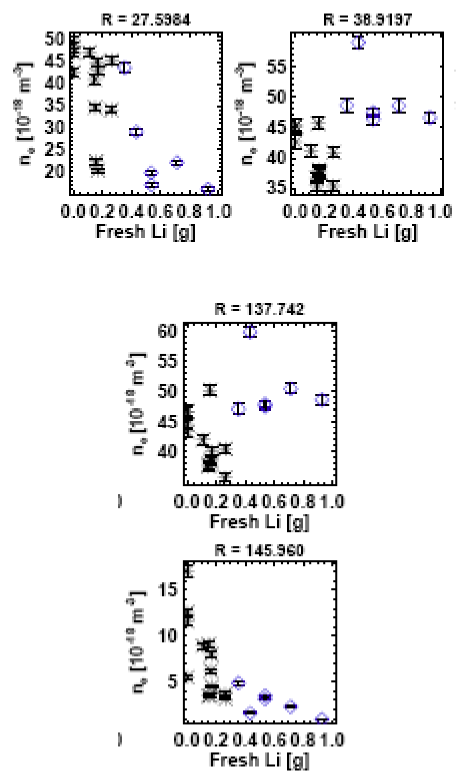
- n_e profile peaking factor first increases as ELM frequency goes down, and then decreases as ELMs disappear and profile becomes hollow

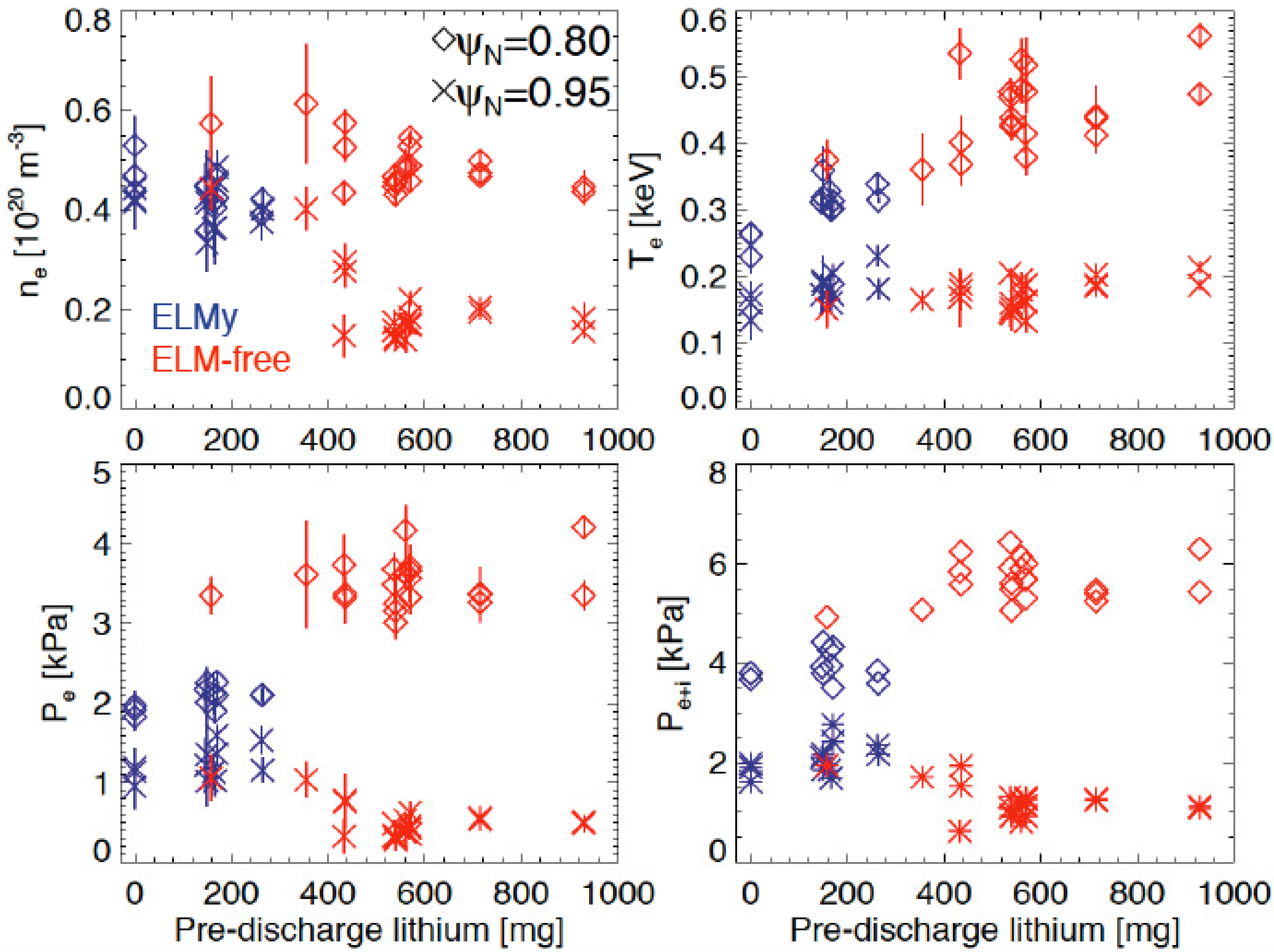
- T_e and P_e profile peaking factors decrease ~ continuously, good for MHD stability

Maingi PRL 2011


R = 27.5984
R = 38.9197
R = 137.742
R = 145.960
p_e [kPa]
Fresh Li [g]

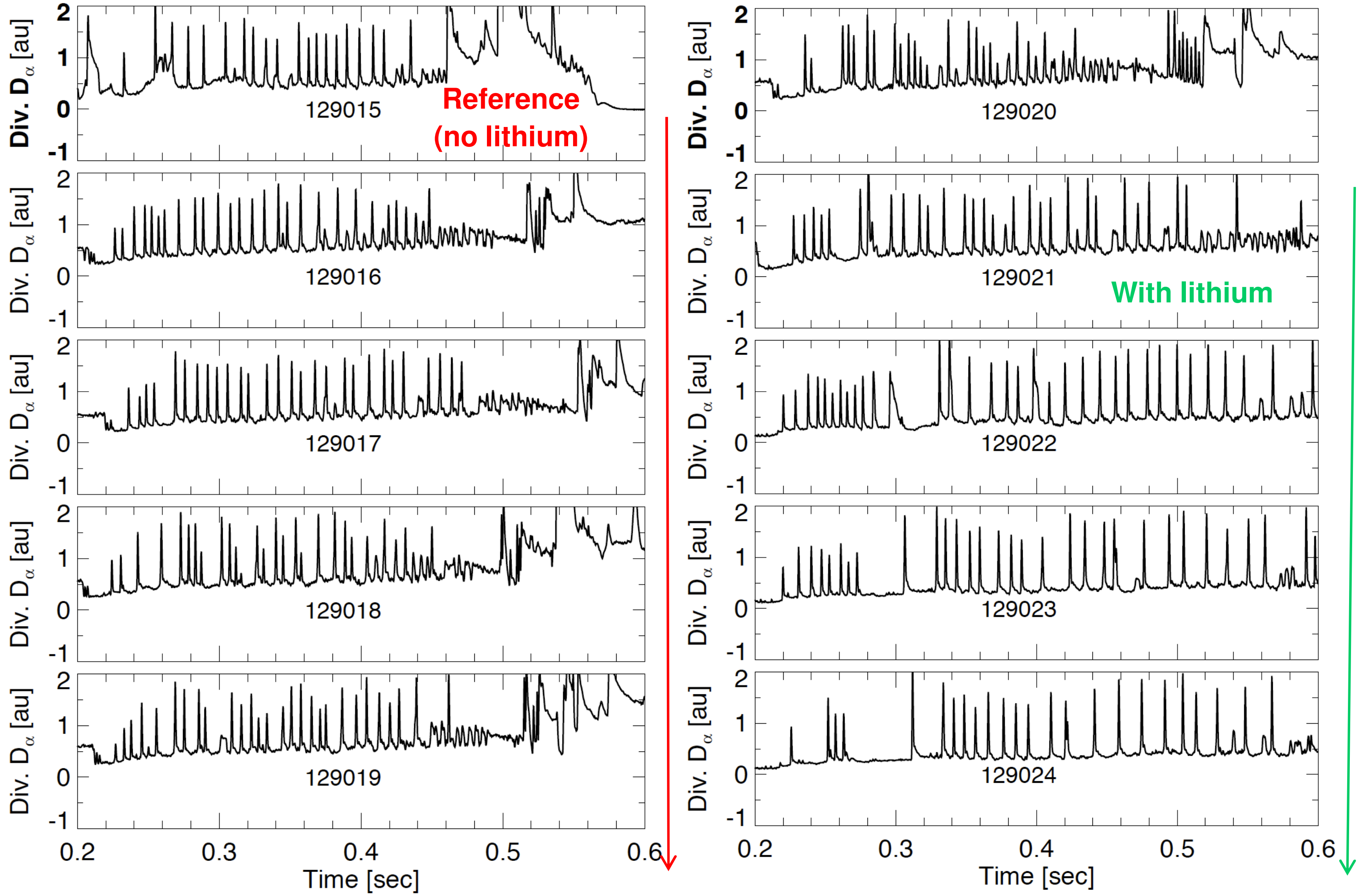

R = 27.5984
R = 38.9197
R = 137.742
R = 145.960
T_e [keV]
Fresh Li [g]


R = 27.5984
R = 38.9197
R = 137.742
R = 145.960
n_e [10^{18} m^{-3}]
Fresh Li [g]

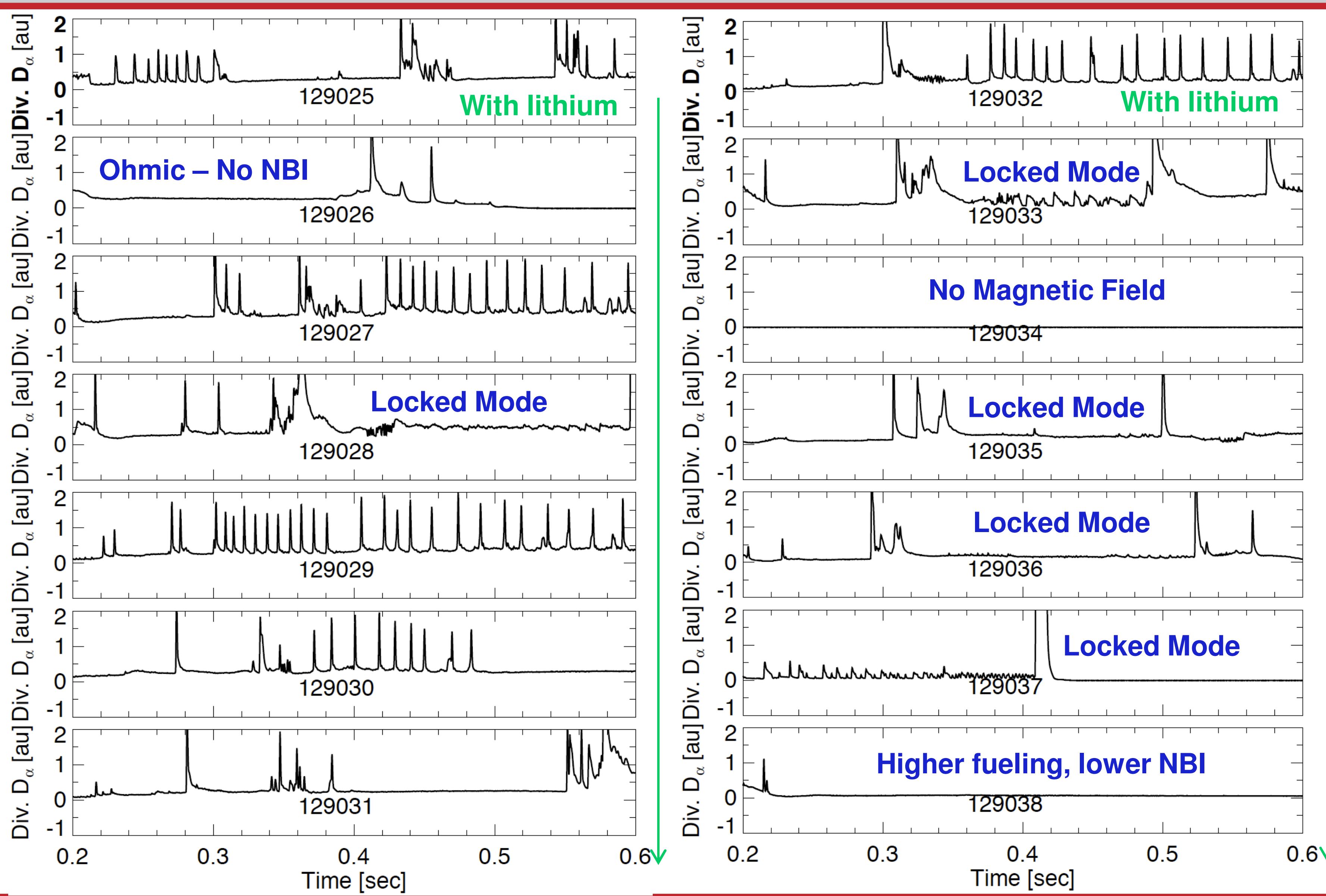


Maingi NF 2012

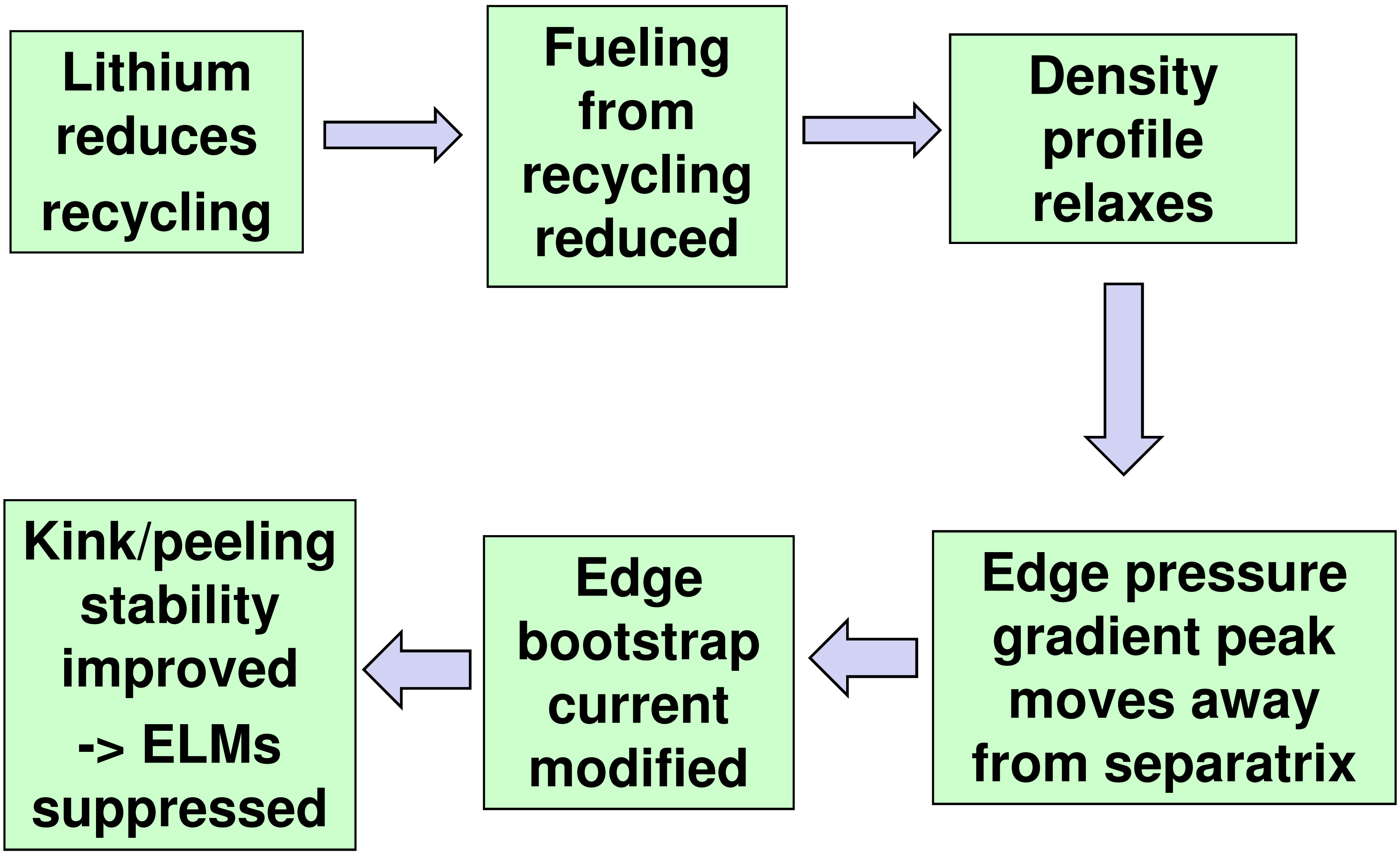
ELM evolution with shot number



Quiescent phases increase with increasing lithium coating

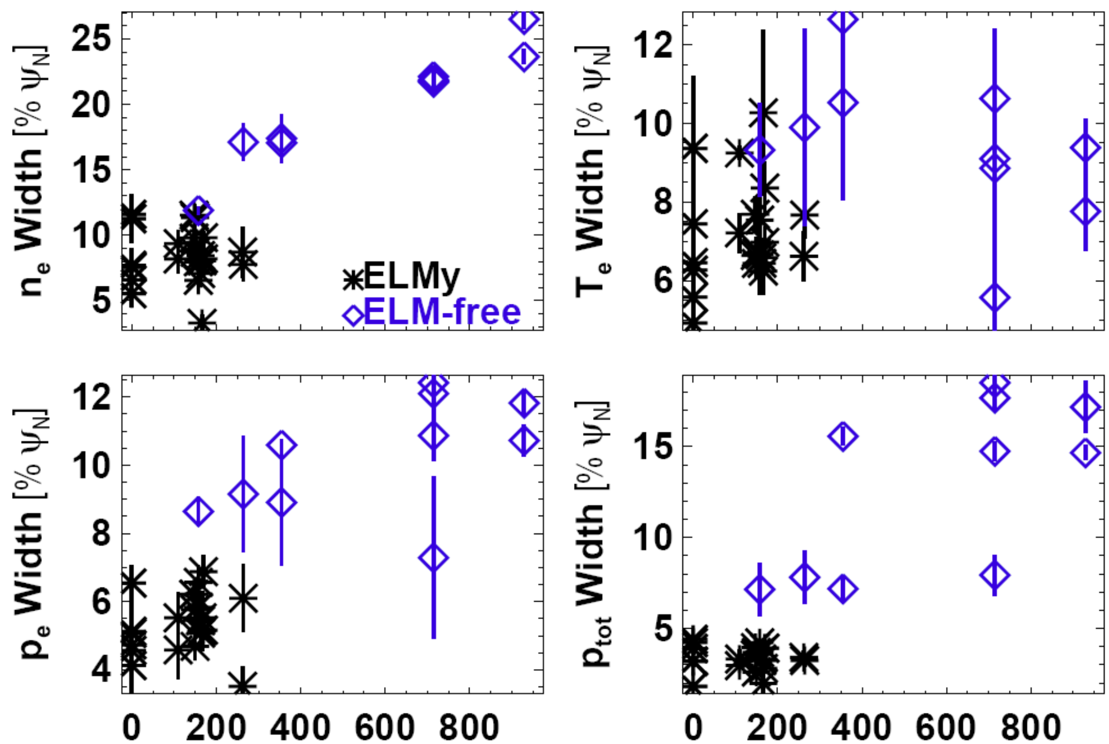


Density profile modification due to lithium pumping is the key in changing edge stability



Density and pressure pedestals wider in ELM-free plasmas

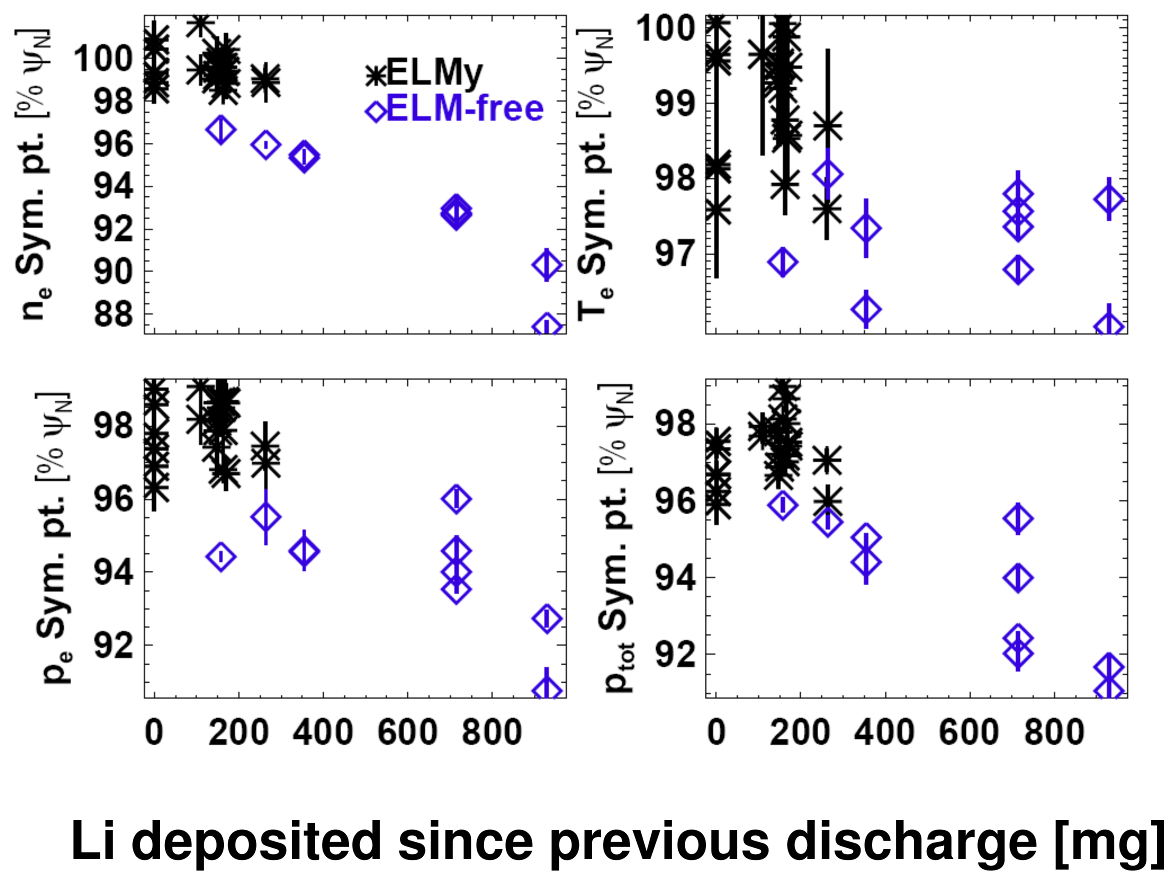
- n_e, p_e, p_{tot} pedestal widths correlated with Li
- T_e pedestal width does not separate ELMy from ELM-free and is not correlated with Li



Li deposited since previous discharge [mg]

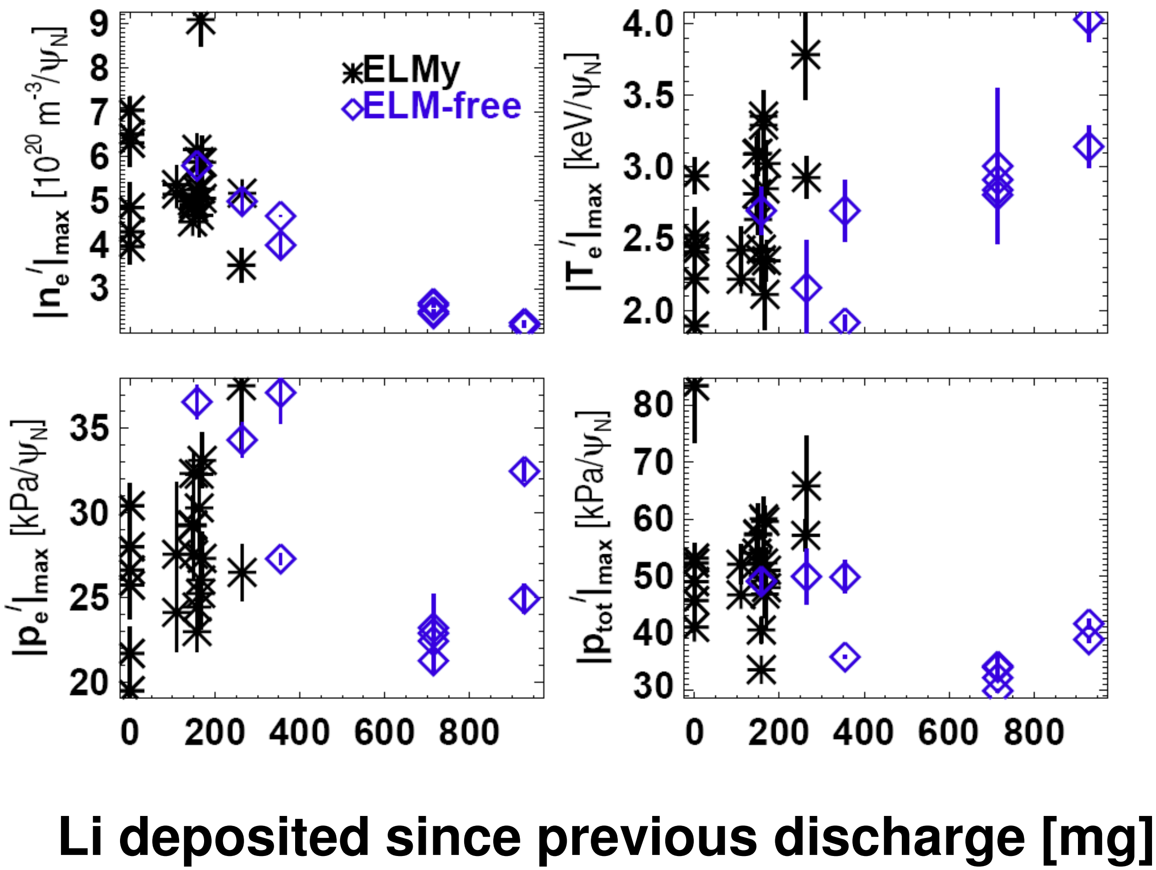
Peak density and pressure gradients farther from separatrix in ELM-free plasmas

- n_e, p_e, p_{tot} symmetry points correlated with Li
- T_e symmetry point does not separate ELMy from ELM-free and is not correlated with Li

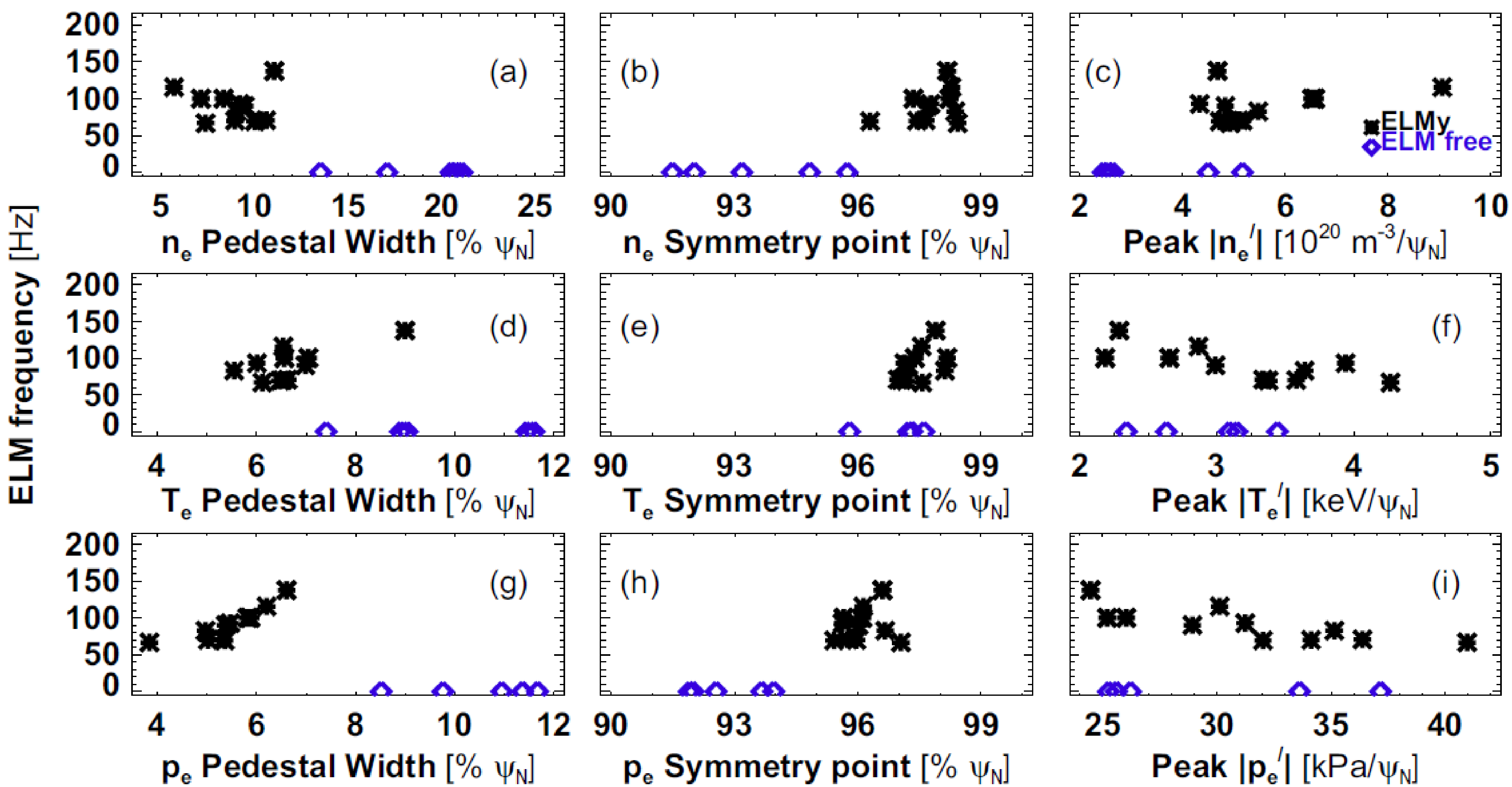


Peak gradients magnitudes do not separate ELMy from ELM-free

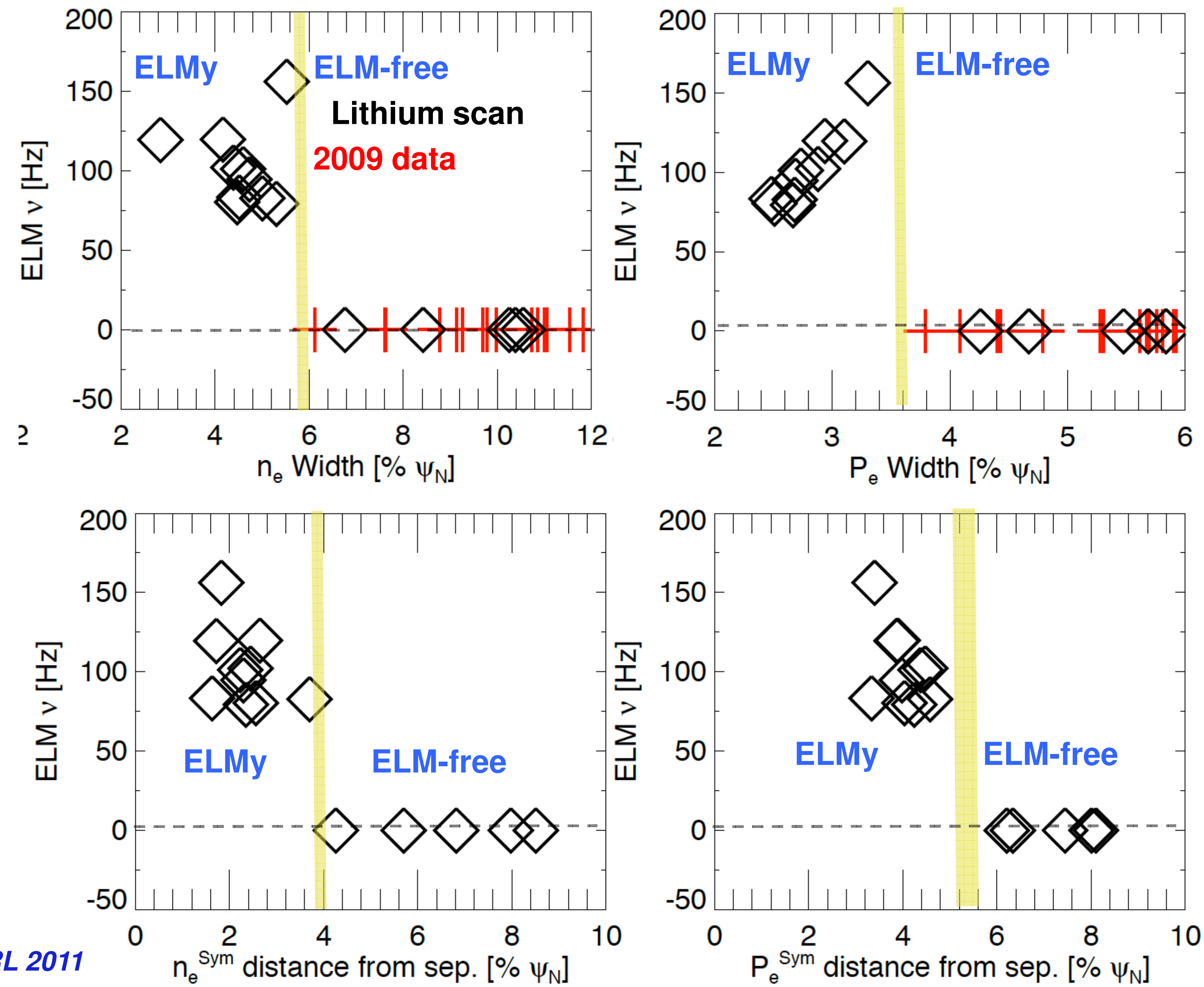
- Peak gradient magnitudes may be correlated with Li



ELM Frequency plots



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

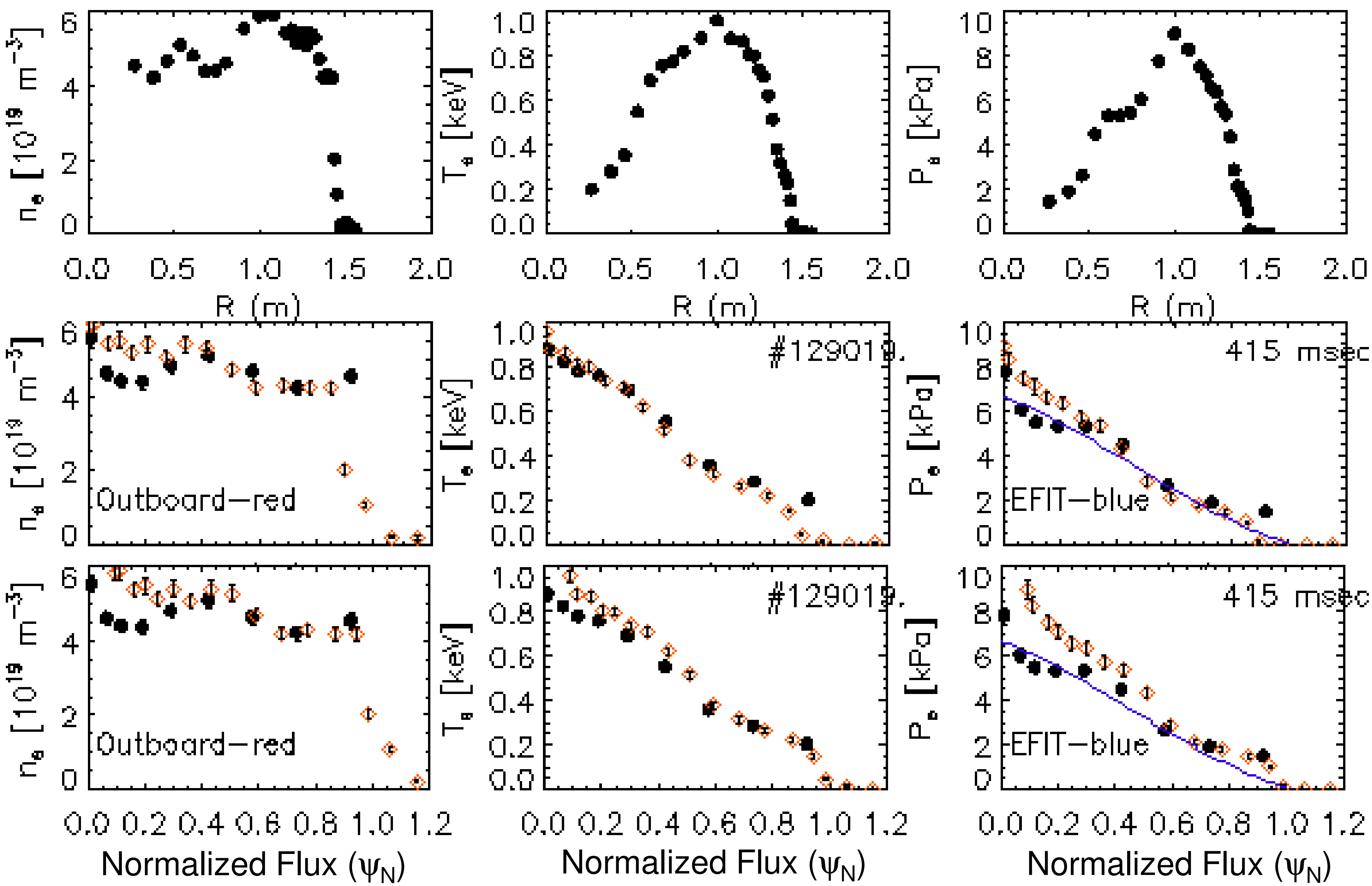


Maingi PRL 2011

Edge profile & stability analysis procedure

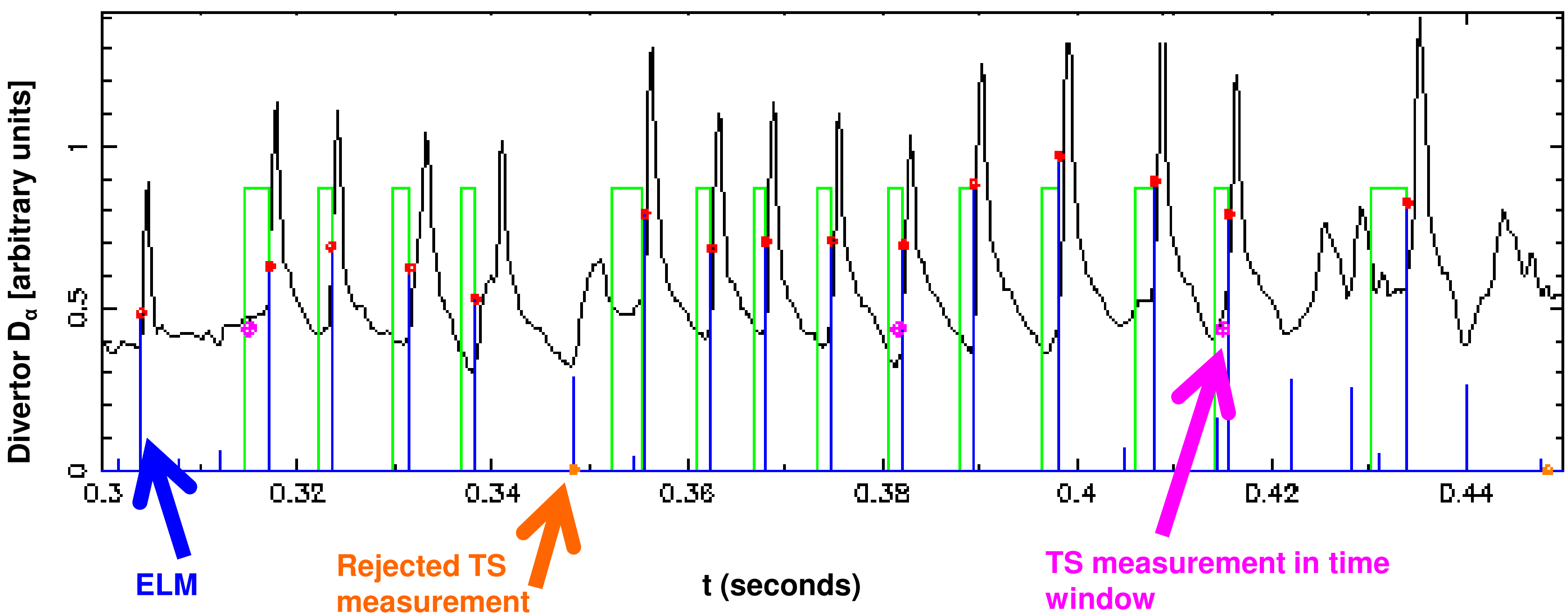
- EFIT equilibrium reconstruction code run at Thomson scattering (TS) profile times for flux (ψ_N) mapping
- Profile fitting with multiple time slices
  - ELMy profiles from last 20-70% of ELM cycle selected
  - ELM-free profiles used in 100-200 msec windows
- Free boundary kinetic EFITs run to match pressure & current profiles
  - Edge bootstrap current computed from Sauter neoclassical model
    - No direct measurement ➡ biggest uncertainty
  - Stability evaluated with PEST code
- Fixed boundary kinetic EFITs run with variations of edge pressure gradient and edge current
  - Stability boundary evaluated with ELITE code

EFITs require setting outboard T_e at separatrix for flux mapping of Thomson scattering profiles



Multiple TS profiles combined for better edge resolution

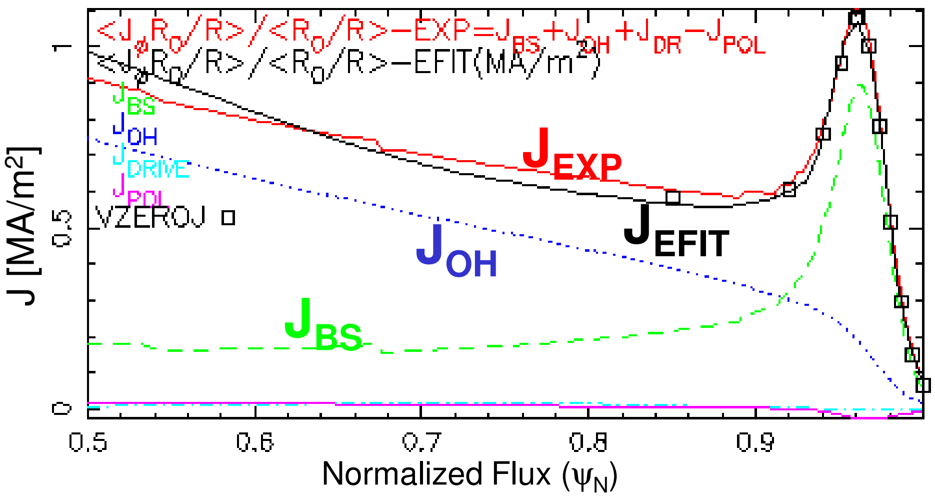
- ELM free shots combined over ~100 ms window
- ELMy shots combined using ELM syncing
  - only use data from end of ELM cycle
- CHERS, magnetics data also combined



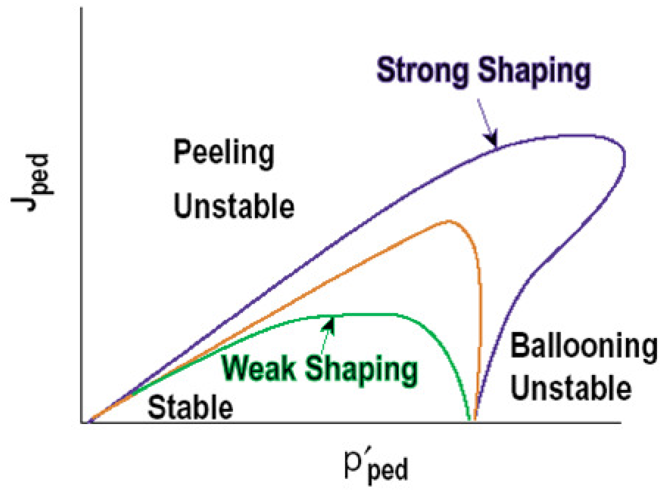
Kinetic EFITs reconstruct equilibria using additional constraints

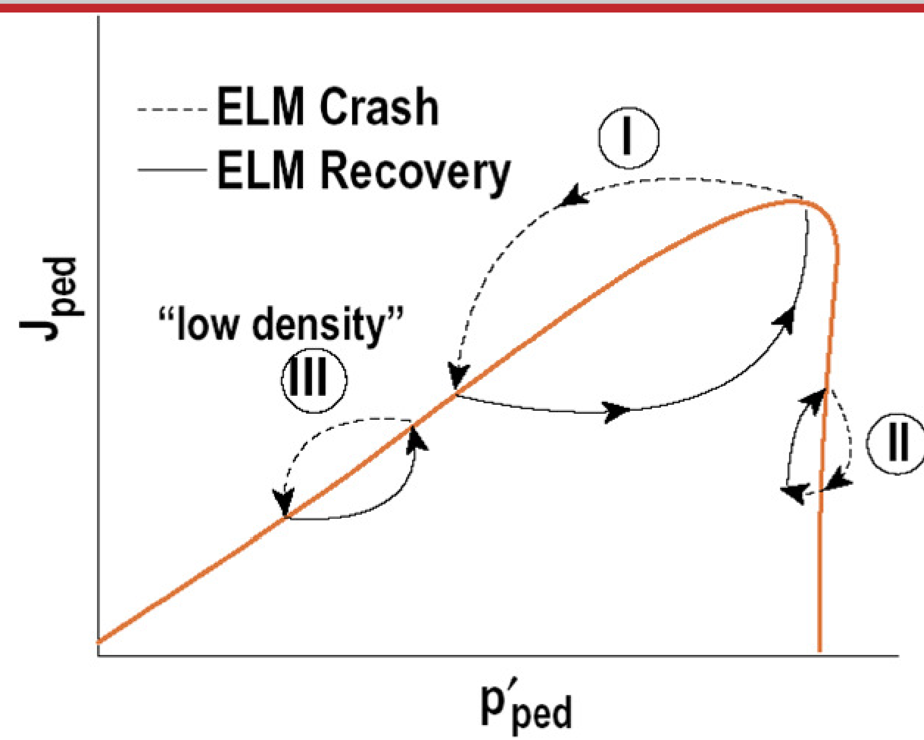
- Constrained by measured P, J profiles
  - Bootstrap current calculated from neo-classical model

$$\mathbf{J}_{BS} \propto \nabla n, \nabla T$$



Different types of ELM cycles can be envisioned





- ELMs triggered by peeling-ballooning modes, ELM size correlates to depth of most unstable mode and to location in parameter space
- Pressure rises up on transport time scale between ELMs, current rises to steady state value more slowly
- Predict changeover in ELM behavior when $J_{ped}<J_{peel} \Rightarrow$ strong density and shape dependence

UKAEA Fusion

Snyder, Wilson

GENERAL ATOMICS

Future Work

- Calculate stability while varying model profiles
- Why are the ELMs not stabilized by diamagnetic drift, as in higher aspect ratio tokamaks?
  - Low growth rates: $\gamma_{lin}/\omega_A \geq 1\%$ unstable experimentally
  - Should be stabilized by diamagnetic drift: $\gamma_{lin}/(\omega^*/2) \leq 5\text{-}10\%$
- Why do ELMs go away the way they do i.e. with increasing periods of quiescence?
  - Details of density/pressure profile modification may be beyond present ability to measure experimentally
    - Additional Thomson channels installed in upgrade
    - Better edge resolution could make multiple TS times unnecessary
  - How do profiles and stability evolve through ELM cycle?