Effect of Lithium Powder Injection on DIII-D discharges, and comparison with EAST and NSTX

by

R. Maingi, on behalf of the DIII-D Li team (G.L. Jackson, D.K. Mansfield, T.H. Osborne, Z. Yan, and the DIII-D team)

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Lithium broadened the edge plasma operating window in DIII-D, NSTX, and EAST

- DIII-D: edge pedestal doubles in width via bifurcation when Li delivered in presence of a pedestal-localized mode
  - Li powder injected (18 mg/s) during discharges; no D_α drop!
  - P_e^{ped} more than doubles, H98 increases by 50-60%
  - Existence proof of reproducible, high performance pedestal, but not yet a scenario!

- EAST uses morning evaporation and Li during discharges
  - Lithium powder injected (40 mg/s) during discharges
  - ELMs eliminated for duration ~ 20 s, no H98 improvement yet

- NSTX eliminated ELMs up to core β_N ~ 6 limit
  - Li evaporated (150-300 mg) before each discharge
  - P_e^{ped}, H98 improvements scale with Li evaporation amount
  - ELMs eliminated up to β_N ~ 6 limit; P_{rad} ramped in time

DIII-D

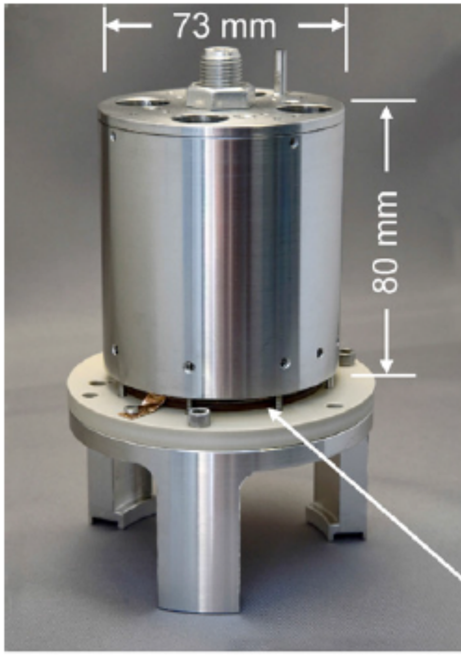
Li injection into discharges with pre-existing separatrix-localized fluctuations alters pedestal and confinement characteristics

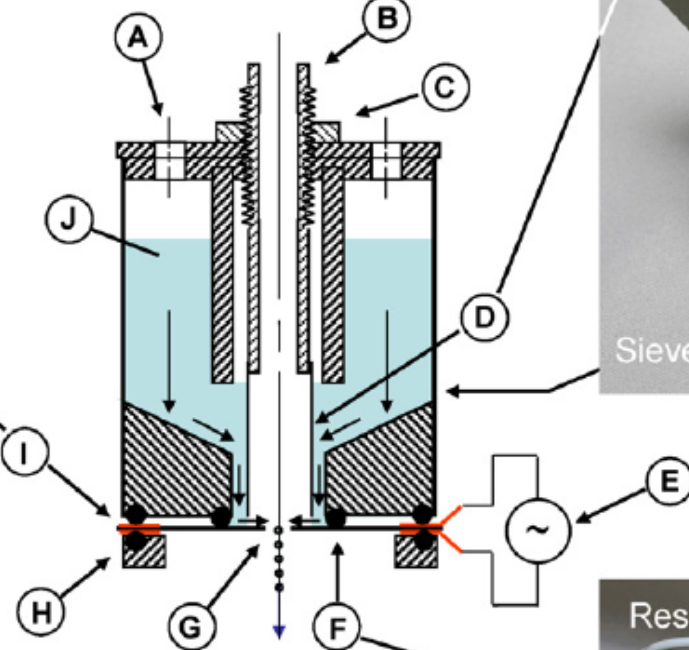
- **There is a 'new' high amplitude 'Bursty Chirping Mode' seen on BES: appears to be coherent and bursty ~ 80 kHz**
  - Seen in reference no-Li discharges between ELMs, leading to broadening of the pedestal; period between ELMs 10-30 msec
  - Without Li injection, the next ELM kills the BCM
  - With Li injection, the ELM-free period grows to < 350 msec, with H_{H98y2} increasing by $\leq$ 60% and P_e^{ped} increasing by 100-150%

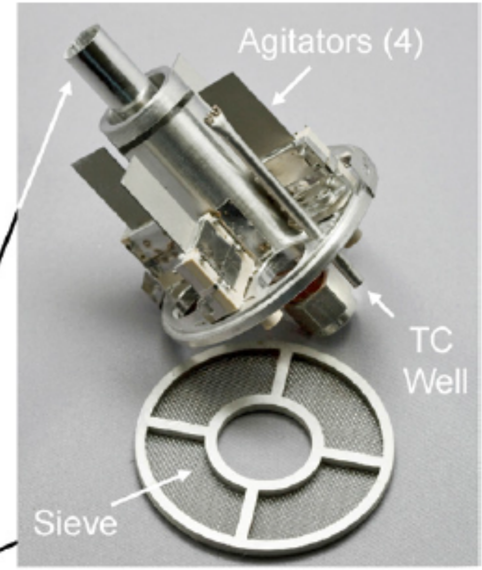
- **There is an optimal injection rate (~ 15 mg/sec) to bifurcate to an ELM-free H-mode with a broad pedestal, but with steady P_{rad}**
  - Substantial Li measured in core and edge (n_{Li}/n_e~10%-15%)
  - Too much Li drives plasma to H-L; too little shows small effect
  - Recycling unchanged: D_α from filterscopes does not decrease
  - Wide pedestal terminated by giant ELM, consistent with ELITE

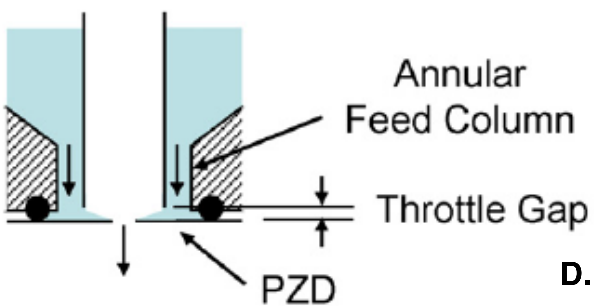
- **Combination of profile flattening near separatrix and ion dilution in edge lead to synergistic enhancement of pedestal**

Piezoelectric crystal and assembly used to drop Lithium into the edge of fusion devices

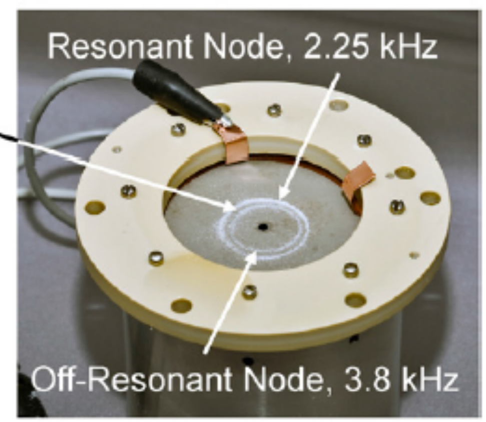








D. Mansfield, FEDC 2010



Lithium dropper deployed in upper divertor in DIII-D

- **Gravitational acceleration of ~ 45 μm commercially available Li spheres**
  - Li injection into plasma results in green light emission
  - Controllable flow rate < 10^{22} atoms/sec

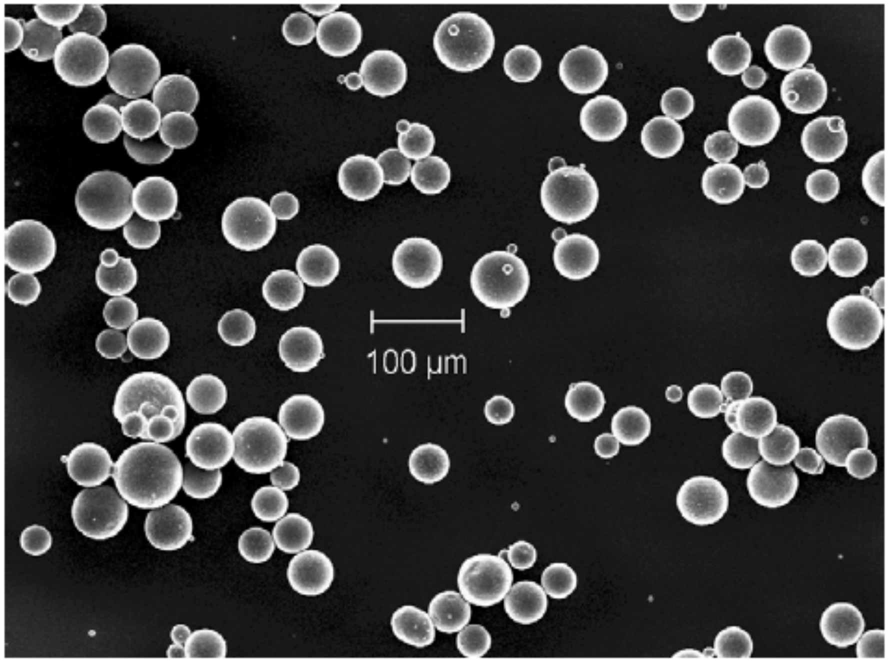
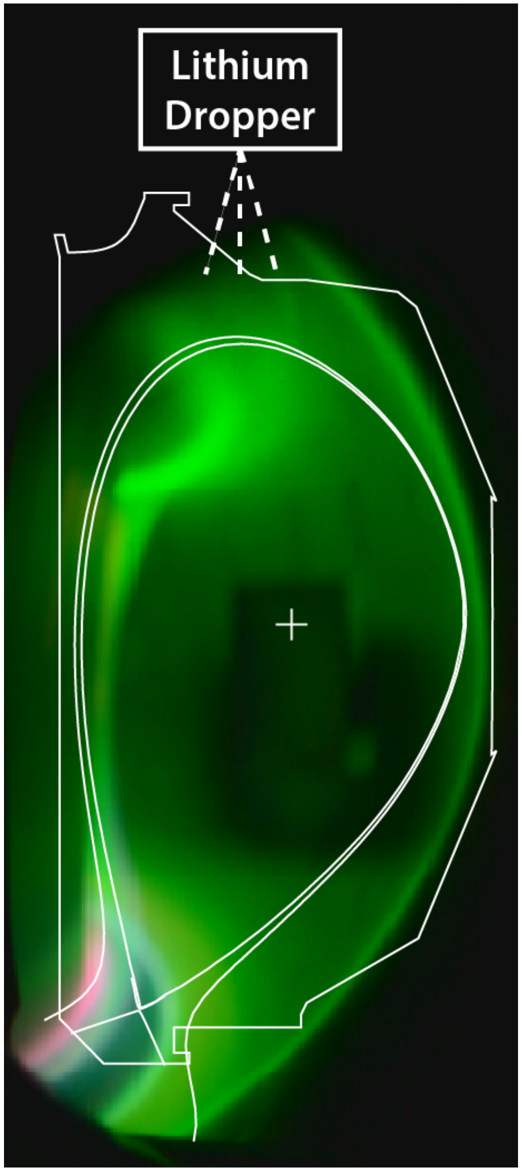
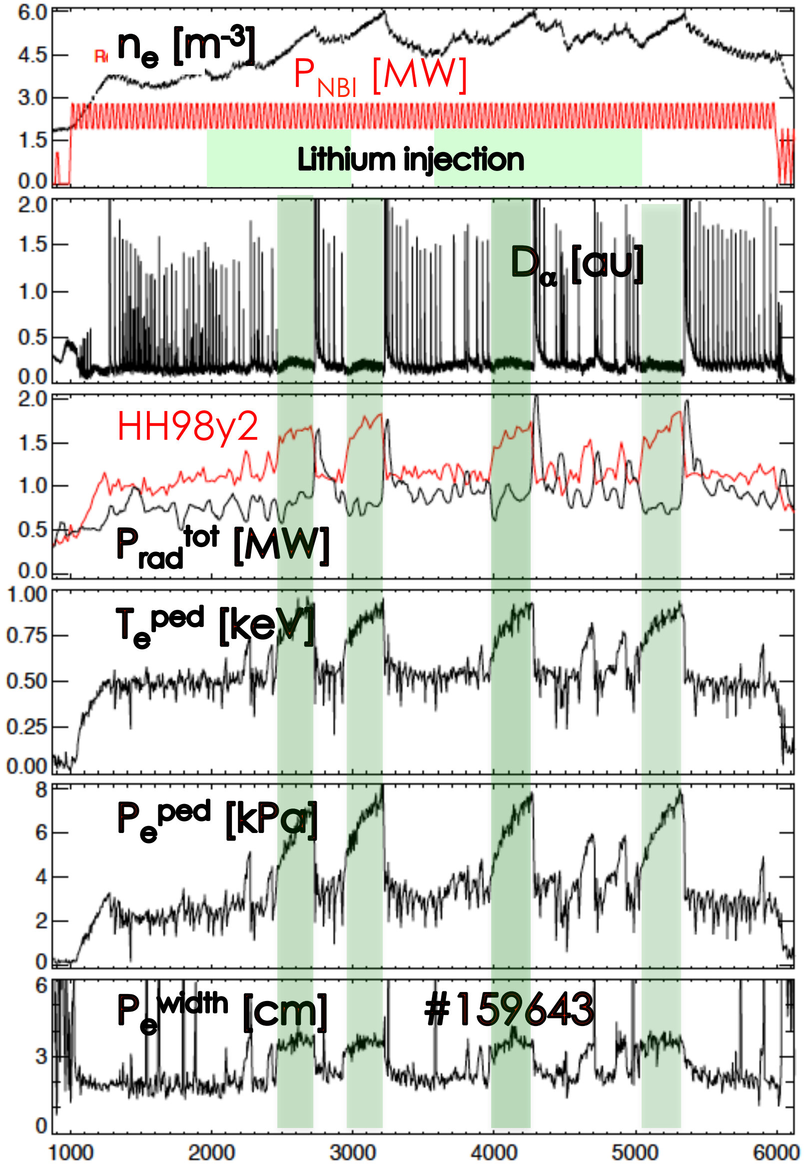


Fig. 1. The SLMP® powder used in this work.



D. Mansfield, FEDC 2010; D3D image courtesy of S. Allen

Lithium injection induces a bifurcation to higher pedestal pressure and width in DIII-D



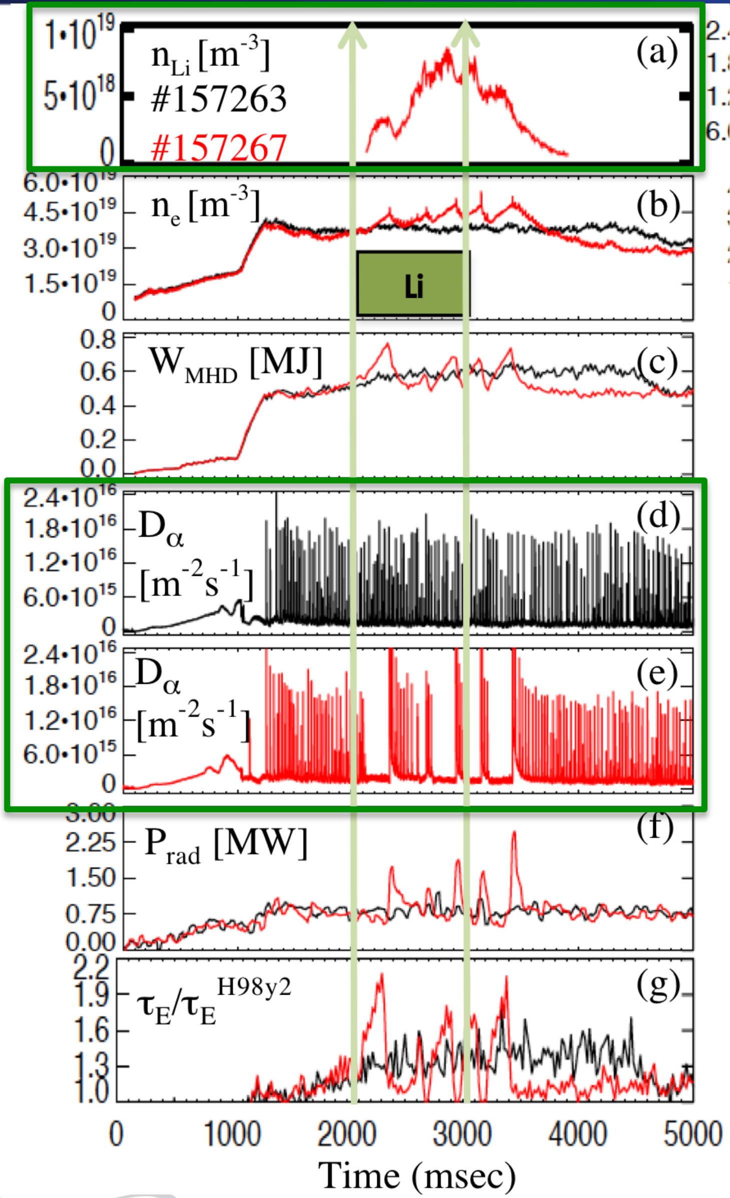
- ELM-free bifurcated state can be seen in D_a emission
- $H_{98y2} \leq 1.8$ here, 2.0 in other discharges; 'flat' P_{rad}^{tot}
- T_e^{ped} nearly doubled during bifurcations
- P_e^{ped} nearly tripled during bifurcations
- P_e^{width} increased by 100% on very short time scale

R. Maingi, PRL submitted; G. Jackson, IAEA FEC 2014 PD

DIII-D – Fluctuations near separatrix – 'Bursty Chirping Mode'

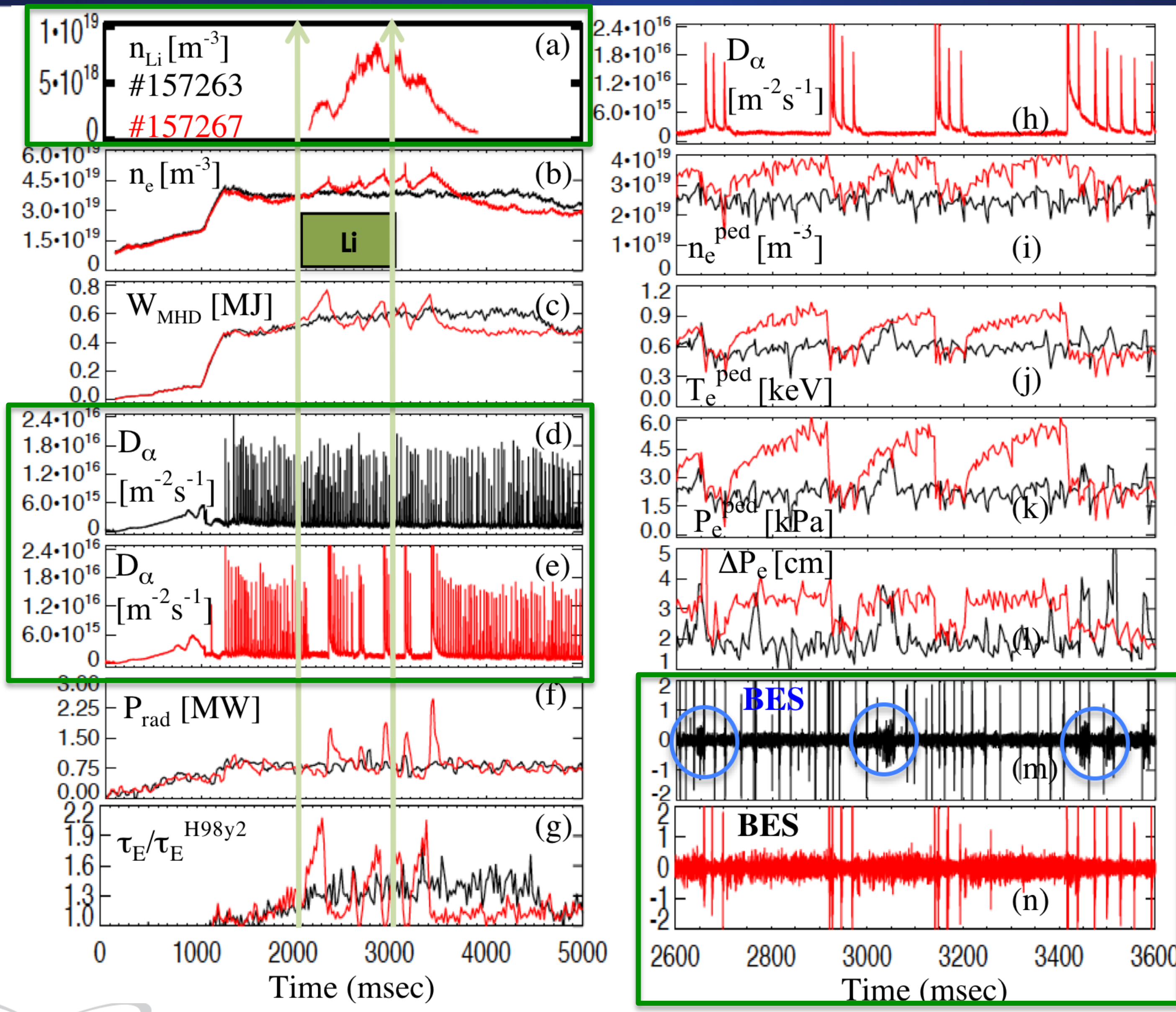
DIII-D NATIONAL FUSION FACILITY SAN DIEGO

Edge pedestal profiles broaden and bifurcate to a high performance (ELM-free) state with Li and existing fluctuations



ELM-free (Li)
ELMy (no Li)

Edge pedestal profiles broaden and bifurcate to a high performance (ELM-free) state with Li and existing fluctuations



ELM-free (Li)
ELMy (no Li)

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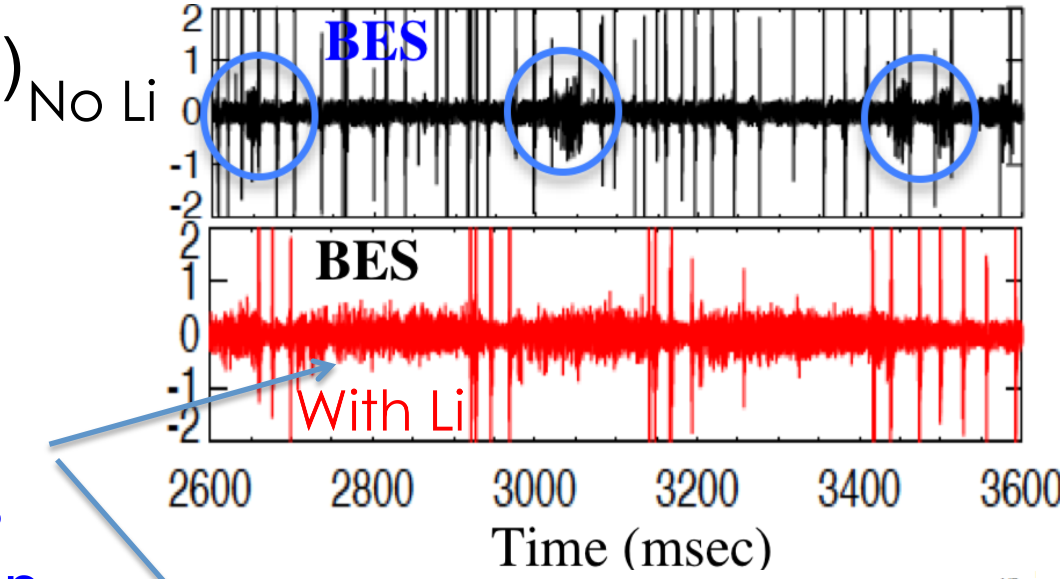
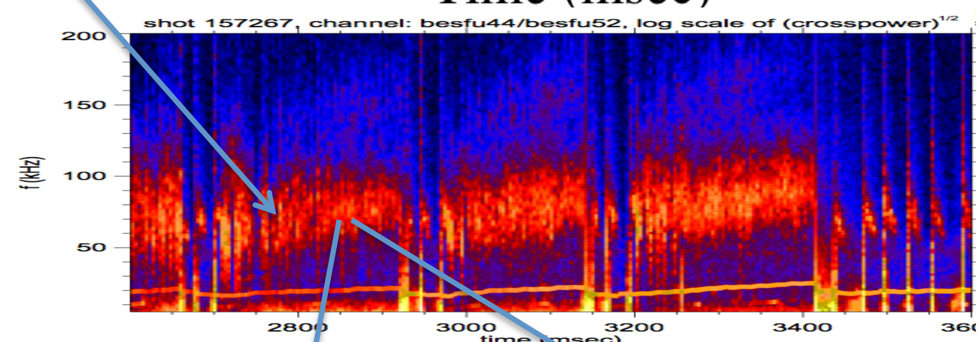
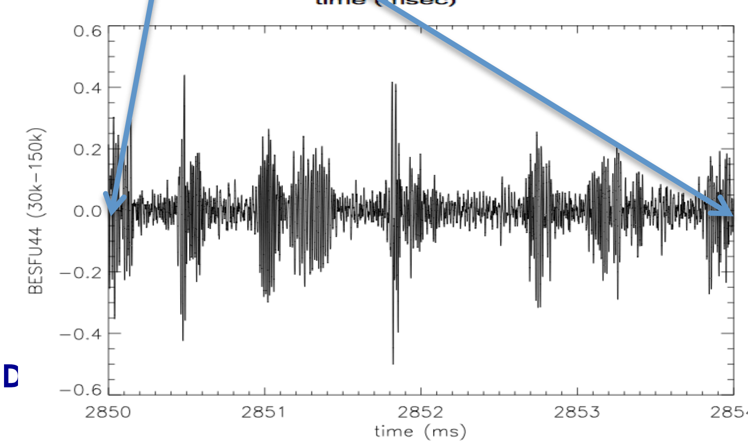
Bifurcation to wide pedestals and improved edge stability with Li injection and enhanced edge fluctuations

- Bursty Chirping Mode (BCM) observed between ELMs in 5-8% of ELM cycles in no-Li reference discharges
  - ELM terminates BCM
  - Pedestal width bifurcates with BCM but pedestal top does not increase much
- Li injection ‘stimulates’ BCM in 10-20% of ELM cycles, and delays ELM that terminates BCM to higher Z_{eff}, lower j_{BS}
  - Pedestal top grows

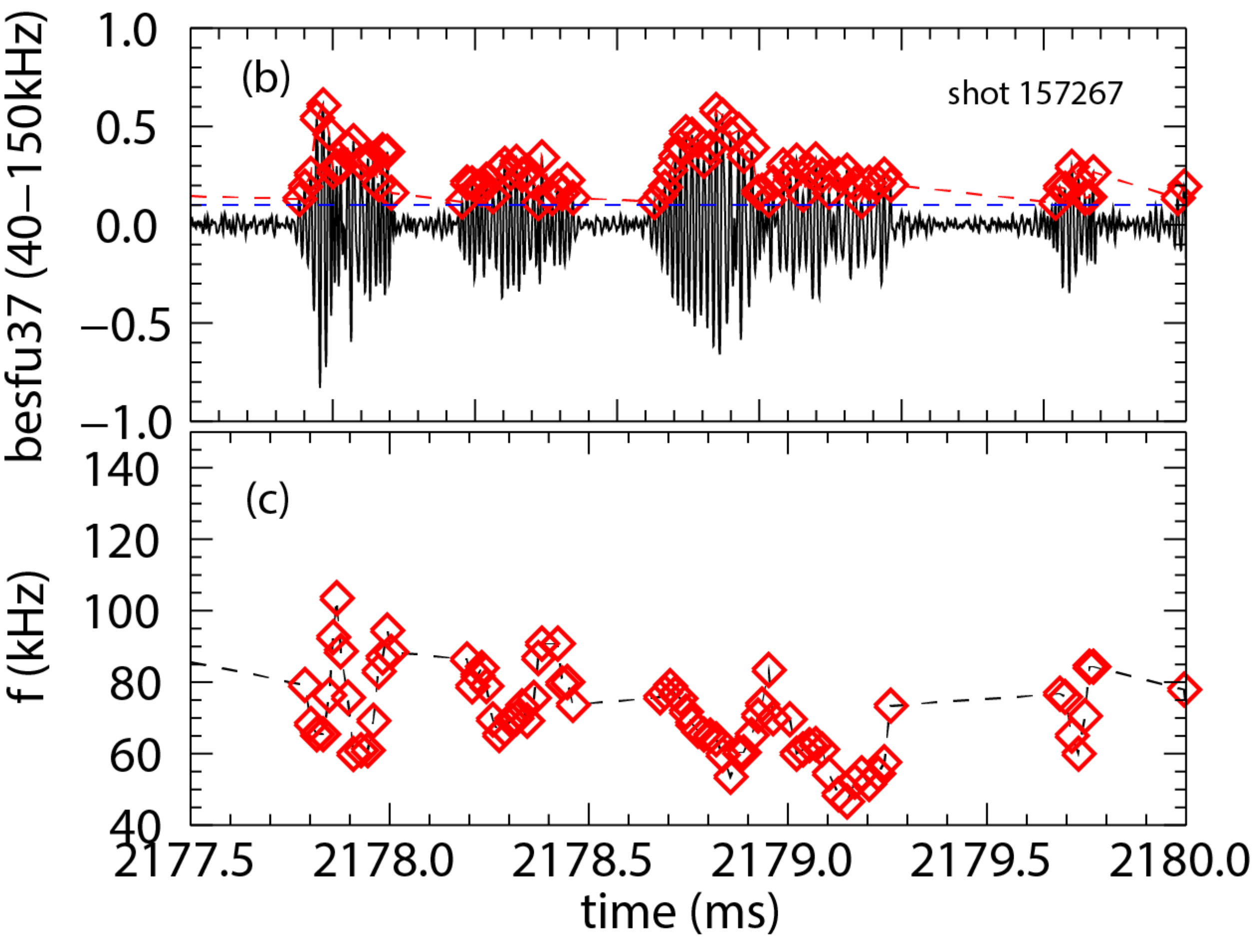


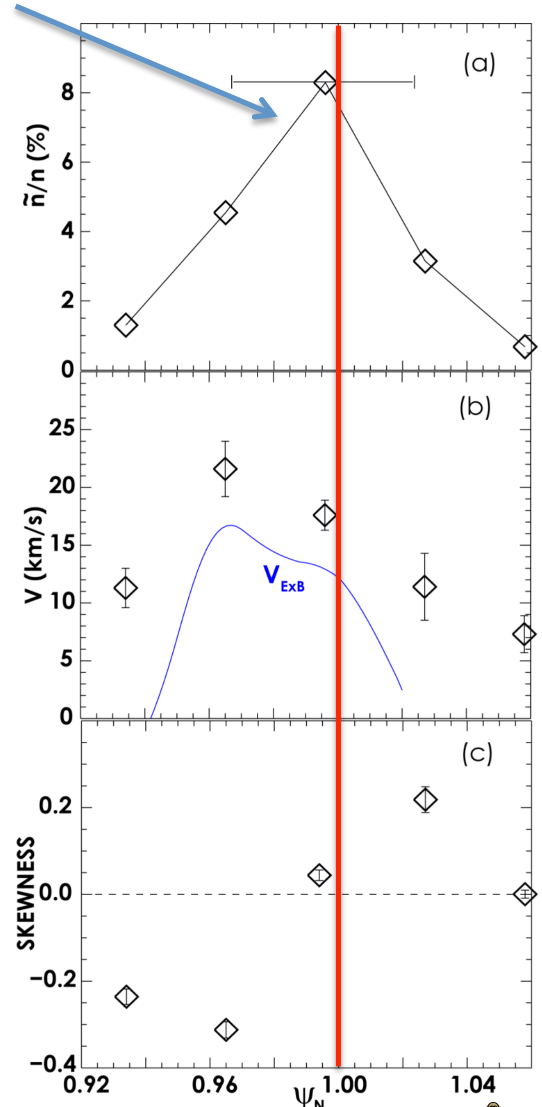




Bursty Chirping Mode has rapid frequency sweeps – makes it appear as weakly coherent

- Bursty Chirping Mode (BCM) localized near separatrix

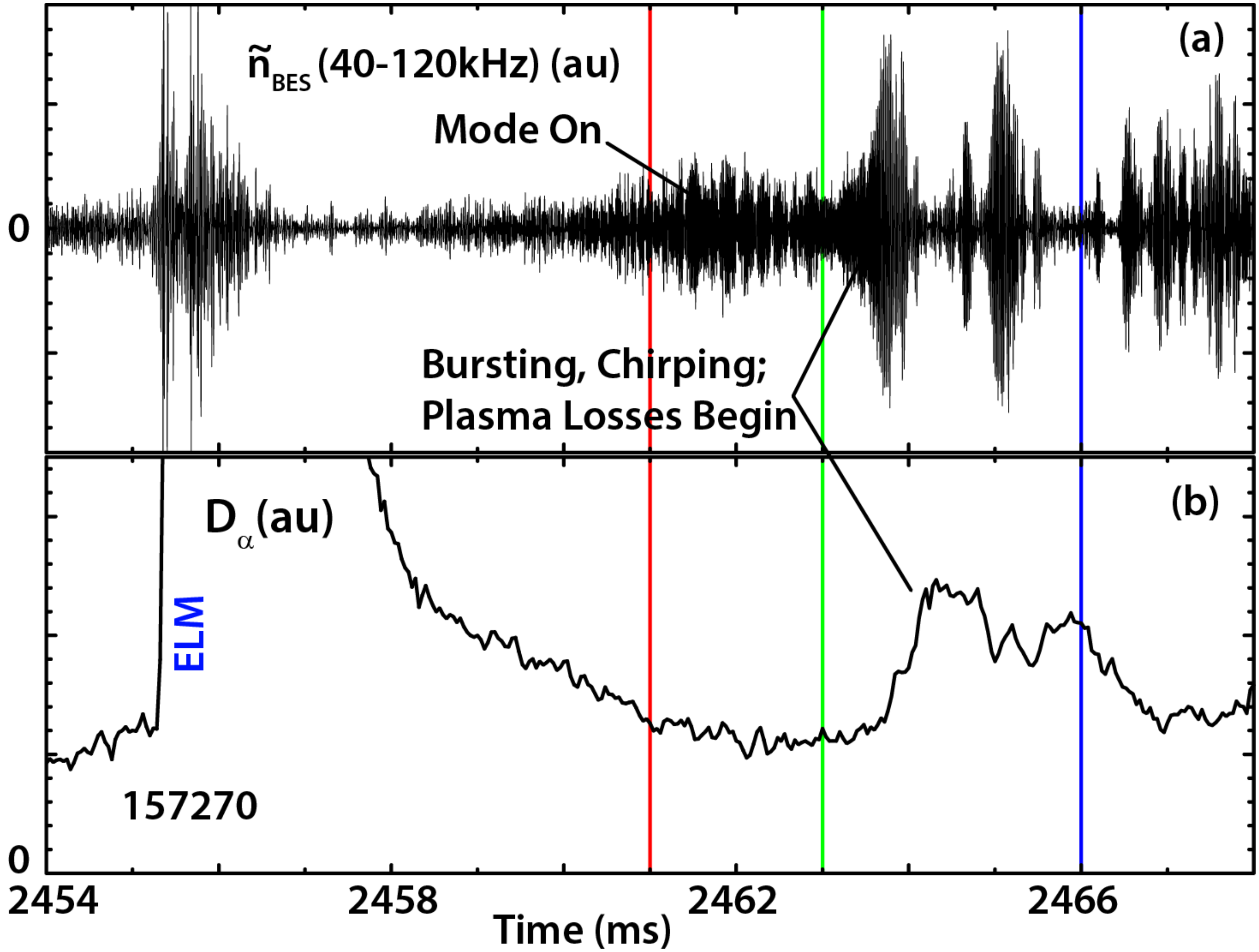




- $k_\theta \sim 0.5$, $k_\theta \rho_s \sim 0.1$-0.2
- Propagates in electron drift direction

T. Osborne, NF to be submitted

Losses from edge plasma (elevated D_α) occur only when mode amplitude bursts in time



T. Osborne, NF to be submitted

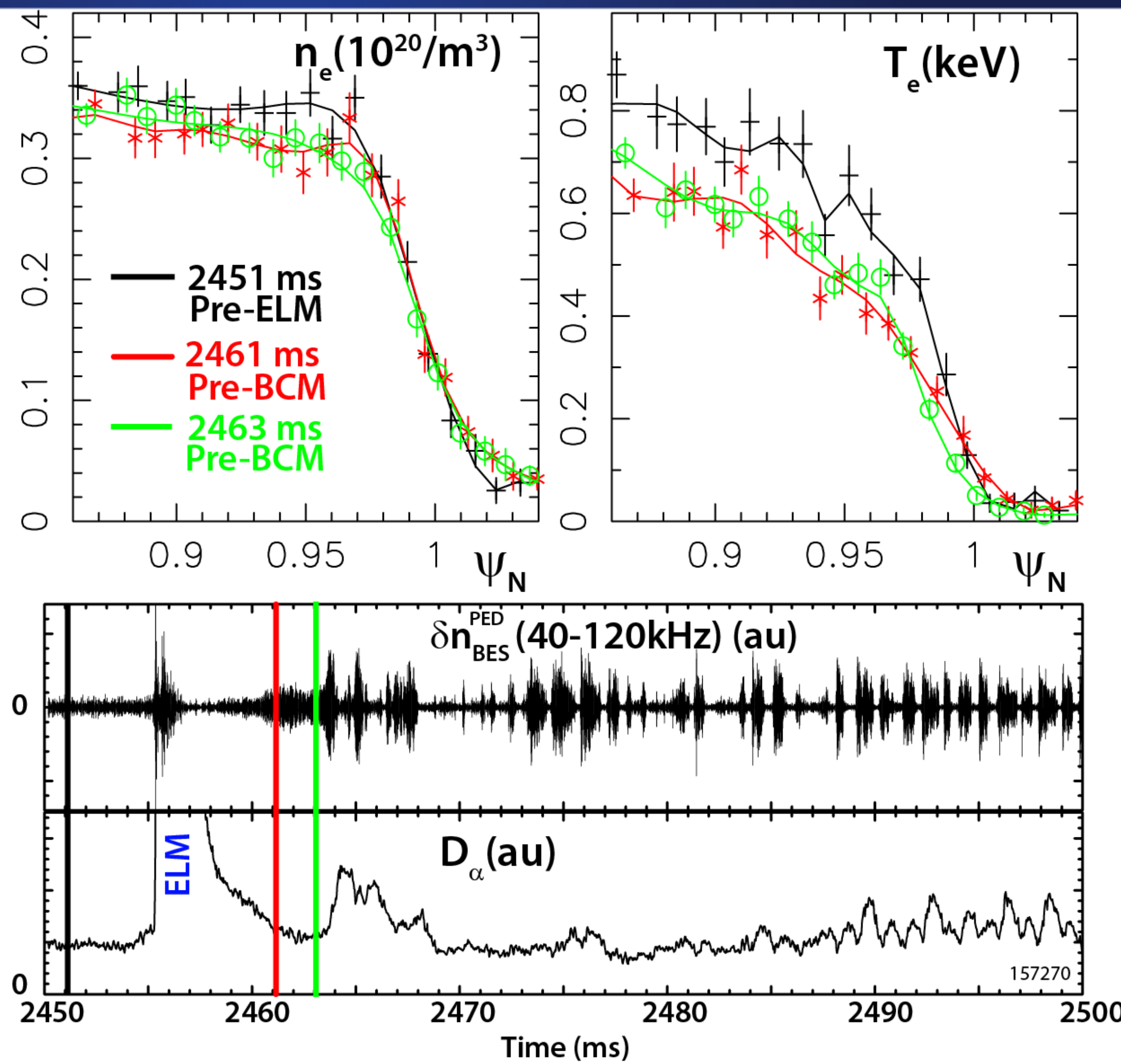
Bursty Chirping Mode alters evolution of inter-ELM pedestal profiles

- BCM results in local flattening of profiles near separatrix
  - Flattening appears at BCM turn on, 10-20ms after preceding ELM
  - Flattening most pronounced on density profile
  - Flattening remains for duration of ELM free period with BCM as pedestal expands further in from separatrix
  - Flattening goes away if BCM turns off before the end of the ELM free period, (but BCM remains on till next ELM that terminates it, in most cases)

T. Osborne, APS 2014

Density gradient quickly recovers to pre-ELM value before BCM onset

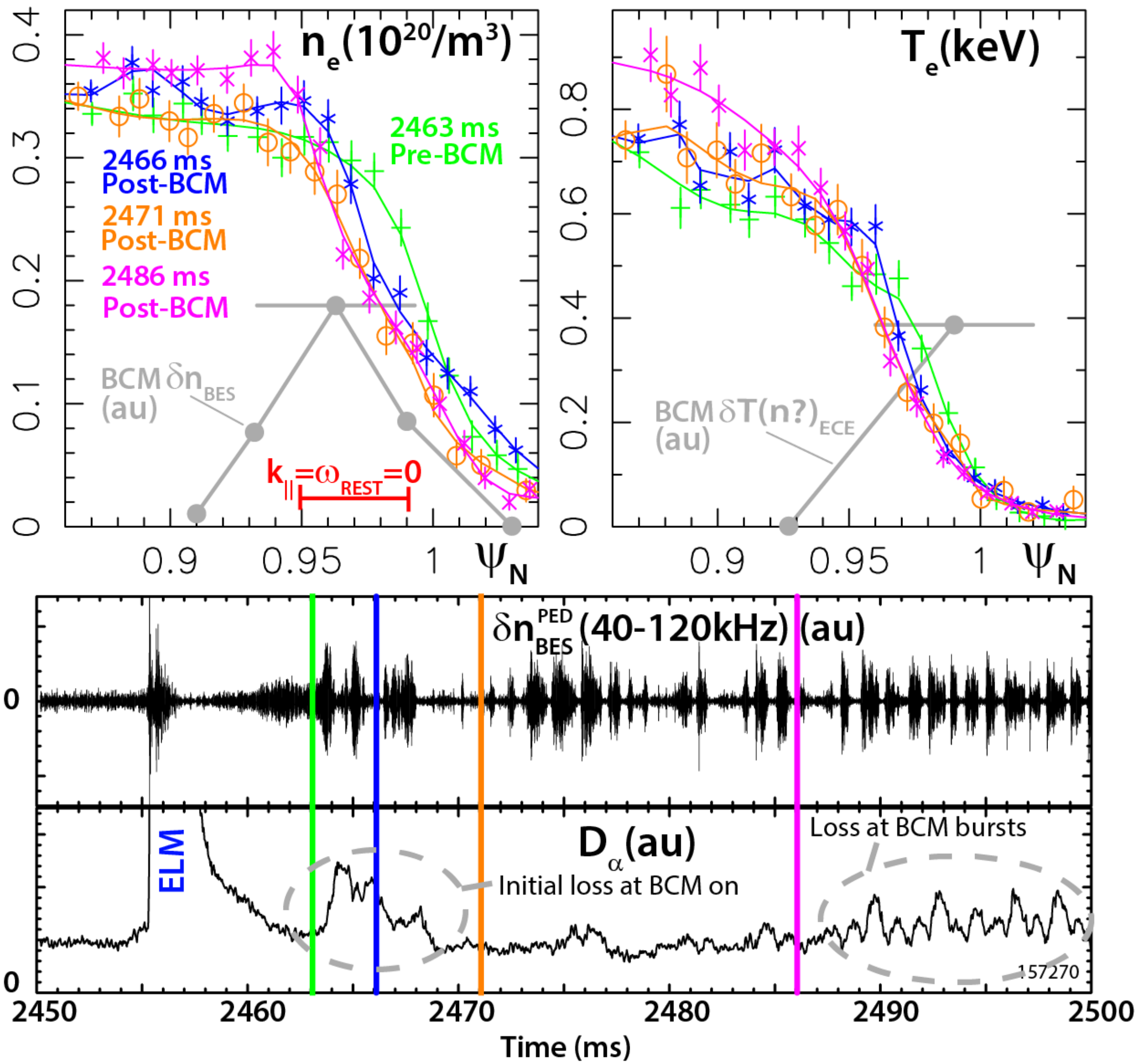
- **BCM turns on within a few ms of previous ELM**
- **n_e gradient before BCM onset quickly (<6ms) recovers to the value reached in the previous inter-ELM period without the BCM**



T. Osborne, NF to be submitted

Density gradient is reduced near separatrix at BCM onset and remains low as pedestal expands

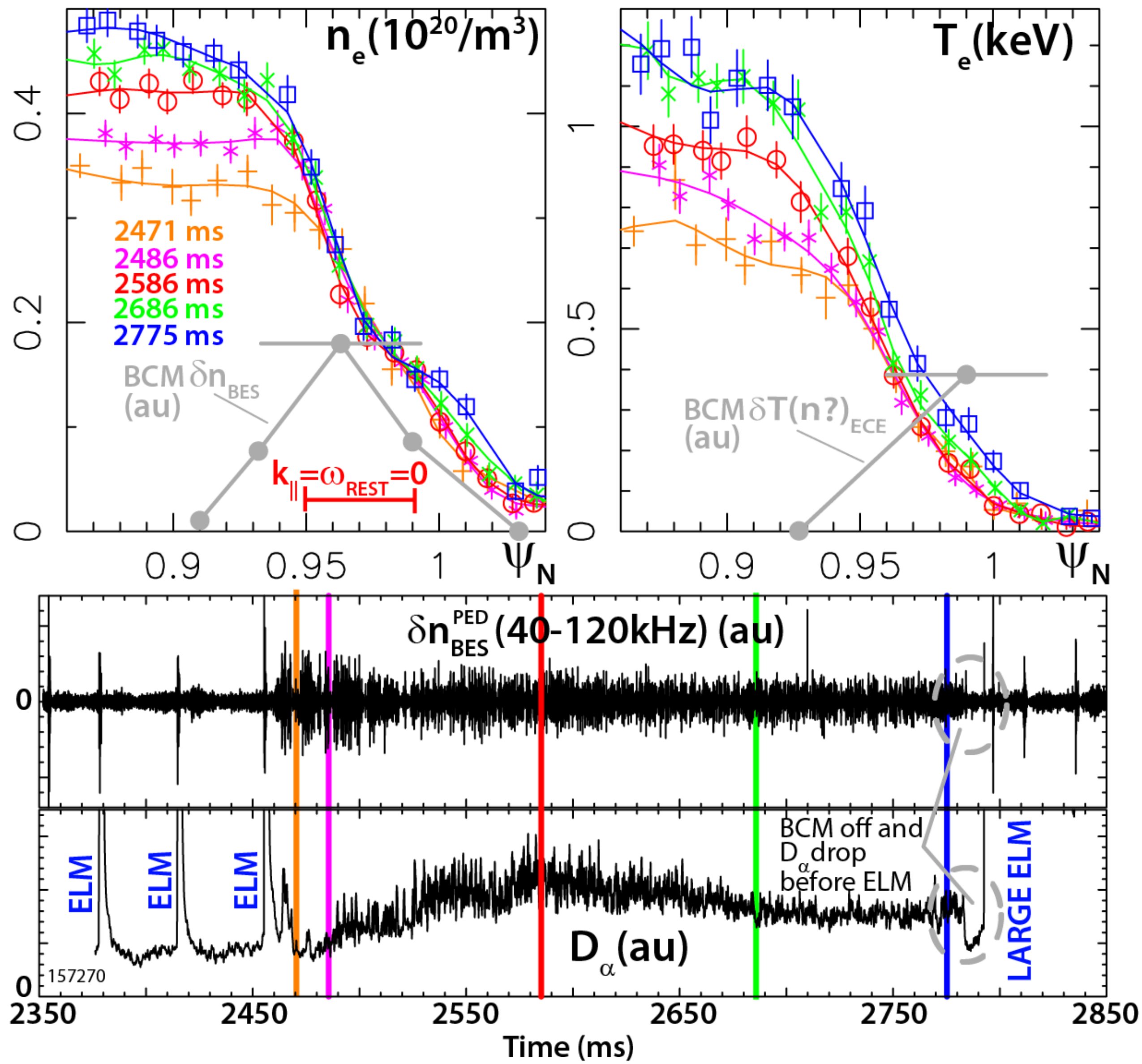
- ∇n_e rapidly (<3ms) reduced near separatrix at BCM onset ⇒ pedestal width increases
- Location of peak of BCM on BES and ECE roughly agrees with location of ∇n_e reduction
- D_α increase at BCM onset consistent with BCM driven losses
- Pedestal expands maintaining reduced gradient near separatrix
- Continued BCM bursts correspond to small D_α increases, maintains profiles?



T. Osborne, NF to be submitted

Pedestal expands and P^{PED} increases through ELM free period with BCM and Li while flat spot near separatrix remains

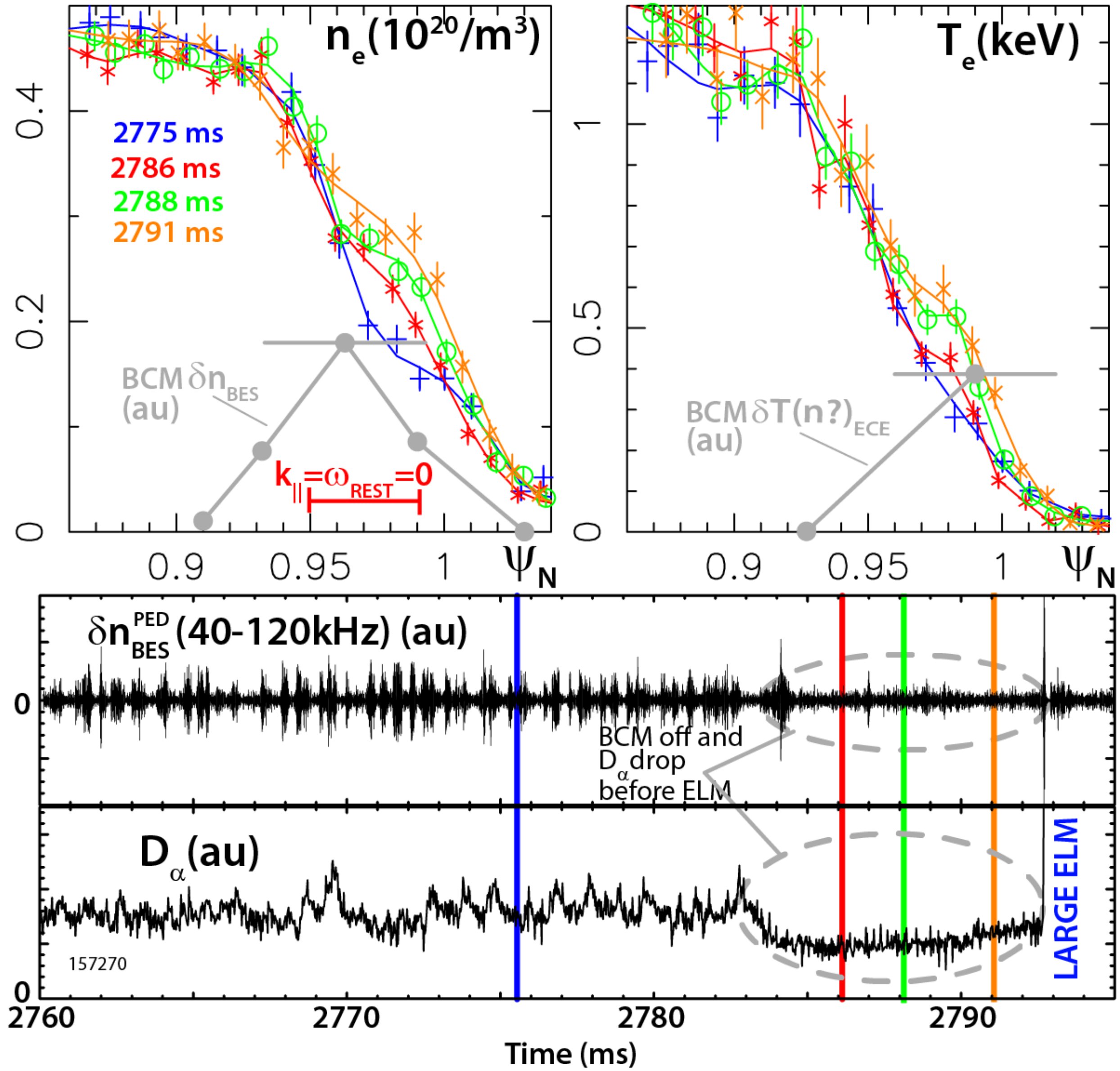
- Pedestal n_e and T_e continue to increase though ELM free phase with BCM
- A flat-spot in the n_e profile near the separatrix and peak of BCM fluctuations remains
- D_α drops before end of ELM free period, indicting a reduction in losses when BCM turns off
  - In most other cases the BCM continues until an ELM occurs



T. Osborne, NF to be submitted

When BCM ends profiles rebuild in region near separatrix before ELM

- **When BCM turns off gradients rebuild in region near separatrix consistent with radial location of the mode**
- **Neither BCM turn off nor rebuilding of the profiles near the separatrix is necessary for the ELM free phase to terminate in a large ELM**



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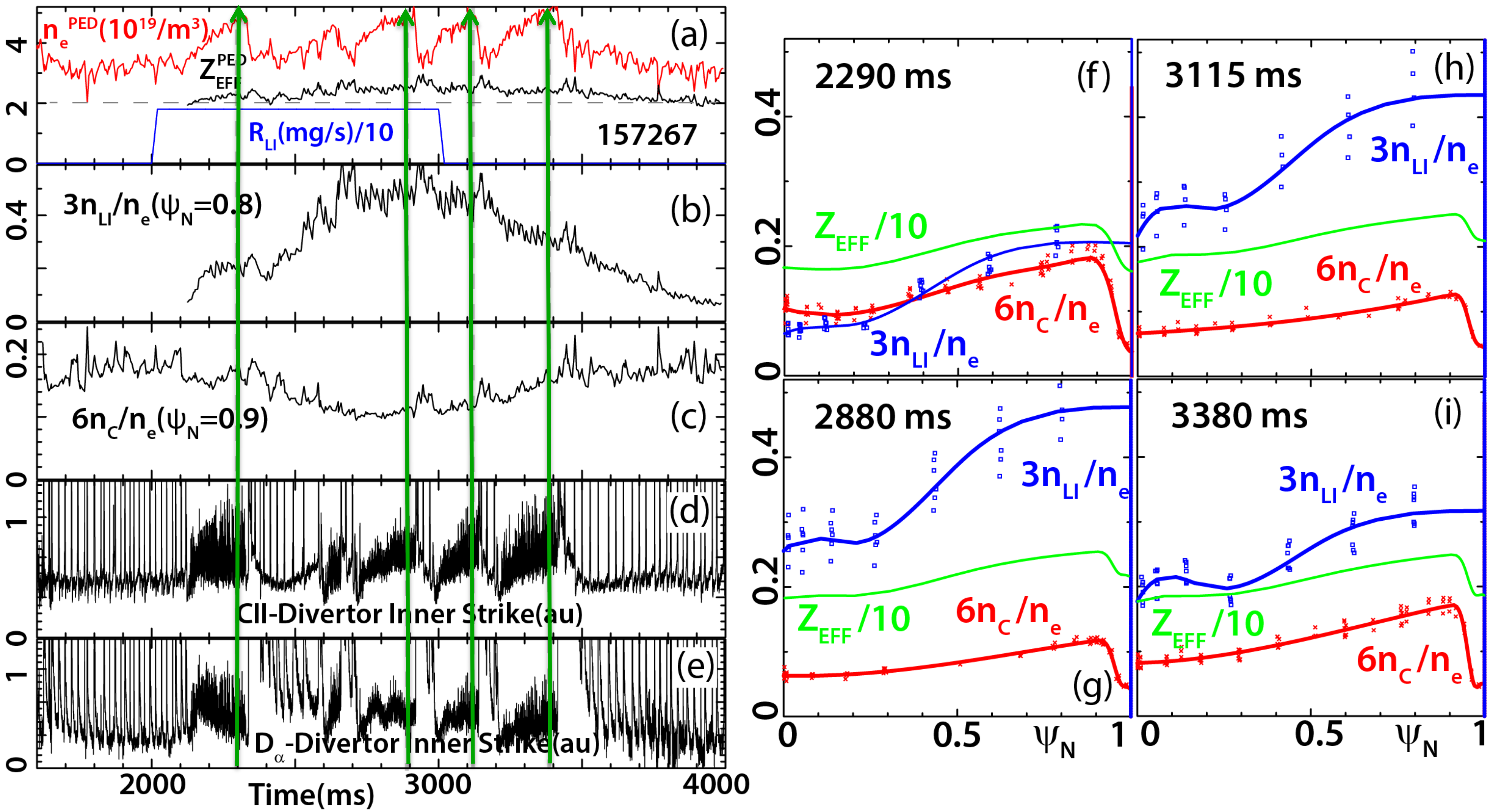
DIII-D – Edge stability calculations

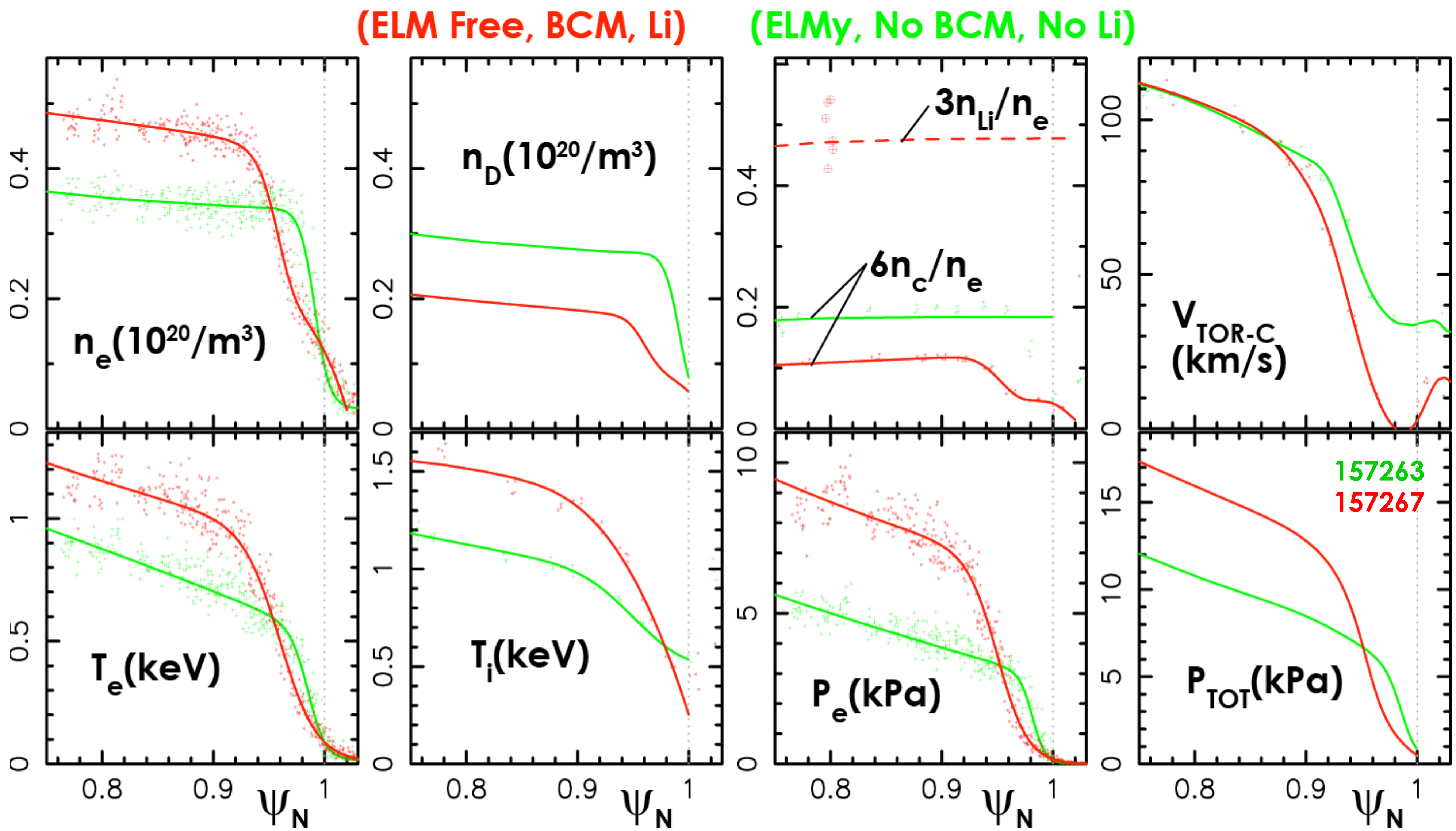
Li injection reduces carbon in the core/edge plasma



T. Osborne, NF to be submitted

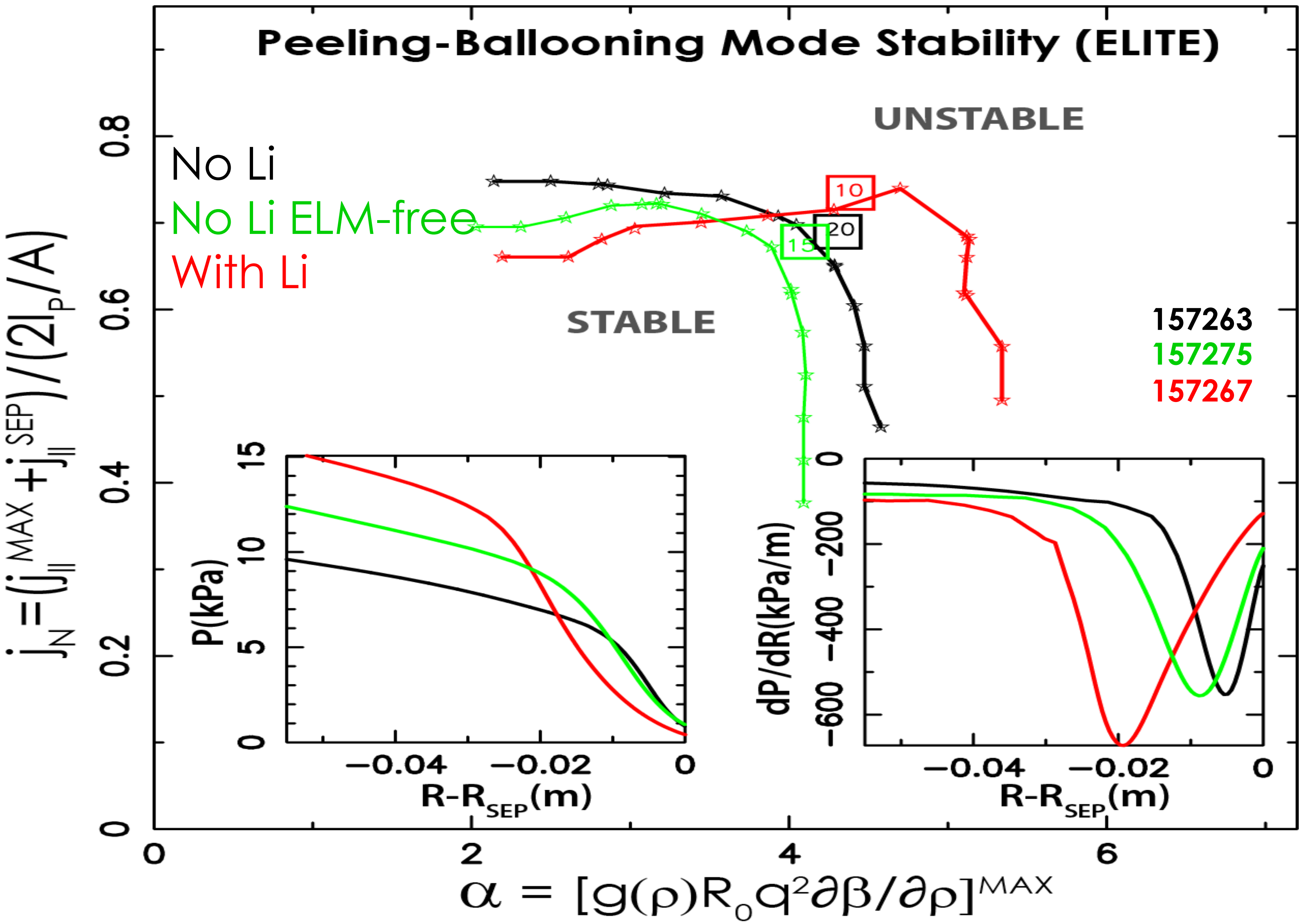
Edge profiles broaden with Li and Bursty Chirping Mode

n_{Li} high but n_C goes down



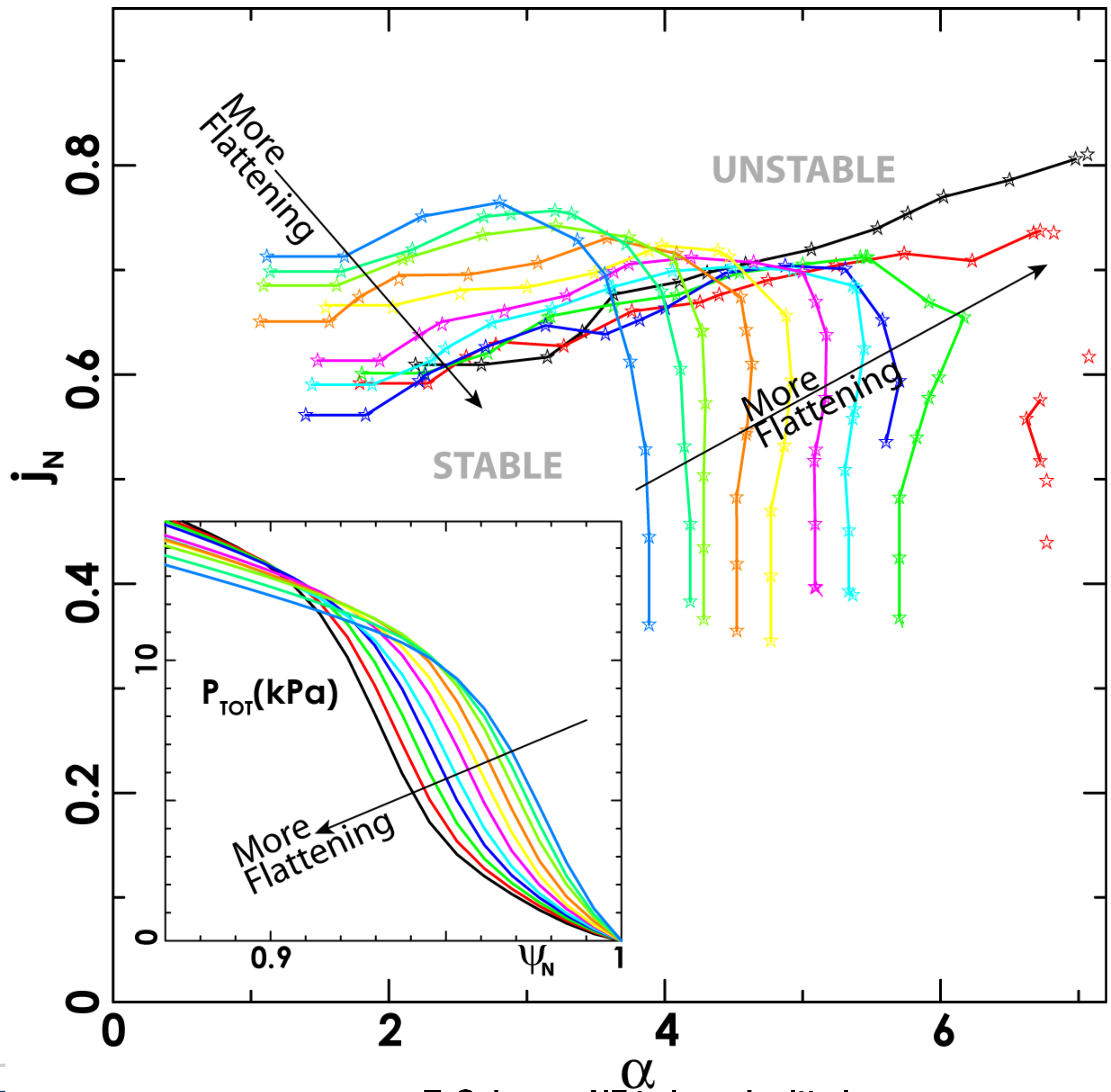
T. Osborne, NF to be submitted

Giant ELM that terminates ELM-free phase at high pedestal pressure consistent with ELITE calculations



T. Osborne, NF to be submitted

Model: profile flattening near the separatrix and rigid shifts inward increase (reduce) ballooning (kink/peeling) stability



T. Osborne, NF to be submitted

Steps and roles to ELM-free H-mode with Li Injection and Stimulated Bursty Chirping Mode

BCM without Lithium (in <10% of natural ELM cycles)

BCM turns on, and pedestal widths increase rapidly → Profiles flatten from $0.98<\Psi_N<1$ → ELM cycle is slightly extended; <30 msec → Next ELM kills BCM

BCM with Lithium injection

Li injection stimulates BCM more frequently → *WHY?*

Li too low ↓

ELM cycle unchanged; next ELM kills BCM

→ Optimal Li injection delays ELM in presence of BCM, initiating long EF period

→ Ped. widths increase; top goes up steadily

High n_{Li} in pedestal, Z_{eff} higher, n_C lower

→ Giant ELM occurs at (very high) ideal limit with wide pedestals and high n_{Li}, high Z_{eff}, low n_c → *HOW TO STOP JUST BEFORE CRASH?*

Li injection in DIII-D, compared with NSTX & EAST

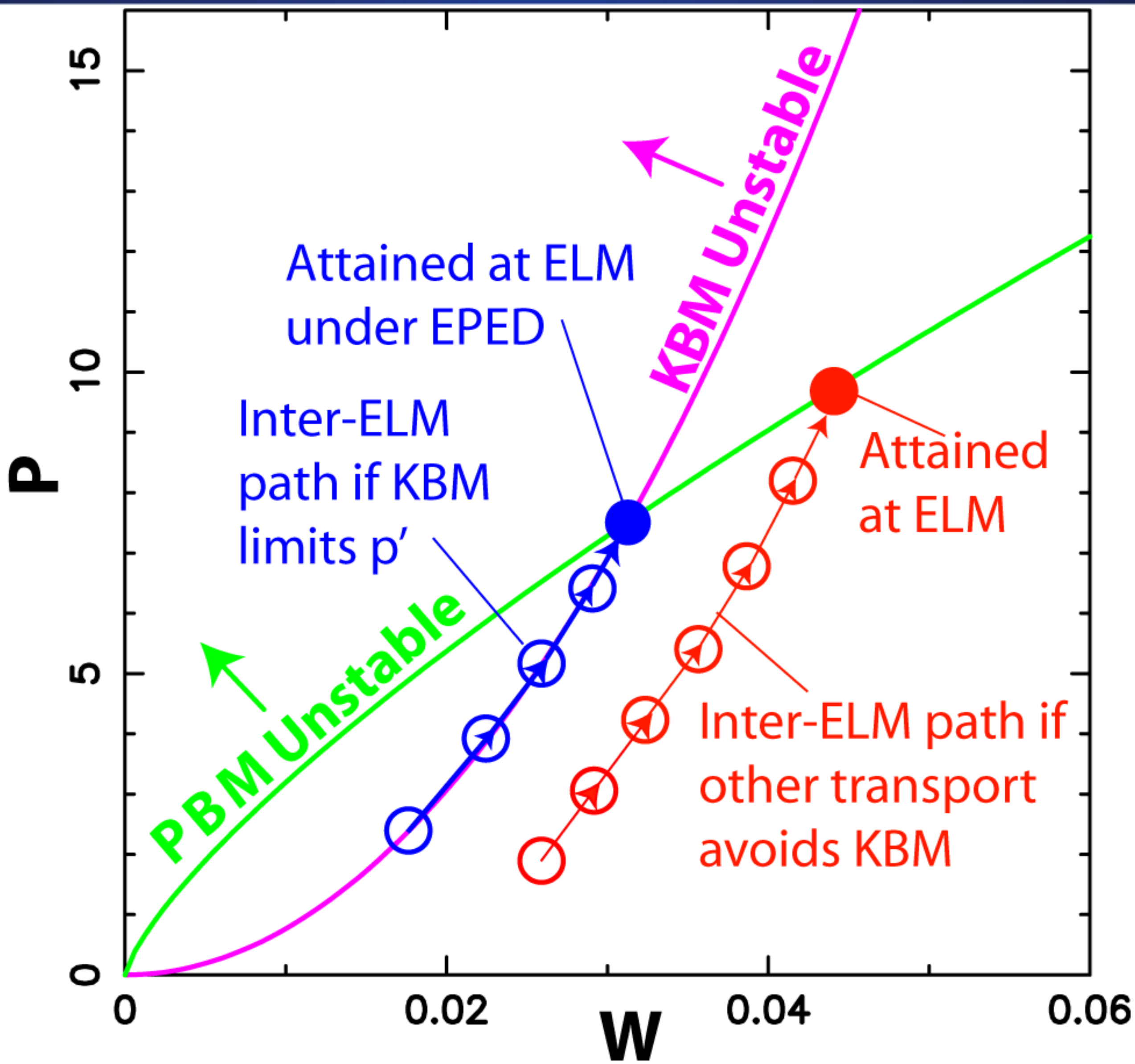
	DIII-D	NSTX	EAST
Delivery method	Dropper	Inter-shot evaporation, (Dropper)	Dropper, (Morning evaporation)
Pedestal Width	**Increased**	**Increased**	**?**
Pedestal Height	**Increased**	**Increased**	**?**
H-factor	**Increased**	**Increased**	**Unchanged**
Edge fluctuations	**Increased**	**Decreased**	**Increased**
Radiated power	**Steady during EF**	**Ramp during EF**	**Steady during EF**
Effect on ELMs	**Delayed**	**Eliminated**	**Eliminated**
Recycling	**Unchanged**	**Reduced**	**Reduced**

Li injection into discharges with pre-existing separatrix localized fluctuations can alter pedestal and confinement characteristics

- 'Bursty Chirping Mode' alters pedestal profiles, by flattening the gradients near the separatrix
- Li injection into discharges with the BCM delays the ELM that would have terminated the BCM, leading to long ELM-free periods with improved confinement and controlled radiation
- Combination of profile flattening near separatrix and ion dilution in edge lead to synergistic enhancement of pedestal
- No reduction in recycling observed – because of 'low' levels of Li used? Is this a special facet of the dropper delivery of Li? (also seen in EAST)
- Future work: understand more about conditions/dynamics of BCM and also how to extend results by avoiding giant ELM

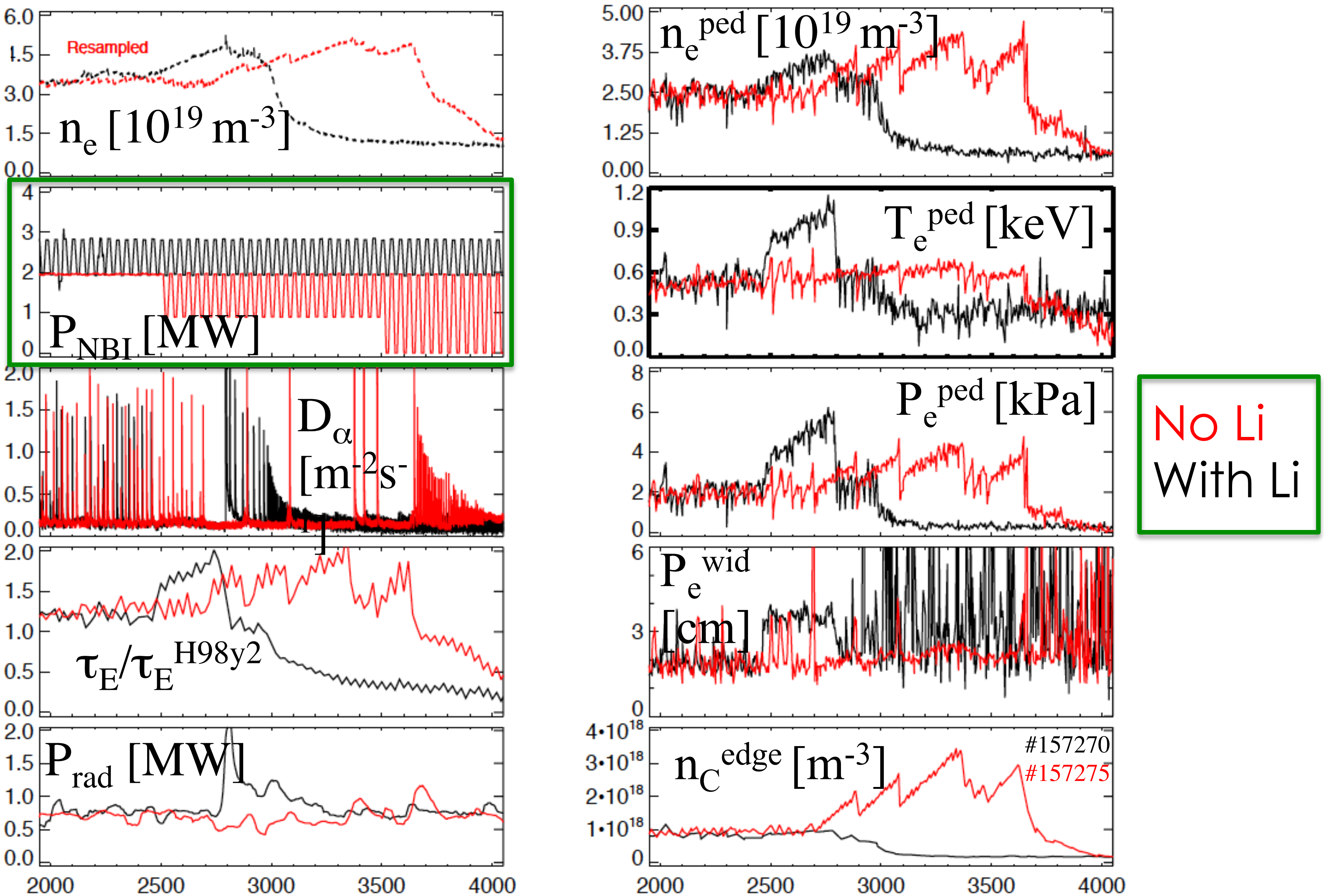
Backup

Pedestal height can increase if transport faster than predicted via kinetic ballooning



T. Osborne, NF to be submitted

Li-enhanced H-mode differs from ordinary ELM-free H-mode: T_e^{ped} increased, n_C did not accumulate



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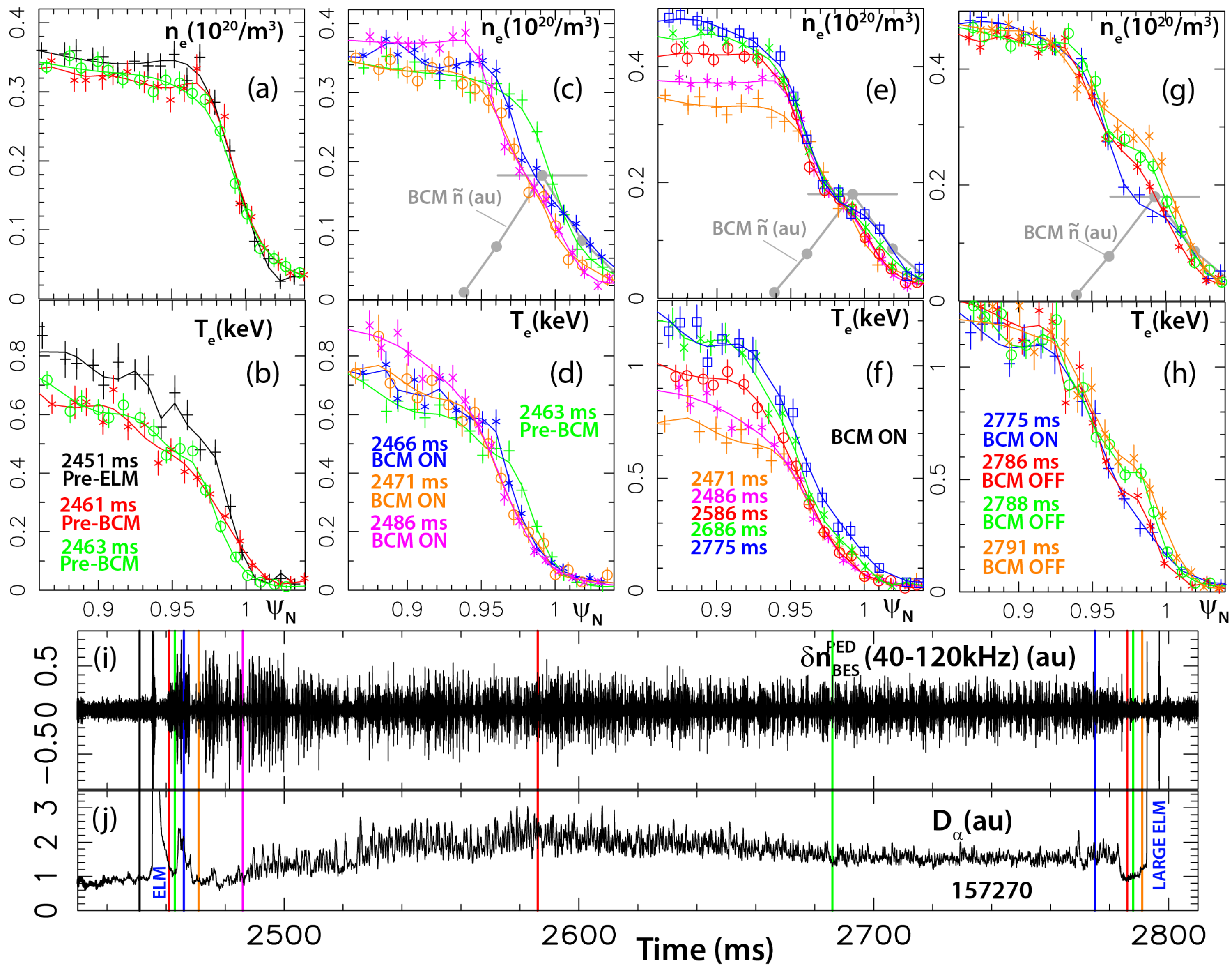

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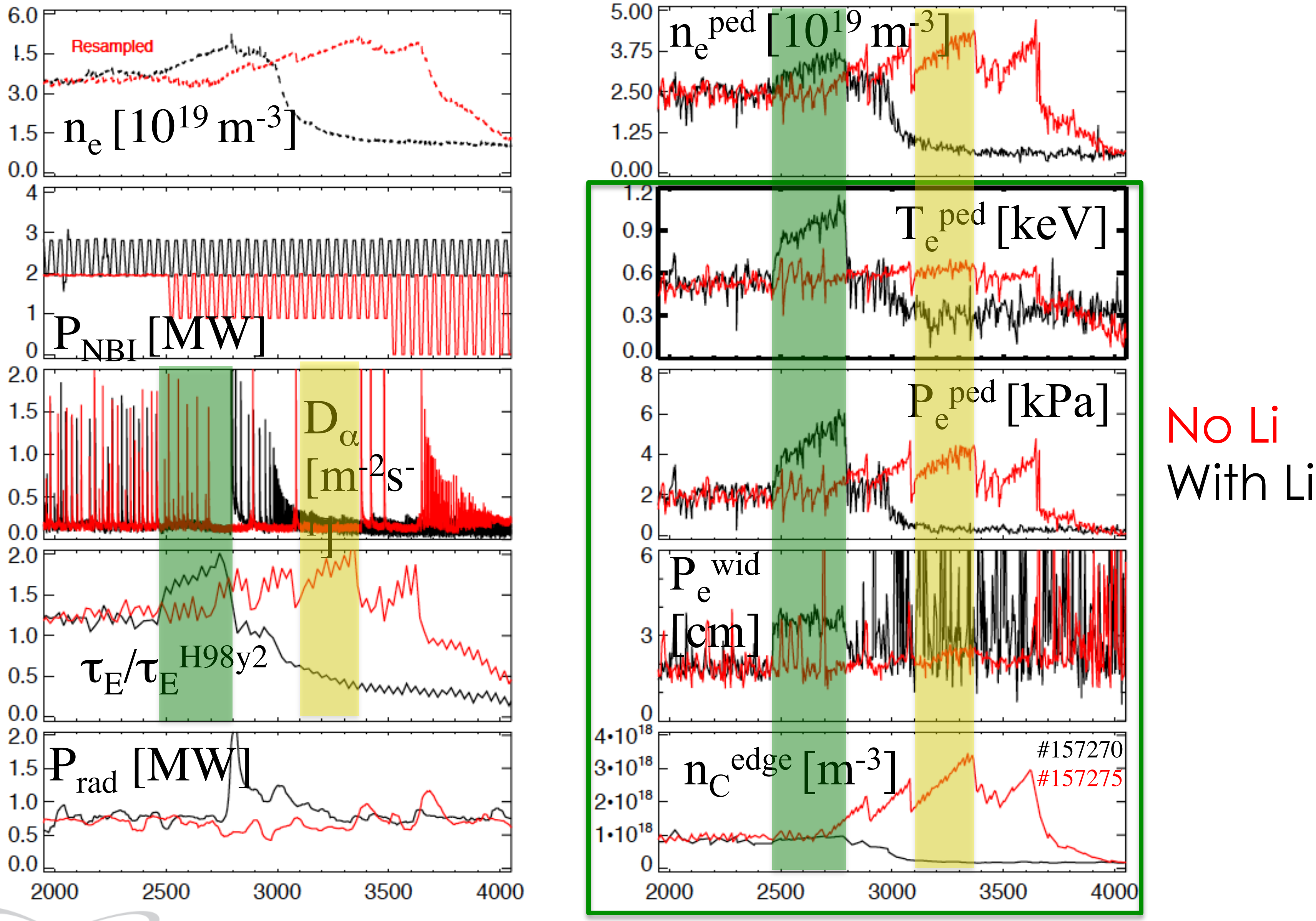

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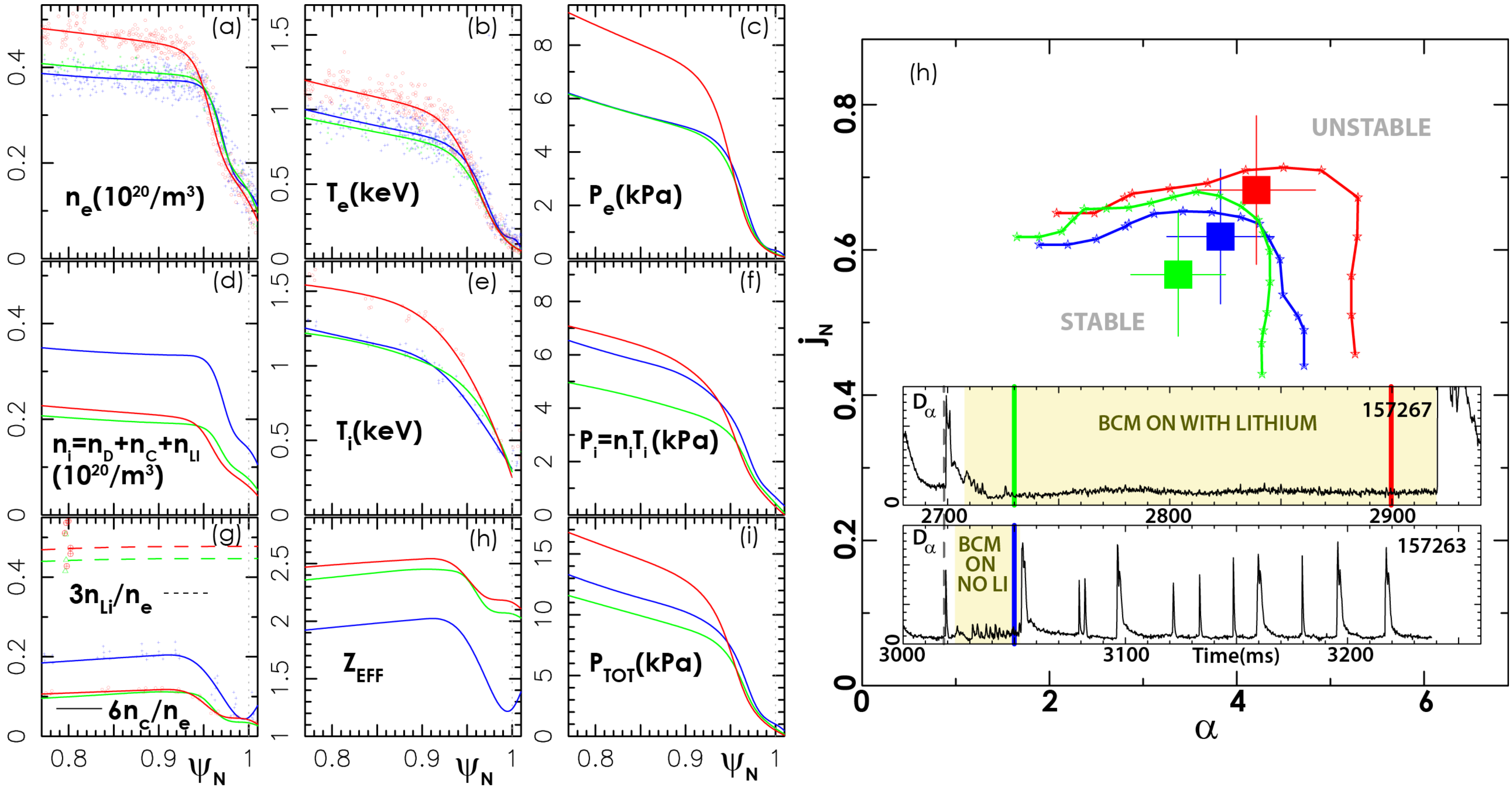


T. Osborne, NF to be submitted

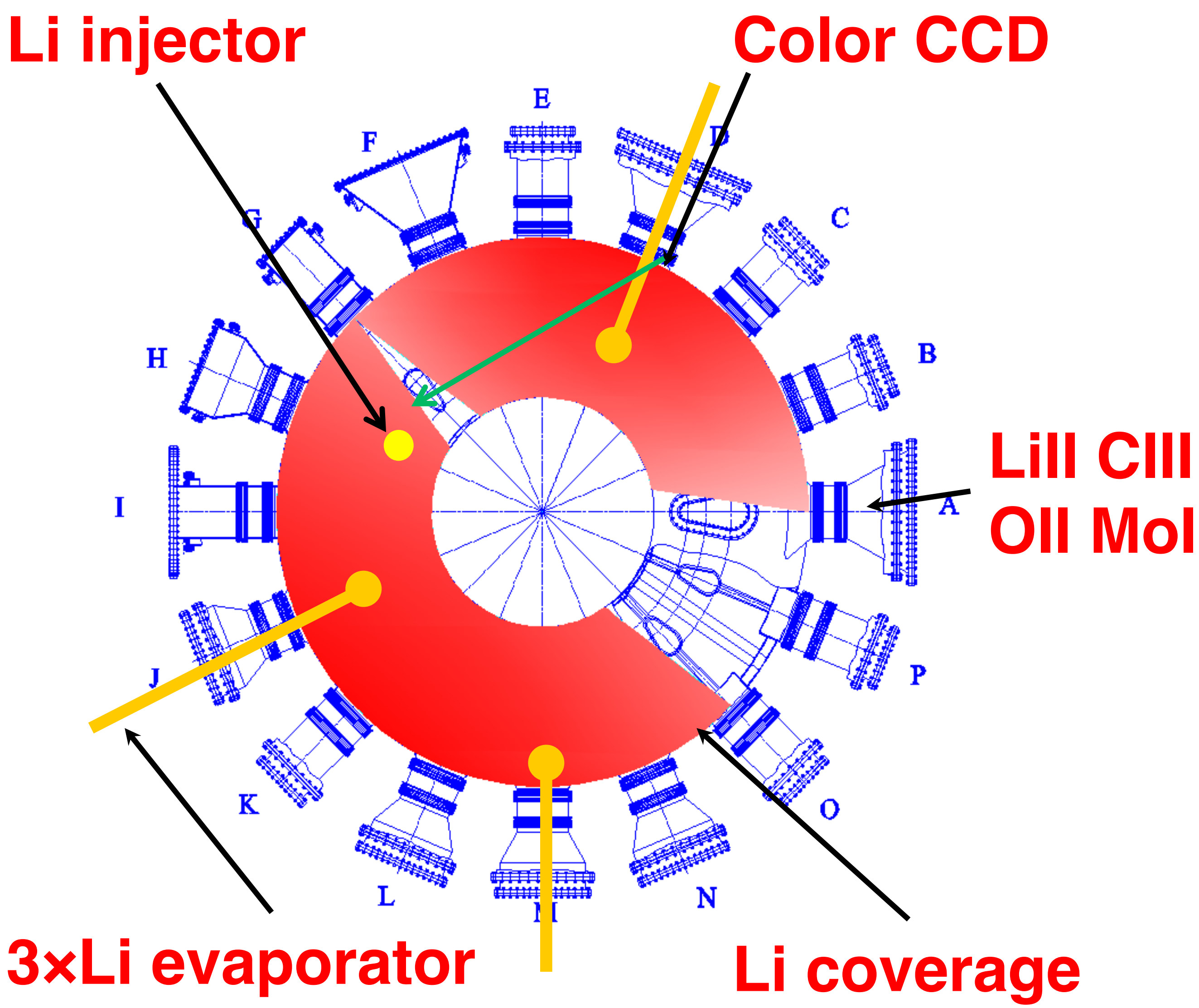
EAST

Real-time conditioning with Li injector eliminated ELMs in 24 sec long H-mode discharges in EAST

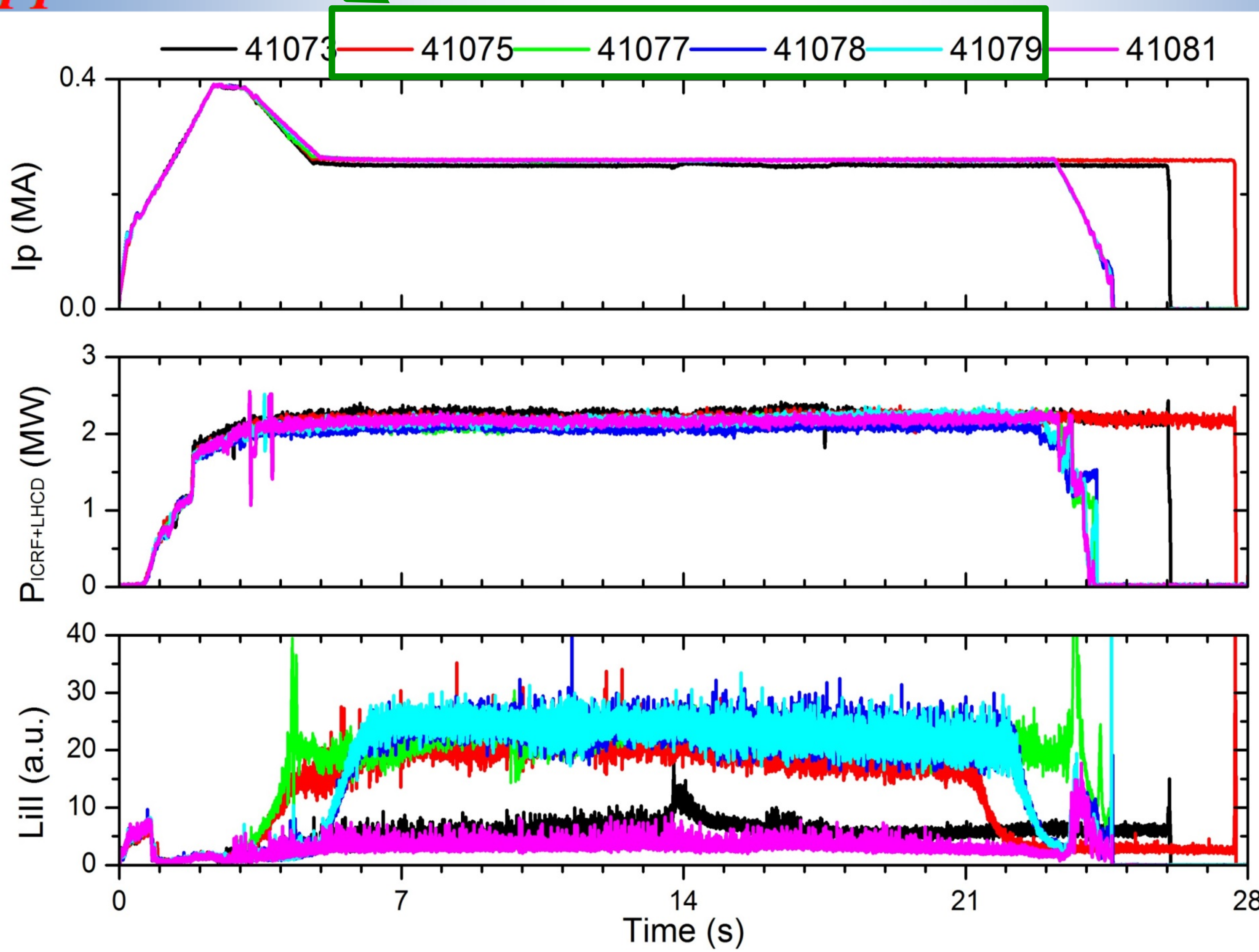
ASIPP

- Large quantities (20-40g) of Li typically evaporated in morning before start of experiments
  - As Li wears off, real-time conditioning with Li dropper used
- Global characteristics changed with real-time Li conditioning
  - Recycling: D_α declined by 10-30% in all measured views
  - ELMs eliminated, but with steady P_{rad}, density
  - Edge Coherent Mode appeared
  - Energy confinement (τ_E, H-factor) steady at H98=0.75-0.8
- Hypothesis: Edge Coherent Mode provides particle transport that changes the edge gradients and eliminates ELMs
  - New profile measurements and stability analysis forthcoming

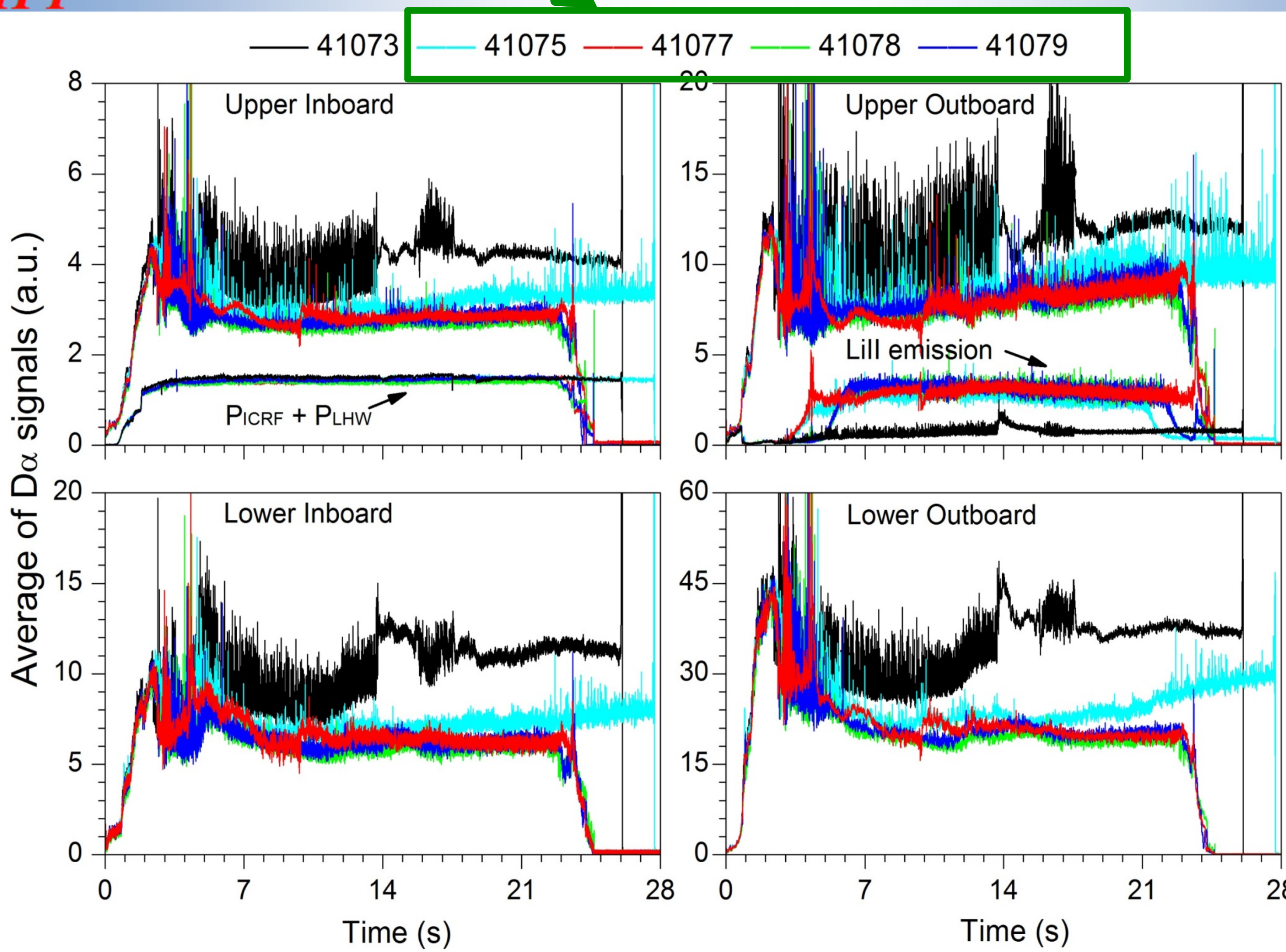
Li evaporators used for morning conditioning in EAST; Li injector used for real-time conditioning



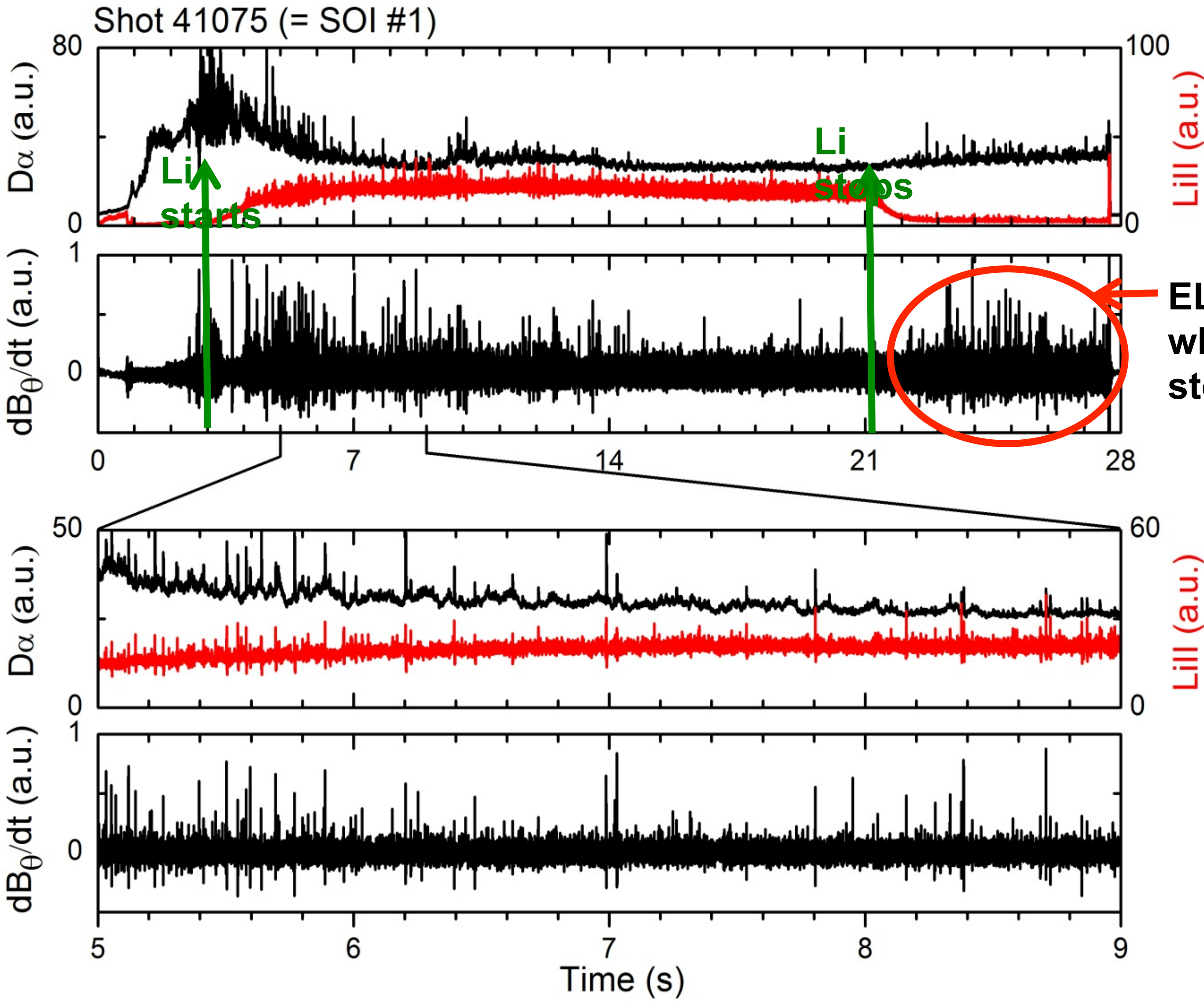
Li injector used for four contemporaneous discharges (41075-41079) in EAST



Recycling dropped in nearly all divertor legs with real time Li injection in EAST (41075-41079)

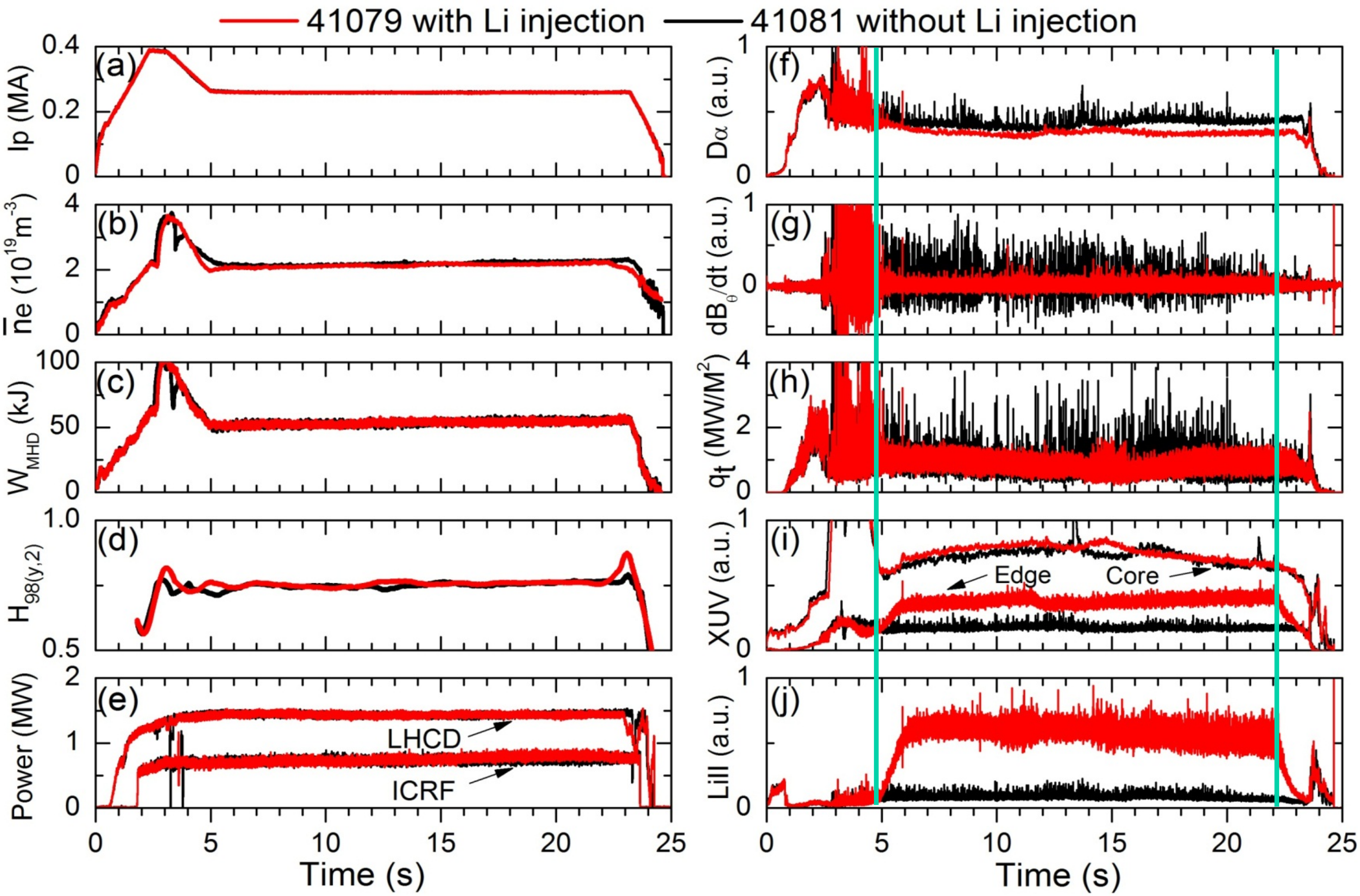


ELM frequency drop correlated with Li injection (first Li shot in sequence) in EAST; elimination required several sec

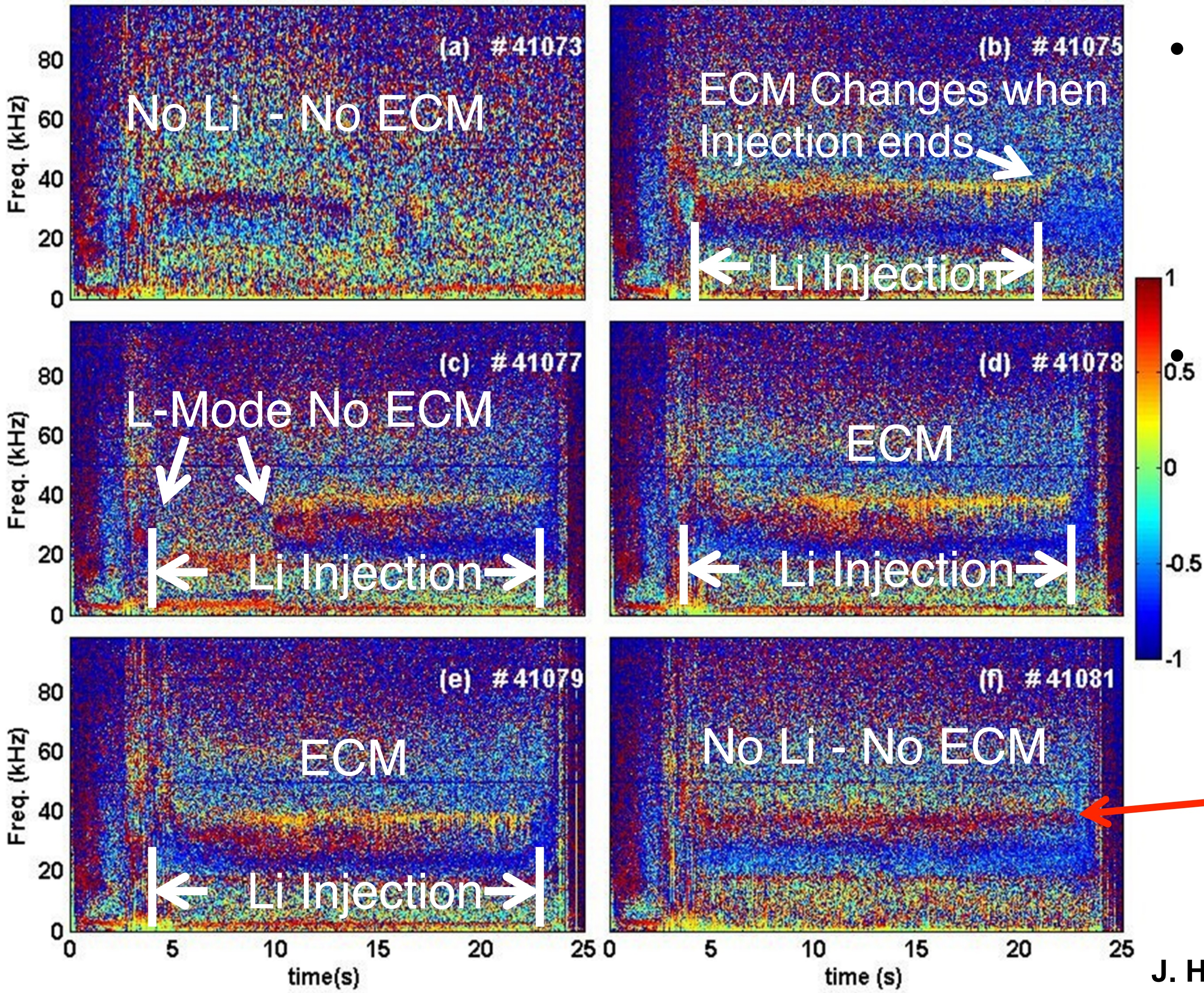


ELMS return when Li stopped!

Radiated power and density remained steady during H-mode with eliminated ELMs in EAST



Edge coherent mode (ECM) turned on with Lithium injection (and correlated ELM elimination) in EAST



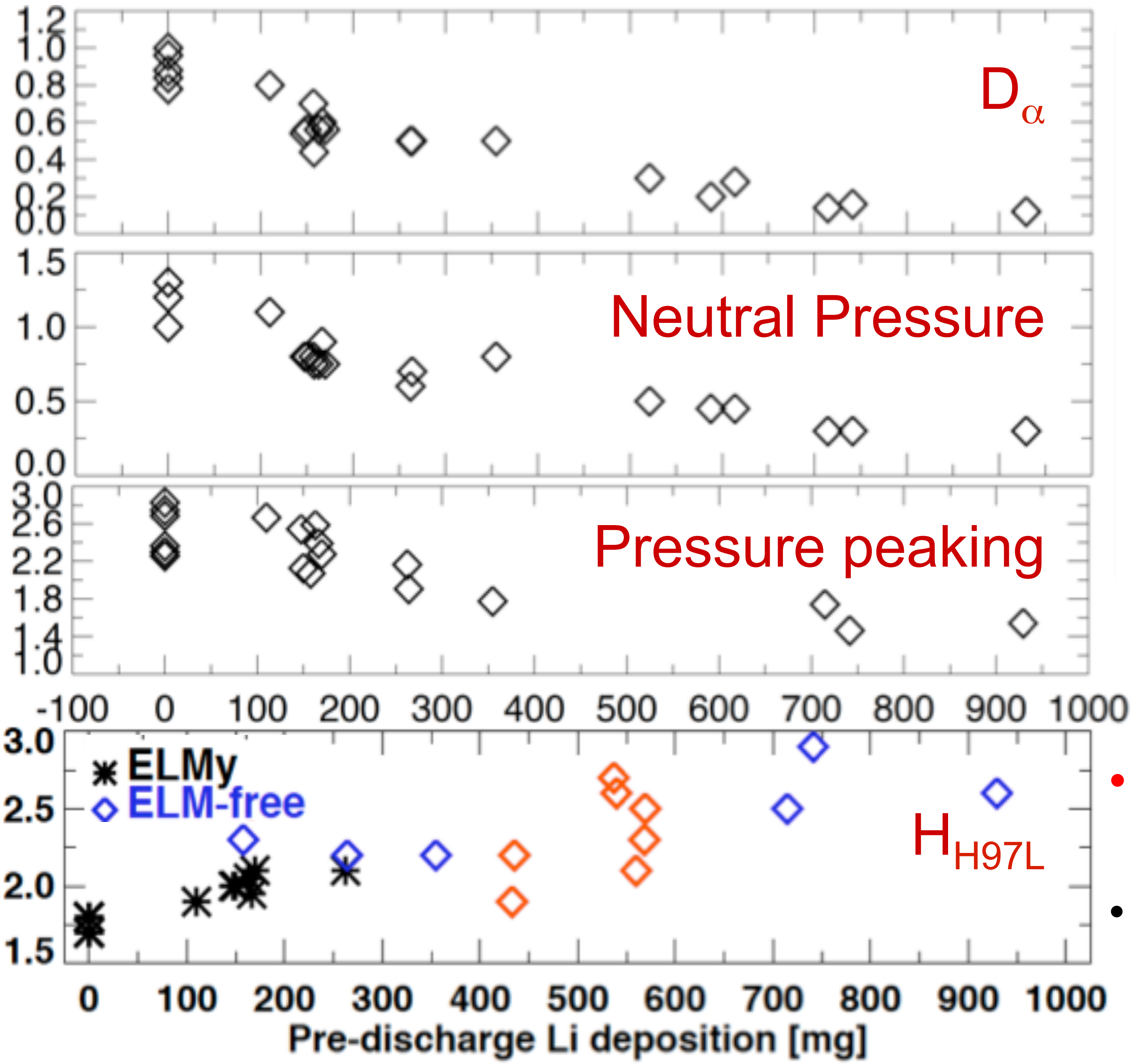
- ECM thought to augment particle transport, which prevents impurity accumulation
- (Data from Mirnov coils)

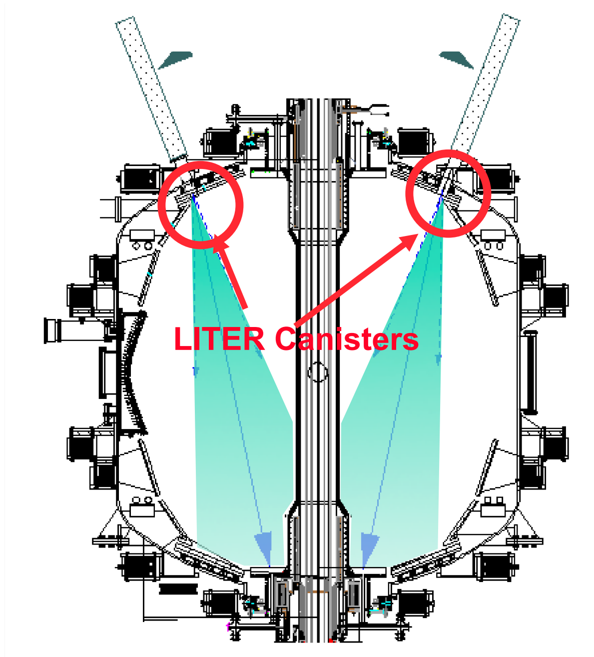
Mode in red color at same frequency as ECM but different poloidal structure

J. Hu, PSI 2014, submitted to PRL

NSTX

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

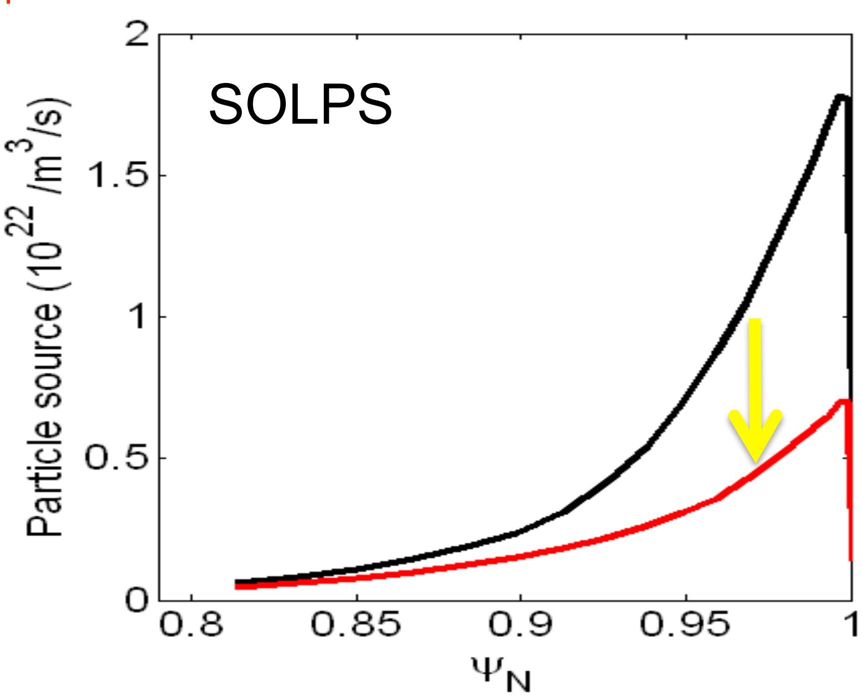


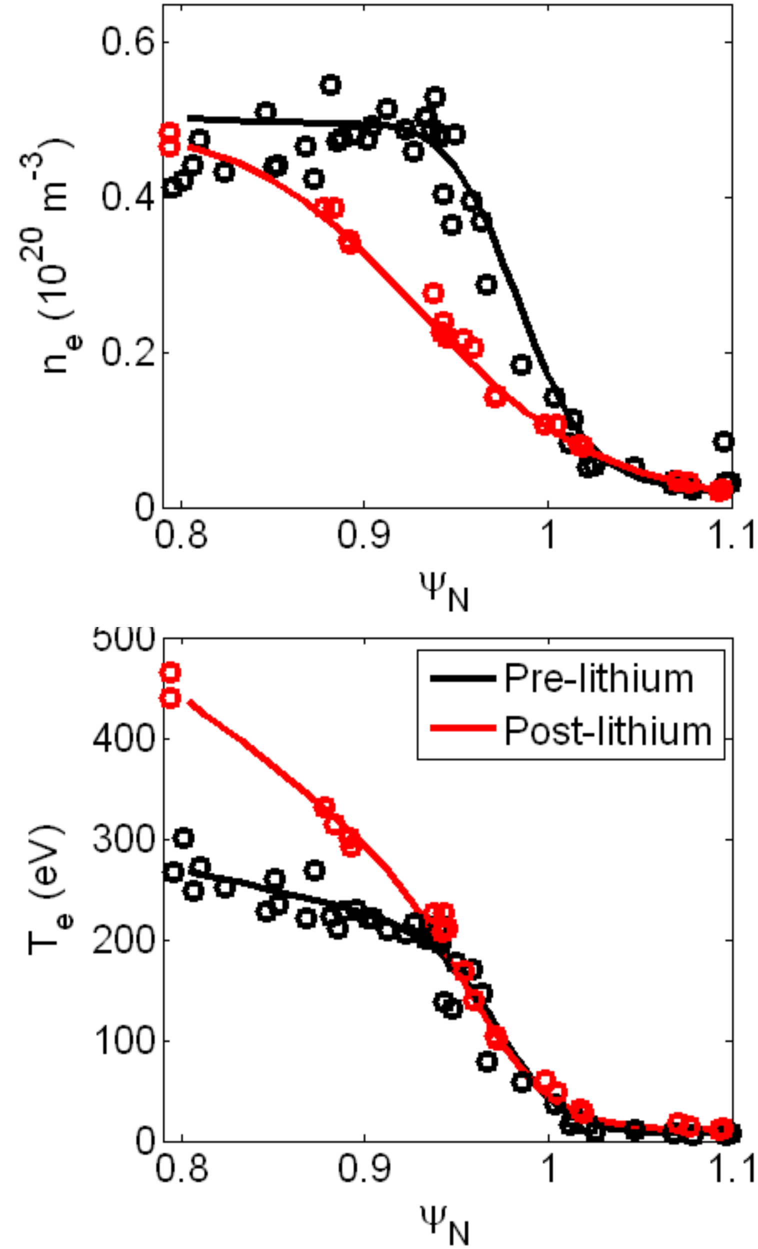


- **H_{H98y2} range from 0.8-1.4**
- Data in orange from other experiment

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

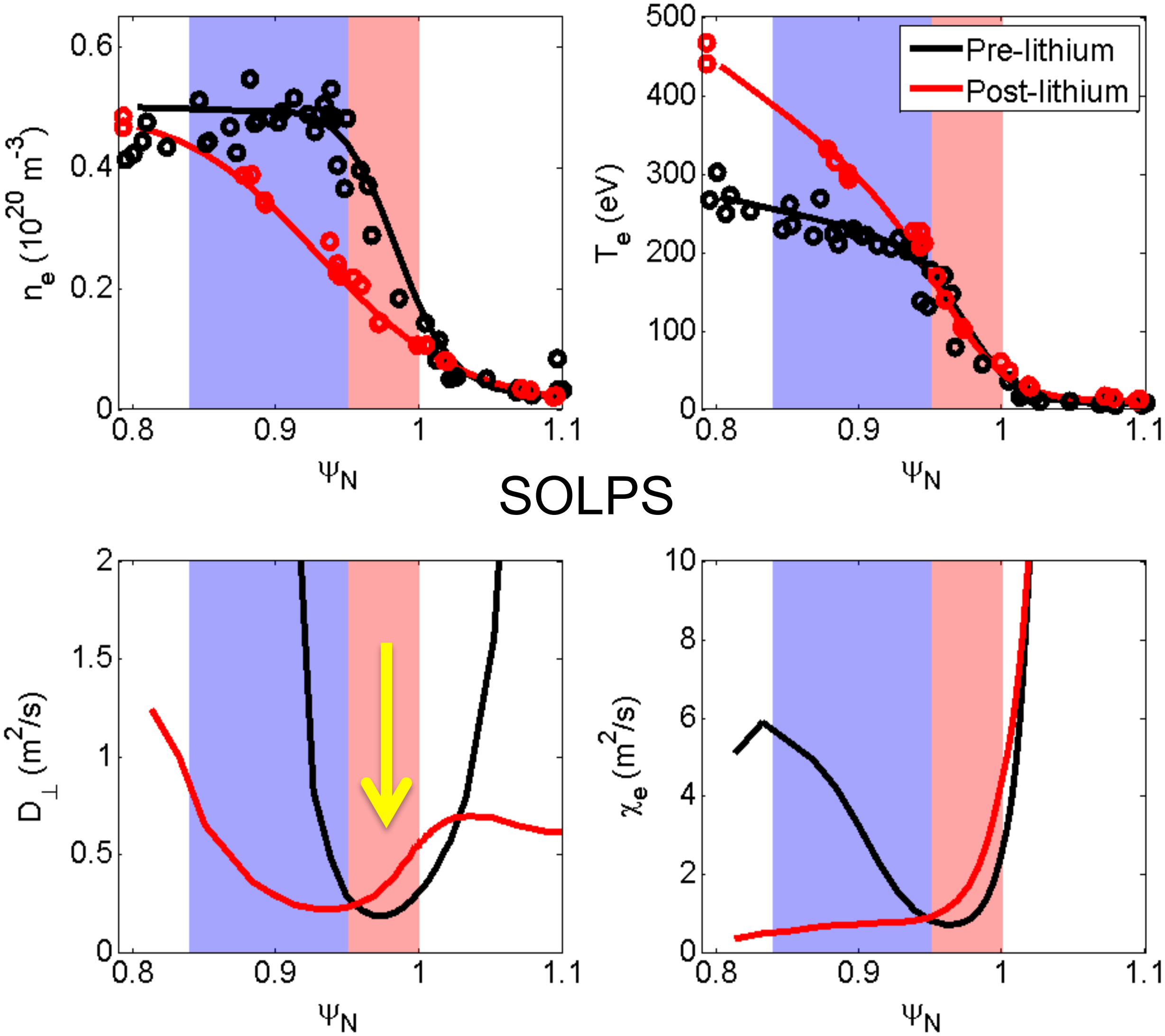




Recycling and edge transport changes interpreted with SOLPS simulations

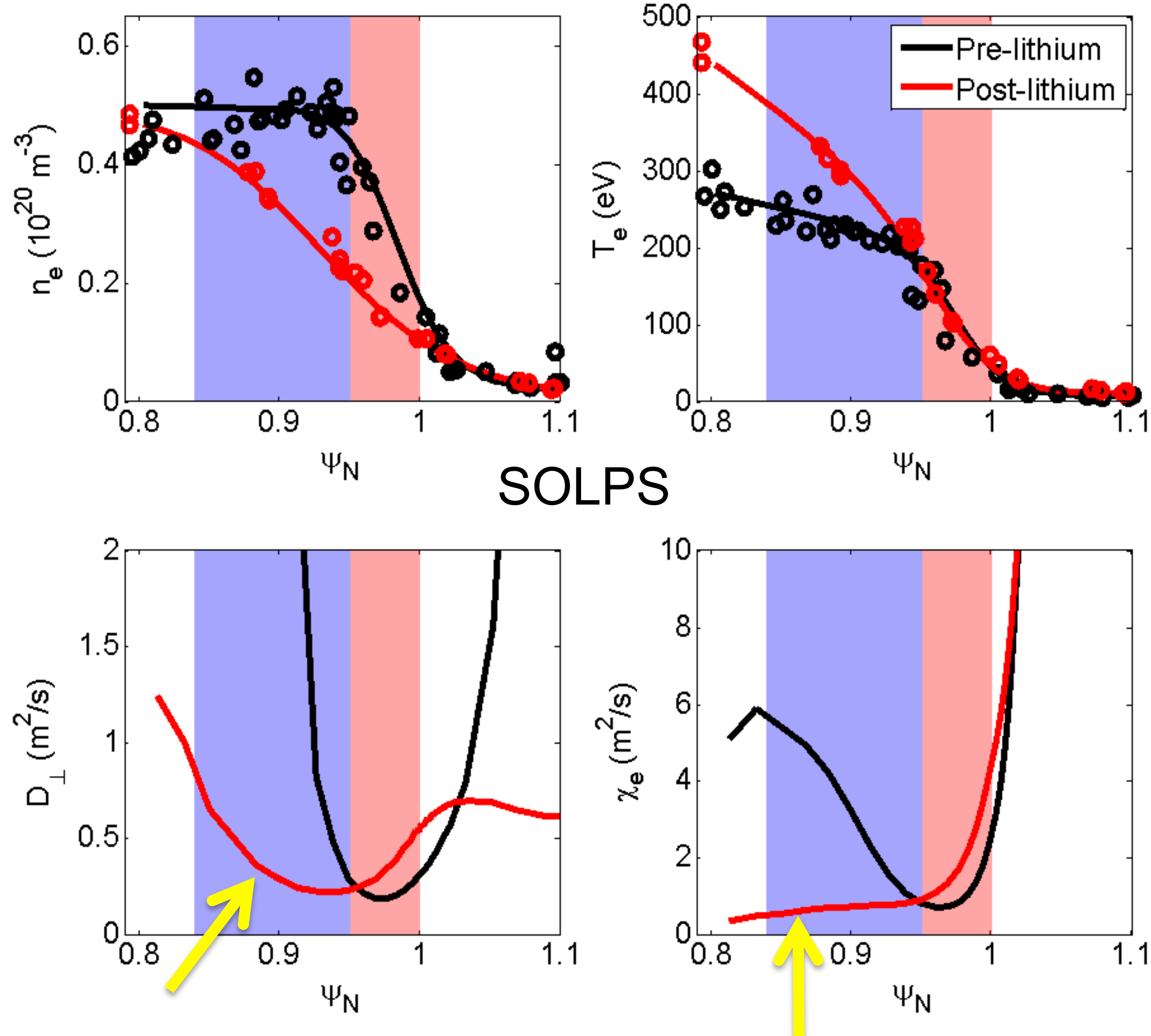
- Pre-lithium case shows typical barrier region inside separatrix
- Change in n_e profile with lithium from $0.95<\psi_N<1$ consistent with drop in fueling at ~ constant transport

(red shaded region)



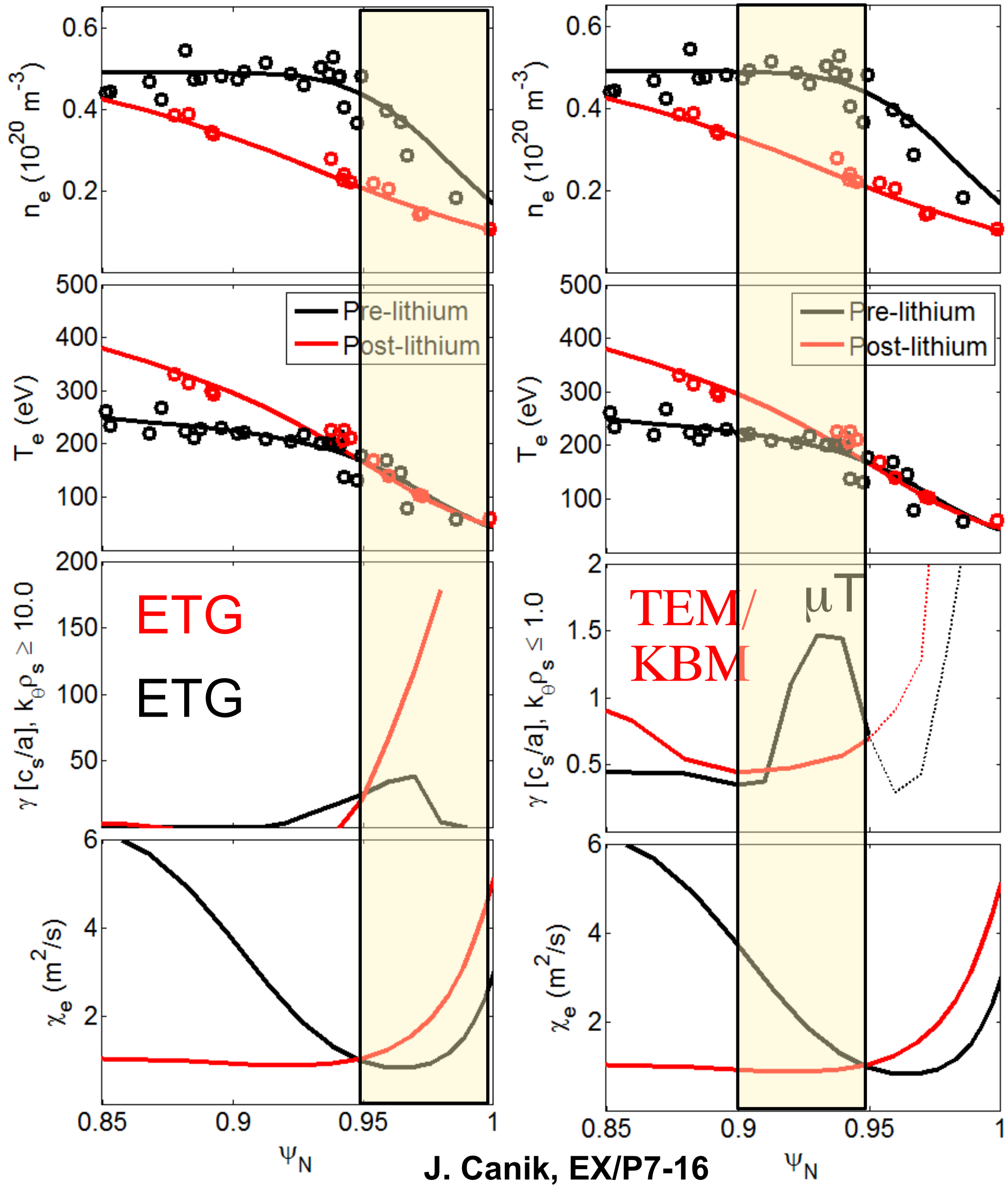
Recycling and edge transport changes interpreted with SOLPS simulations

- 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)



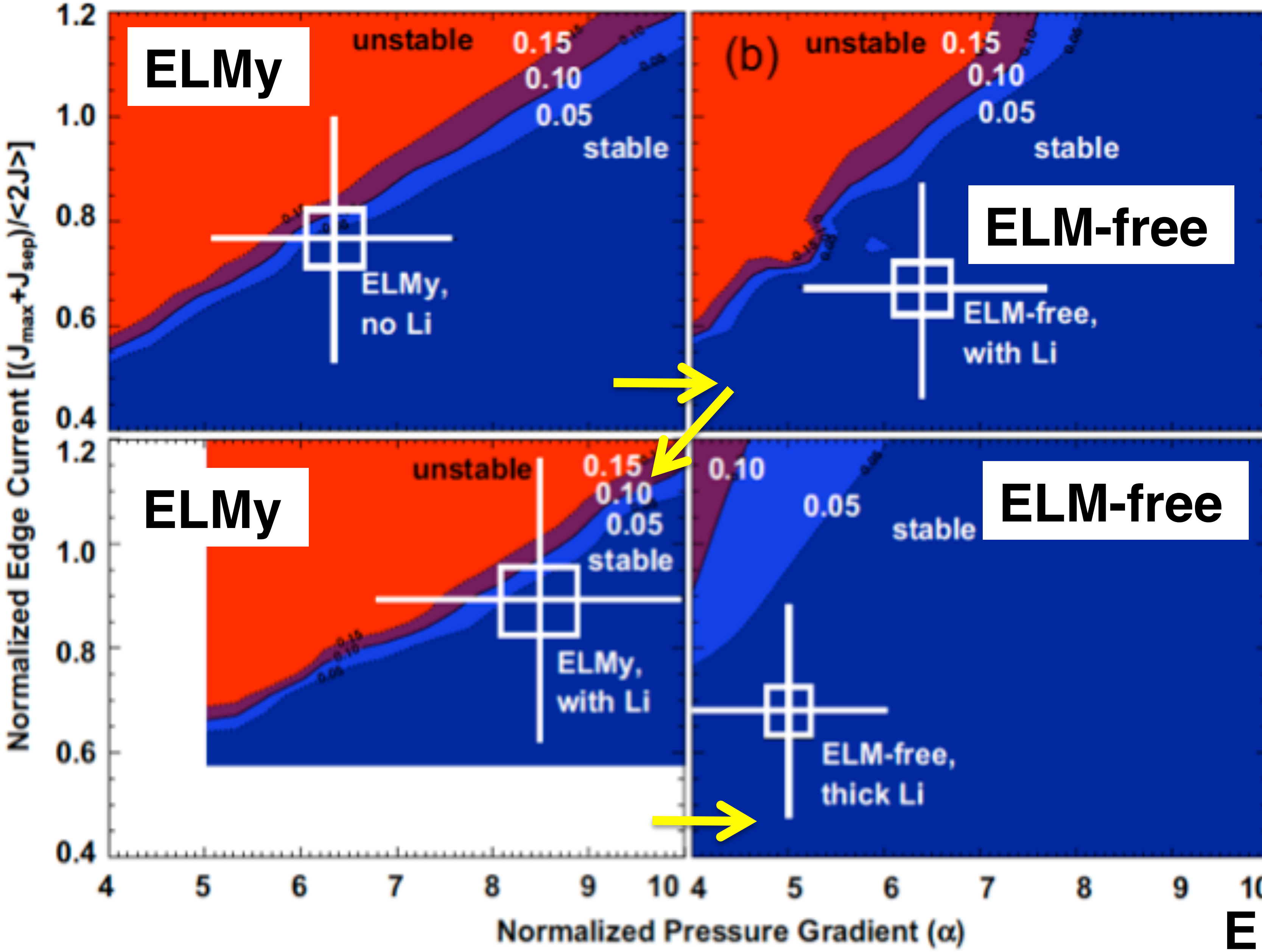
Work in progress: change in edge density gradient with lithium coatings alters the edge micro-stability properties

- 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, EX/P7-16

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



ELITE

What is the role of lithium in NSTX ELM suppression? 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)

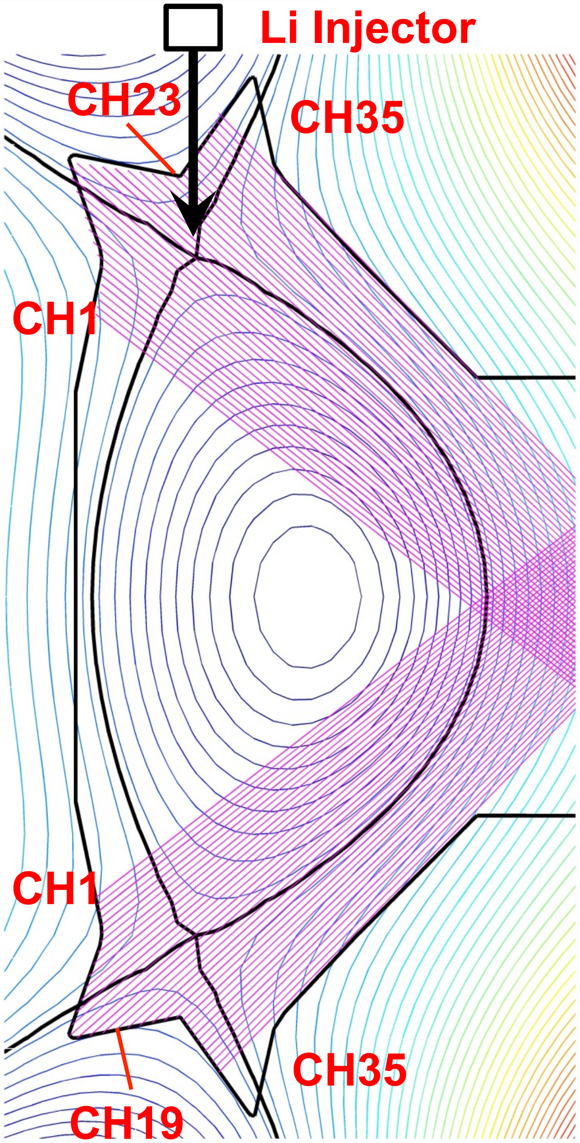
→ Edge P_e follows n_e and T_e; peak P' shifts farther from separatrix

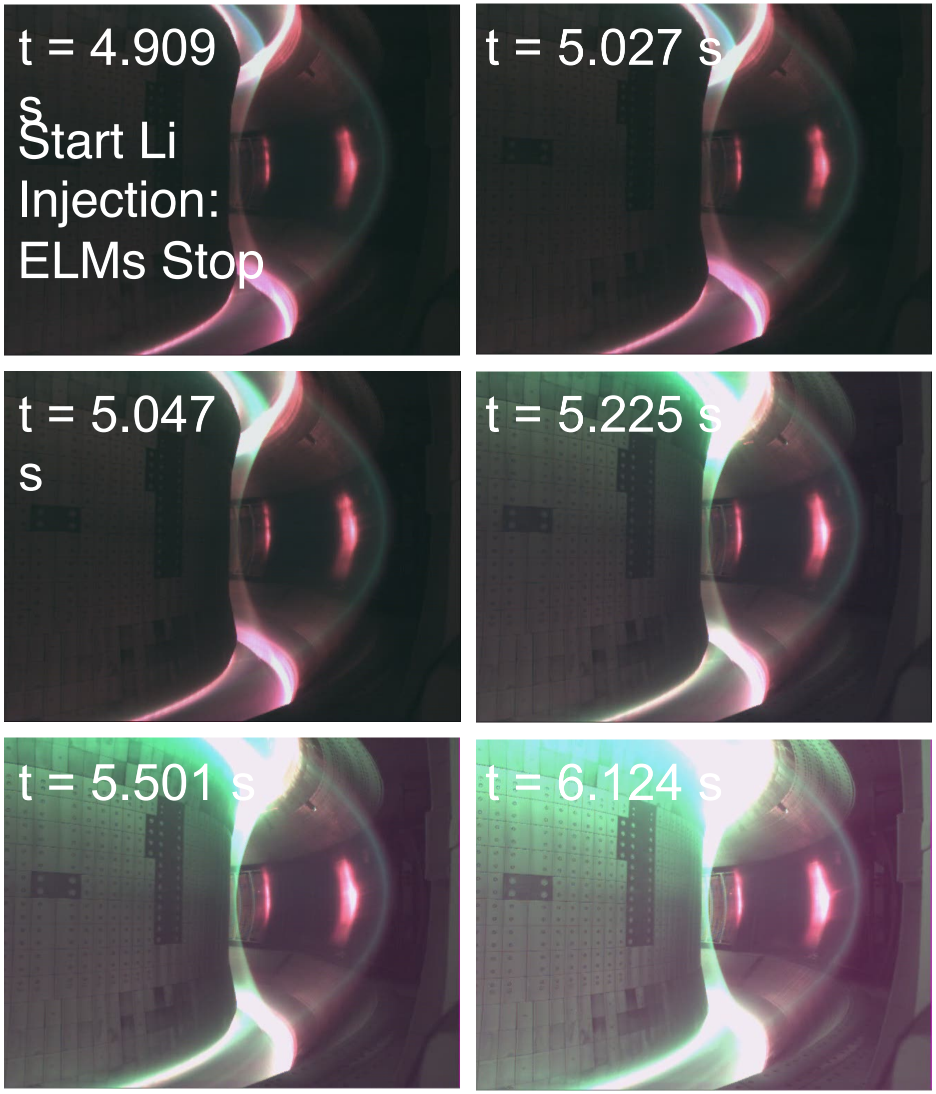
→ J_{bs}, $J_{||}$ increased but far from separatrix; improves stability to kink/peeling modes (ELITE)

Lithium injection can substantially alter pedestal and ELM characteristics, delaying ELMs and improving confinement

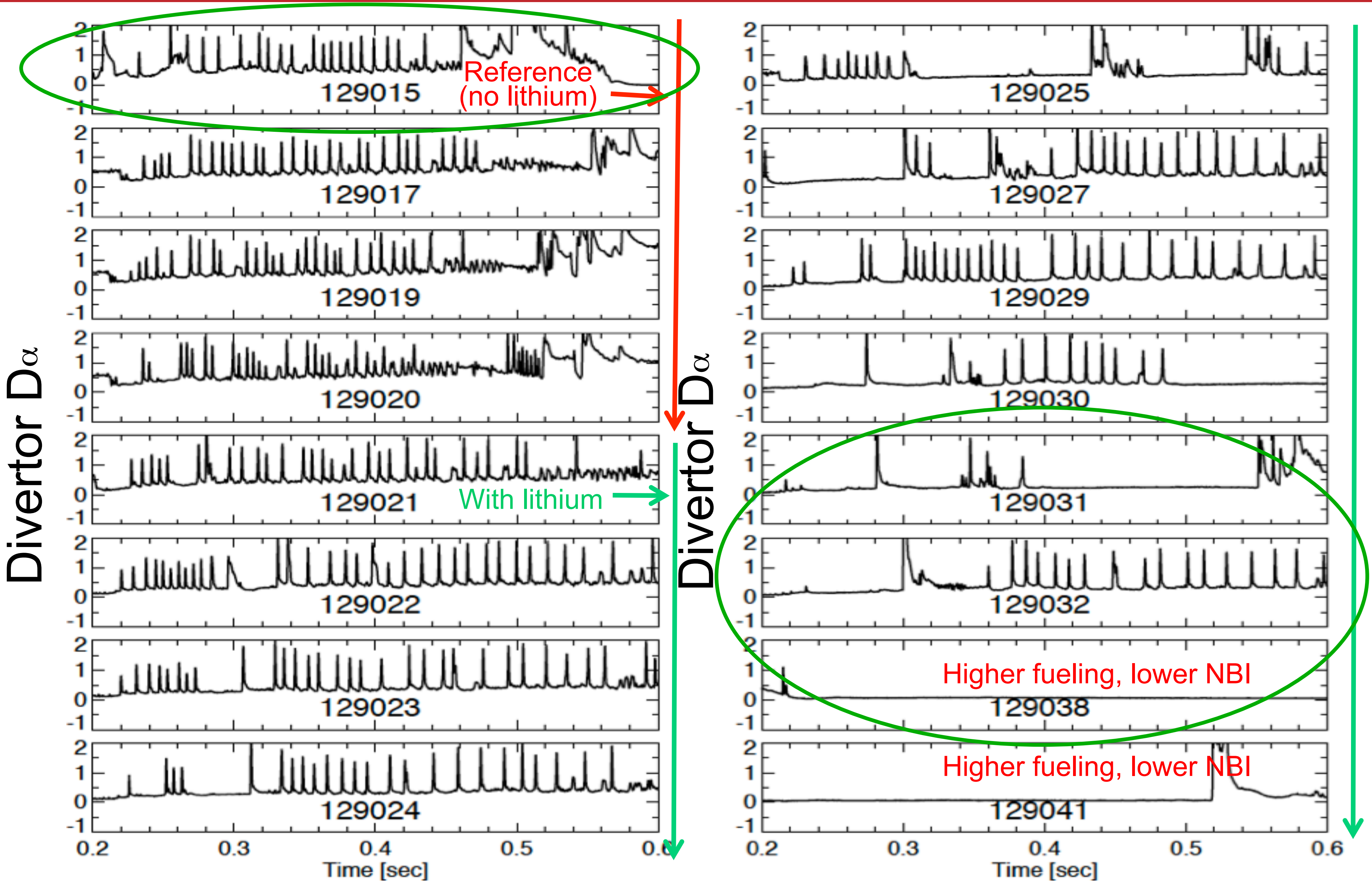
- Combination of Li injection with Burtsy Chirping Mode improves edge stability limit and global confinement
- Ongoing work: trying to understand how the Li injection ‘stimulates’ the Bursty Chirping Mode
- Near term work: test against EPED (role of BCM vs KBM)
- Future work: test mechanisms to arrest pedestal height

Li injector used for real time conditioning in near double-null discharges in EAST

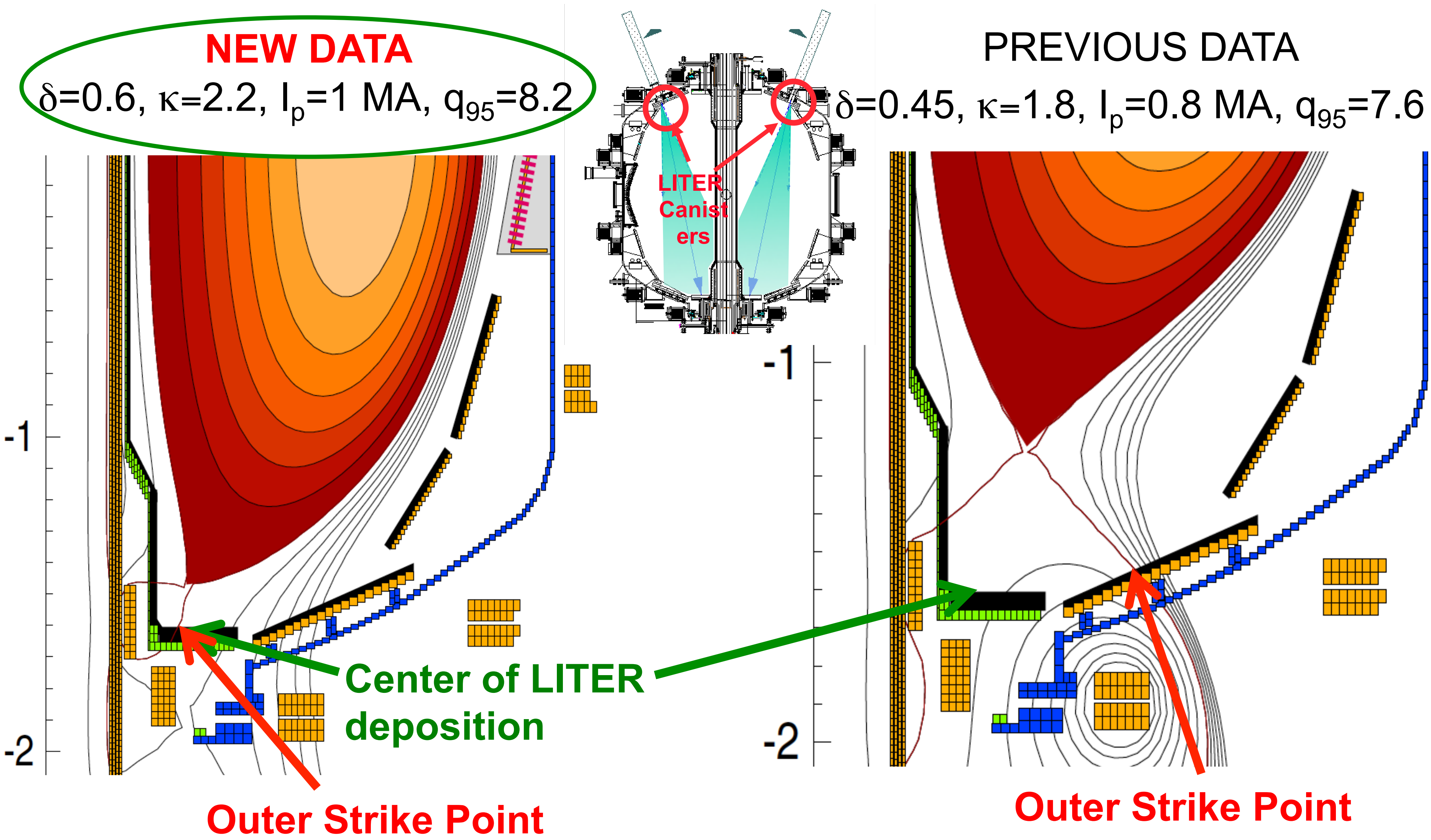




ELM elimination was not quite monotonic

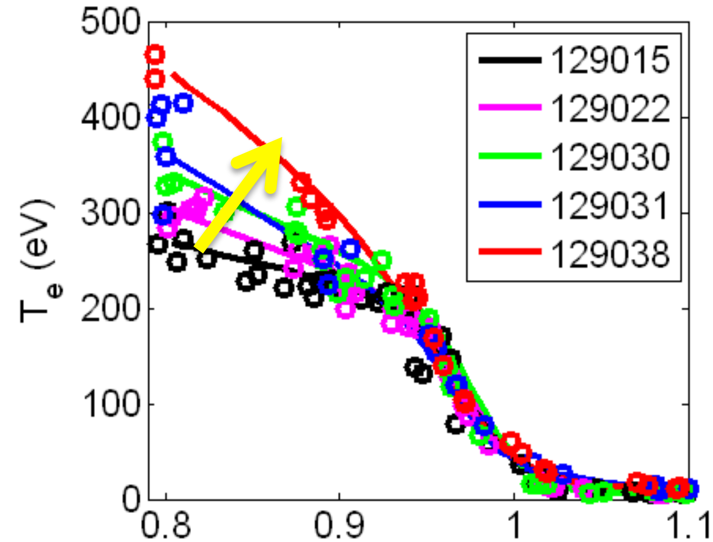


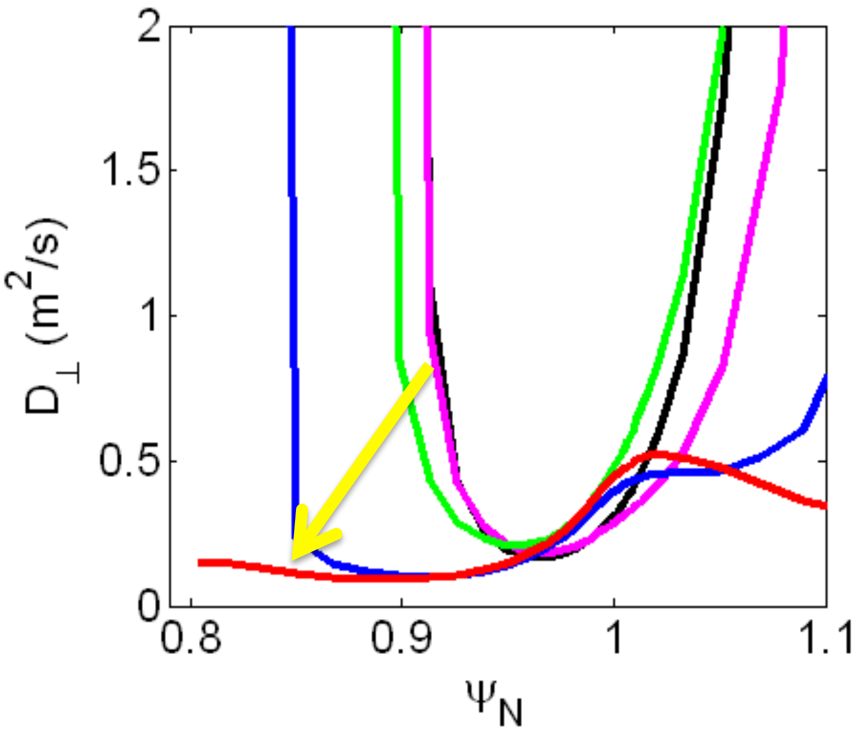
New dataset from highly shaped plasmas in NSTX has center of Li deposition close to Outer Strike Point

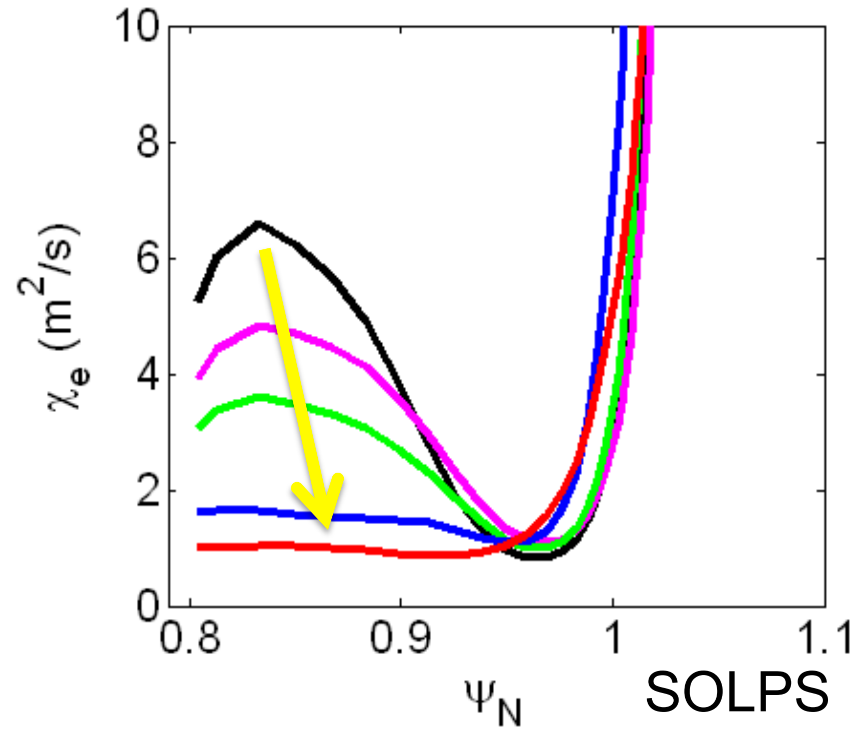


Spatial extent of low D, χ_e region expanded continuously with increasing pre-discharge lithium

- 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

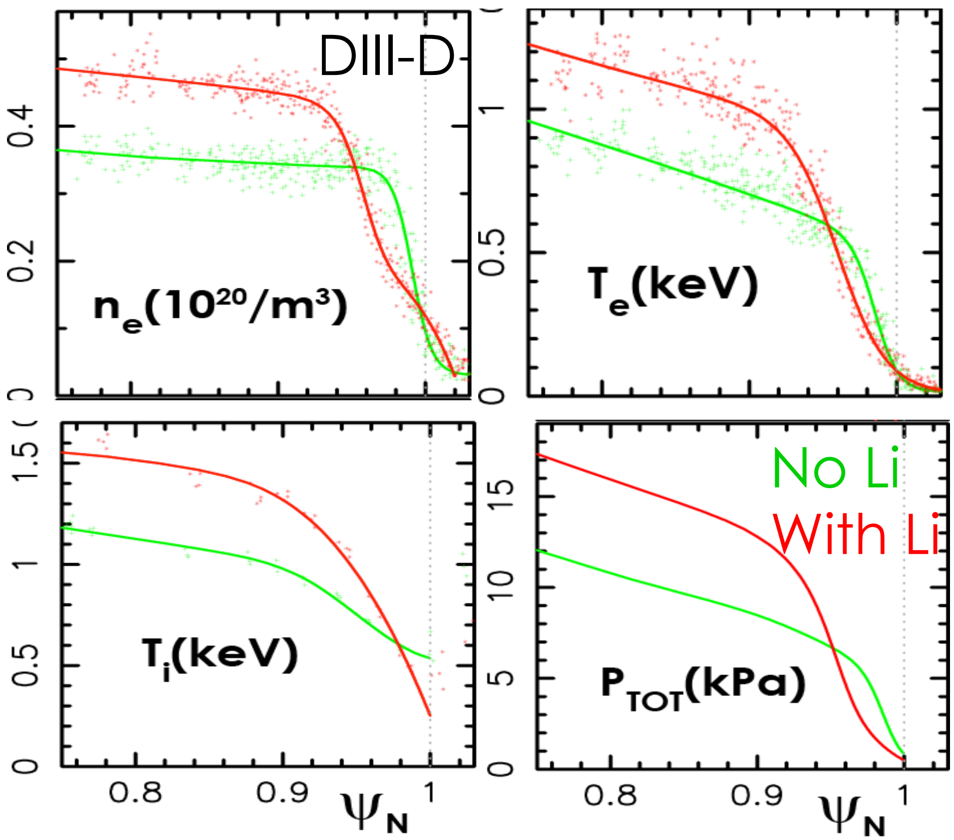


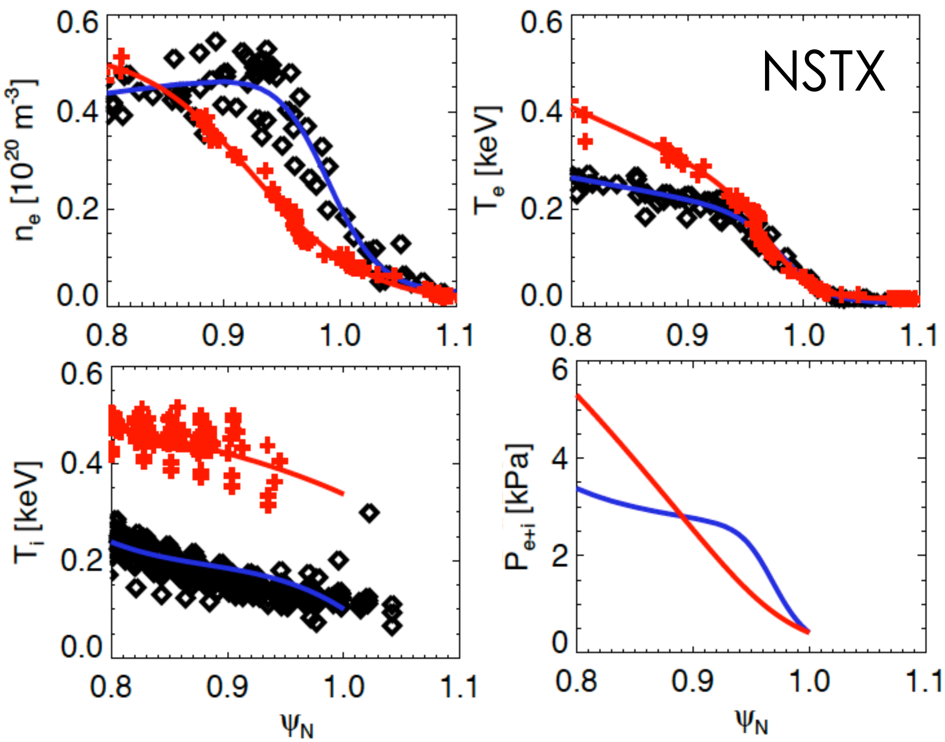




Profile changes in DIII-D in ELM-free H-mode qualitatively similar to NSTX ELM-free H-mode with inter-shot Li evaporation

- Shifting gradients away from separatrix improved edge stability in both DIII-D and NSTX





NSTX: Maingi, NF 2012