NSTX

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The Enhanced Pedestal H-mode and the Effect of Li on Peeling/Ballooning stability in NSTX

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and the NSTX Research Team

C-Mod/NSTX Pedestal Planning
PPPL, Princeton NJ
7-8 Sept. 2010

PPPL Princeton Plasma Physics Laboratory

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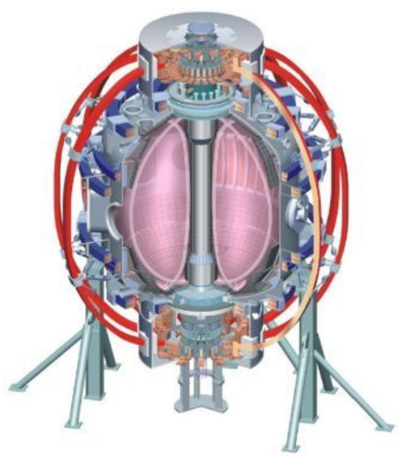

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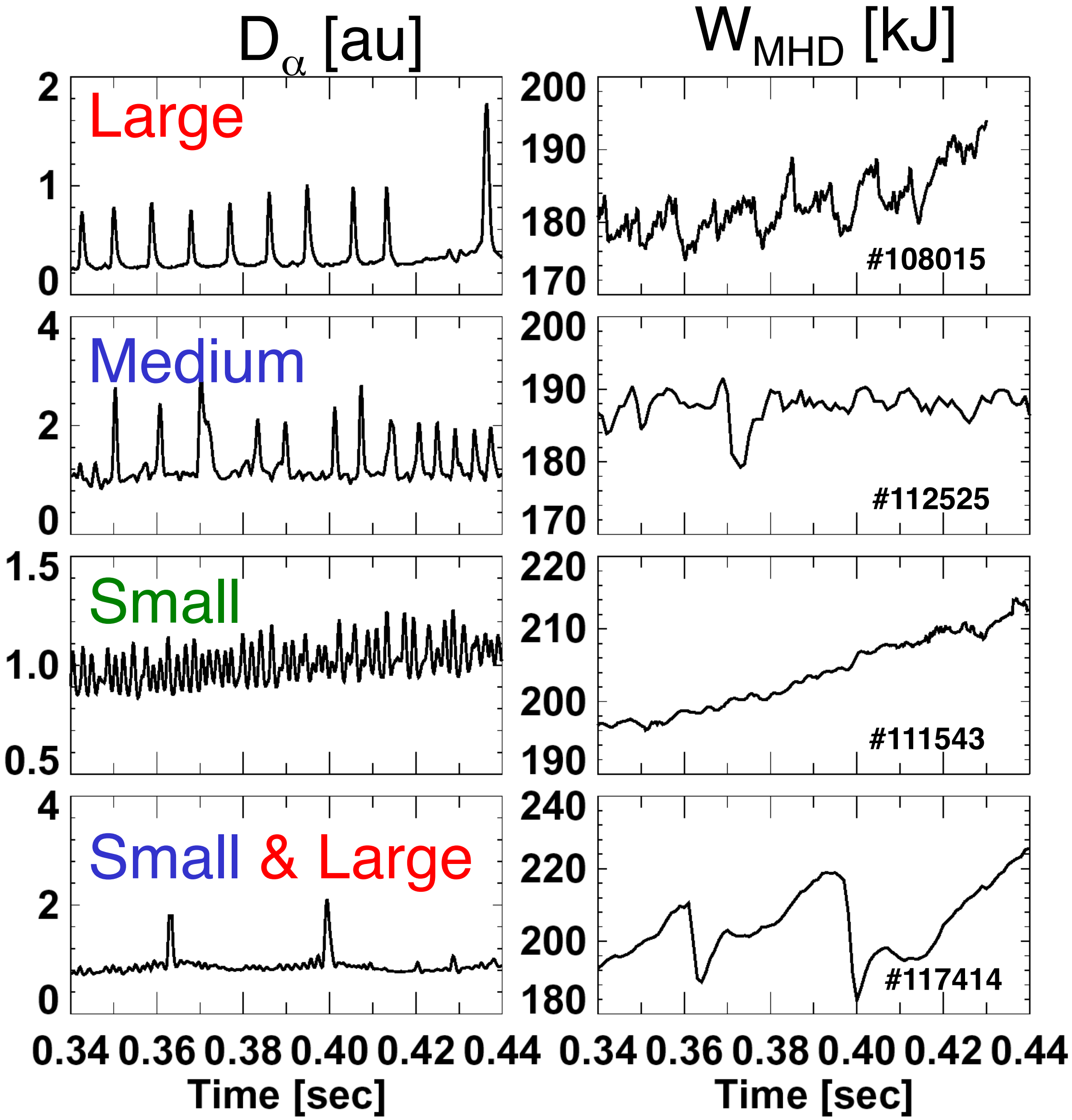
Lithium wall coatings used in NSTX to control recycling and edge density

- End points of a well-controlled lithium coating sequence that resulted in ELM suppression
  - Edge density and temperature profile modifications with lithium, and inferred changes in cross-field transport
- Edge pressure profile modifications and stability calculations
- Few slides on Enhanced Pedestal H-mode

Edge localized modes (ELMs) observed in many non-lithium NSTX H-mode discharges



$\Delta W_{MHD}/W_{MHD} \sim$ 3-20%

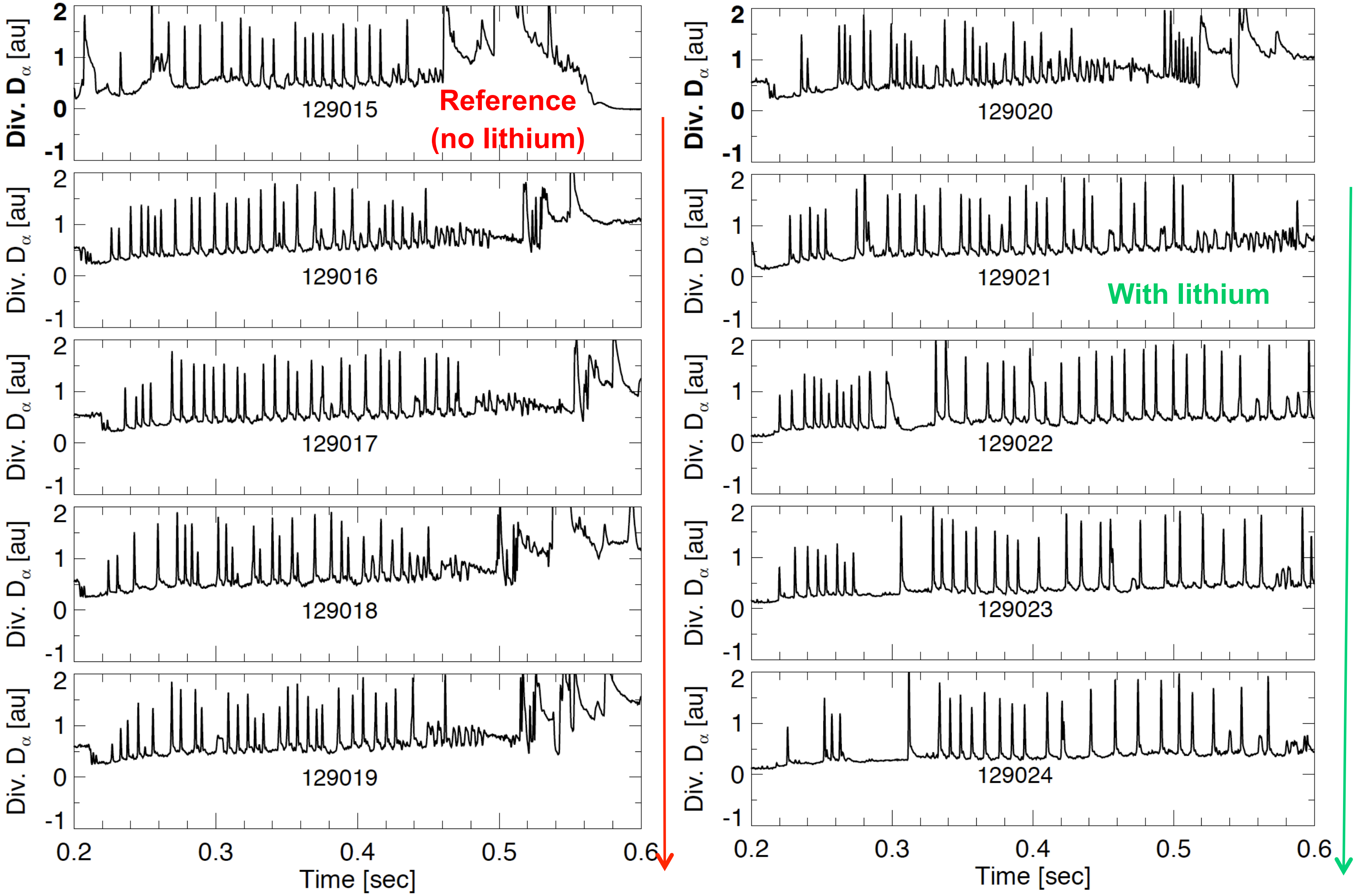
$\Delta W_{MHD}/W_{MHD} \sim$ 1-5%

$\Delta W_{MHD}/W_{MHD} \leq$ 1%

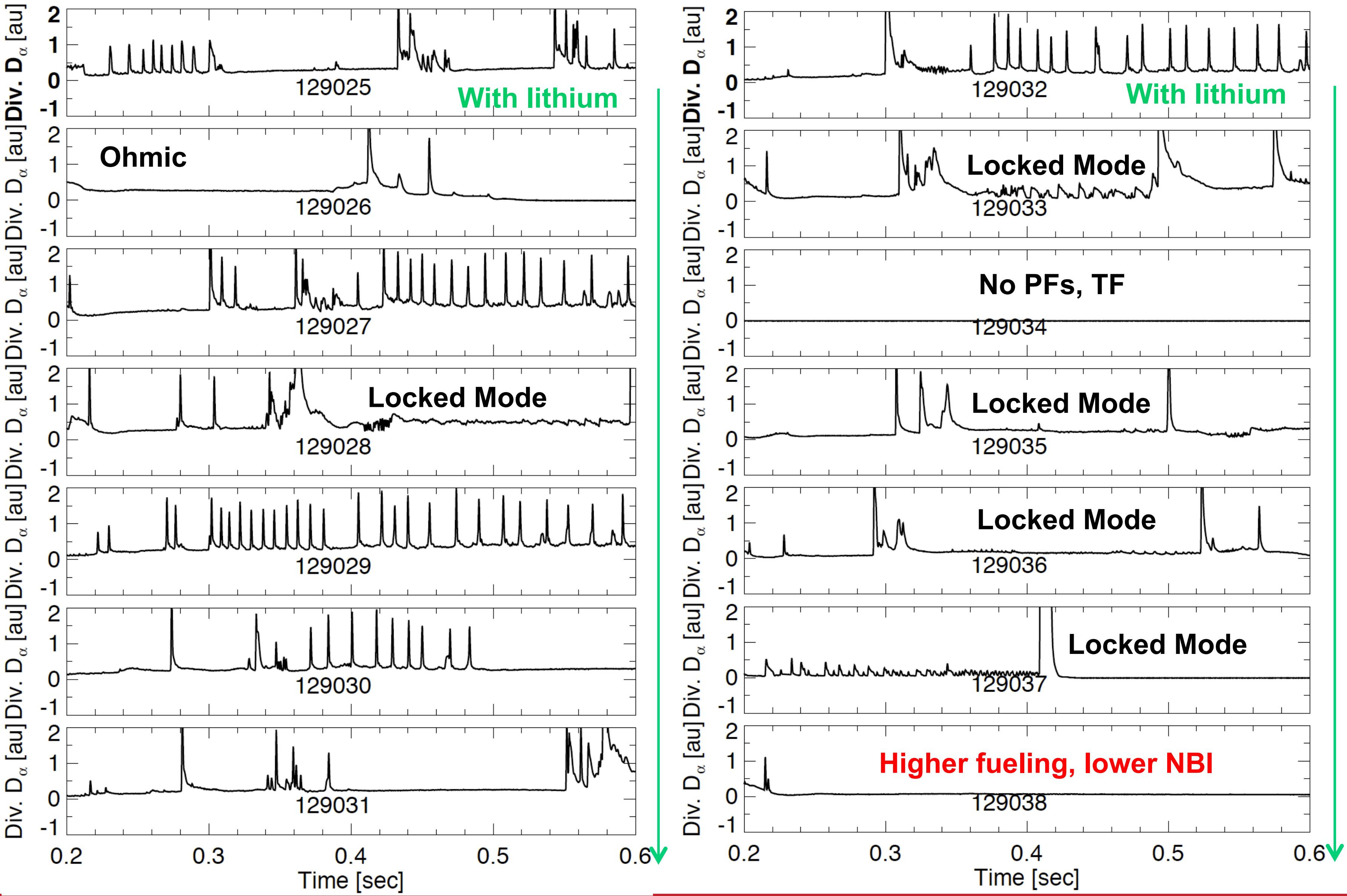
$\Delta W_{MHD}/W_{MHD} \leq$ 30%

R. Maingi, JNM 2005

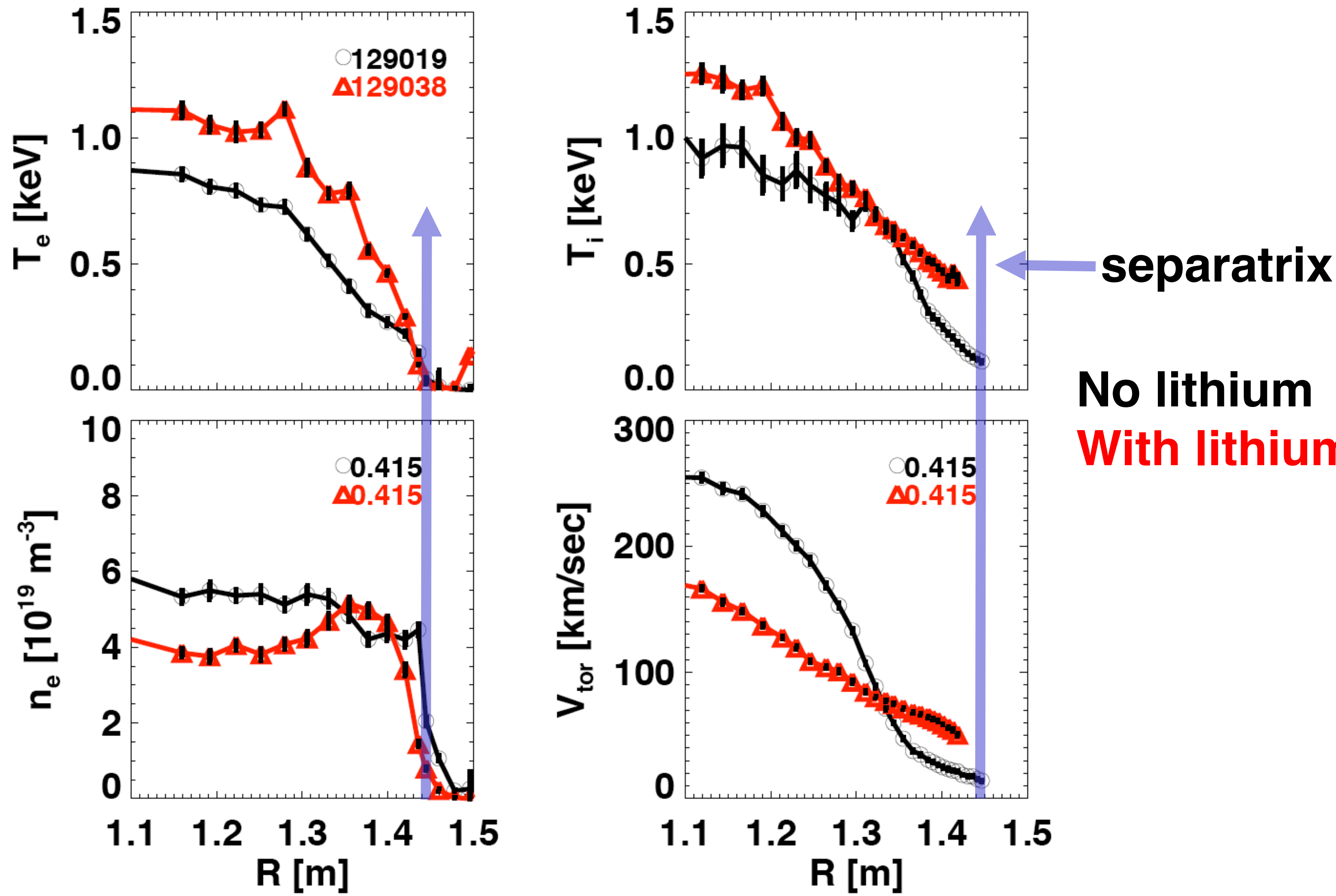
ELMs disappeared gradually with increasing lithium wall coatings



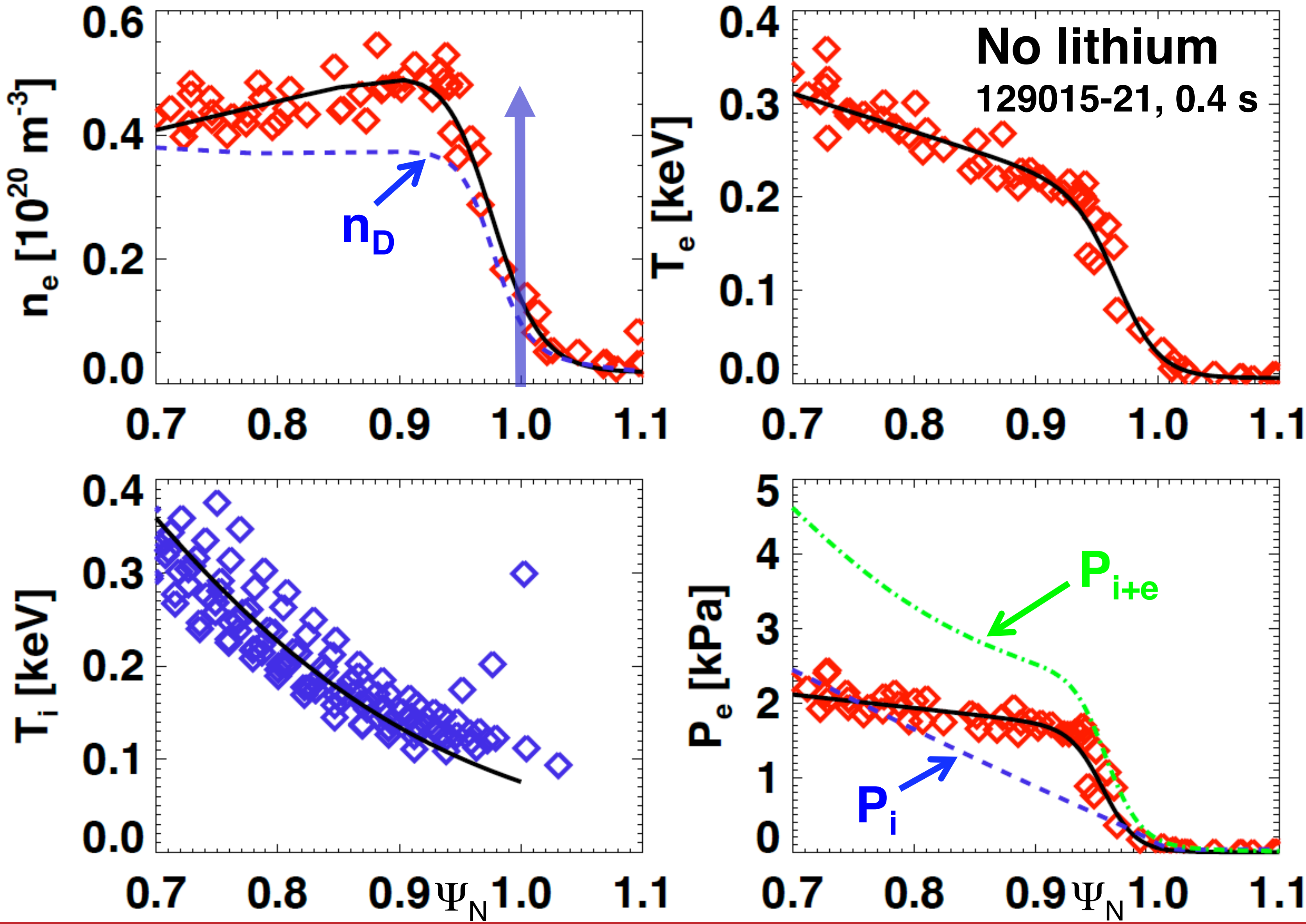
ELM evolution with shot number



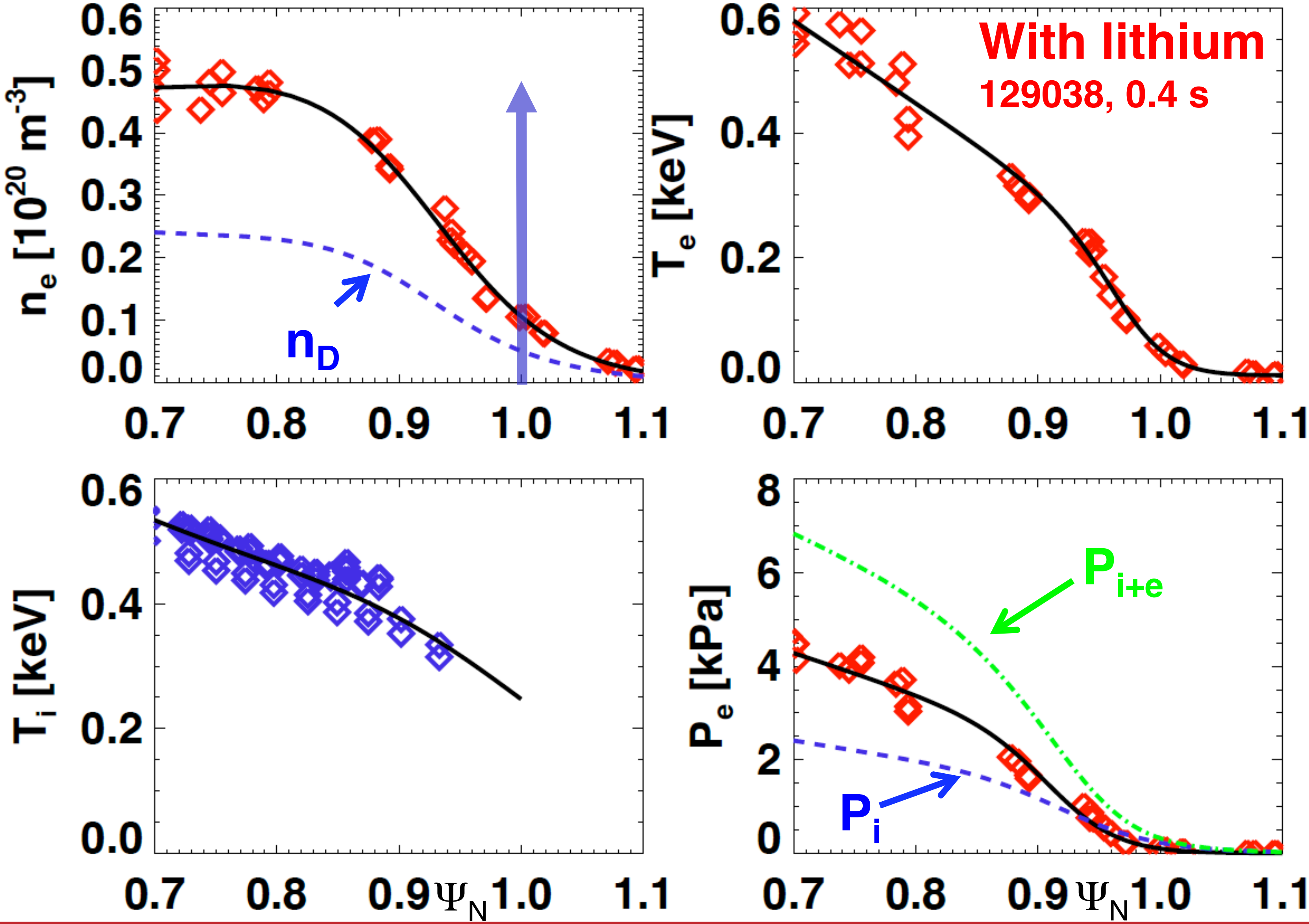
T_e, T_i increased and edge n_e decreased with lithium coatings



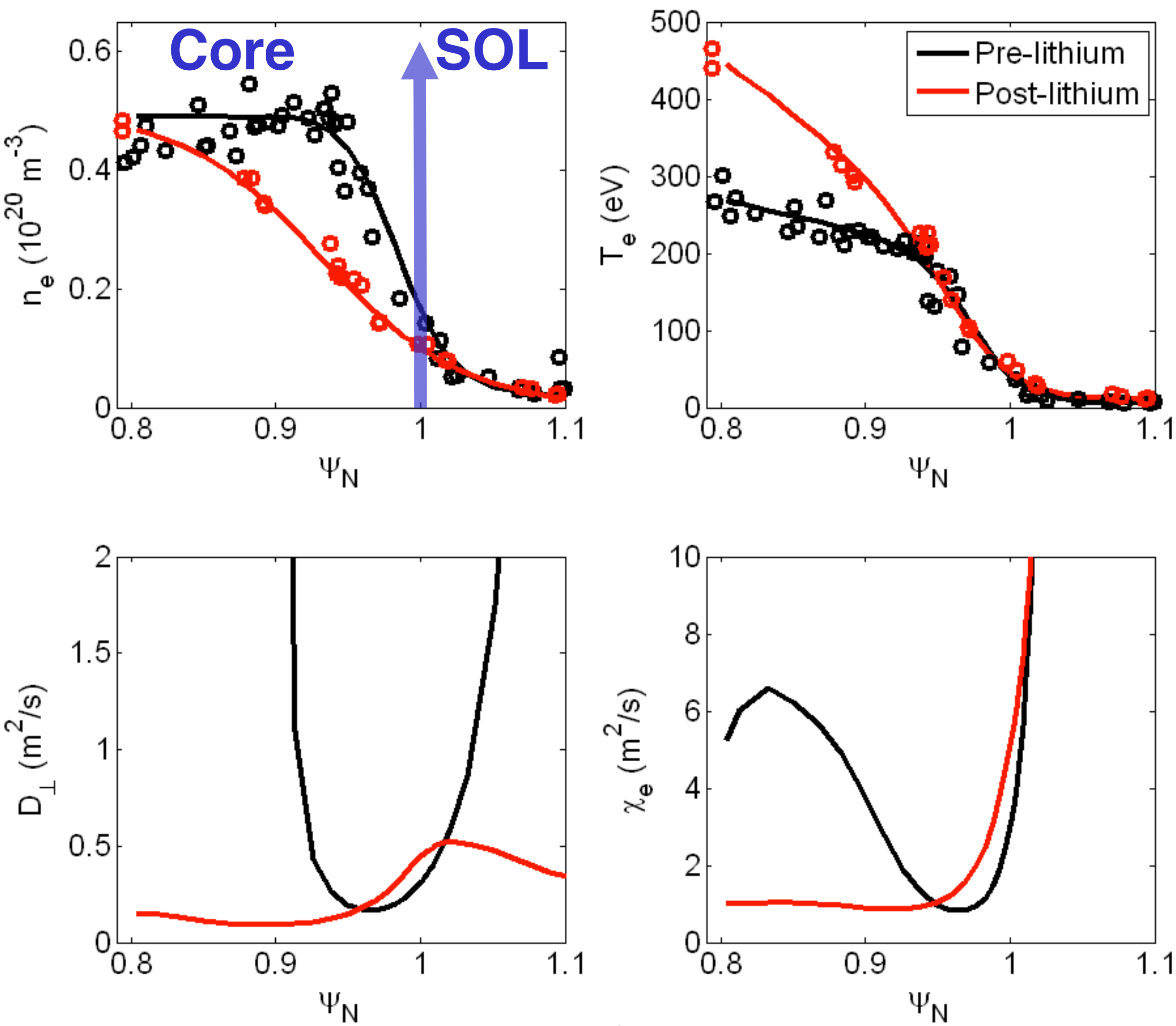
Electron pressure gradient dominates total pressure gradient (last 20% of ELM cycle)



Electron pressure gradient dominates total pressure gradient (all data from 350-450 msec)



Profiles in discharges with lithium wall coatings require recycling coefficient *and* transport change



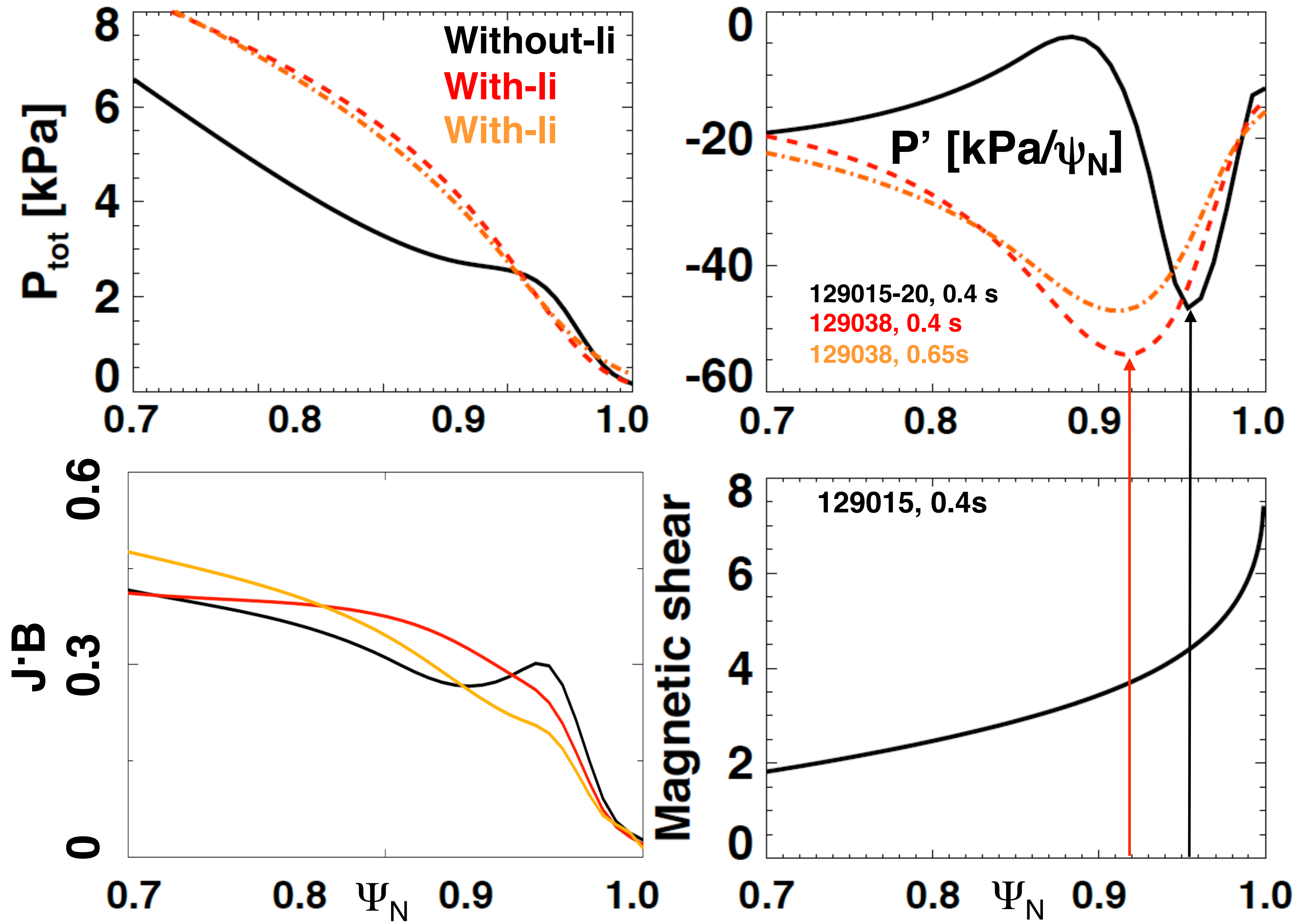
J. Canik, PSI 2010

R_p=0.98, P=3.7 MW

R_p=0.92, P=1.9 MW

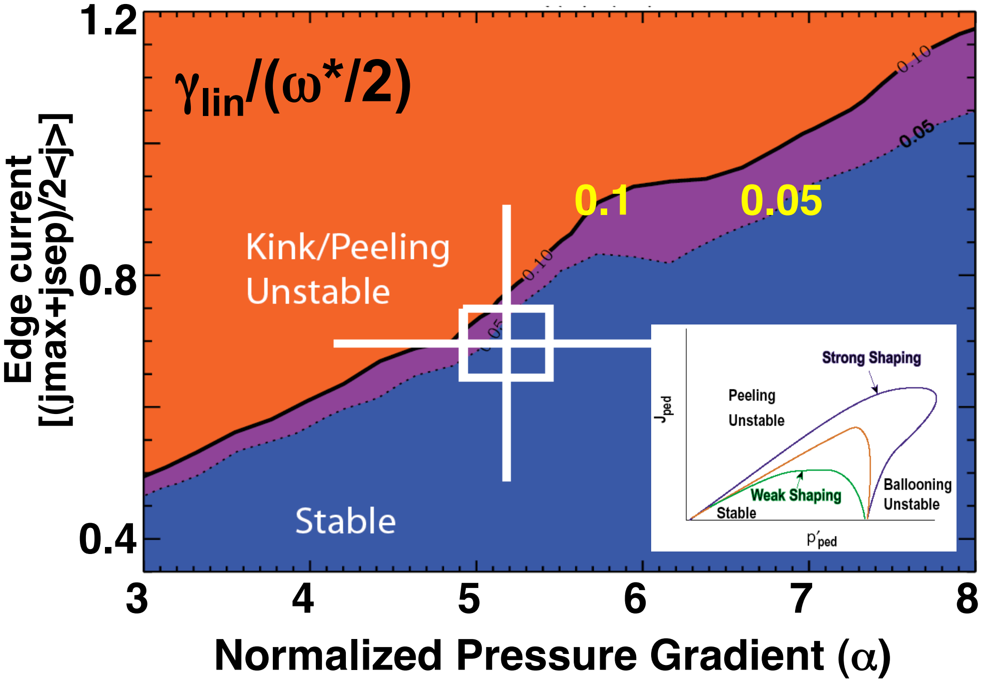
(SOLPS)

Peak edge pressure gradient and bootstrap current moved to region of reduced magnetic shear

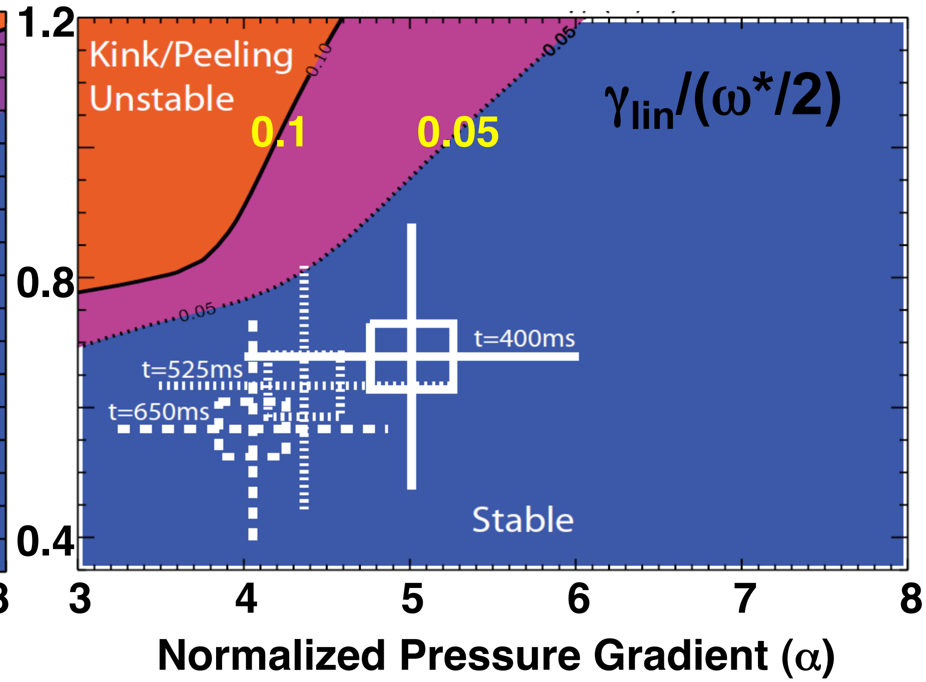


Pre-lithium edge profiles close to kink/peeling instability threshold (ELITE)

No lithium - ‘varyped’ EFITs



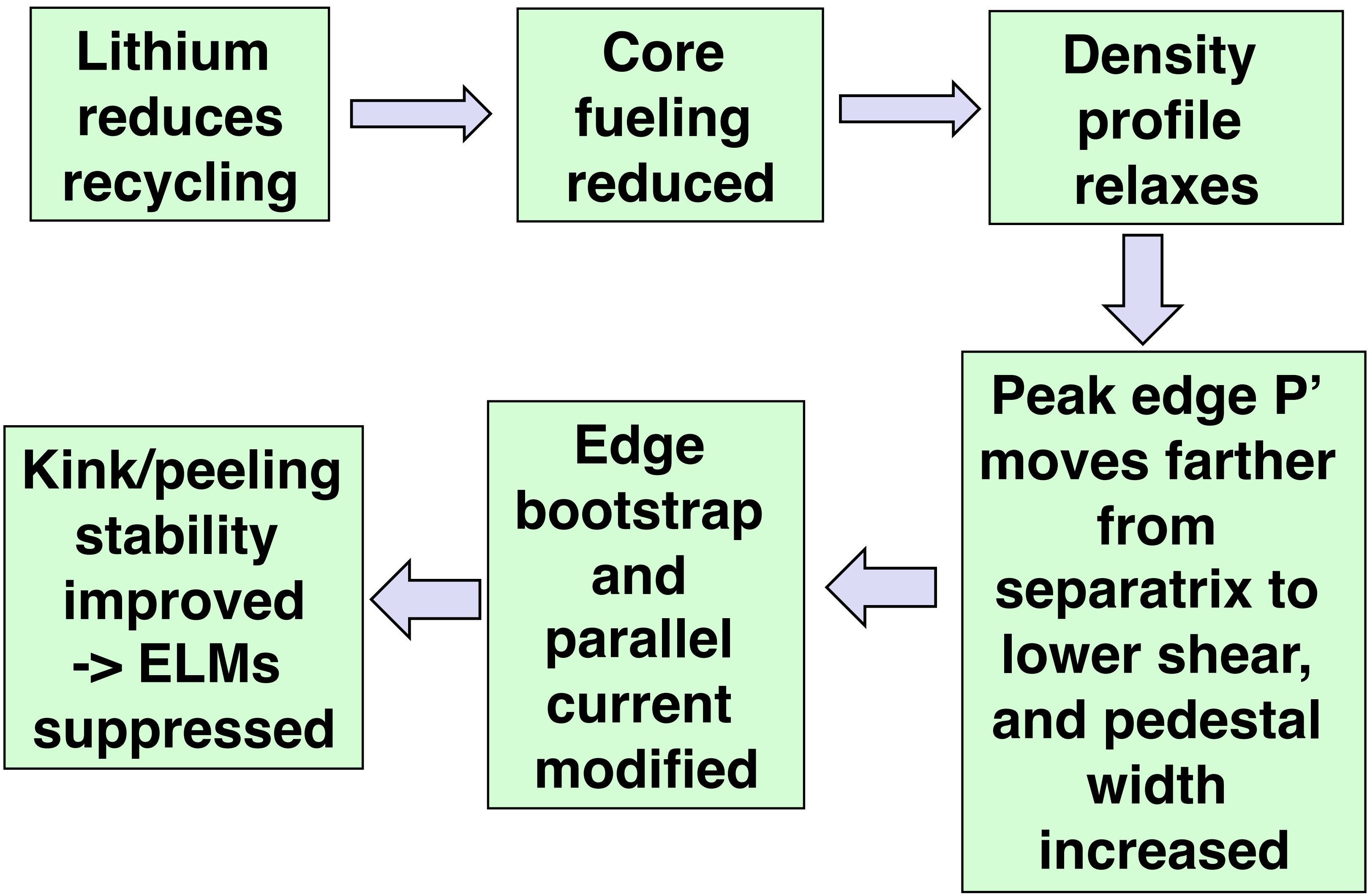
With lithium –‘varyped’ EFITs



- Low n=1-5 pre-cursor oscillations observed before ELM crash

R. Maingi, PRL 2009

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



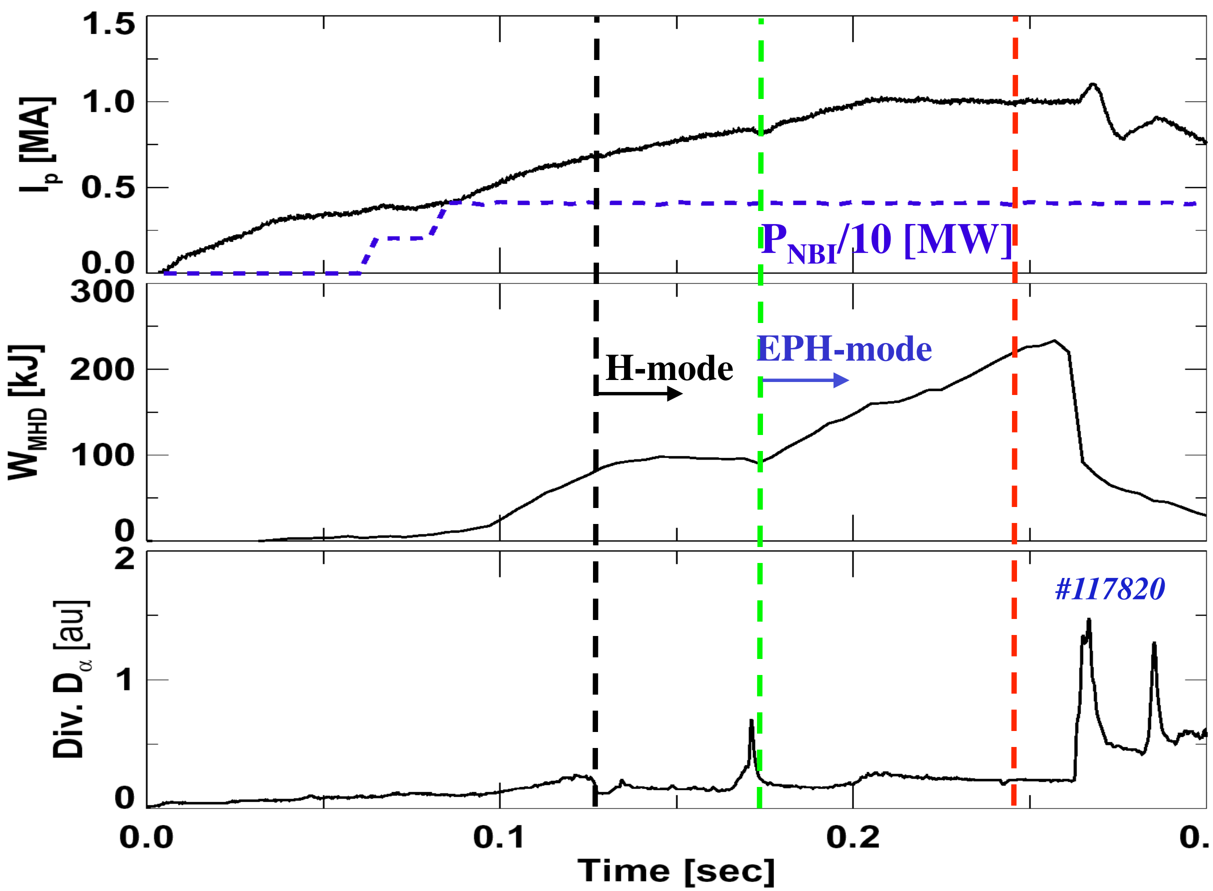
Details of precise evolution toward ELM suppression not well understood

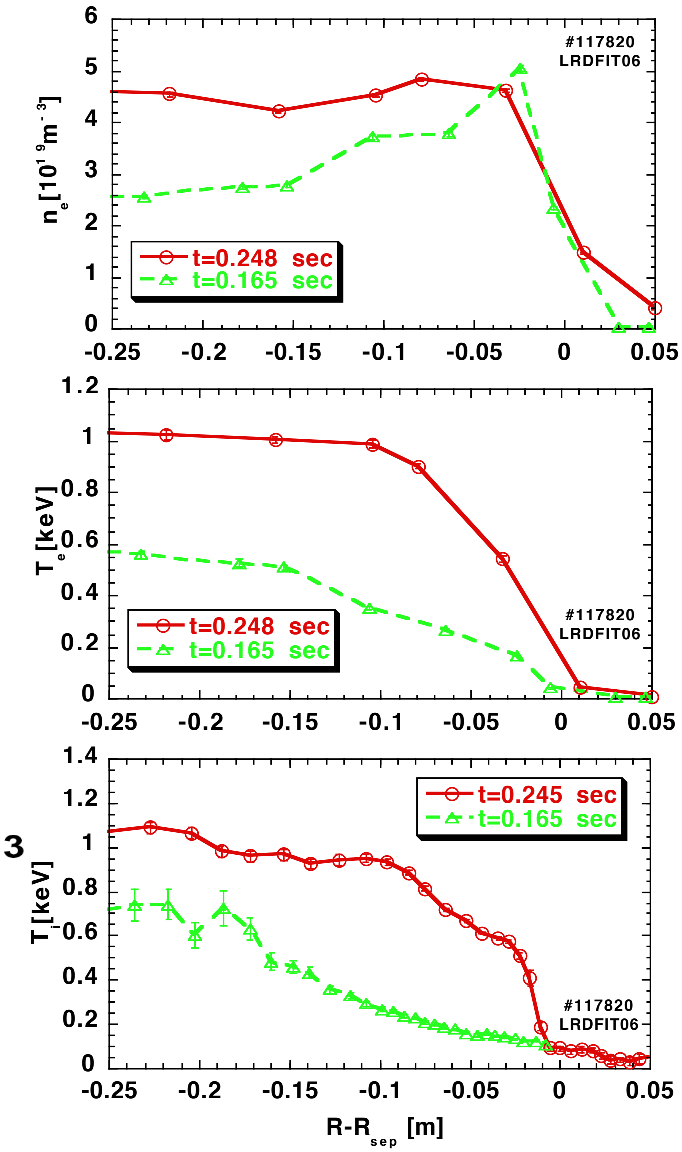
- Why are the ELMs not stabilized by diamagnetic drift, as in higher aspect ratio tokamaks?
  - Look carefully: the $\gamma_{lin}/(\omega^*/2)$ ratio ~ 0.05-0.1 at instability
- Complete evolution: why do ELMs go away the way they do i.e. with increasing periods of quiescence?
  - Shot by shot stability analysis in agreement with observed trends, but gradient resolution limited during ELMy discharges
  - Maybe the improved Thomson resolution next year can enable single time slice analysis?
- What is the role of failed discharges/L-mode in the observed ELMs on following discharges?
- What keeps the transport rate high near the separatrix?
  - Paleoclassical? ETG? KBM?

The Enhanced Pedestal H-mode (EPH) has favorable characteristics and improved long pulse prospects

- τ_E in NSTX H-modes is generally 0.8-1.2* ITER98y2 scaling
- A transition to an improved τ_E with higher edge T_e, T_i at similar n_e observed: an ELM-free thermal barrier
- Characteristics of EP H-mode
  - Highest normalized energy confinement of any regime in NSTX, with H89P $\leq$ 3.5 and H98y2 $\leq$ 1.8
  - Second transition after large ELM, either natural or triggered w/RMP
  - Common feature: edge v_ϕ develops large gradient, with a large drag, often near the q=3 surface
- Low loop voltage, high β_N scenario
  - Maximum pulse length ~ 300 msec (3 τ_E)
  - Difficult to generate on demand

Transition to an Enhanced Pedestal H-mode enables lower pedestal $\nu_{e,ped}$* ~ 0.1 in NSTX

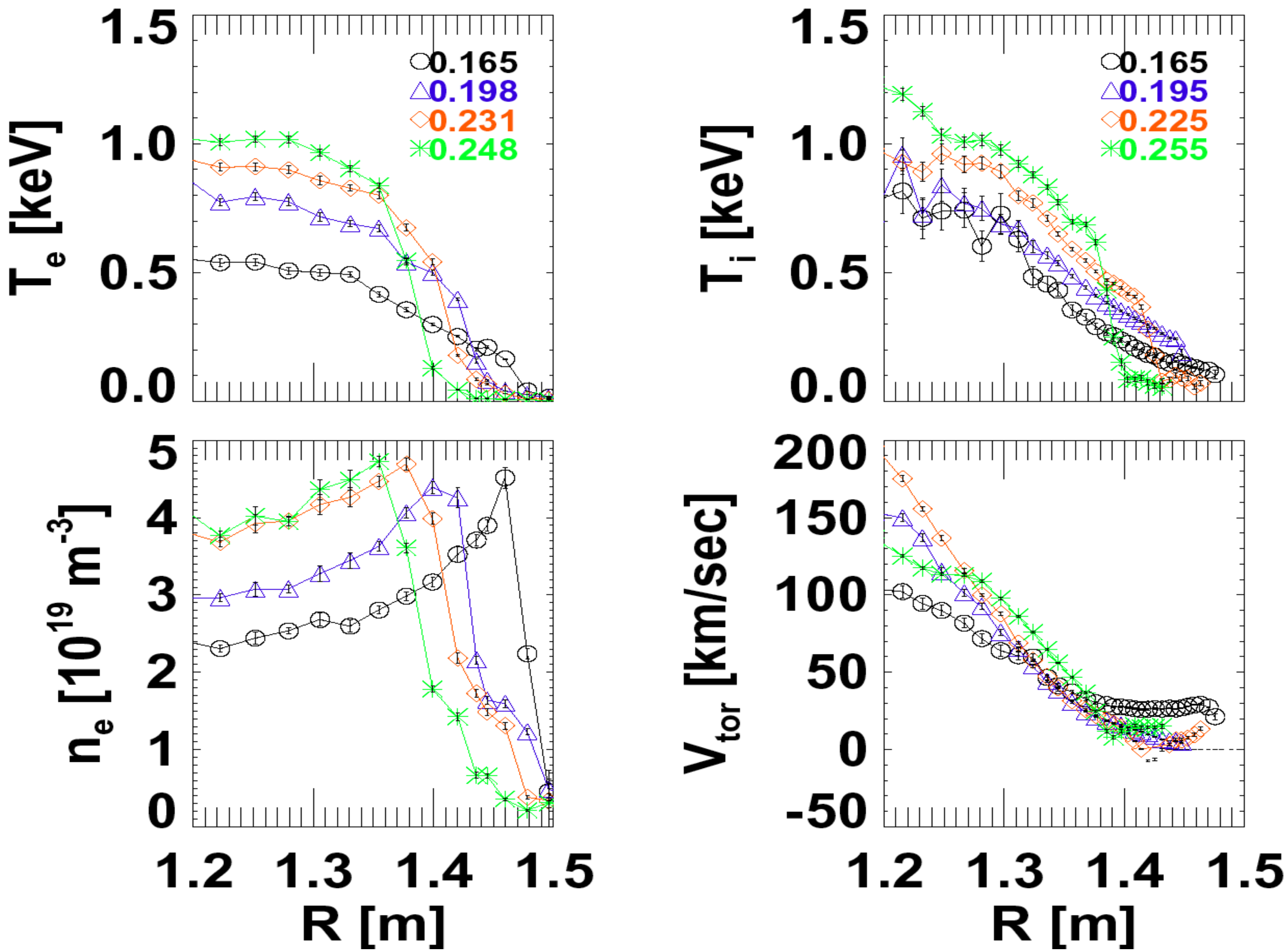




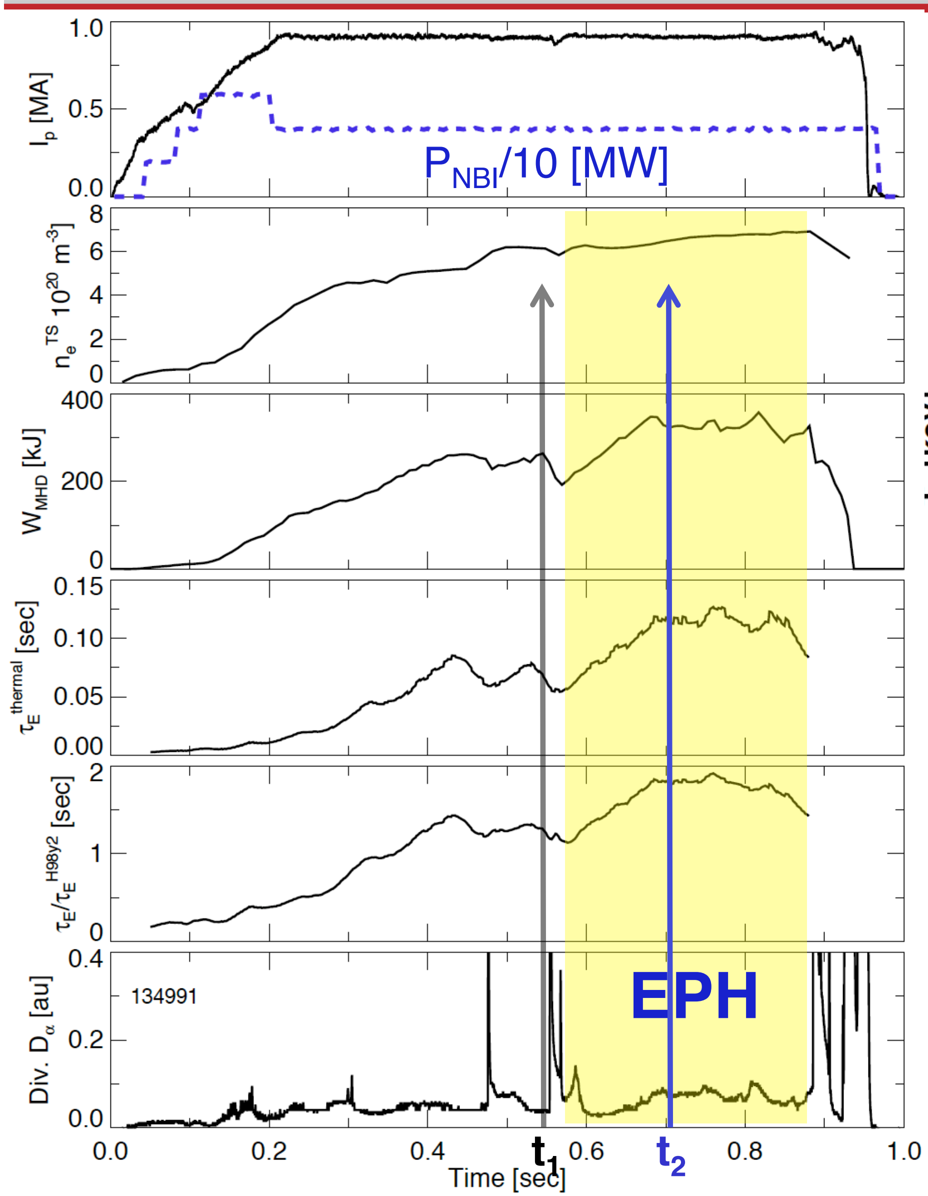
- ***Note: Pedestal ν_e^* ~ 0.5-1 in H-mode***

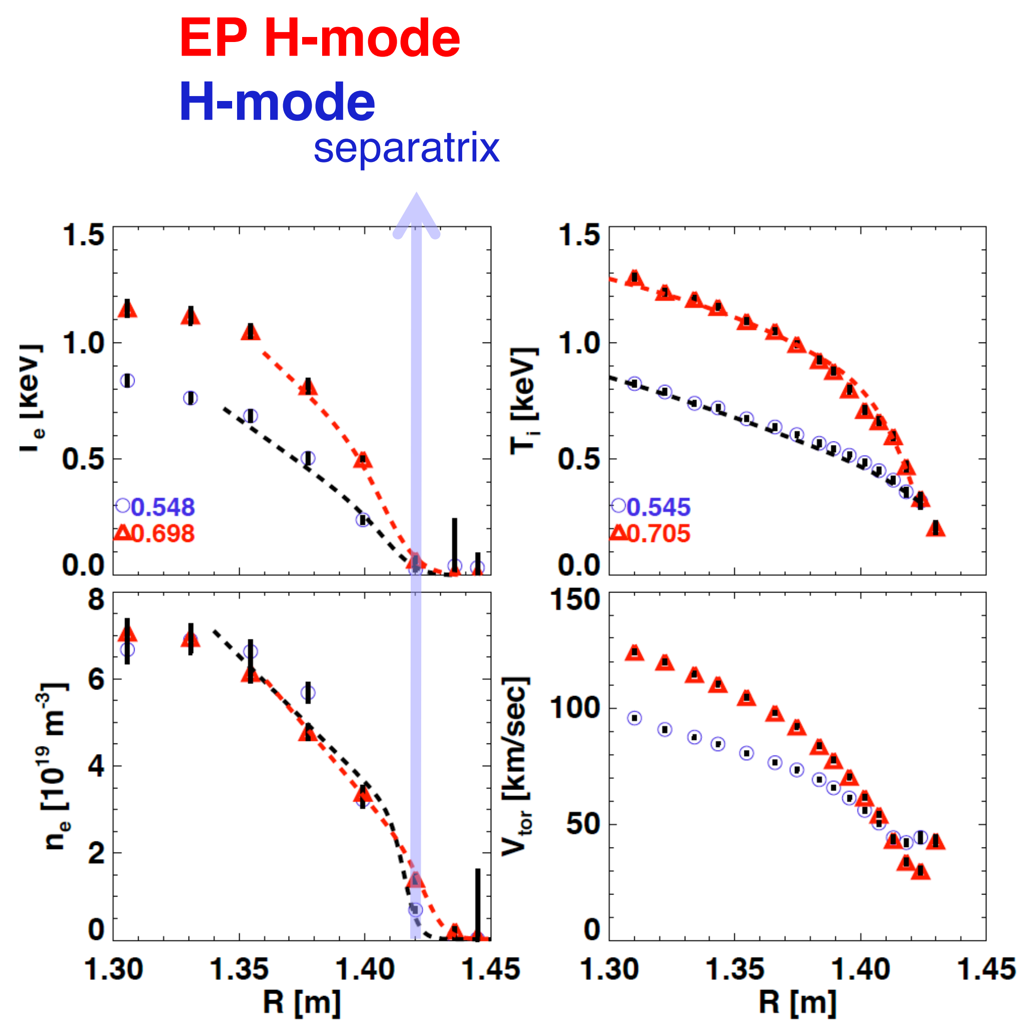
Maingi, JNM 390-391 (2009) 440

EP H-mode profiles evolved continuously during I_p ramp



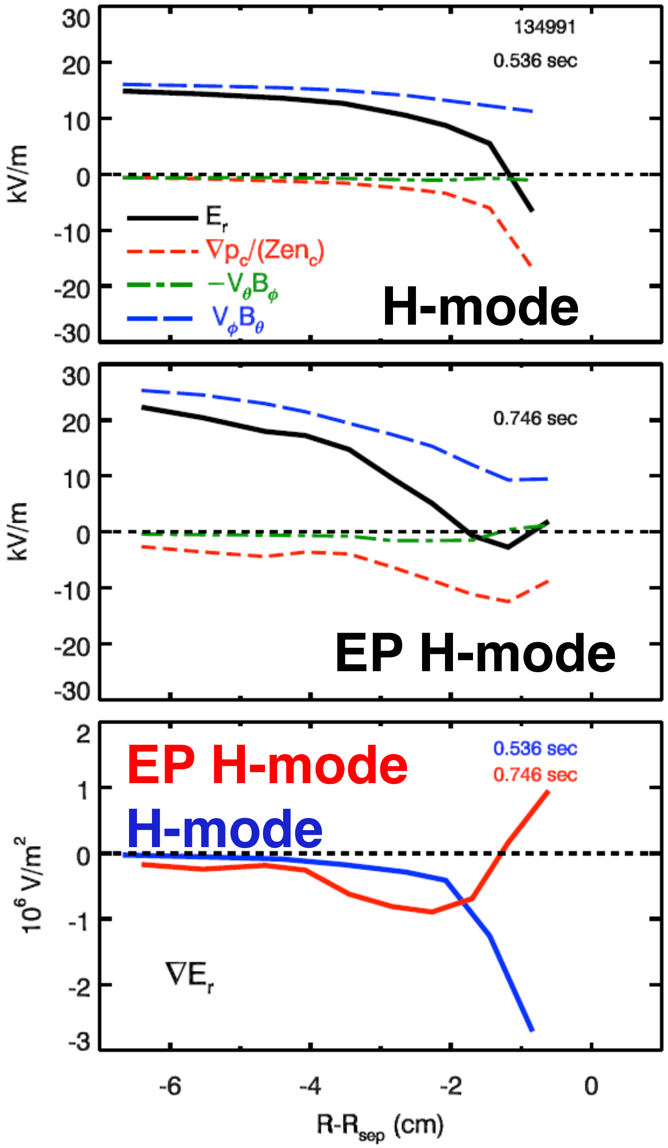
EPH-mode phase observed for several τ_E, up to ~ 300 msec



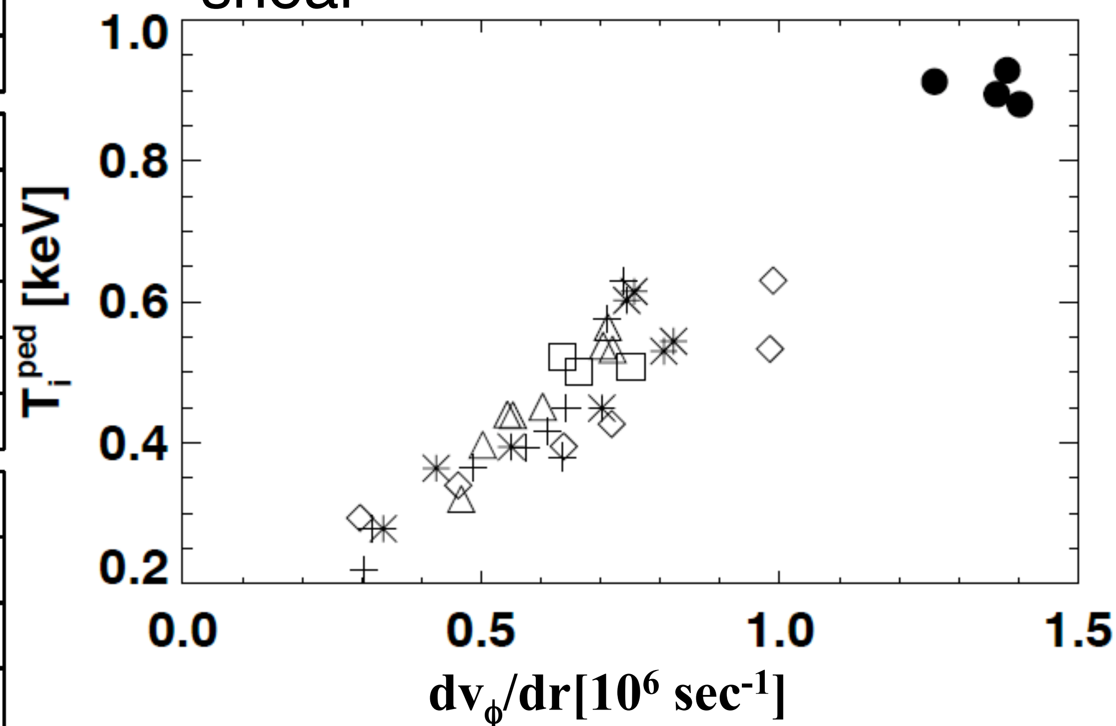


Maingi, PRL (2010) at press

Spatial extent of significant E_r shear region doubled in size during EP H-mode



- T_i pedestal height correlates with edge toroidal rotation shear



Many outstanding question on EP H-mode

- How can we reliably trigger on demand?
  - RMP with proper spectrum? Low q_{95}?
- What are the changes in the turbulence?
  - FIReTIP indicates 50% reduction in density fluctuations
- Does lithium enable these in some way?
  - More frequent in past few years with increasing Li usage
- What is the role of edge resonances?
  - q=3 special?
- Is it some combination of VH-mode and QH-mode?
  - Need to assess edge turbulence: any EHO here?
- What is the limit on achievable 'pedestal width'?
  - Should we be calling this a pedestal even?

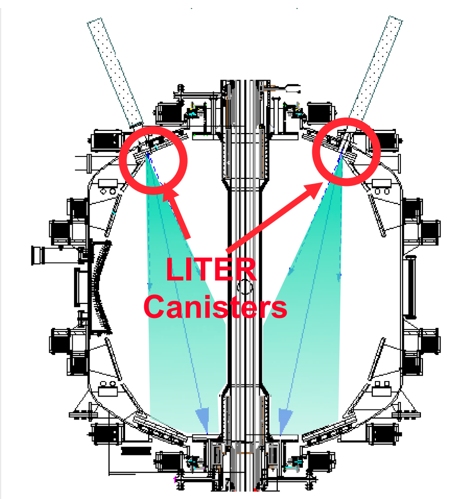
BACKUP

Lithium wall coatings modify edge transport and stability in NSTX

- ELM-free phases increase gradually with lithium deposition, with discharges eventually becoming ELM-free
  - n_e profile shifts inward gradually with increasing lithium
  - T_e, T_i increase and profiles change substantially
- H-factor increased up to 50% for thickest lithium coatings
  - Region of low D, χ_{eff} extends inward from H-mode barrier
  - Global stability limits (β_N ~ 5.5-6) encountered before edge (ELM) stability limits
- Peak pressure gradients shifted inward -> ELMs suppressed
  - Density profile modification crucial step toward ELM suppression
- *Impurities accumulate and radiated power increases monotonically in the discharge*
  - ➢ Present remedy: use 3d fields to trigger ELMs to purge impurities while looking to reduce impurity influx, e.g. via ‘snowflake’ divertor

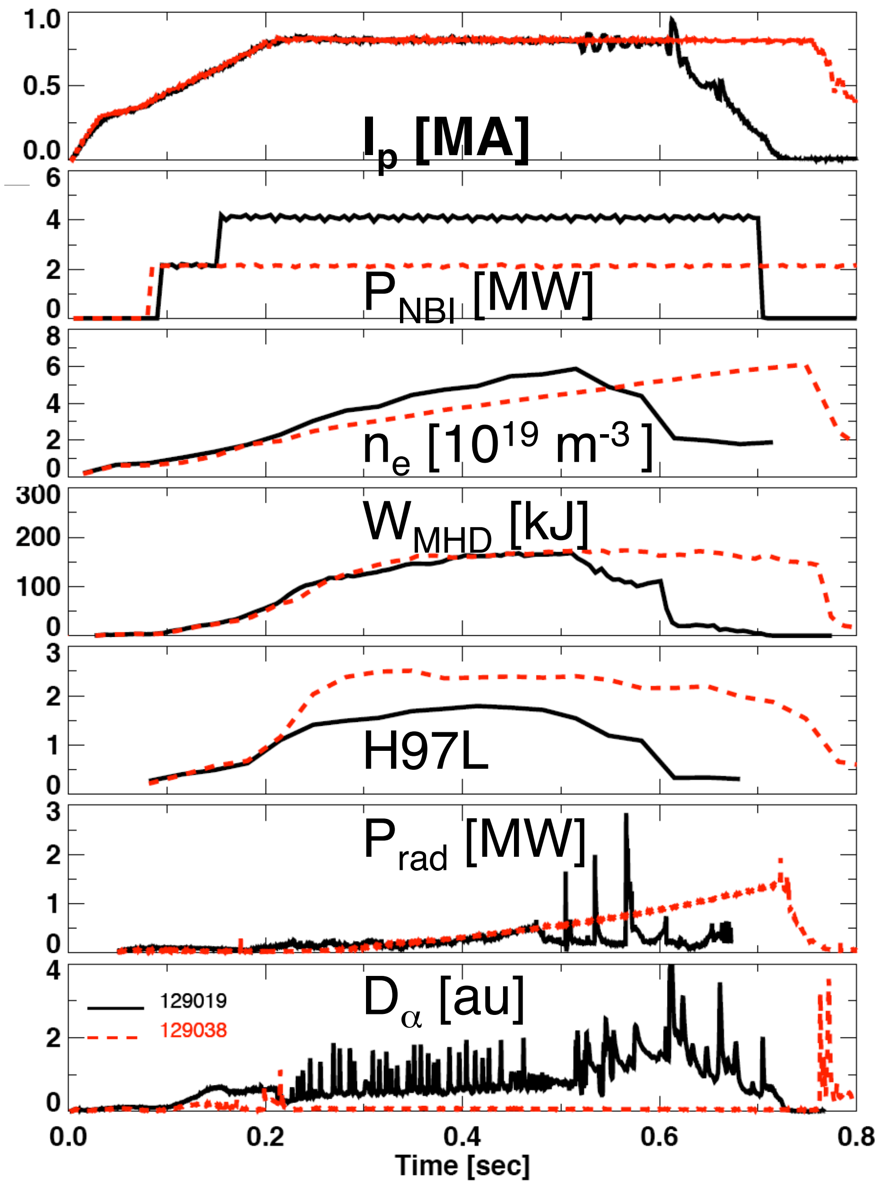
ELM-free H-mode induced by lithium wall coatings

Predicted* by
L. Zakharov
in 2005



~ 700mg Li
before 129038

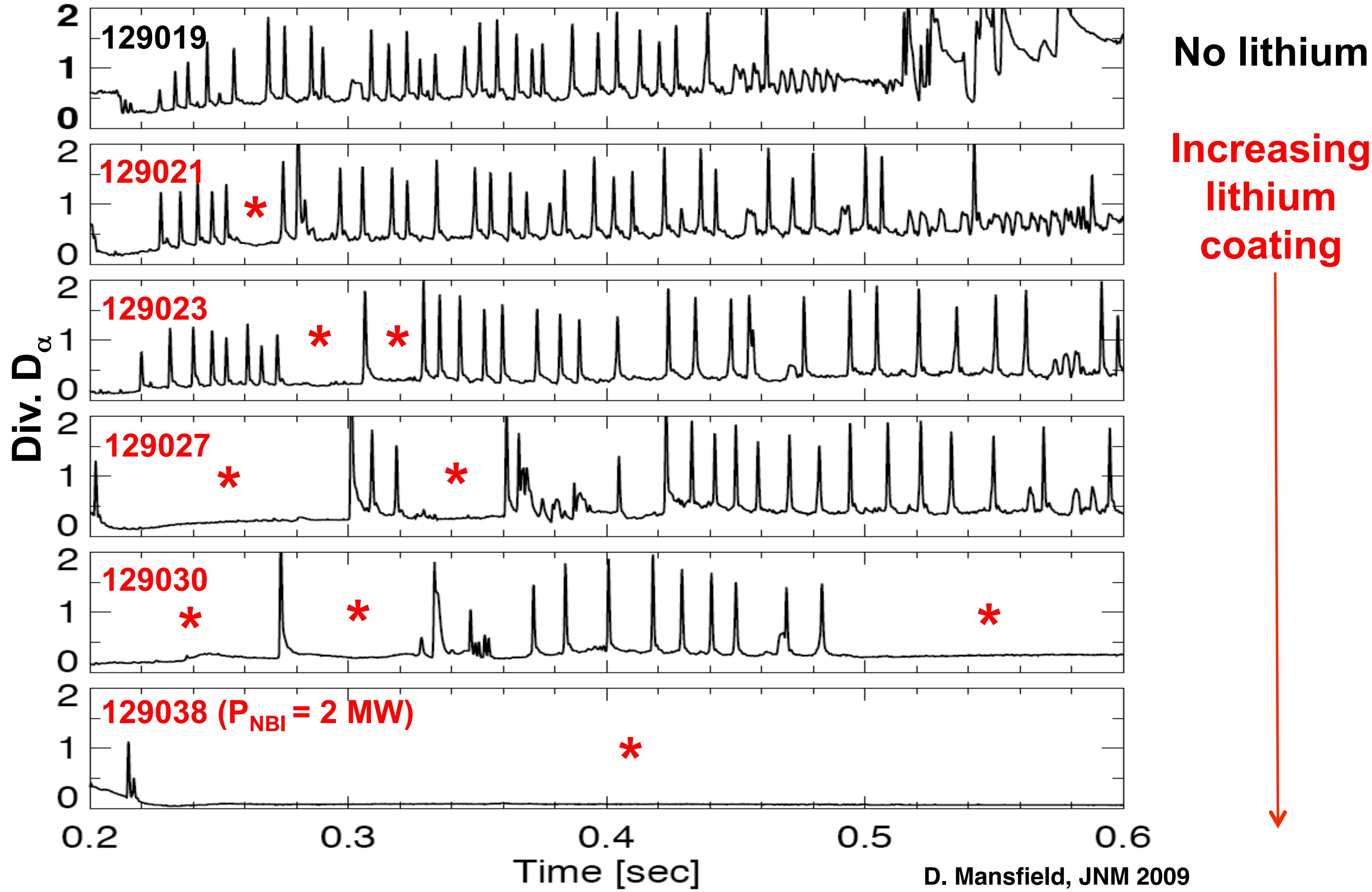
* L. Zakharov, JNM 2007



- Without-Li, With Li
- Lower NBI to avoid β limit
- Lower n_e
- Similar stored energy
- H-factor 40%↑
- Higher P_{rad} /P_{heat}
- ELM-free, reduced divertor recycling

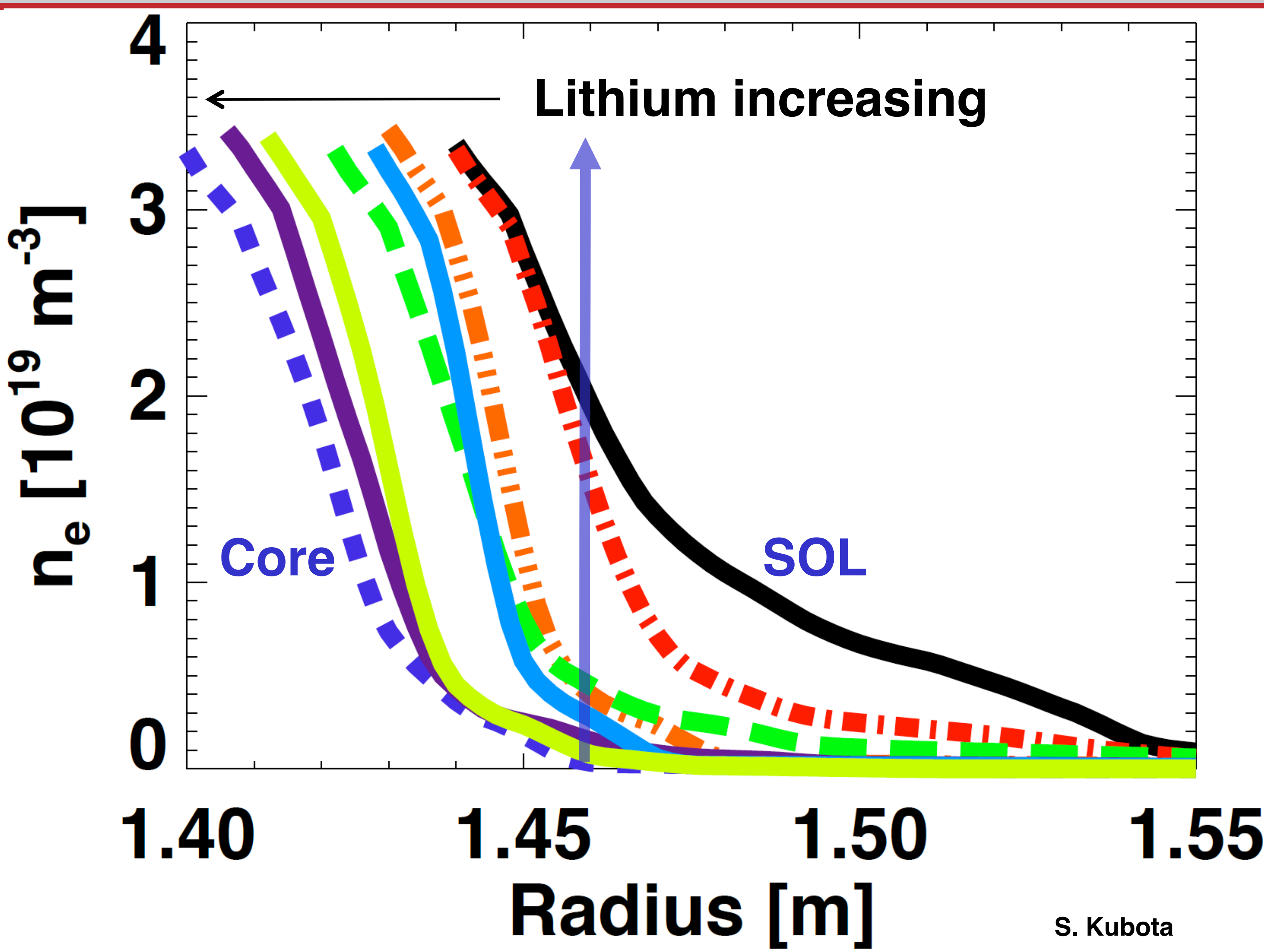
R. Maingi, PRL 2009

Quiescent phases (*) increase with increasing lithium coating (P_{NBI} = 4 MW)



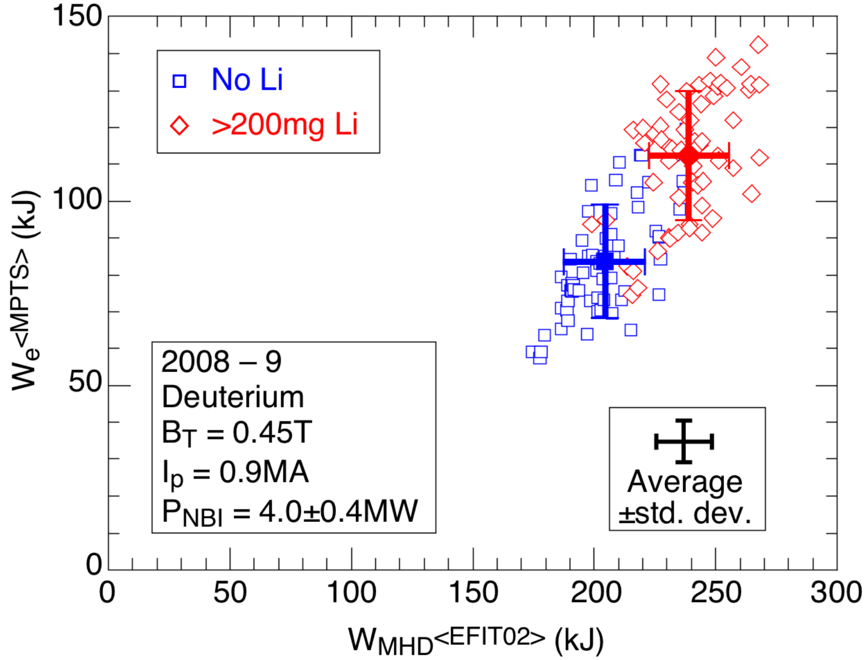
D. Mansfield, JNM 2009

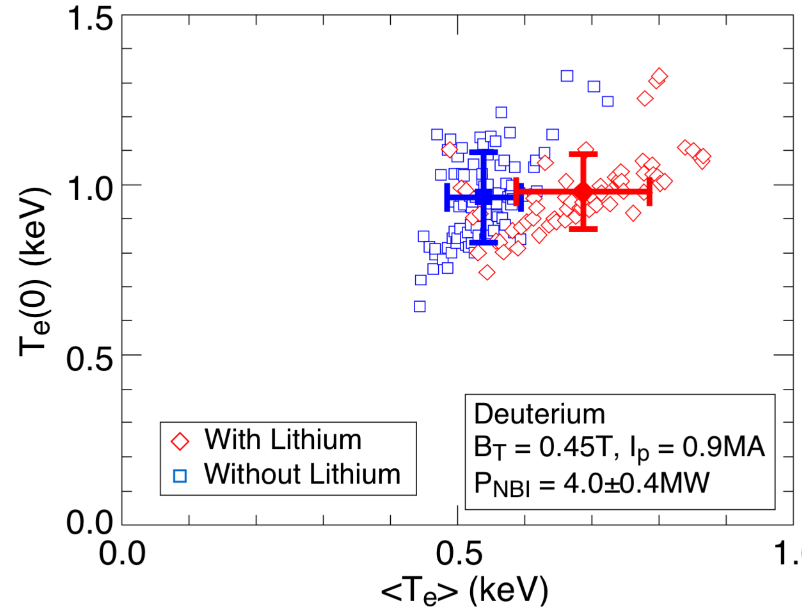
Density profile shifted inward near the magnetic separatrix

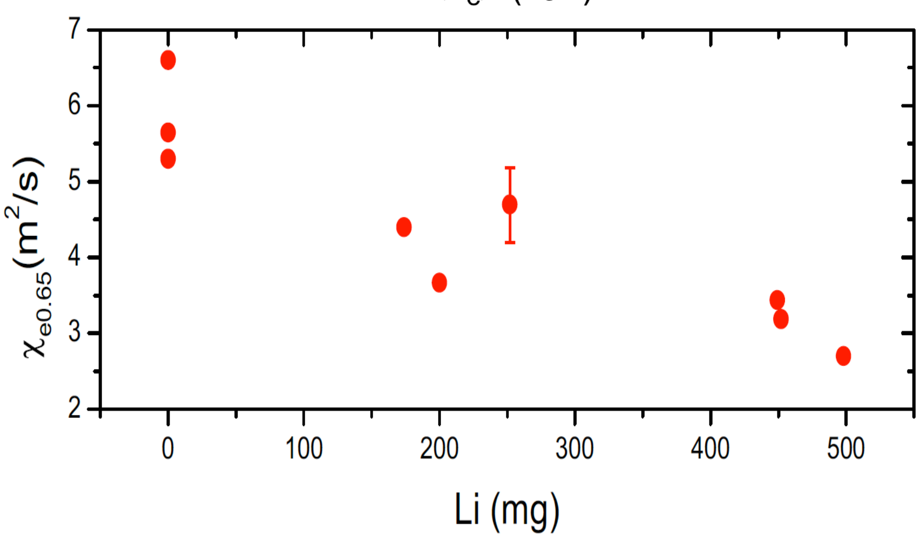


S. Kubota

Confinement improves with lithium coatings, due to broadening of the temperature profiles







- TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium

M. Bell EPS09, S. Ding PPCF at press

NSTX Developing Lithium-Coated Plasma Facing Components (PFCs)

2005: Lithium pellet injection for wall coatings

2006: LIThium EvaporatoR (**LITER**) deposited lithium on center column and lower divertor

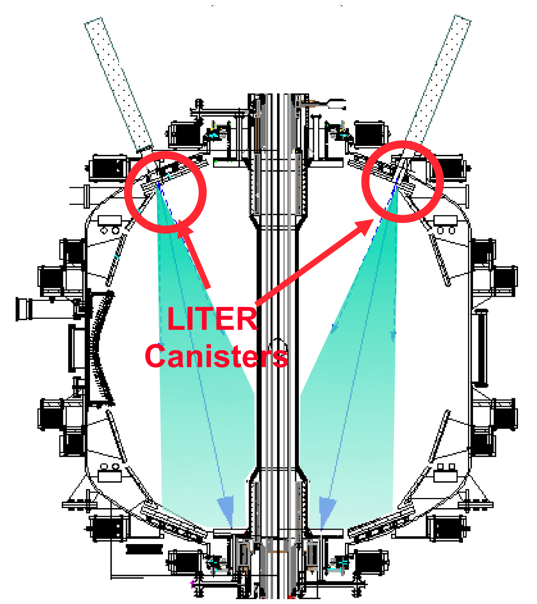
2007: Larger evaporator re-aimed to increase deposition rate on lower divertor

2008: Dual LITERs to eliminate shadowed regions

– Also used "lithium powder dropper"

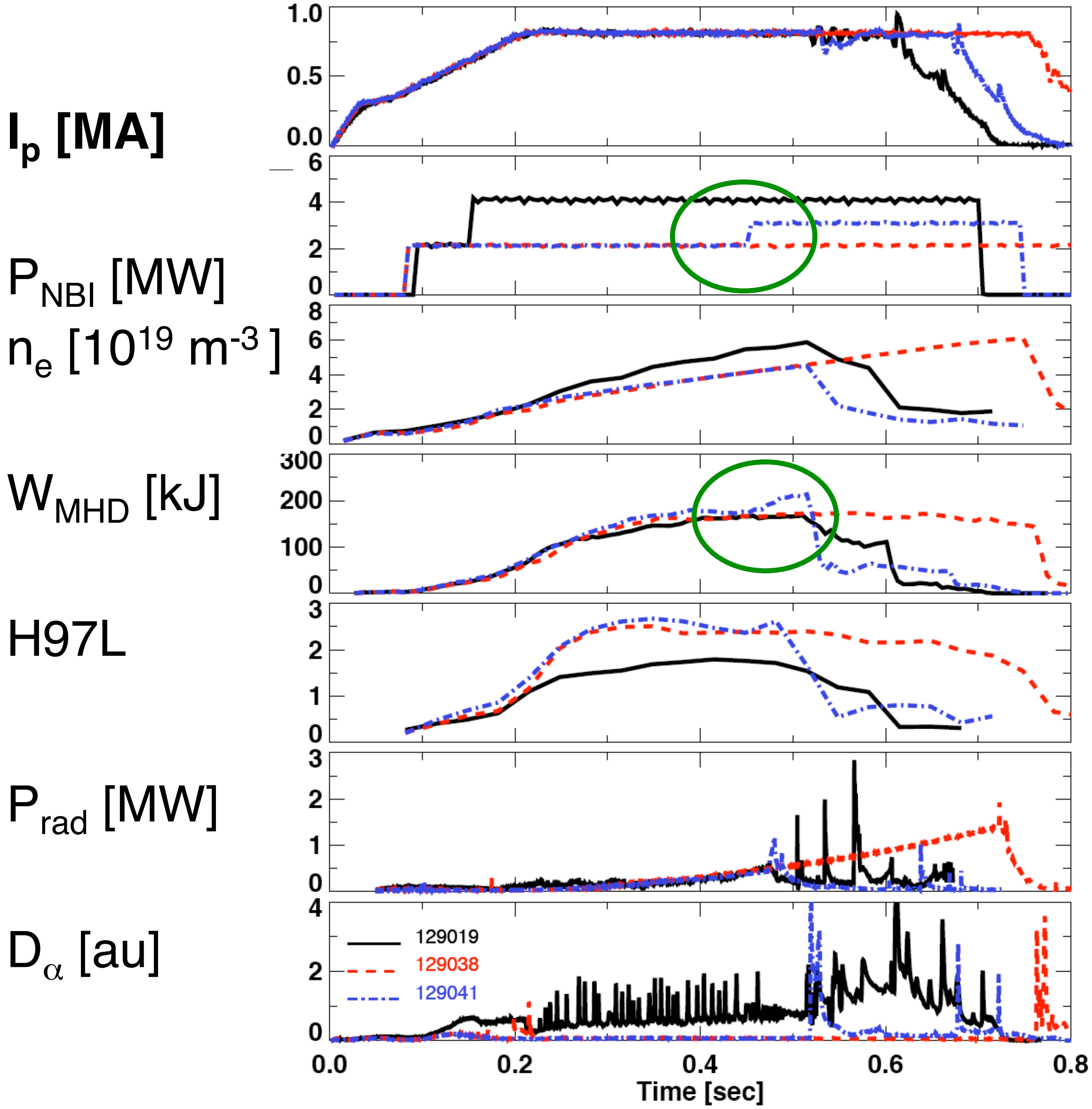
2009: Routine use of dual LITERs

- 80% of discharges now have lithium applied beforehand



- Complements and builds on experience with lithium coating of limiters in tokamaks TFTR, CDX-U (liquid), T-11, FTU, HT-7
  - Now also used in stellarator TJ-II

Global β_N limit encountered before edge stability limit with lithium coatings

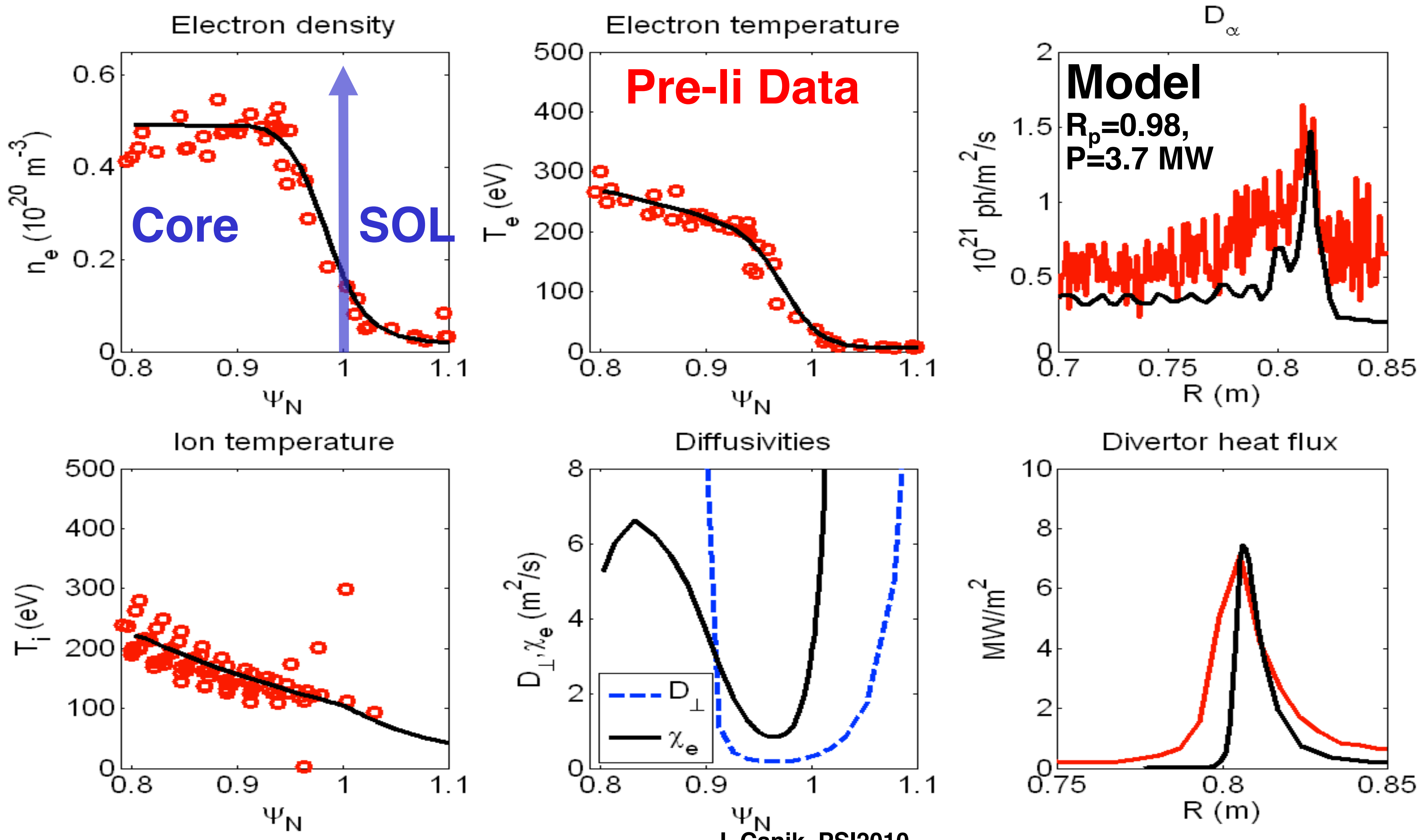


- Pre-Li, Post-li, Post-li at β limit
- Intermediate NBI to probe β limit

- β_N limit ~ 5.5 with P_{NBI}=3 MW

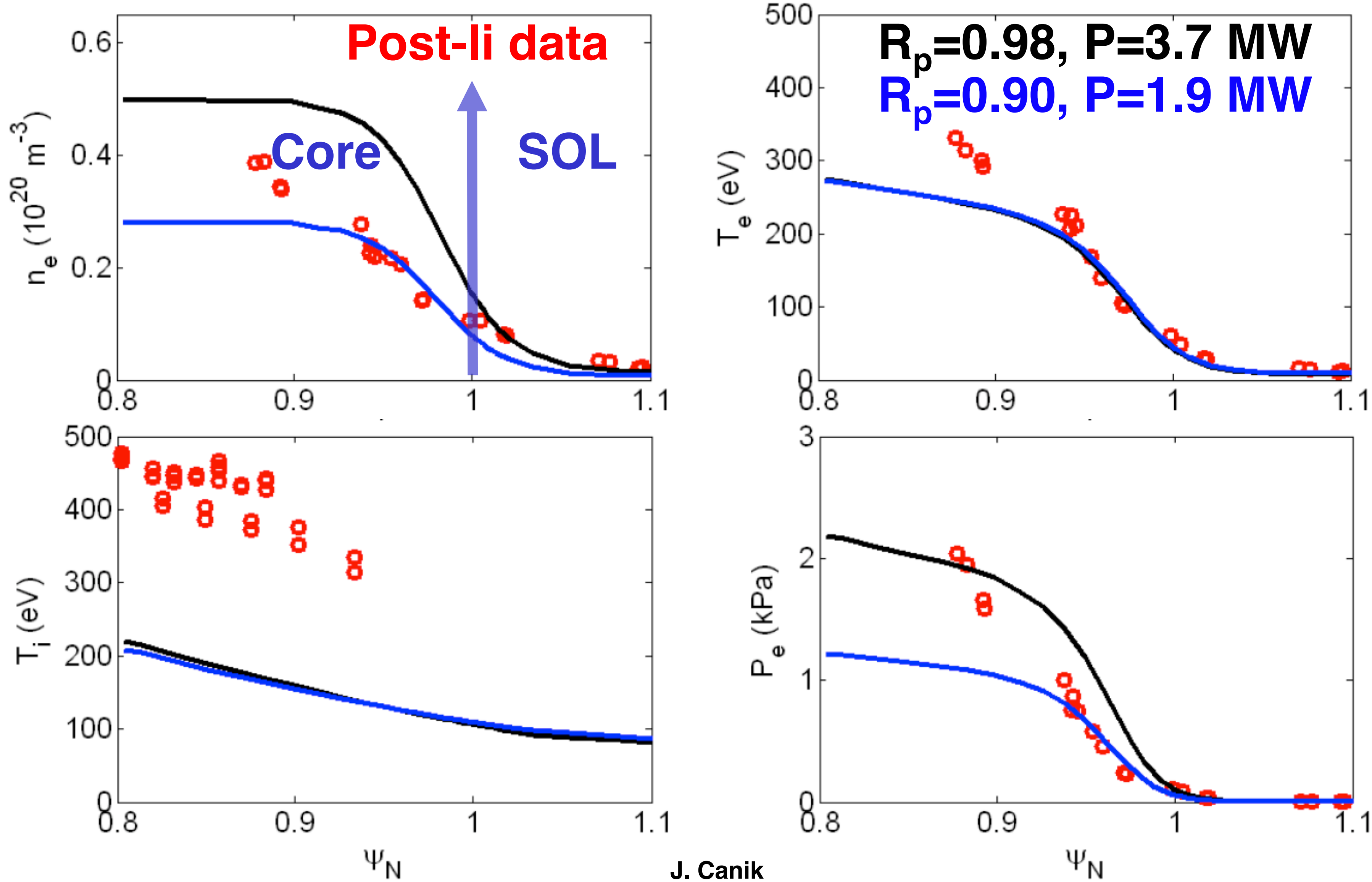
R. Maingi, PRL 2009

SOLPS modeling used to model power and particle balance of baseline ELMy discharge



J. Canik, PSI2010

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



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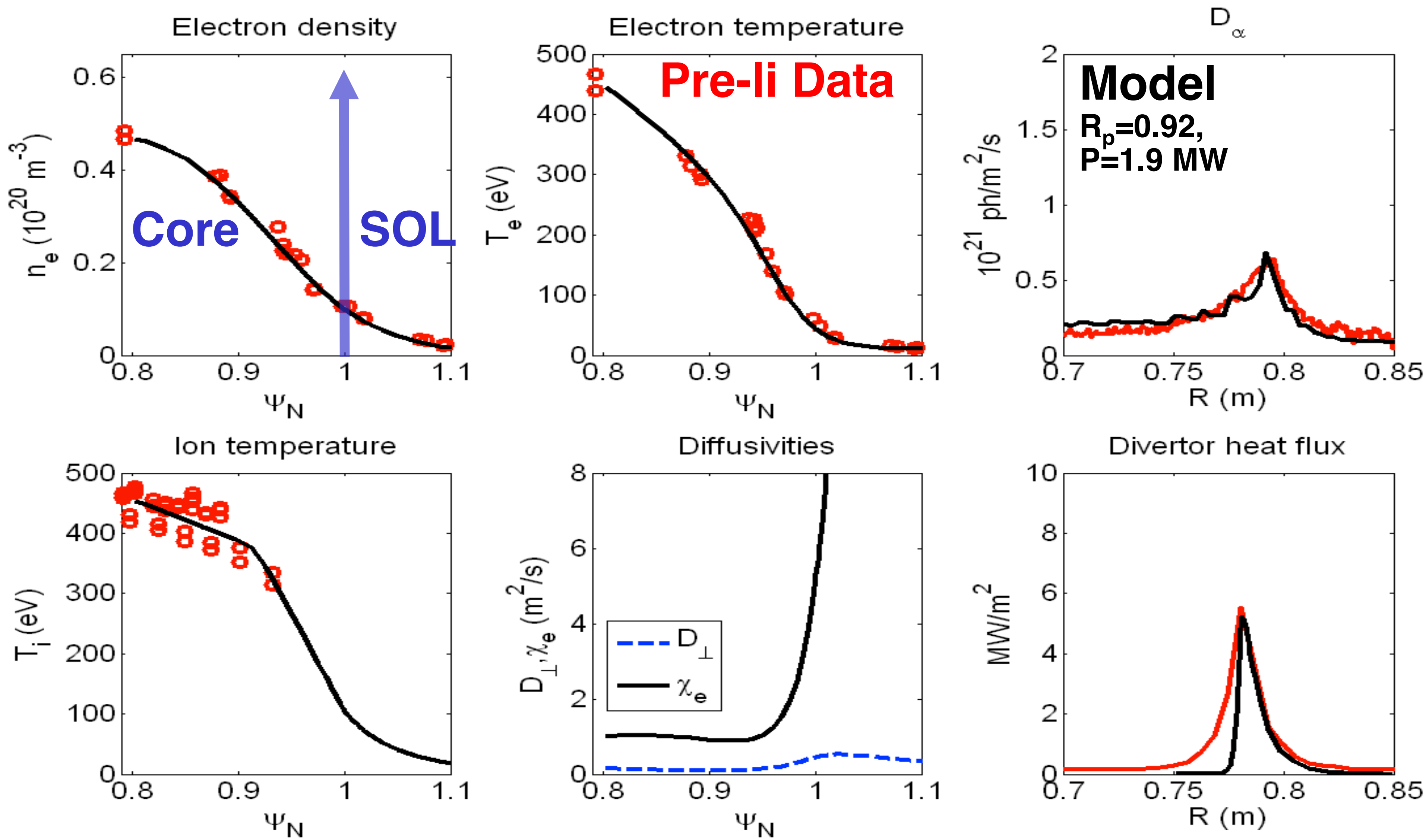
Post-lithium discharge profiles better matched with transport and recycling coefficient change



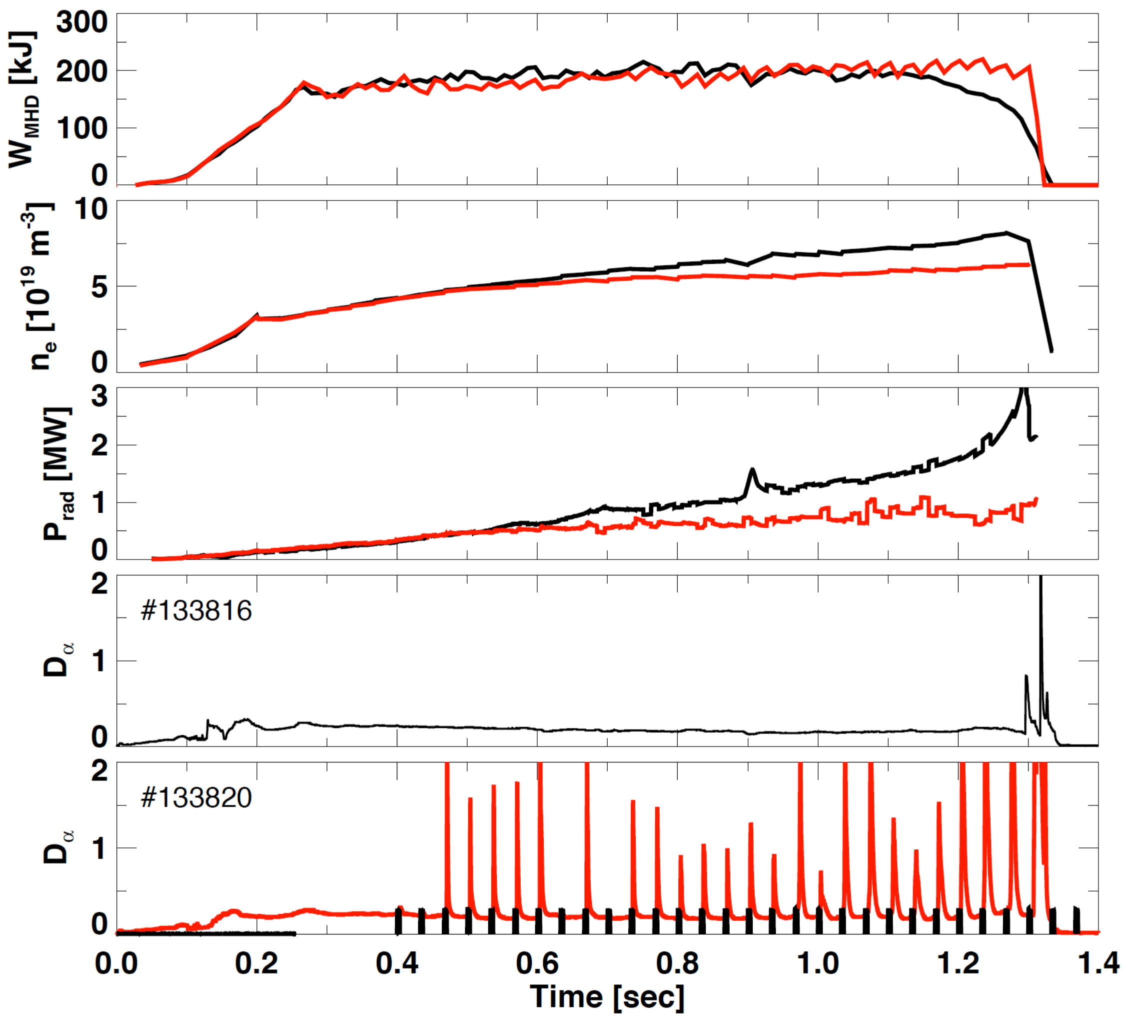
J. Canik

Edge stability analysis procedure

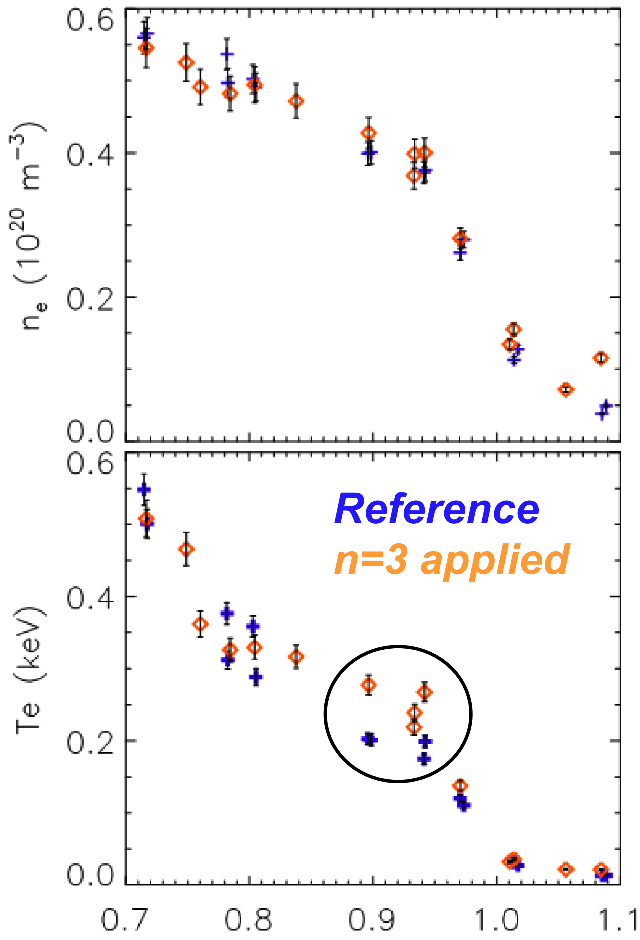
- EFIT run at Thomson profile times for ψ_N mapping
- Profile fitting of multiple time slices with standard procedures used as target for kinetic EFITs
  - Pre-lithium discharge profiles from last 20% of ELM cycle selected
  - Post-lithium discharge profiles used in 100-200 msec windows
- Free boundary kinetic EFITs run to match kinetic pressure 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

3D external fields used to trigger ELMs, prevent radiation buildup while keeping high energy confinement from lithium

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

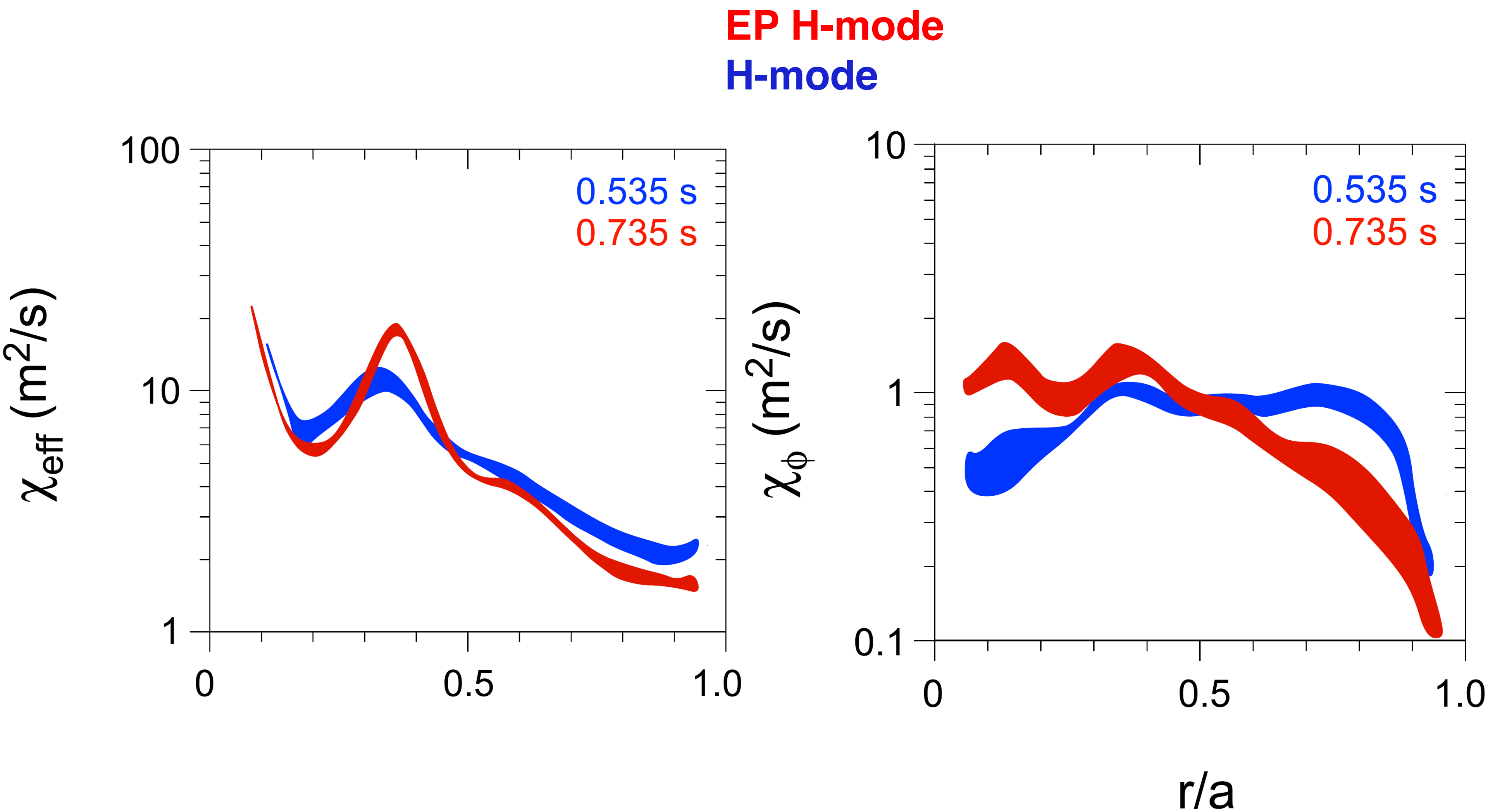


Edge T_e and dT_e/dr increased --> n=3 more unstable (PEST)

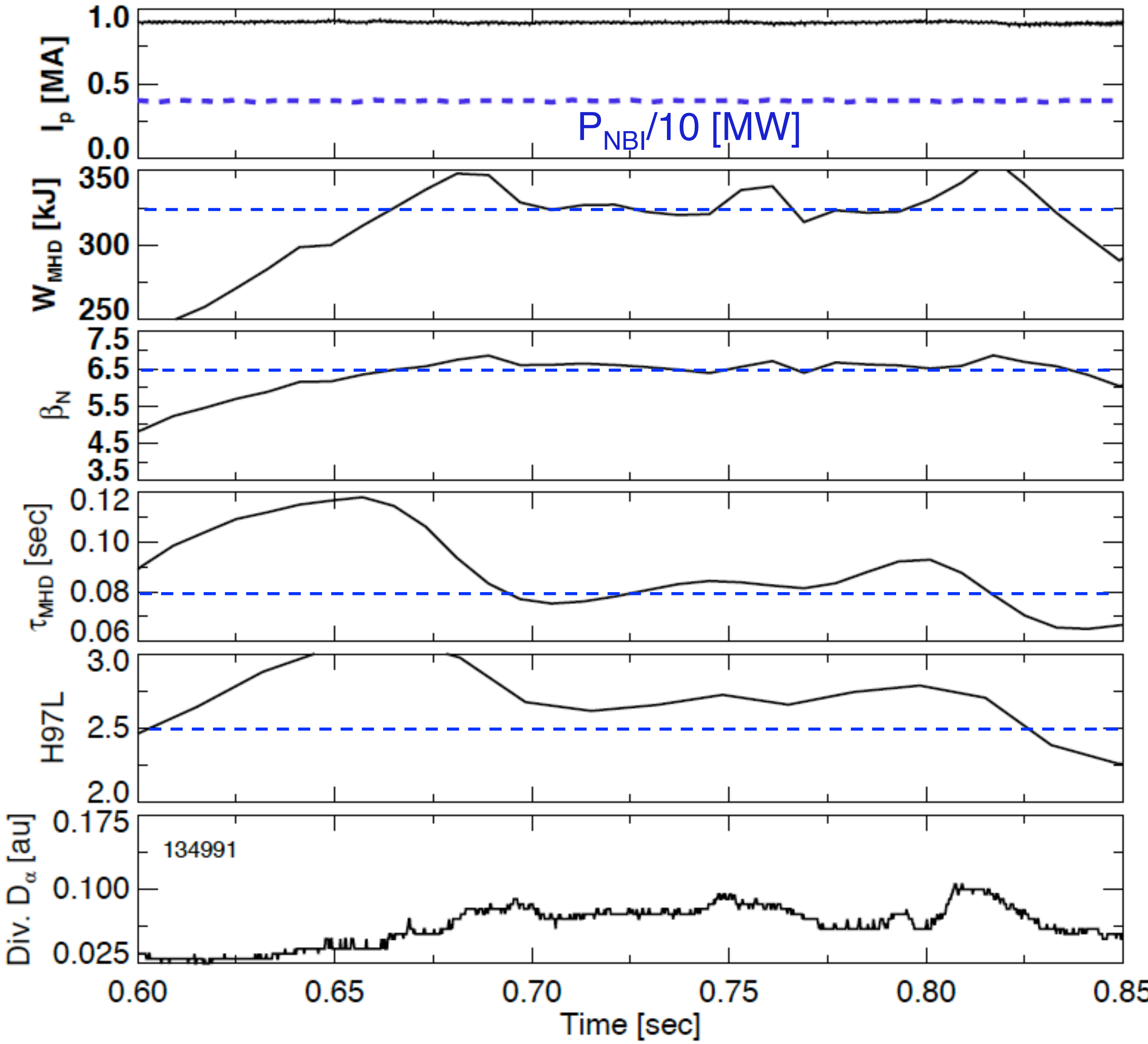


J. Canik, PRL 2010

Thermal and angular momentum transport reduced over outer half of plasma

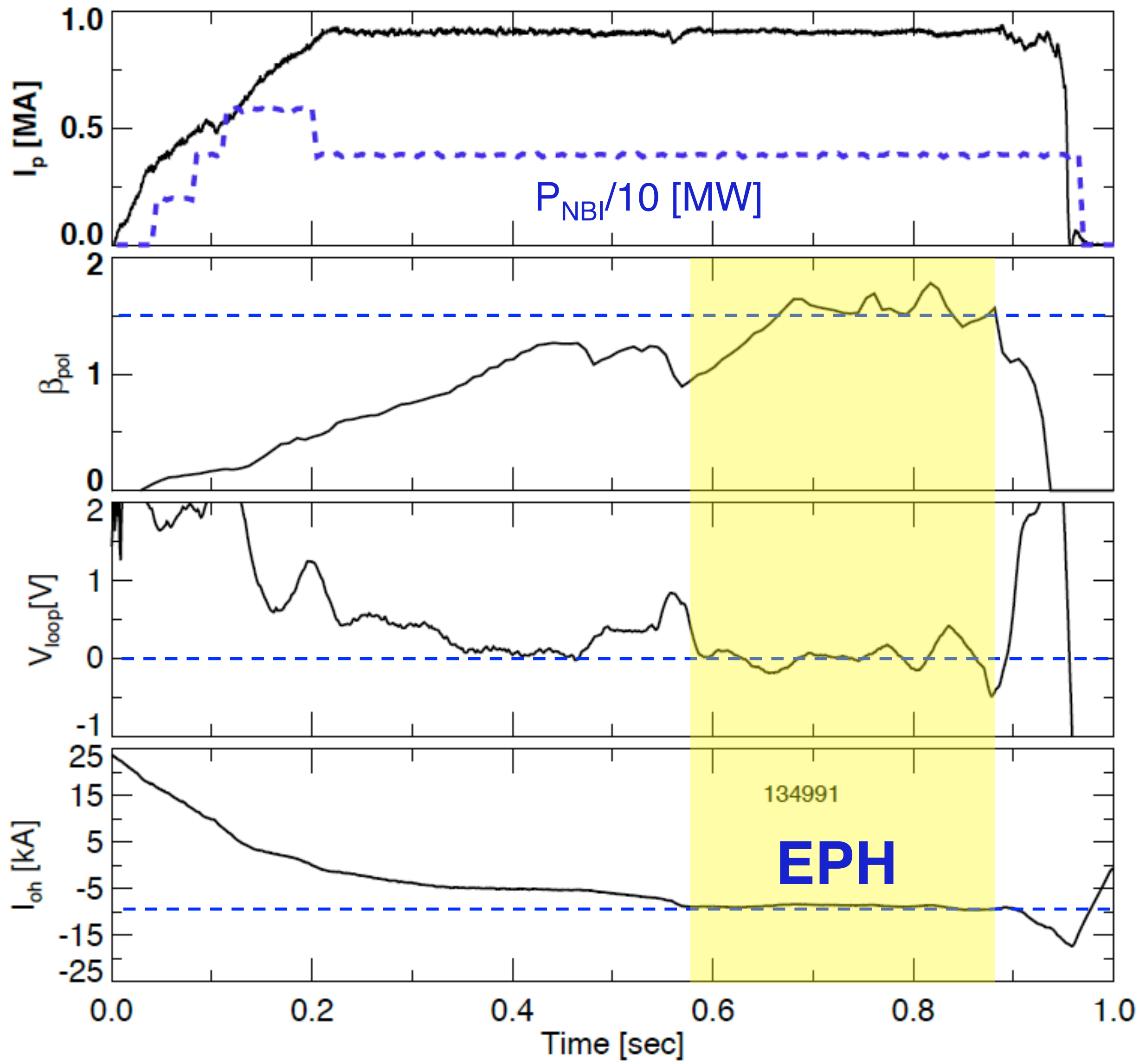


High β_N phase maintained for 2 τ_E



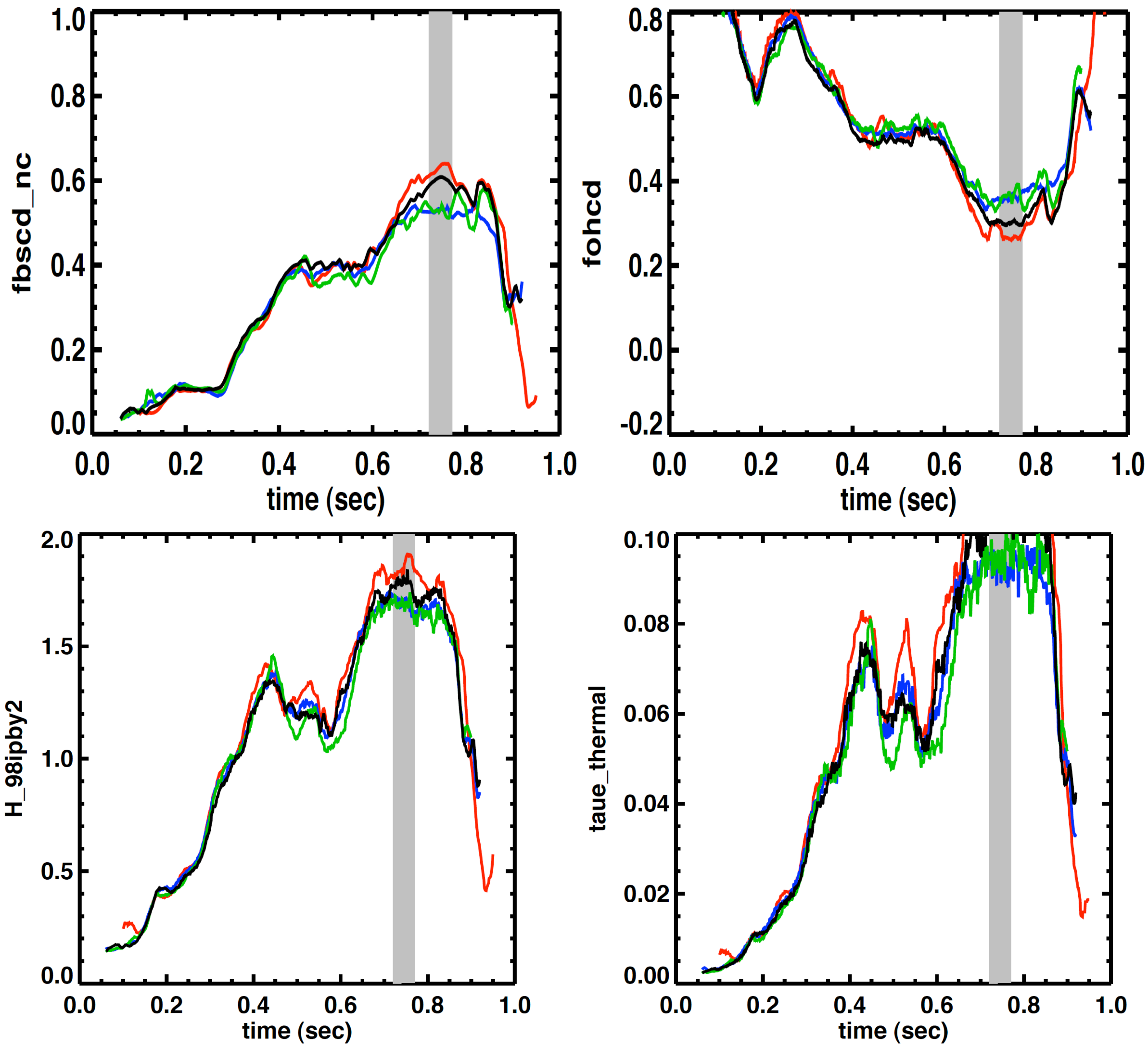
- I_p = 0.9 MA, P_{NBI} = 3.8 MW
- $W_{MHD} \simeq$ 325 kJ
- $\beta_N \sim$ 6.5
- $\tau_E \geq$ 80 msec for 225 msec
- H97L $\geq$ 2.5
- EPH phase is ELM-free

High β_{pol} results in high bootstrap and non-inductive fraction (f_{NI} ~ 0.65 from TRANSP)



- I_p = 0.9 MA, P_{NBI} = 3.8 MW
- β_p ~ 1.5, very high for 0.9 MA
- Loop voltage low during EPH, due to high bootstrap
- Very little or no flux consumption

High bootstrap and non-inductive fractions, high thermal τ_E during EPH phase



- f_{bs} between 0.5-0.6, and f_{NI} between 0.6-0.7
- H98y2 between 1.6 and 1.8, with τ_E^{th} between 90-100 msec

S. Gerhardt, S. Kaye

Long pulse EPH – density still evolving slowly, Z_{eff} rising, but P_{rad} seems reasonable