Effect of low-Z Impurities on H-mode Pedestal Structure, Performance, and ELMS

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Acknowledgements: A. Bortolon, J. Canik, M. Dunne, J.S. Hu, R. Majeski, T. Osborne, P. Snyder

ITER School on Pedestal Physics
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Outline

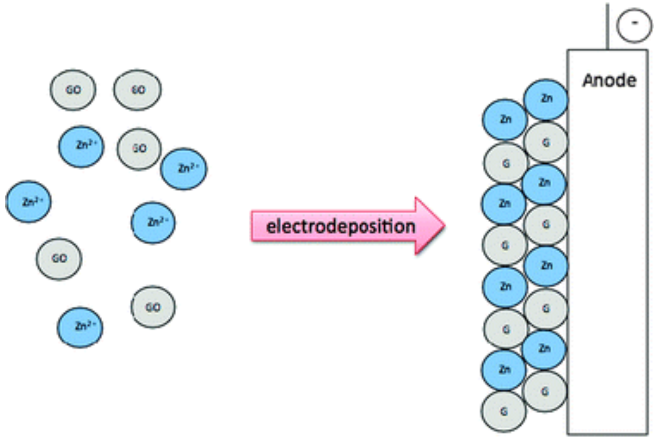
- Pedestals with carbon walls and high-Z walls
  - Brief history of PFC materials in fusion devices

- Purposeful introduction of low-Z
  - Real time injection with gas/aerosol [JET, AUG, DIII-D, EAST]
  - Inter-discharge Coatings (lithium, (boron)) [NSTX, (LTX, C-Mod, EAST)]
  - Real-time injection with pellets [DIII-D, (EAST)]
  - Low-Z liquid metal PFCs: static, flowing [(LTX, FTU), EAST]

- Prospects and open questions

Tritium retention is strongly affected by choice of PFC materials

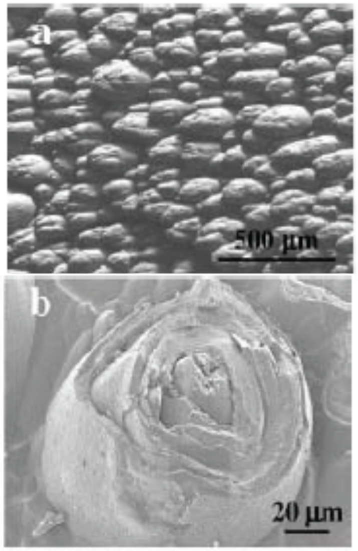
- Graphite was PFC of choice in 90's, but it captures hyrogenic species via unsaturable co-deposition
  - e.g. Graphene & Zn shown on right



- C advantages
  - Good power handling, good thermal shock and thermal fatigue resistance (low crack propagation)
  - Doesn't melt (but sublimes), low radiated power
  - Good joining technology, low-Z
- C disadvantages
  - Chemical erosion and co-deposition; dust generation
  - May require conditioning
  - Physical and mechanical properties degrade w/low neutron fluence

G. Federici, Nucl. Fusion **41** (2001) 1967

Co-deposits in Tore Supra



P. Roubin, J. Nucl. Mater. **390-391** (2009) 49

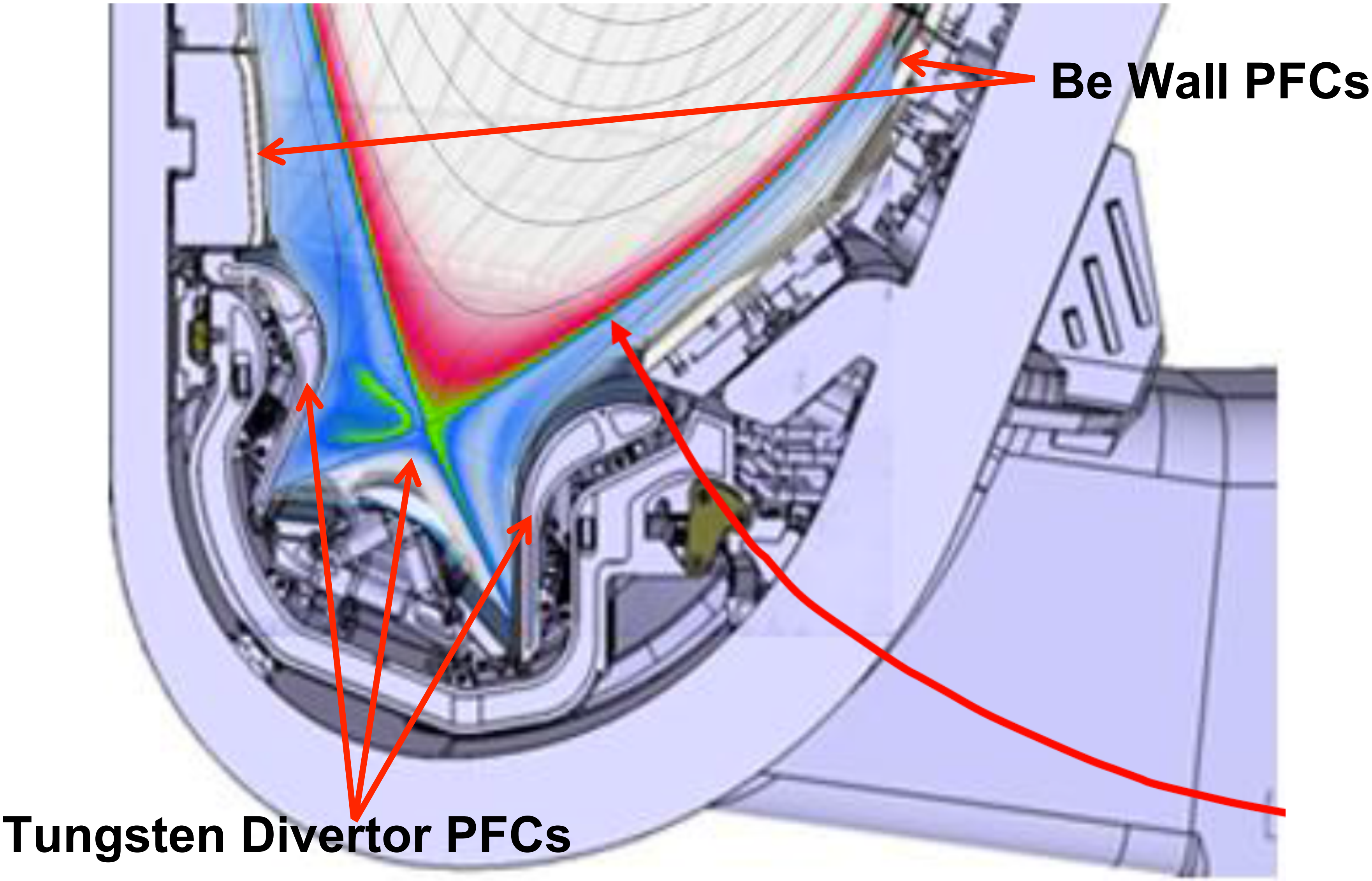
Tungsten chosen for divertor & beryllium chosen for wall PFCs of ITER

- Tungsten advantages
  - Low in-vessel tritium retention (at T $\leq$ 500 ^{o}C)
  - Low physical sputtering yield with a high energy threshold
  - No chemical sputtering with hydrogen
  - Reparable by plasma spray; good joining technology

- Tungsten disadvantages
  - Low allowable core concentration
  - Melts under large transient loads
  - High ductile-brittle transition temperature (DBTT), which increases with neutron damage
  - Recrystallizes, becomes brittle at temperatures >1500 K
  - High activation
  - Blisters and generates ‘fuzz’ under He bombardment
  - Confinement reduced in tokamaks as compared with carbon PFCs

G. Federici, Nucl. Fusion **41** (2001) 1967

ITER divertor is "W"-shaped, with tungsten divertor and Beryllium wall plasma facing components



Plasma facing surfaces in present and past tokamaks

Device	Lim/ Div	PFC mat'l	Device	Lim/Div	PFC mat'l
JET (2010+)	Divertor	W div. & Be wall	JET(-2009)	Divertor	Carbon
AUG(2007+)	Divertor	W divertor & wall	AUG(-1999)	Divertor	Carbon
C-Mod	Divertor	Mo divertor & wall	DIII-D	Divertor	Carbon
NSTX	Divertor	C Wall/Li coating	NSTX-U plan	Divertor	High-Z + Liq. Li
EAST	Divertor	W upper, Mo wall, C lower, Li coat	KSTAR	Divertor	Carbon
JT-60U	Divertor	Carbon	TFTR	Limiter	Carbon
Tore Supra	Limiter	Carbon	WEST	Divertor	W wall
MAST-U	Divertor	Carbon	COMPASS	Divertor	Carbon
RFX	Limiter	Liq. Li - Mo mesh	LTX	Limiter	Liq. Li on SS

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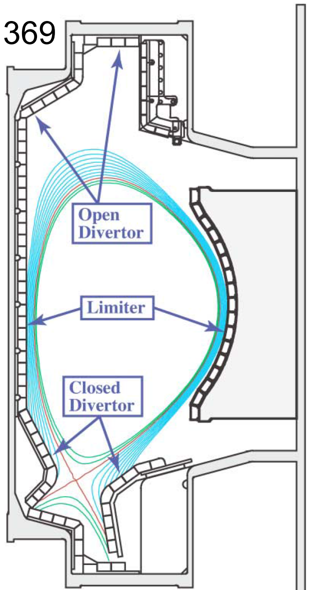
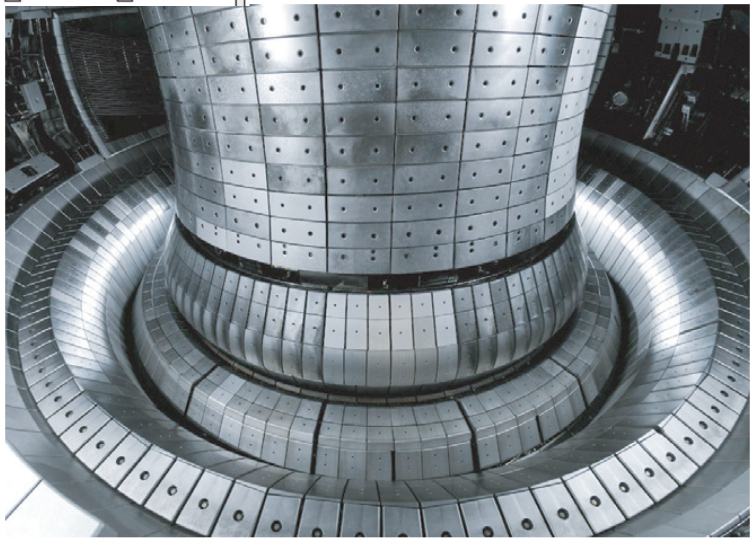
C-Mod and ASDEX-U experience with high-Z PFCs

- C-Mod experience
  - Started with solid Mo tiles
  - Mostly good, but damage does not ‘repair’ itself
- AUG experience
  - W changed in stepwise fashion from 1999-2007
  - W coatings (4 μm PVD main chamber, 200 μm VPS divertor) on fine grain graphite
  - Delamination occurred for high power;
  - Divertor re-coated with 10 μm W on 4 μm Mo via PVD

B. Lipshultz, FST **51** (2007) 369



J. Coenen, JNM **438** (2013)



R. Neu, Phys. Scr. **T138** (2009) 014038

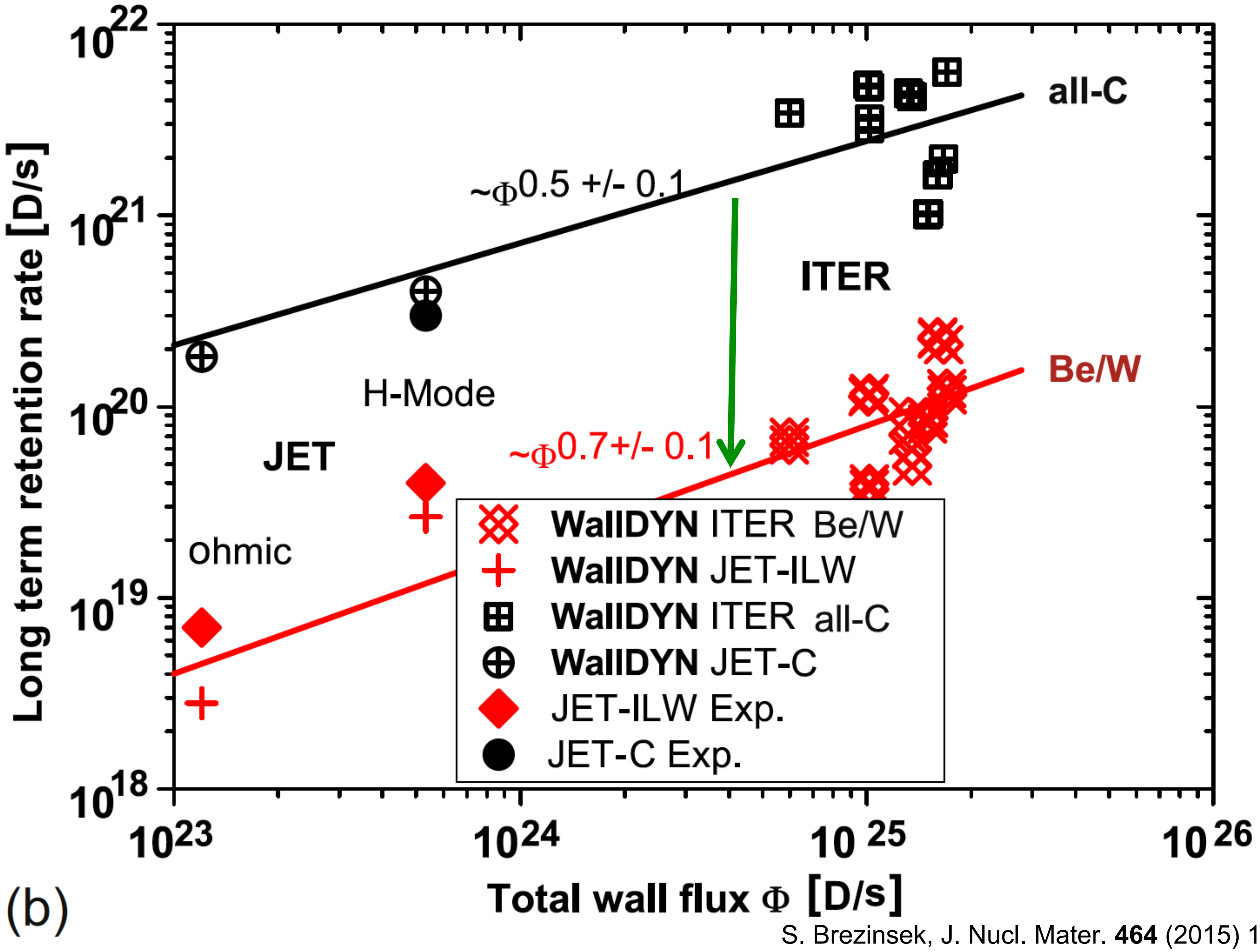
Picture of JET with carbon and then ITER-like wall

Carbon PFCs
(pre-2009)

ITER-like wall PFCs
W in divertor
Be on the wall
(2010+)

S. Brezinsek, J. Nucl. Mater. **464** (2015) 11

Long term deuterium retention reduced ~10-20x in JET with ITER-like wall (also in AUG and C-Mod), but…

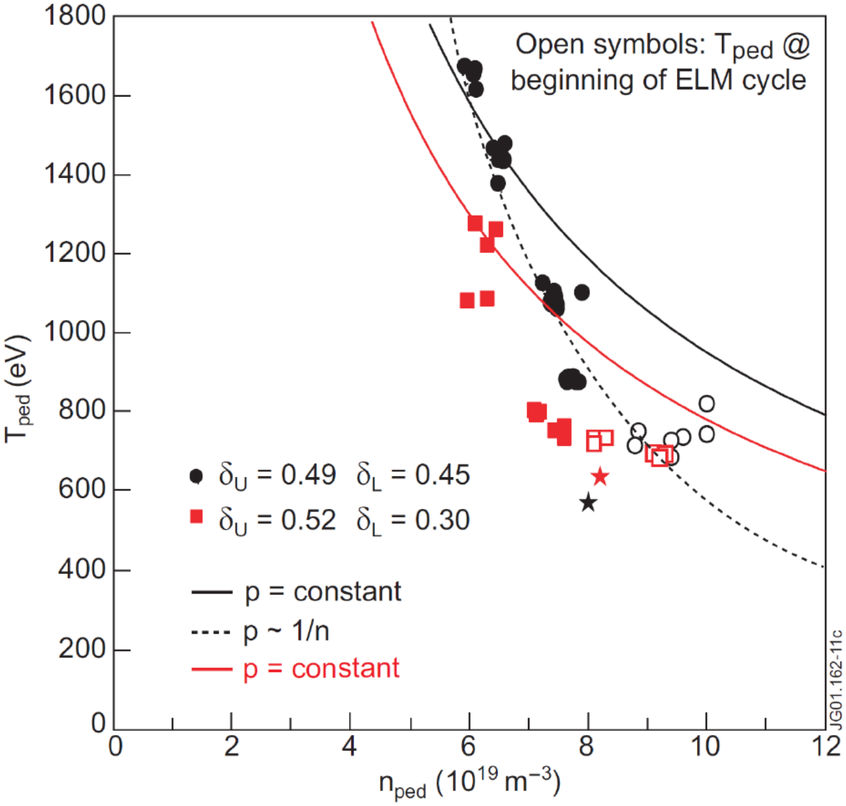


S. Brezinsek, J. Nucl. Mater. **464** (2015) 11

Edge pedestal T_e reduced in JET with increasing density in both the carbon and ITER-like wall

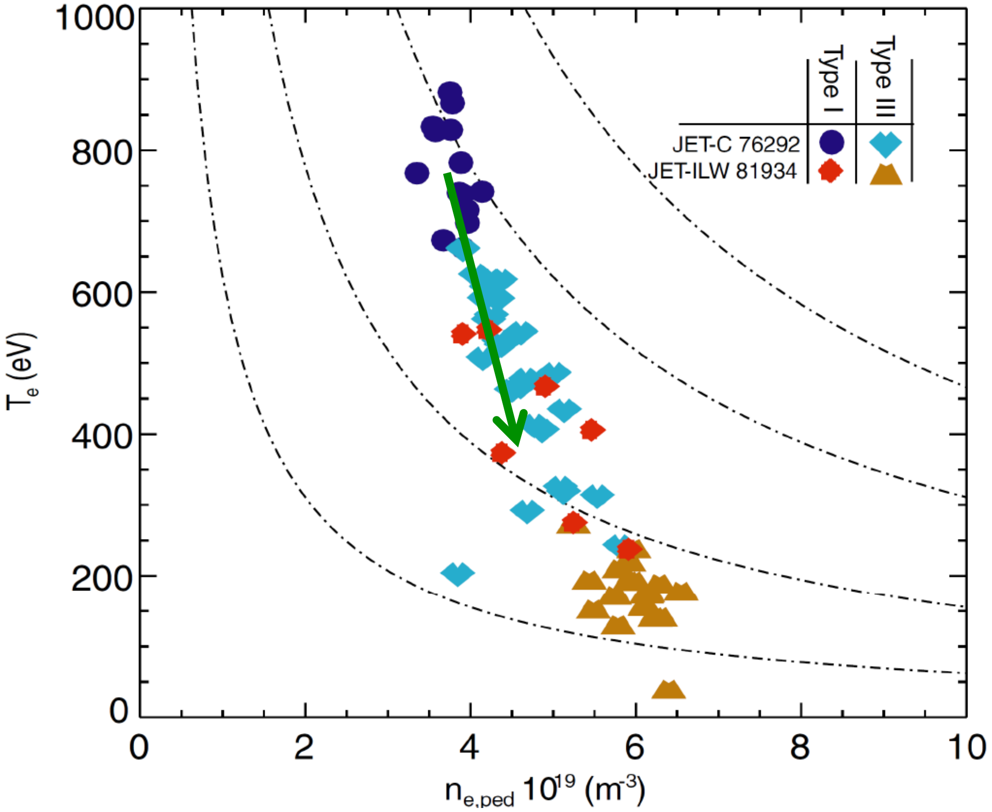
- Additional pedestal T_e reduction in JET-ILW vs. JET-C

JET-C



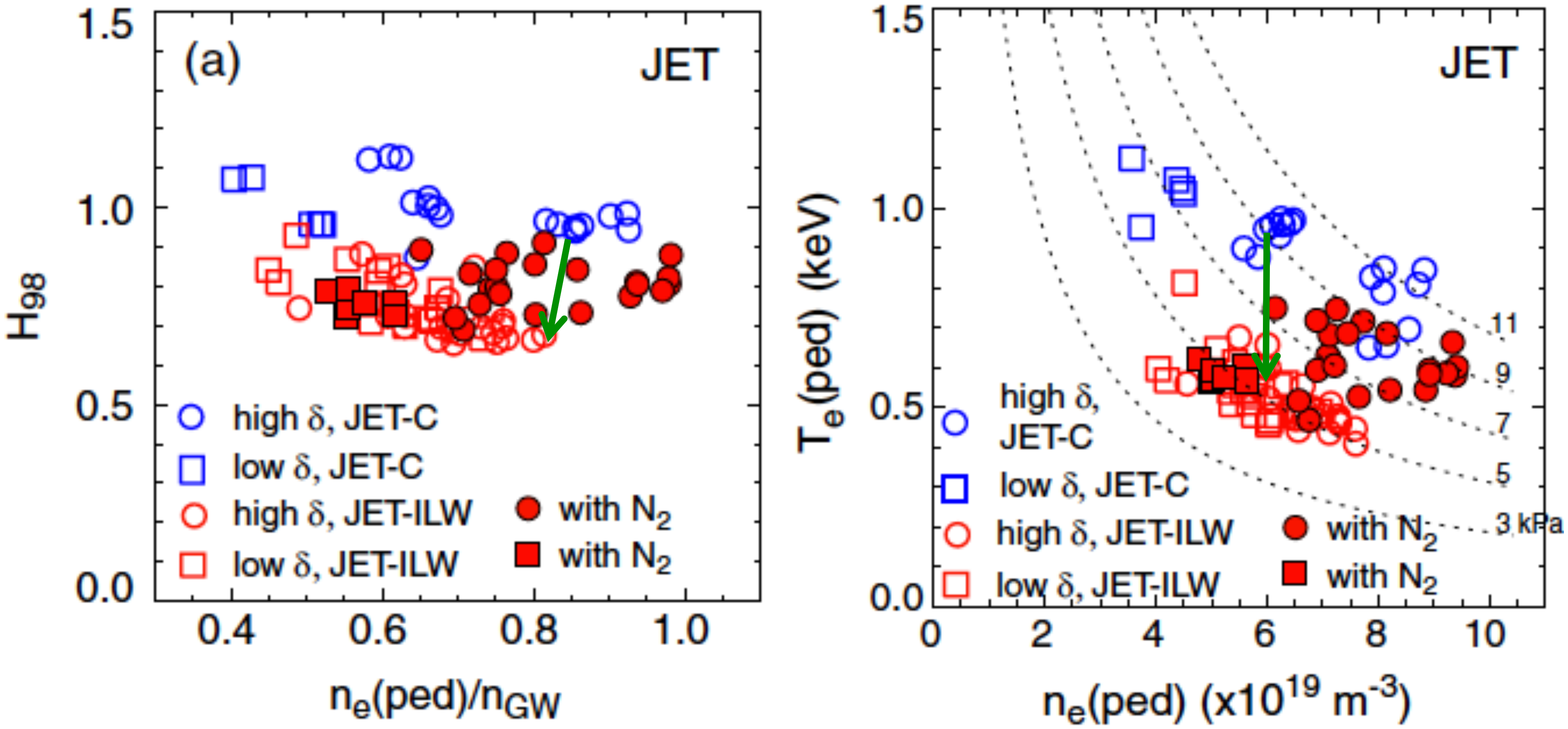
G. Saibene, PPCF **44** (2002) 1769

JET-ILW



M. Beurskens, NF **54** (2014) 043001

Edge and core plasma confinement in JET scenarios was reduced with installation of ITER-like wall

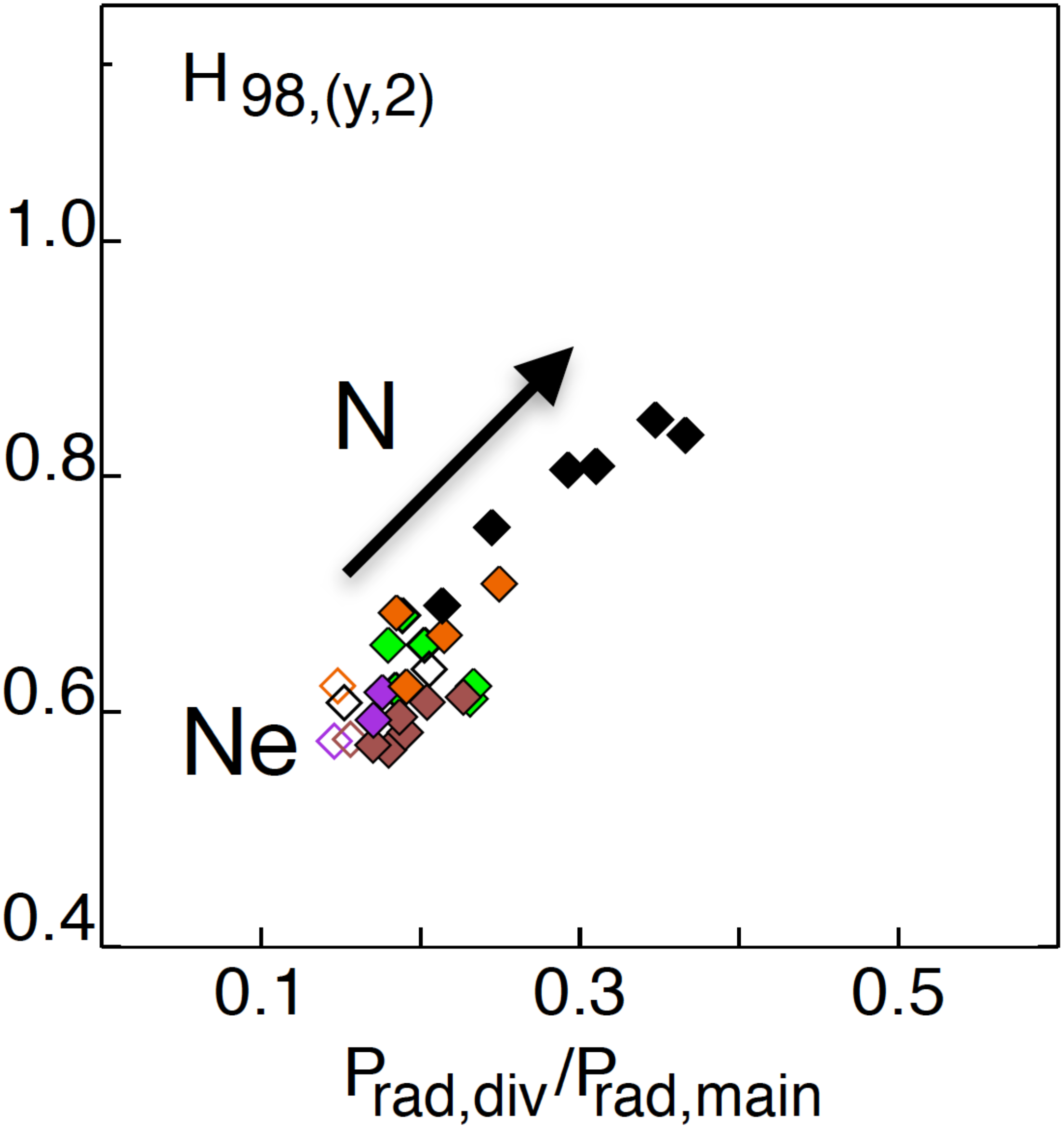


- Partial performance recovery with N_2 seeding
- Less favorable results with Ne
- Projected performance less than in 1990’s D-T experiment -> will need to increase the NBI heating power for JET DT 2018+

M. Beurskens, PPCF **55** (2013) 124013

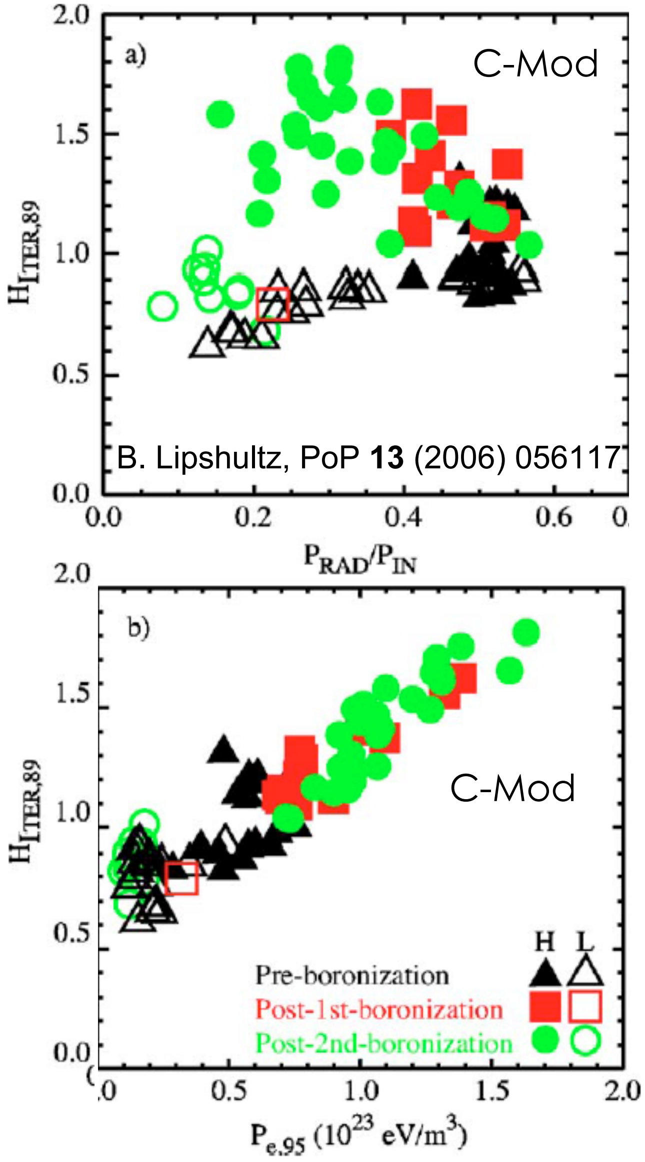
Nitrogen seeding improves pedestal performance in JET

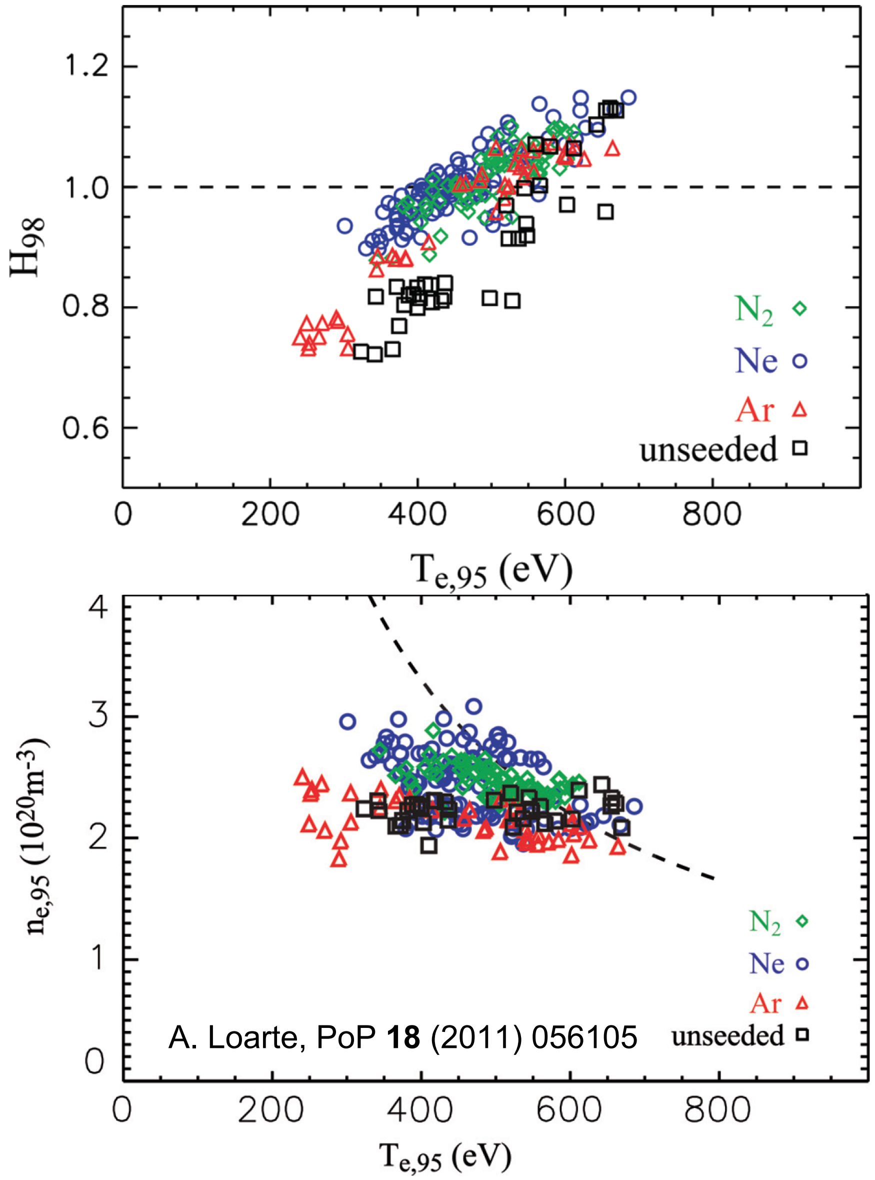
- N_2 seeding increases pedestal pressure, even if not limited by P/B modes
- N_2 seeding $\nu_{e,ped}^*$, while Ne seeding increases $\nu_{e,ped}^*$
- Hypothesis: Ne radiates inside separatrix and changes pedestal dynamics directly



C. Giroud, H-mode WS, Oct. 2015

H-factor also reduced in C-Mod without conditioning; Boronization or N_2 seeding can recover some or all H-factor


B. Lipshultz, PoP **13** (2006) 056117


A. Loarte, PoP **18** (2011) 056105

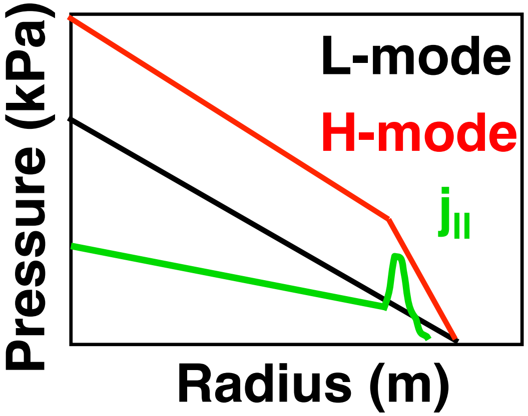
Brief background on edge stability calculations (see edge stability theory in lecture by P.B. Snyder)

- ELMs appear to be the consequence of violating ideal or resistive magneto-hydrodynamic stability limits

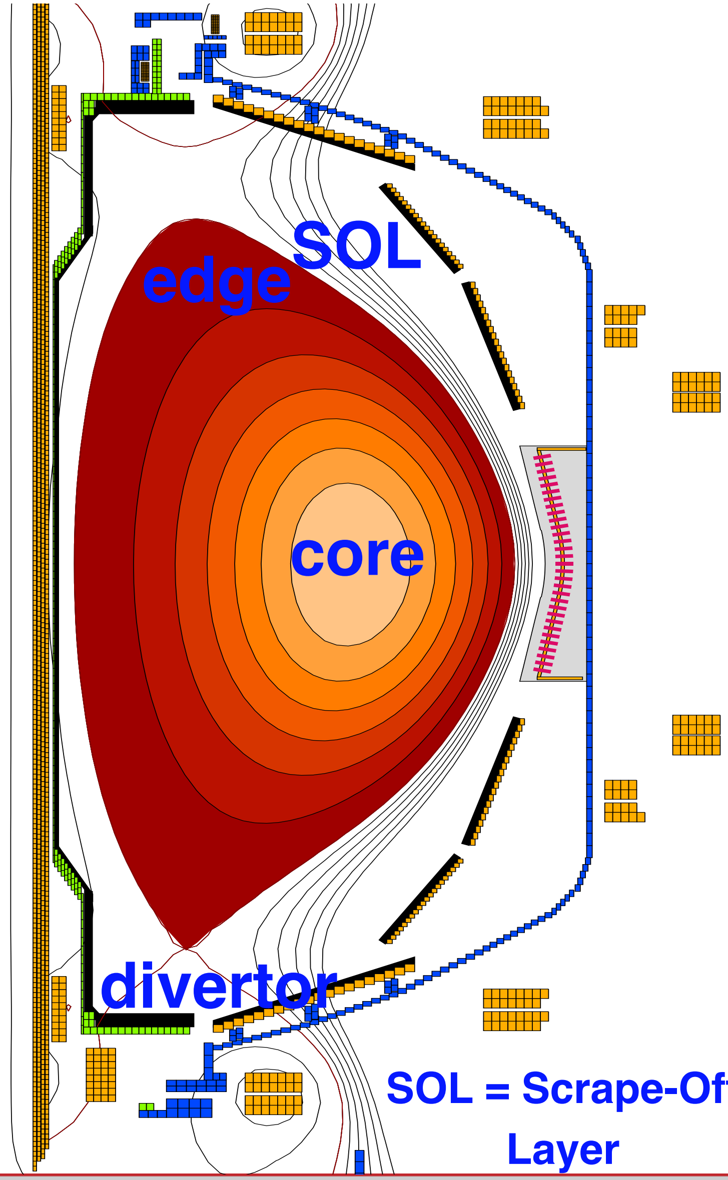
- ELMs expel up to 20% of the plasma stored energy in less than one ms, resulting in 10x or larger increases in the peak divertor heat flux

Edge Localized Modes (ELMs) appear to be violations of ideal or resistive MHD stability limits

- Plasmas undergo a transition from low (L-mode) to high (H-mode) when enough heating power is added
- The edge plasma pressure develops a stair-step or "pedestal" in H-mode



- The steep edge pressure gradient and/or edge current can destabilize Edge Localized Modes (ELMs), where a portion of the pedestal pressure and energy is periodically expelled



SOL = Scrape-Off Layer

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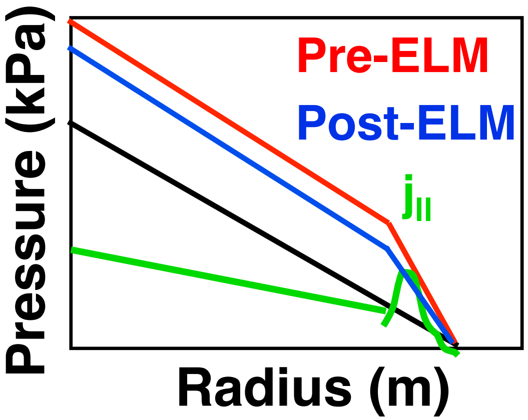

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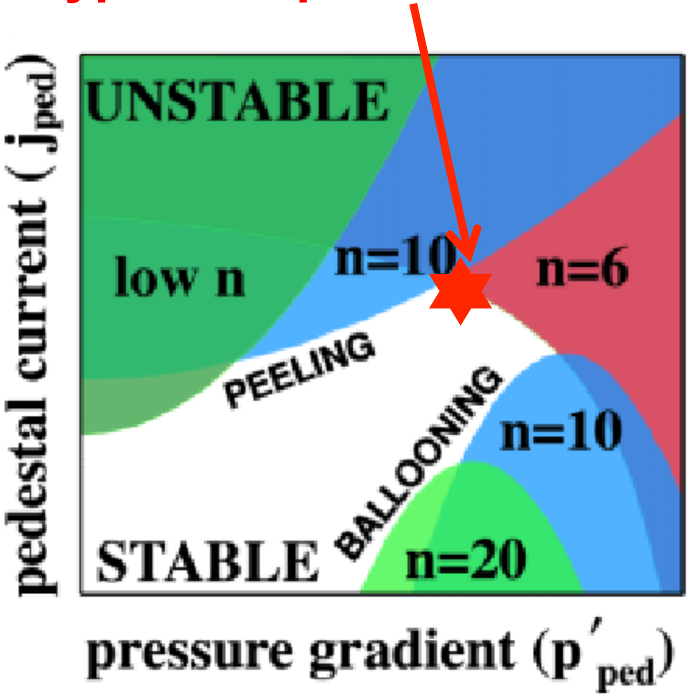
Typical Experimental Data



Courtesy of P.B. Snyder

ELMs expel particles and energy from the low field side, which is prone to ballooning-type pressure driven modes

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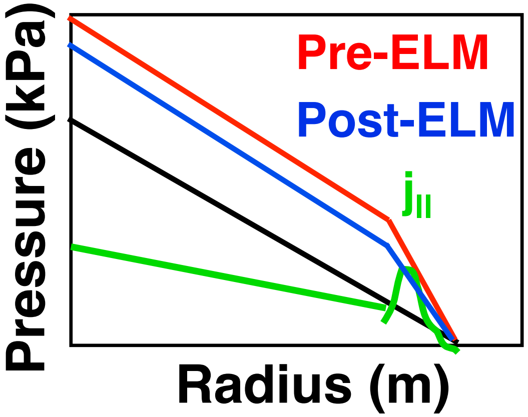

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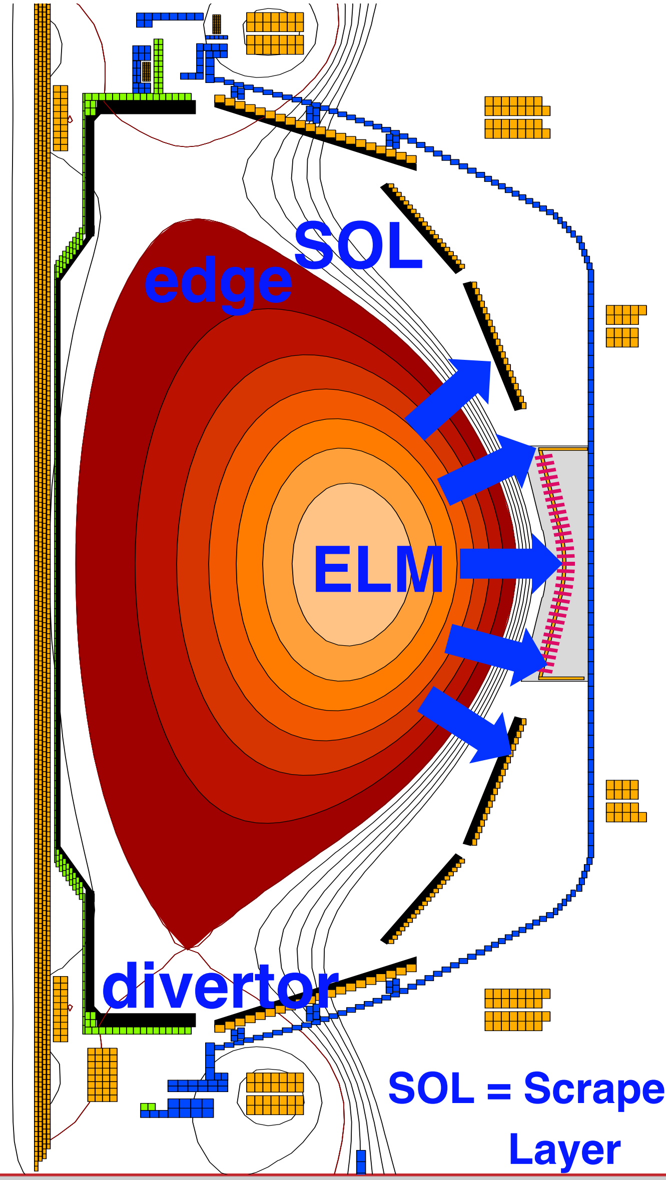

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Power and particle fluxes from ELMs are transported to divertor

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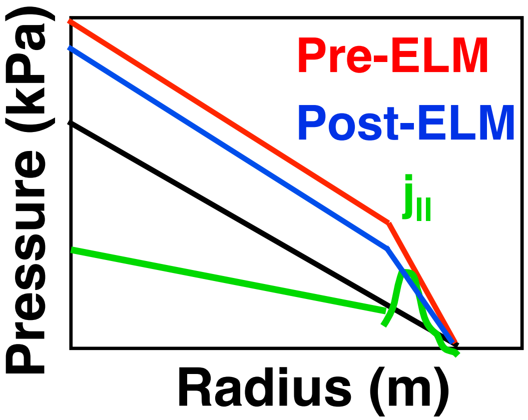

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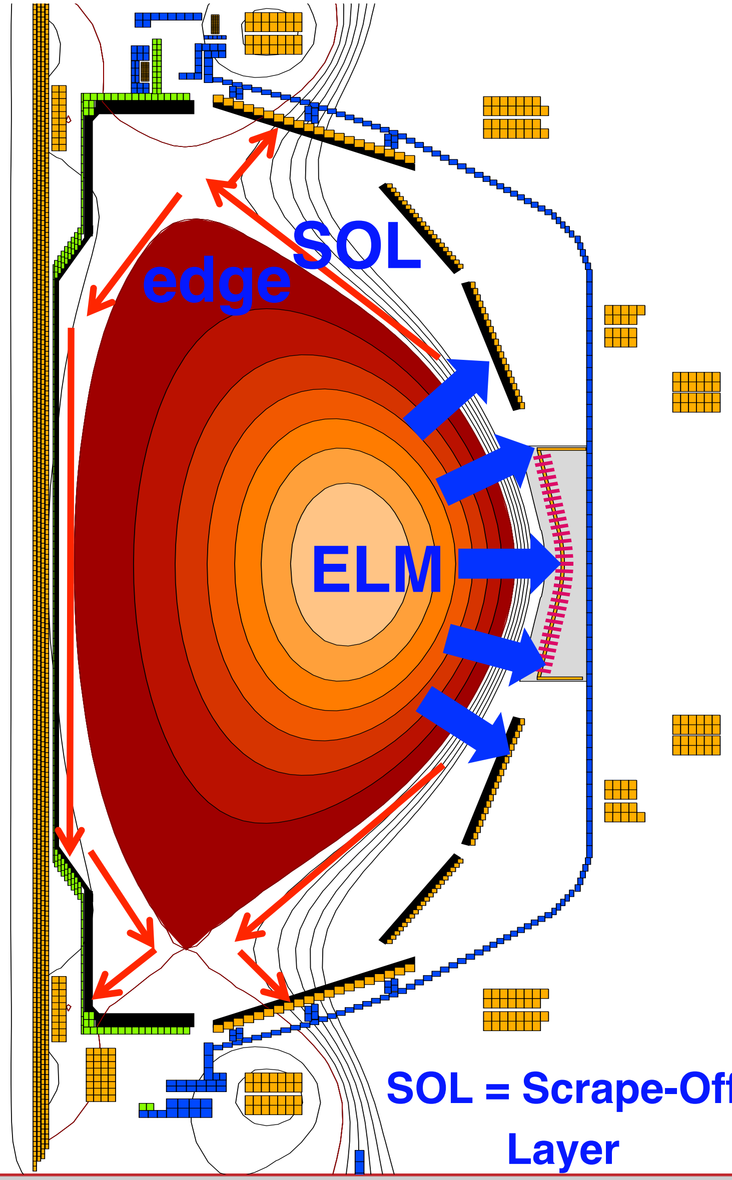
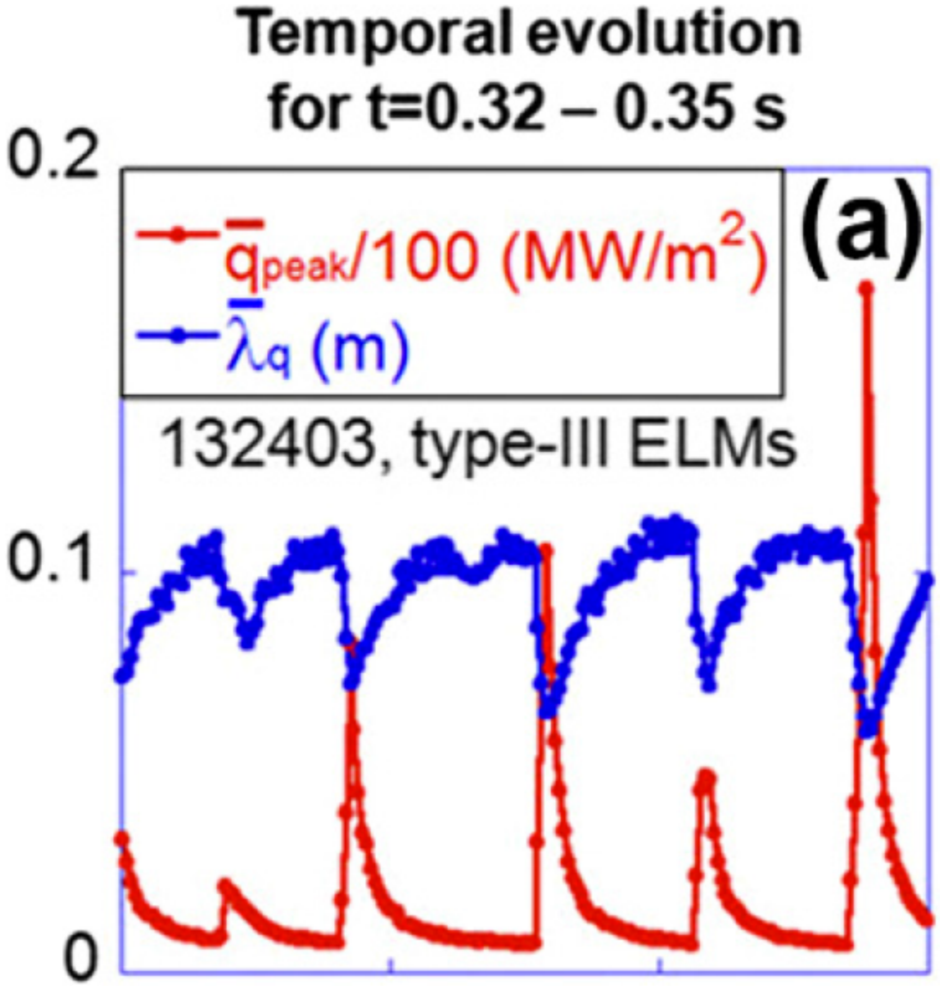
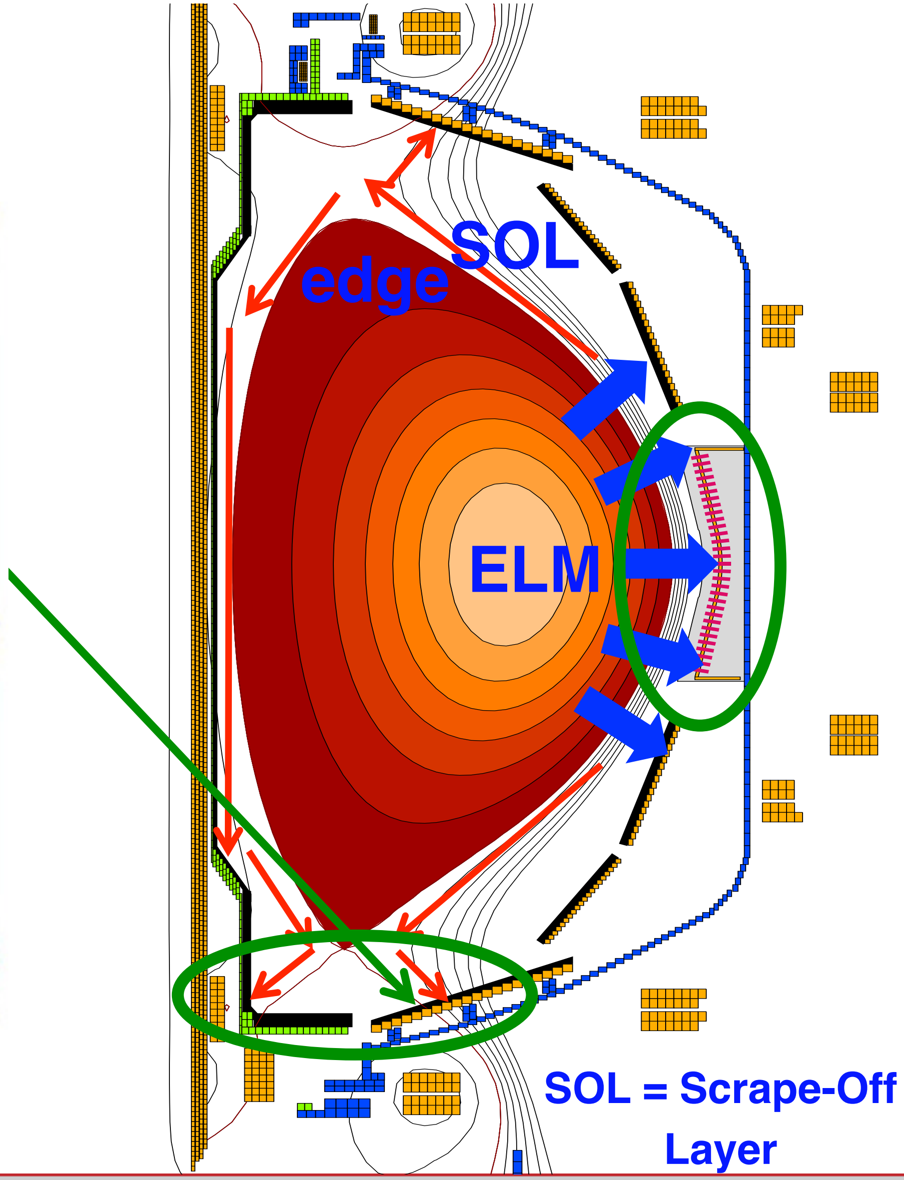


SOL = Scrape-Off Layer

Power and particle fluxes from ELMs on outer wall and divertor are 10 times higher than steady inter-ELM fluxes



J.W. Ahn, J. Nucl. Mater. **438** (2013) S317

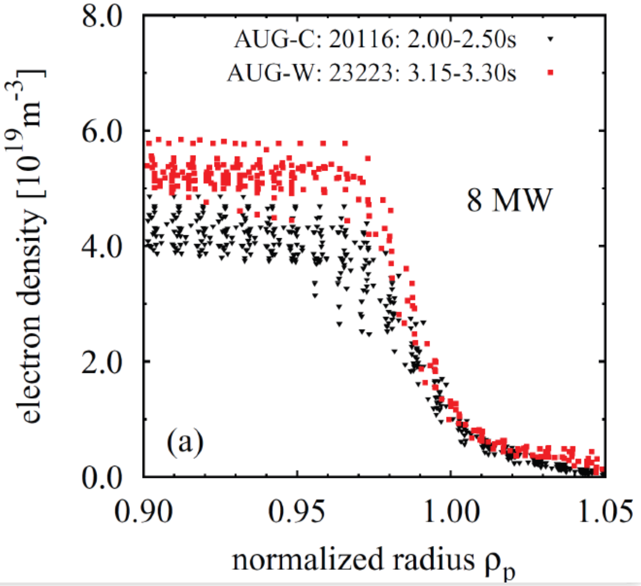


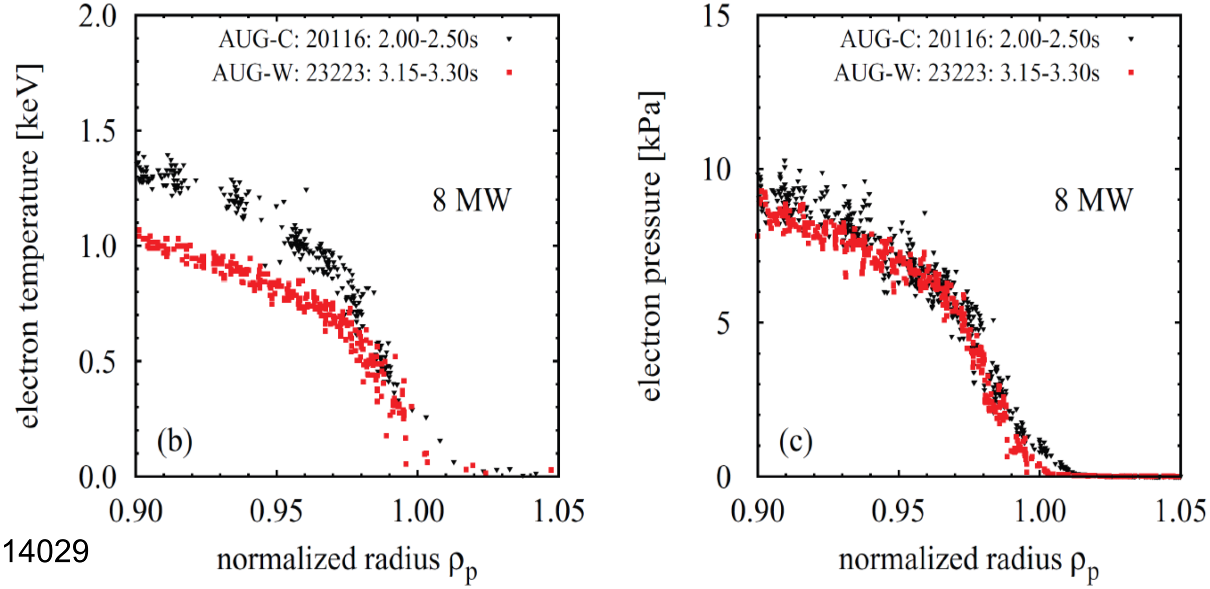
SOL = Scrape-Off Layer

ASDEX-U studies with W wall and N_2 injection

AUG naturally operates at higher n_e, lower T_e with W wall (zero extra fueling, no seeding)

- Zero fueling comparison in AUG shows higher n_e, lower T_e, same P_e with W wall
- H-factor reduction because there is no observed increase of H with n_e, as comes from the H98 scaling law

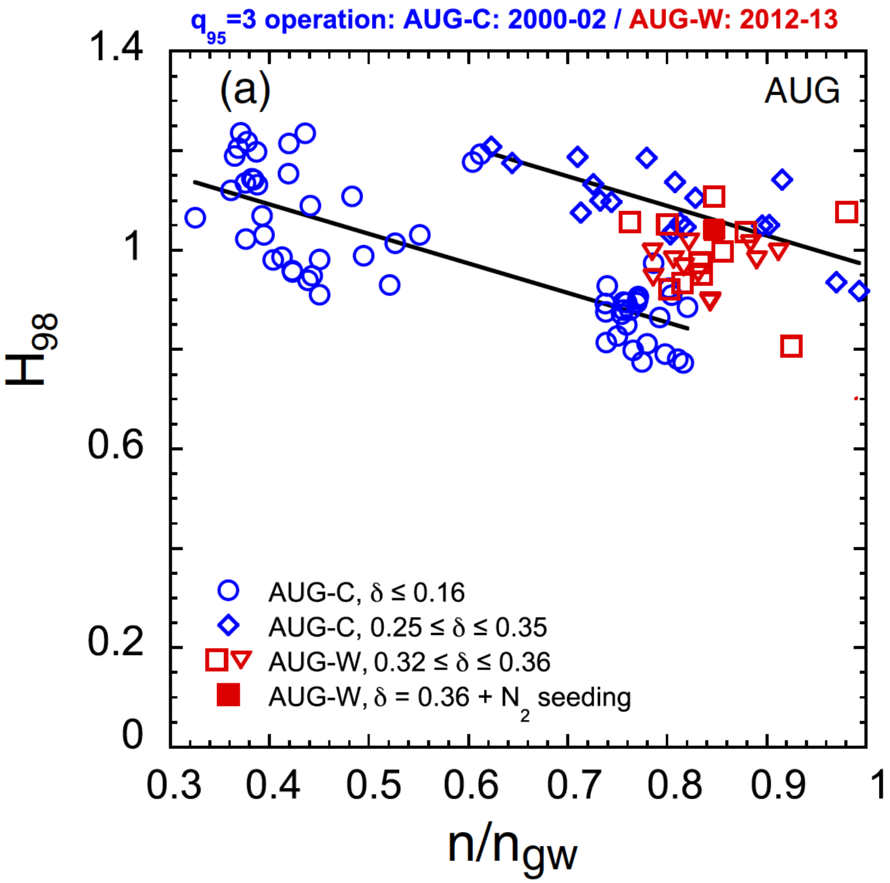




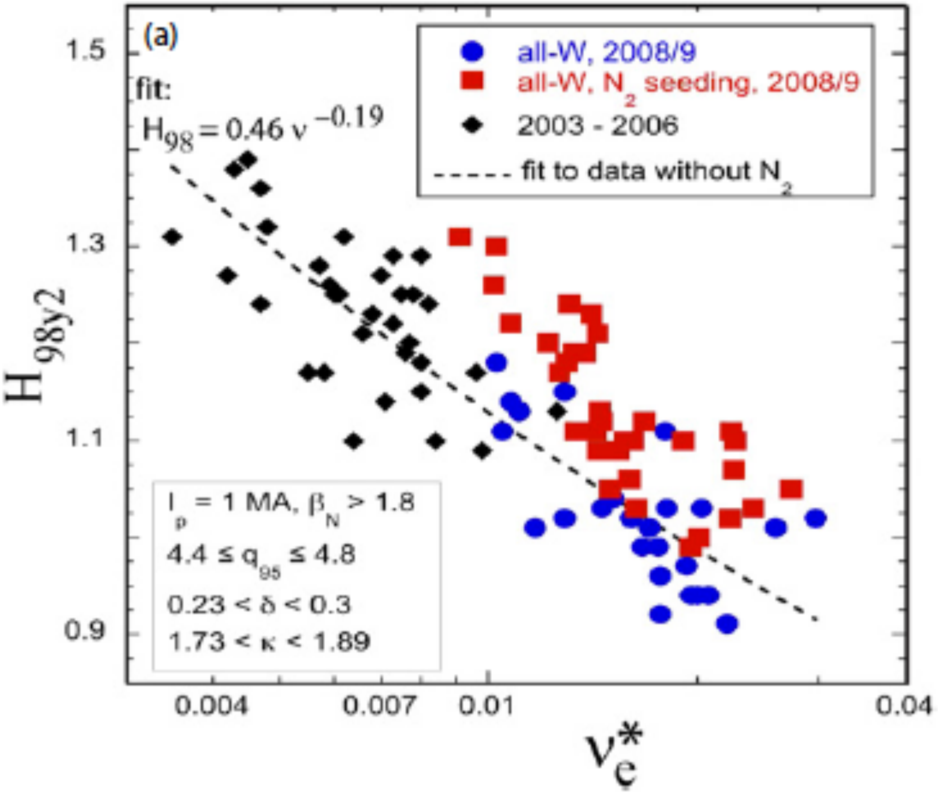
P. Schneider, PPCF **57** (2015) 014029

N_2 seeding can recover some or all H-factor loss in AUG

- Degradation with increasing n_e seen with C and W wall

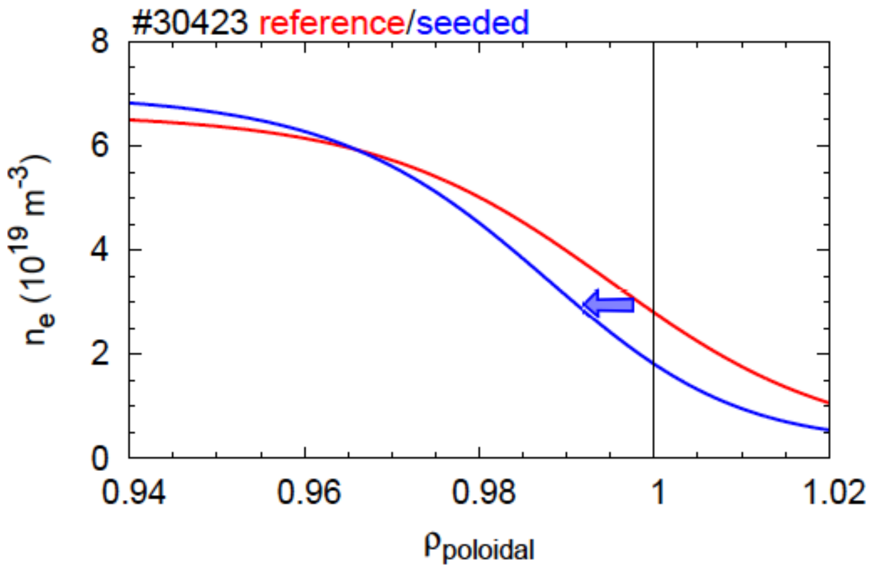


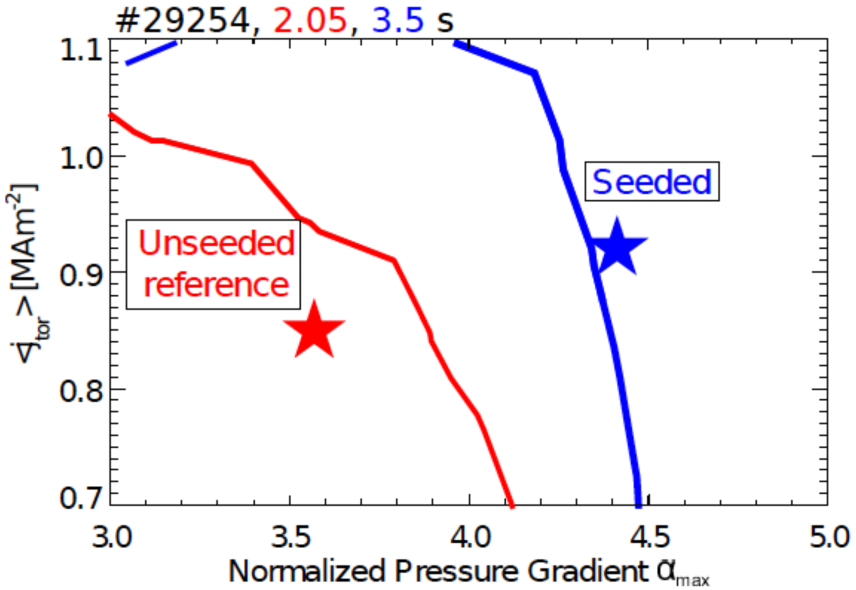
M. Beurskens, PPCF **55** (2013) 124013

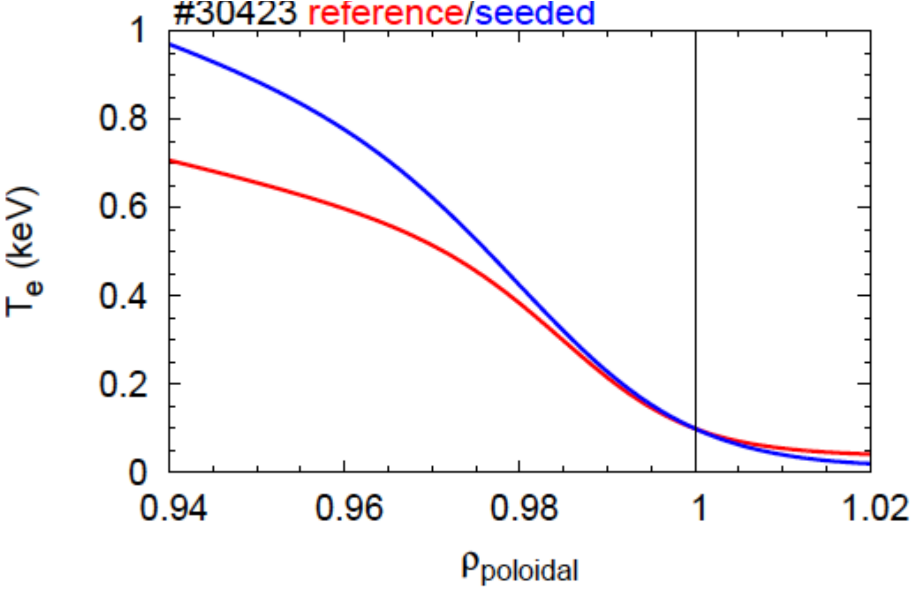


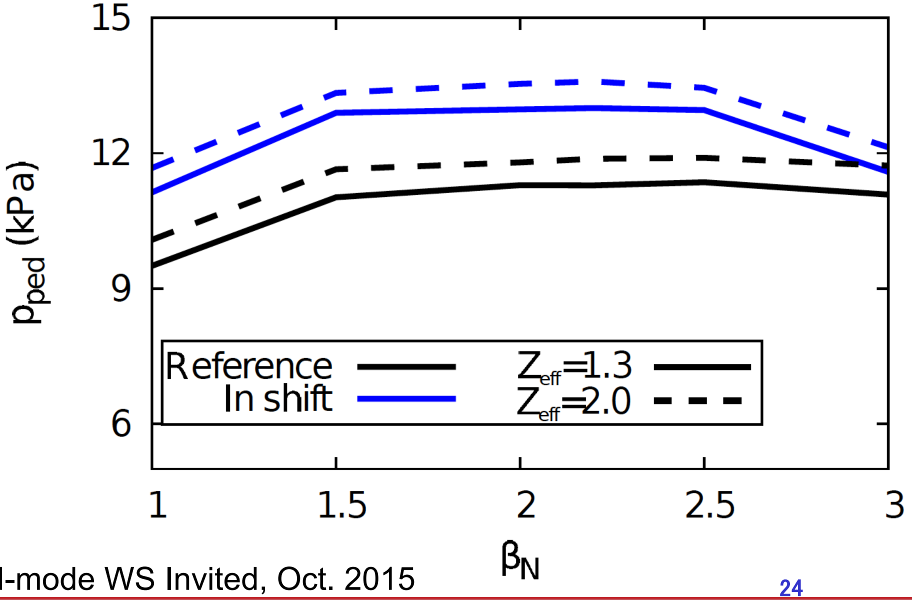
A. Kallenbach, NF **51** (2011) 094012

Nitrogen seeding shifts n_e profile radially inward in AUG, improving edge stability to ballooning modes





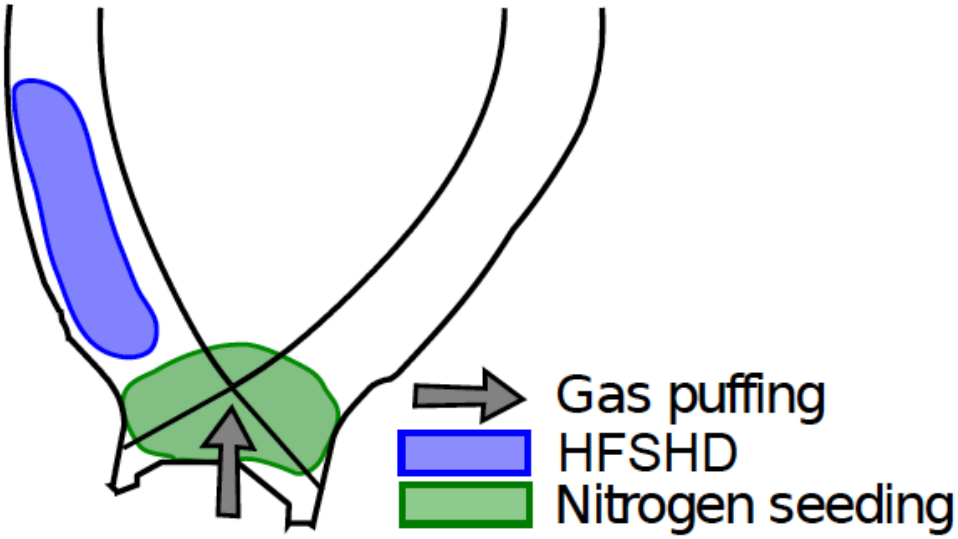




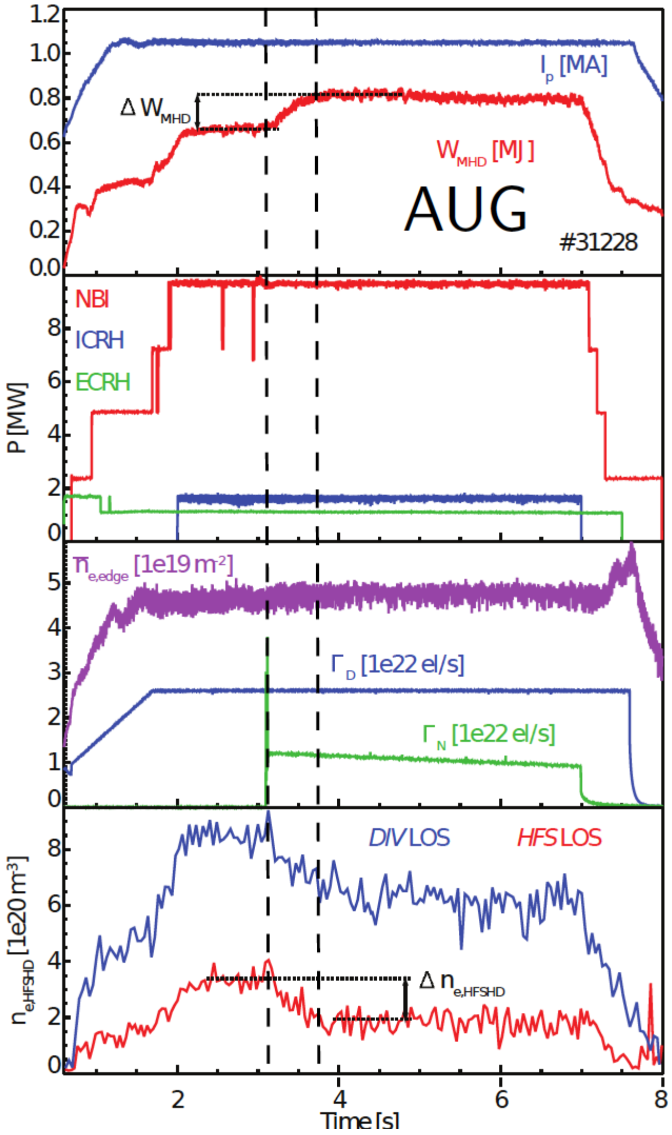
M. Dunne, APS 2015 & H-mode WS Invited, Oct. 2015

N_2 seeding reduces density in HFS high density region: reduced recycling from inner leg?

- Hypothesis: inward n_e shift caused by reduced fueling from HFS high density region, because N_2 radiates power in edge, reducing n_e in HFSHD by ~ 50%



M. Dunne, APS 2015 & H-mode WS Invited, Oct. 2015



S. Potzel, EPS 2015

Summary and Open Questions: effect of high-Z walls on pedestal, including low-z coatings

- Installation of a metallic wall in AUG and JET reduced pedestal T_e and H-factor, raised n_e
  - Why does this happen even at zero fueling? Simply from going to higher recycling with metals?

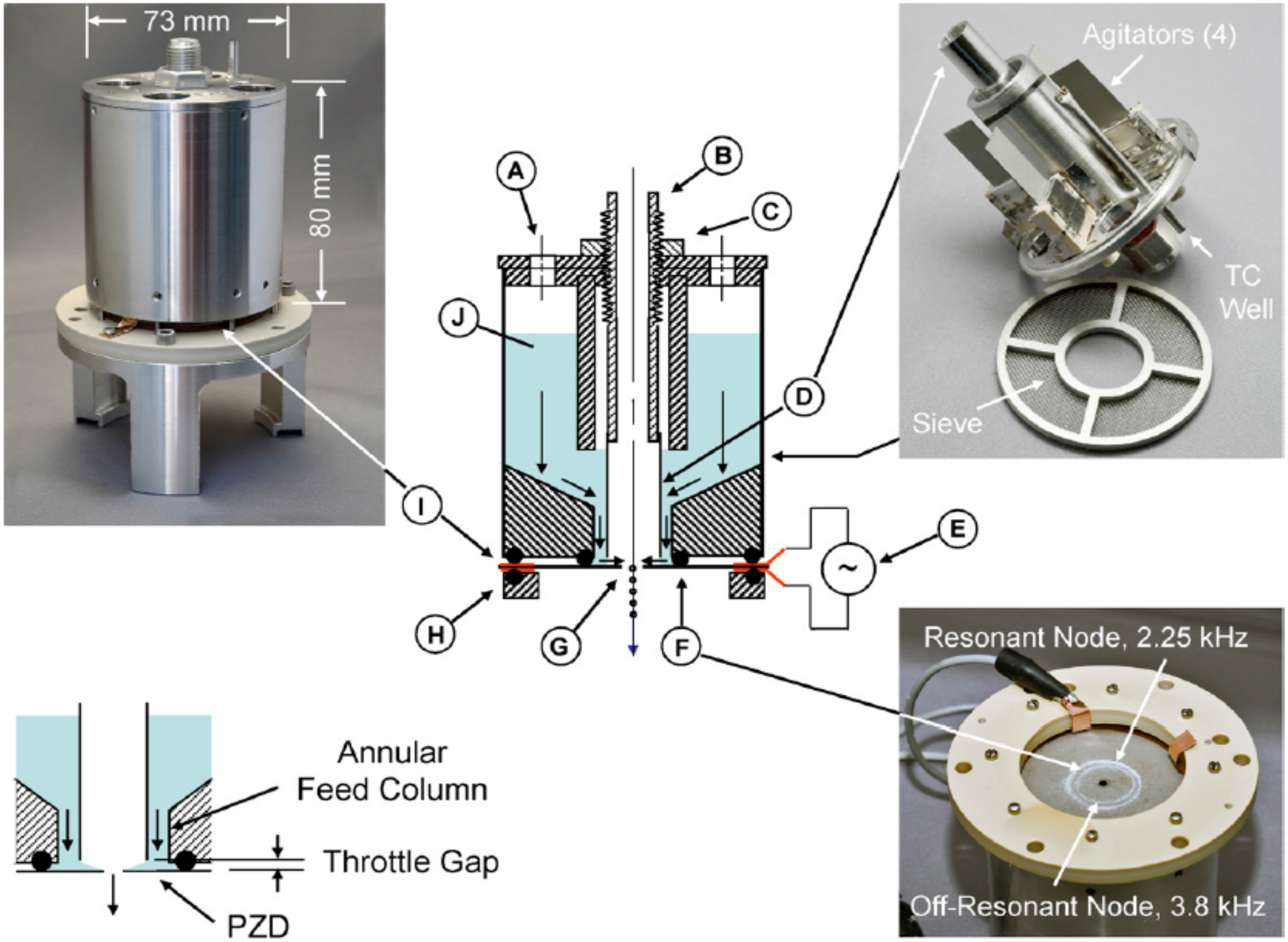
- N_2 seeding increased H-factor and pedestal pressure in AUG and JET
  - n_e profile shifts away from separatrix, while T_e profiles stays ~ constant; improves edge stability
  - No effect with Neon; why?
  - Can the fueling from the HFS high density region be connected to the profile shift via SOL modeling?
  - Can the profile be further shifted inward for more stability improvement?

Even lower-Z: Lithium aerosol injection in DIII-D (in-depth presentation of the research)

Li injection can alter pedestal and ELM characteristics, delaying ELMs and improving confinement in DIII-D

- Li aerosol injection results in reduced C and metal concentration
  - High Li conc. ($\leq$ 15%) consistent with neoclassical transport
- Periods of increased pedestal pressure and width that are observed in conjunction with pedestal density fluctuations increase in frequency and duration with Li injection
  - "Bursty Chirping Mode" causes $\delta n_e/n_e$ ~8%; constant P_{rad}
  - With Li injection, the ELM-free period grows to < 350 msec, with H_{H98y2} increasing by $\leq$ 60% and P_e^{ped} increasing by $\leq$ 150%
  - Recycling unchanged: D_α does not decrease
  - Too much Li drives plasma to H-L; too little shows small effect
- Density fluctuations flatten pressure profile near separatix improving peeling-ballooning stability -> higher P_{ped}
  - Wide pedestal terminated by giant ELM, consistent with ELITE
- Li dilution of main ion density contributes to long ELM-free periods with Li injection

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



D. Mansfield, FEDC **85** (2010) 890

Lithium dropper deployed in upper region of 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

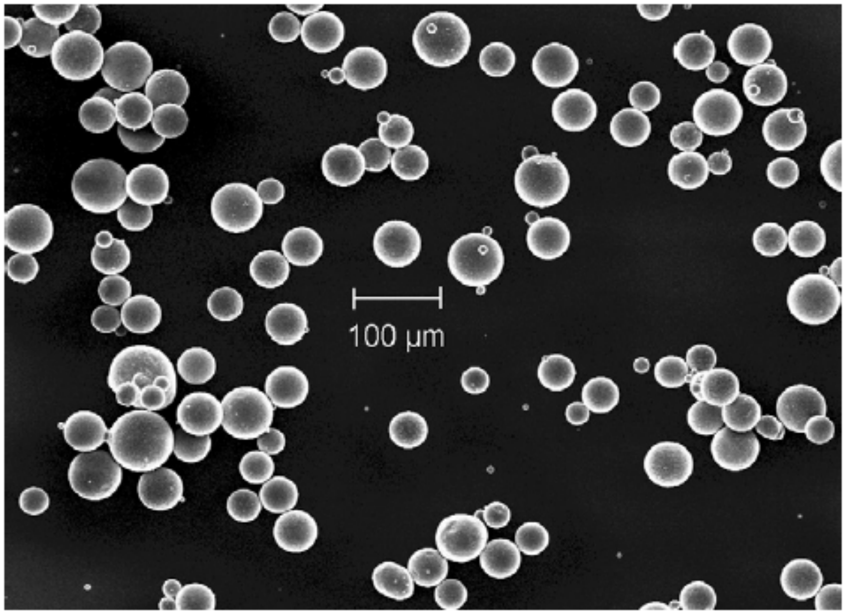
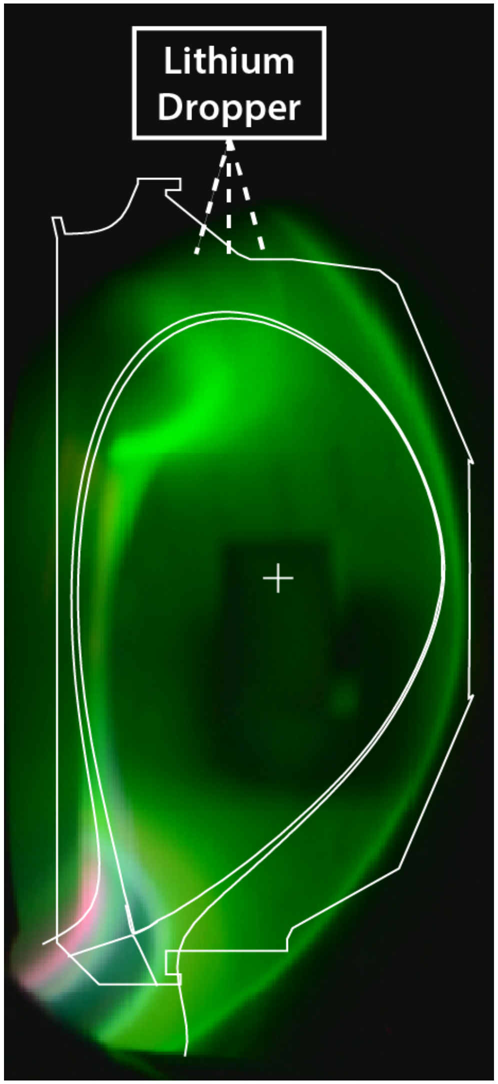
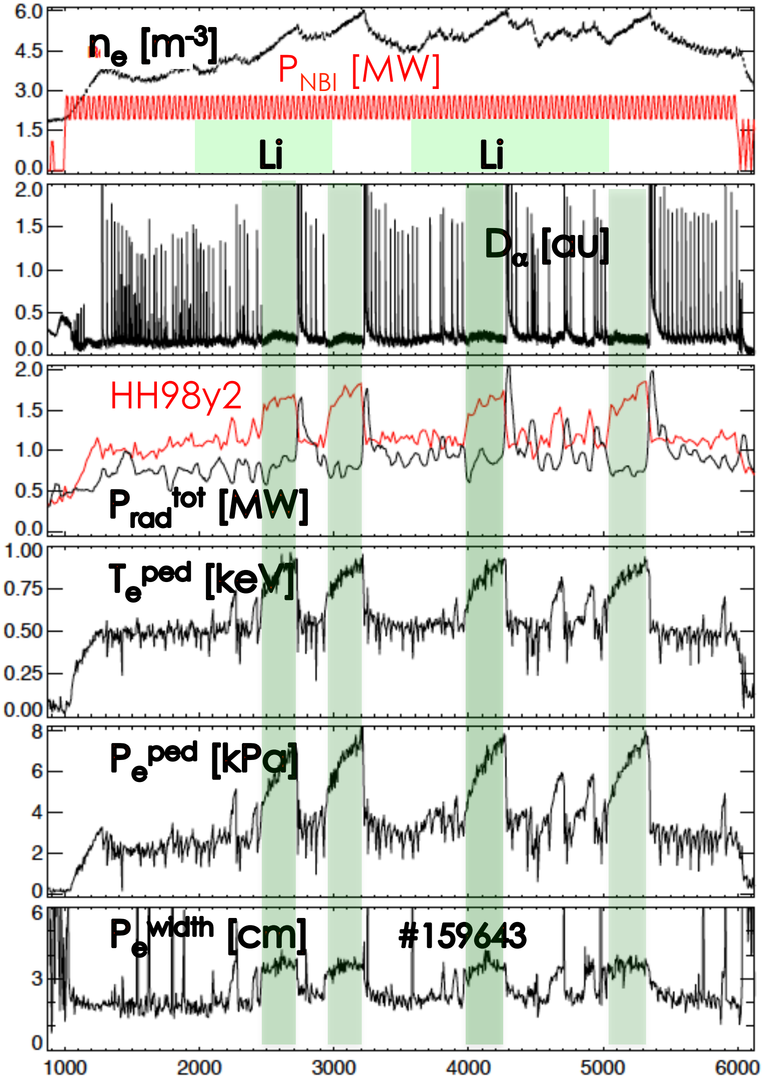


Fig. 1. The SLMP® powder used in this work.



D. Mansfield, FEDC **85** (2010) 890

Lithium injection and BCM induce a rapid increase to larger pedestal width, but pressure builds up more slowly

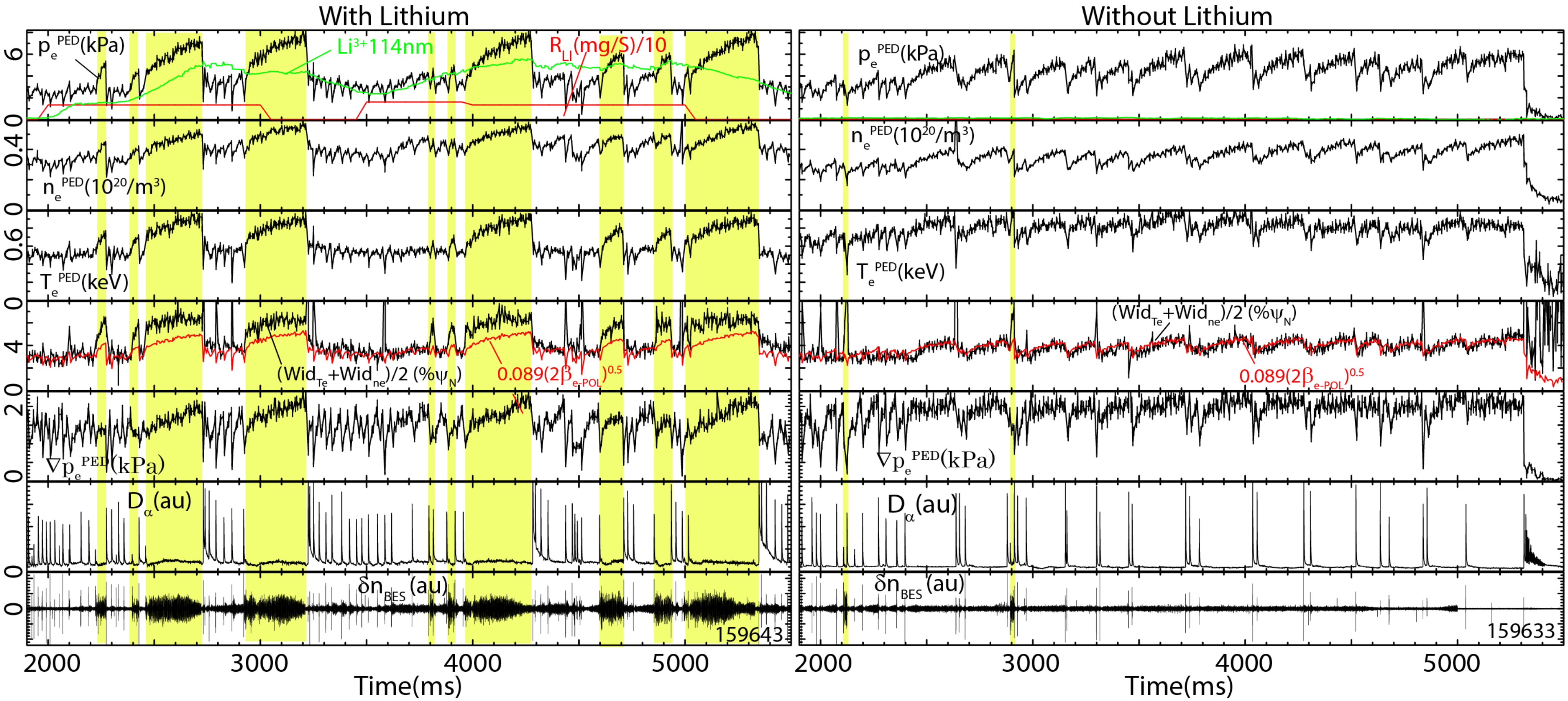


R. Maingi, H-mode WS, Oct. 2015

- ELM-free bifurcated state can be seen in D_α emission
- $H_{98y2} \leq 1.8$ here, 2.0 in other discharges
- T_e^{ped} nearly doubled during bifurcations
- P_e^{ped} nearly tripled during bifurcations
- P_e^{width} increased by 100%

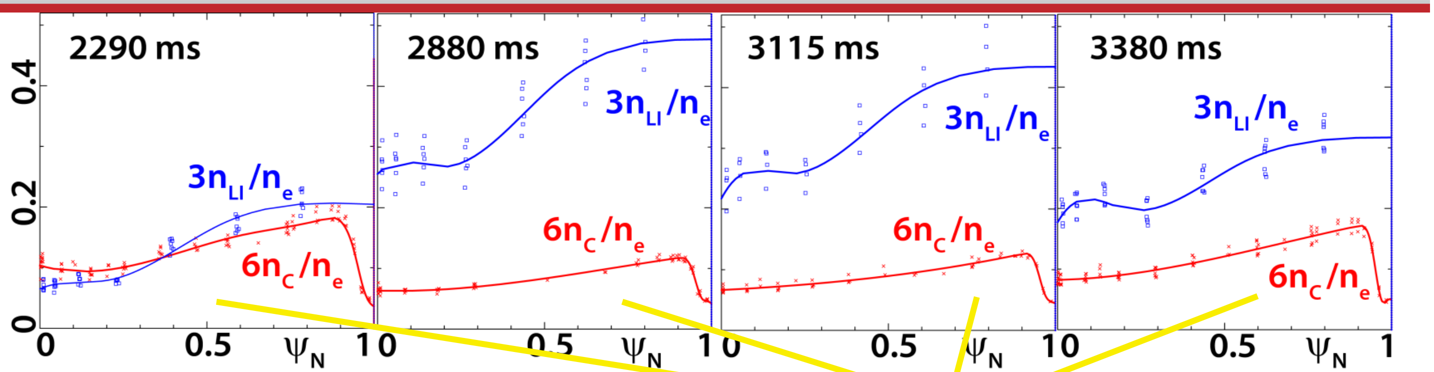
Extended (short) periods with enhanced pedestal pressure and width observed with (without) Li injection

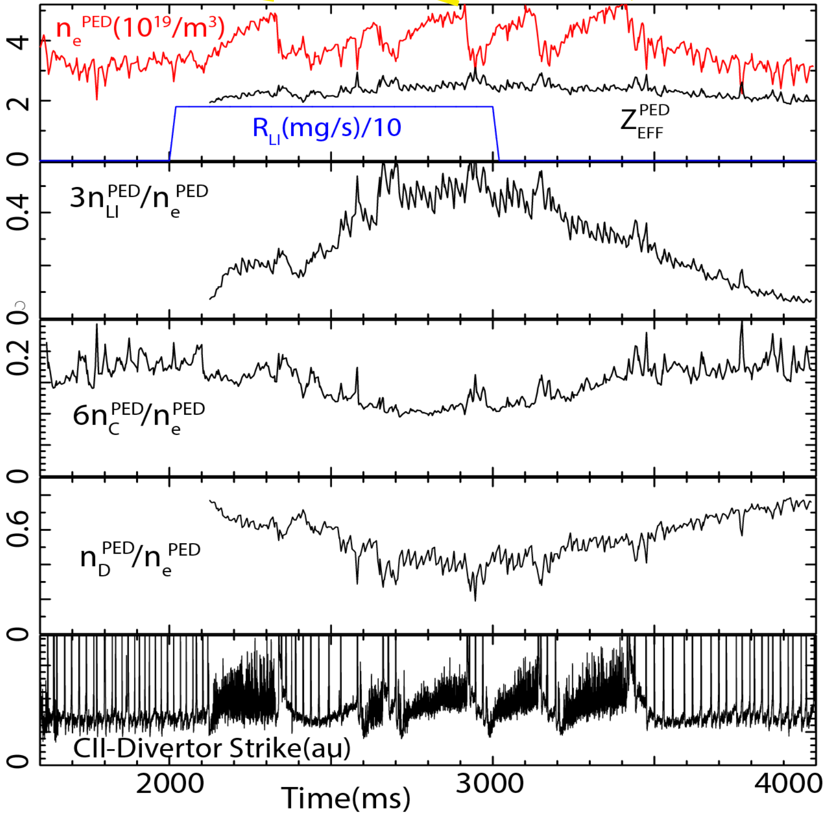
- Periods with enhanced p_{PED}, Δ_{PED} (tanh profiles) extended to 350ms with Li
  - Short periods (~20ms) occasionally observed even without Li
- n_e fluctuations located in pedestal region during enhance periods



T. Osborne, Nucl. Fusion **55** (2015) 063018

High levels of Li observed in plasma core at injection levels sufficient for triggering pedestal improvements



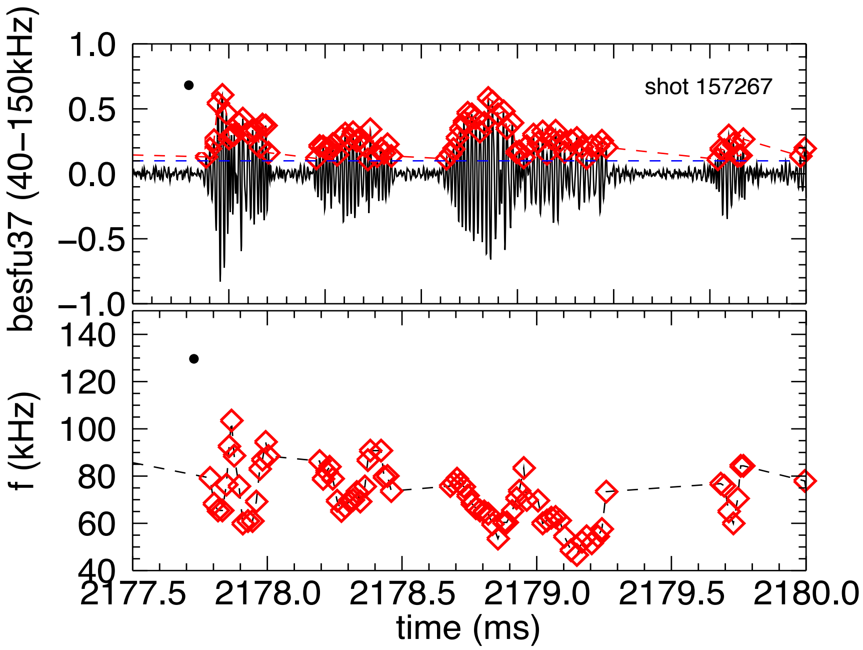


- Li contribution to charge balance can be large (~50%)
- C and D reduced as Li increases
    - Neutron rate decreases consistent with D decrease
- Z_{EFF} increased by $\leq$20% (2 ⇒2.4)
- C-II light from divertor has no obvious baseline decrease with Li increase but small 'fuzz' seen in ELM free periods
- Lower Li injection rates increase likelihood of coherent fluctuations, but not their duration

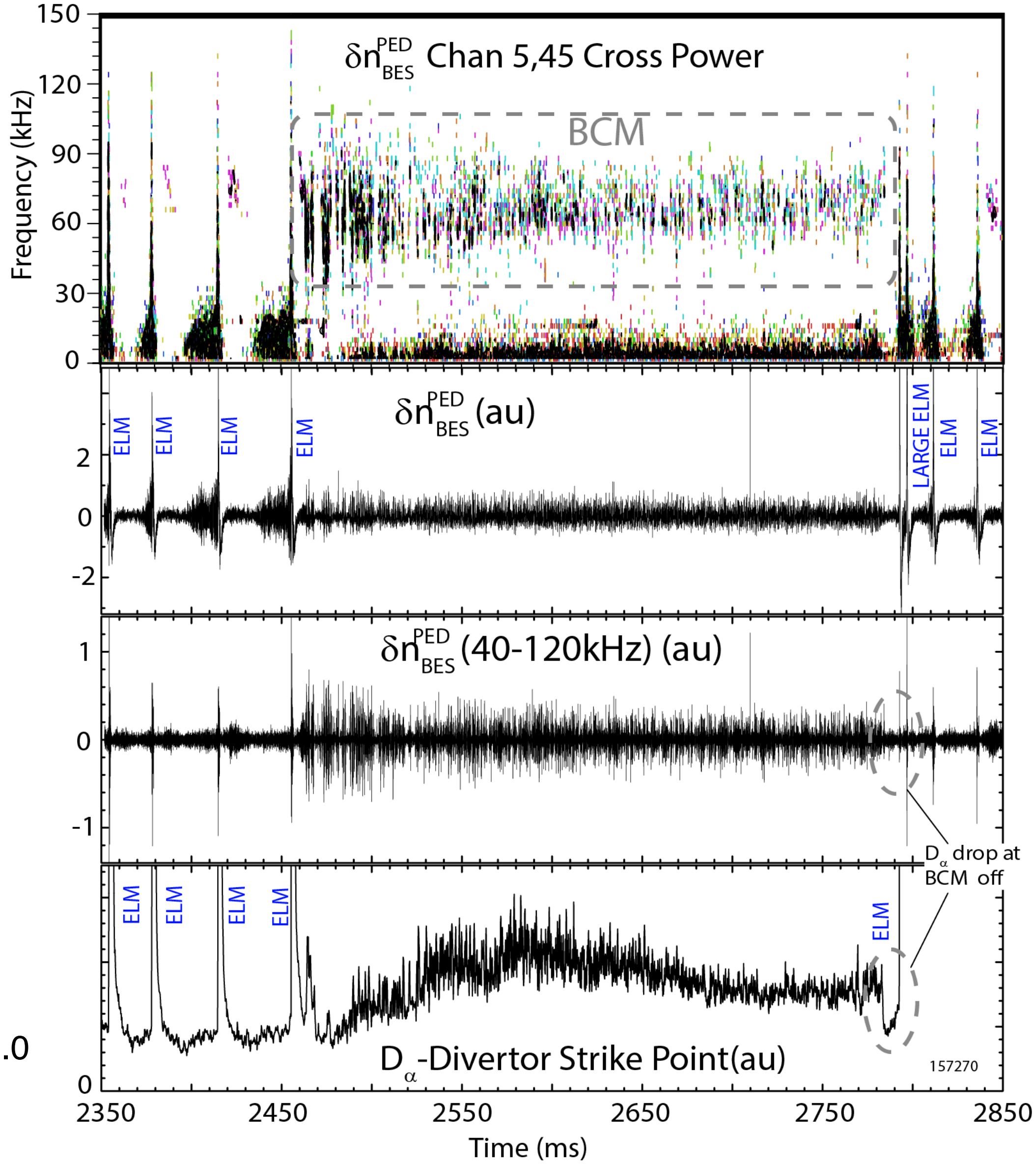
T. Osborne, Nucl. Fusion **55** (2015) 063018

Bursty Chirping Mode (BCM) observed in periods of pedestal enhancement

- $f_{MODE} \approx 70$kHz , $f_{BURST} \approx 1$kHz
  - Coherent on short time scale
  - f_{MODE} varies within burst
- $k_{POL} \approx 0.1$ cm^{-1} , $k_{POL}\rho_s \approx 0.1$
- Rotates in electron drift direction in plasma frame ⇒ MTM or DTEM, not KBM



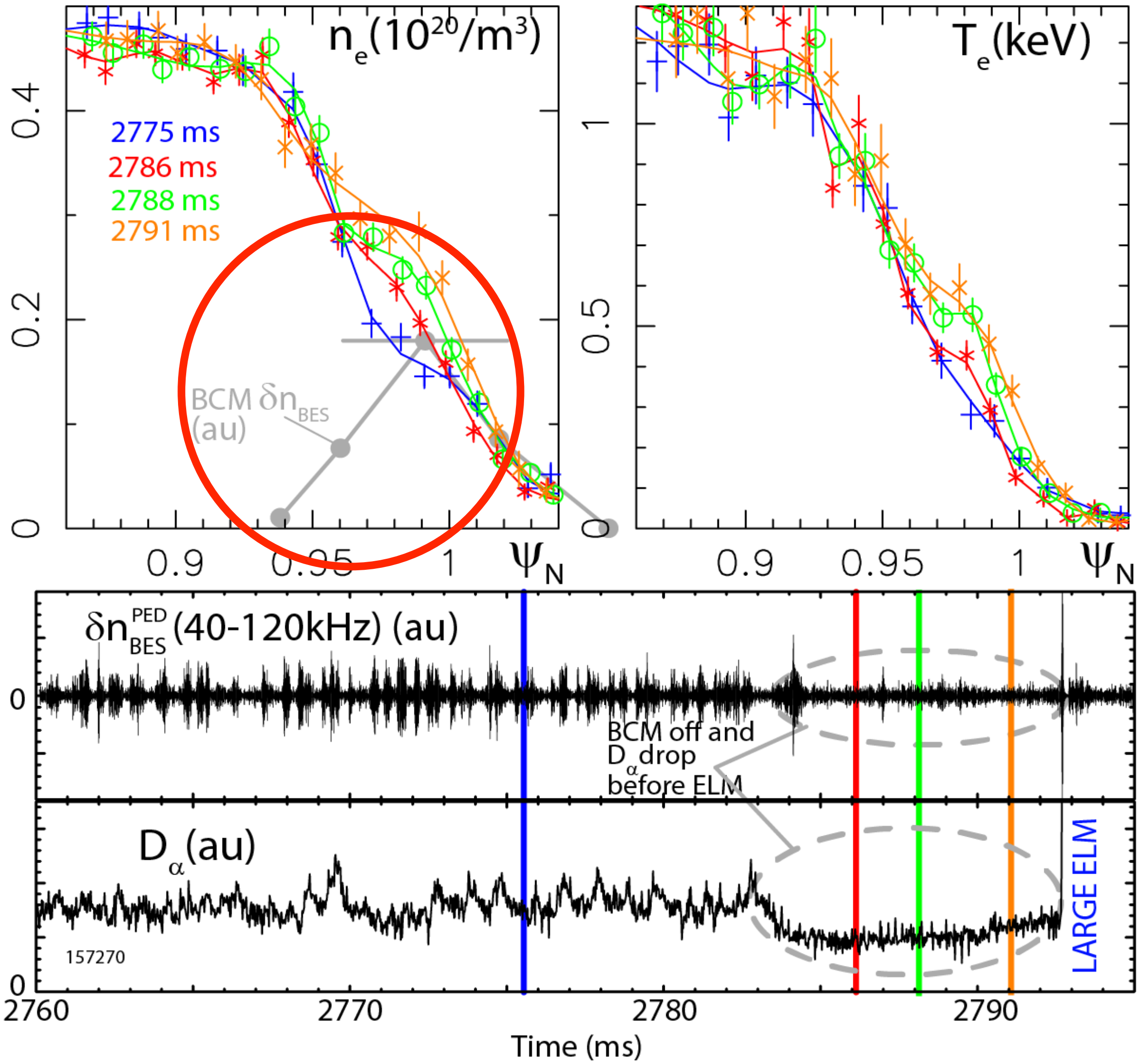
Z. Yan, 42nd EPS, Lisbon, Portugal



Profiles rebuild in region near separatrix before ELM after BCM terminates

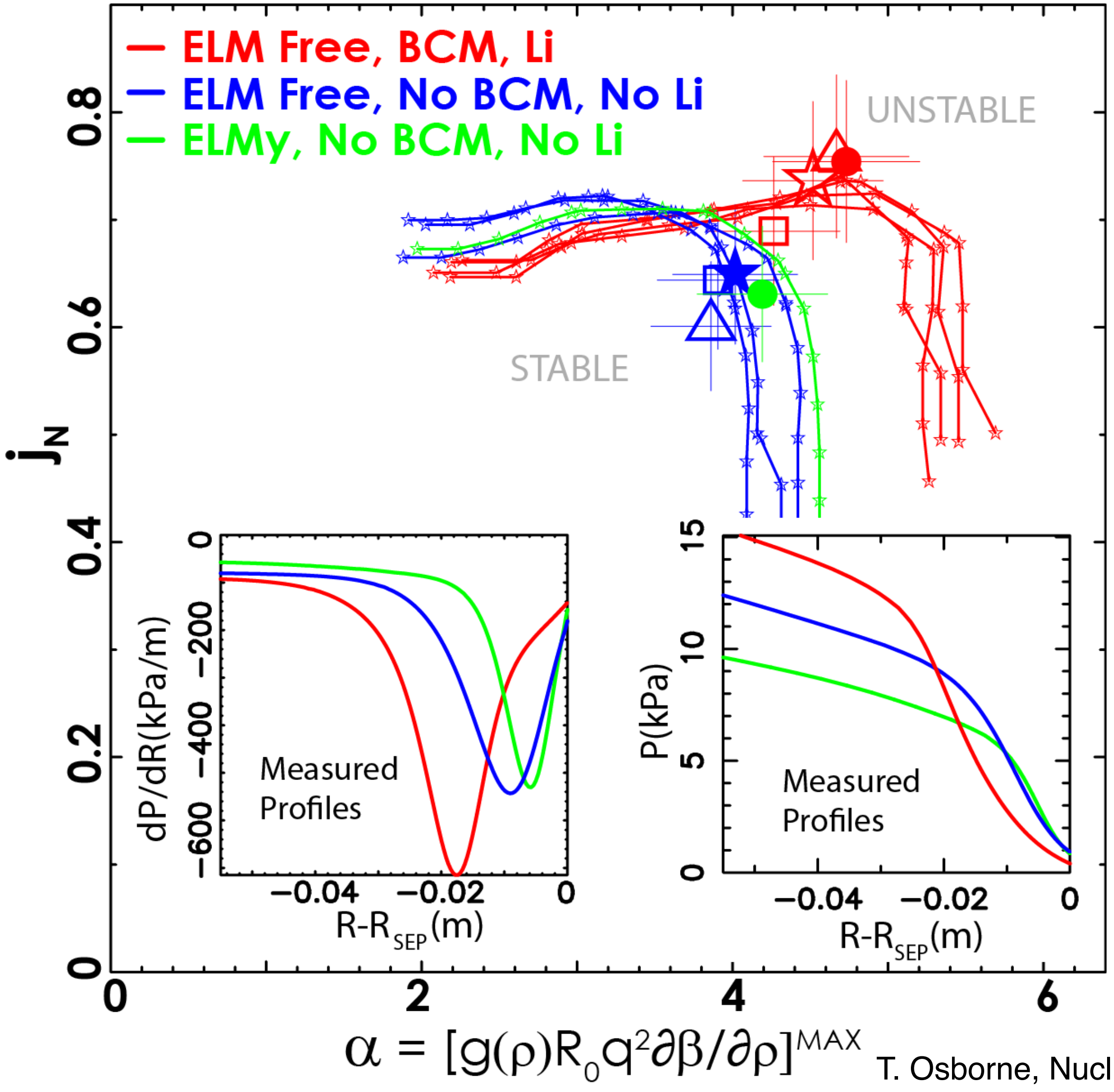
- D_α drops when BCM turns off before end of ELM free period
  - In most cases the BCM continues until an ELM occurs
- Gradients rebuild in region near separatrix consistent with radial location of BCM when it turns off
- Giant ELM terminates ELM-free phase with or without BCM

BCM flattens electron profiles near separatrix



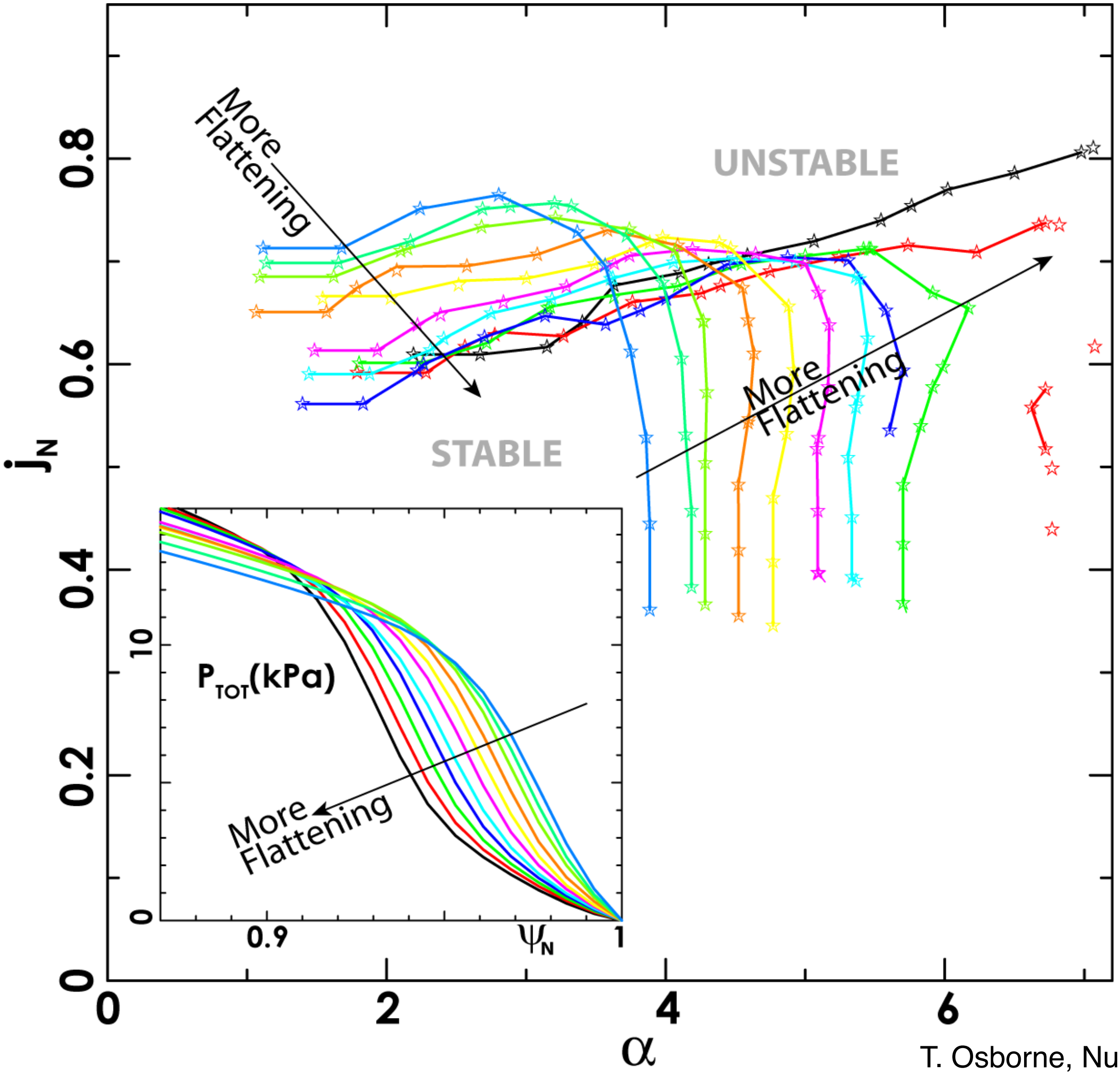
Reduced ∇p near separatrix with BCM shifts high ∇p region inwards and improves PBM stability allowing higher p^{PED}

ELITE with kinetic equilibria



T. Osborne, Nucl. Fusion **55** (2015) 063018

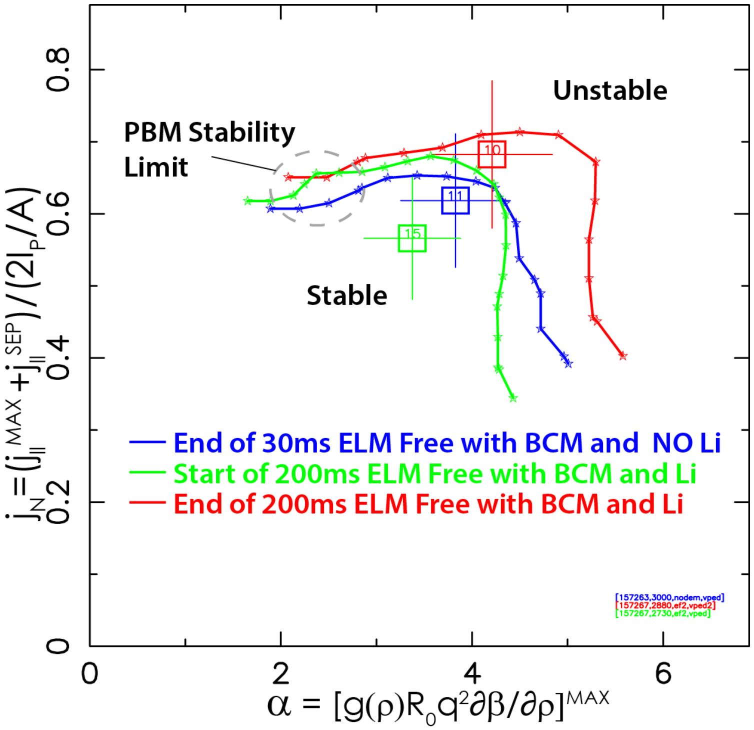
Ballooning stability improves but kink/peeling stability decreases with increased profile flattening (model equilibria)

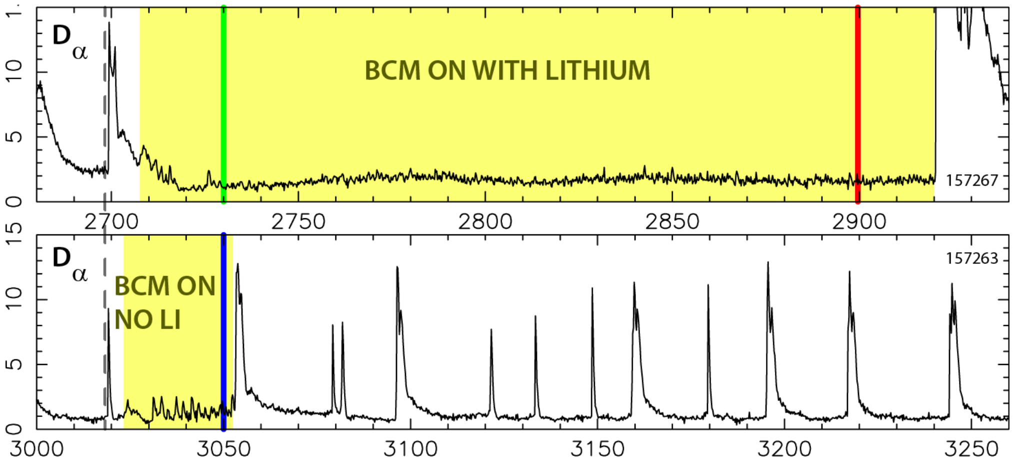


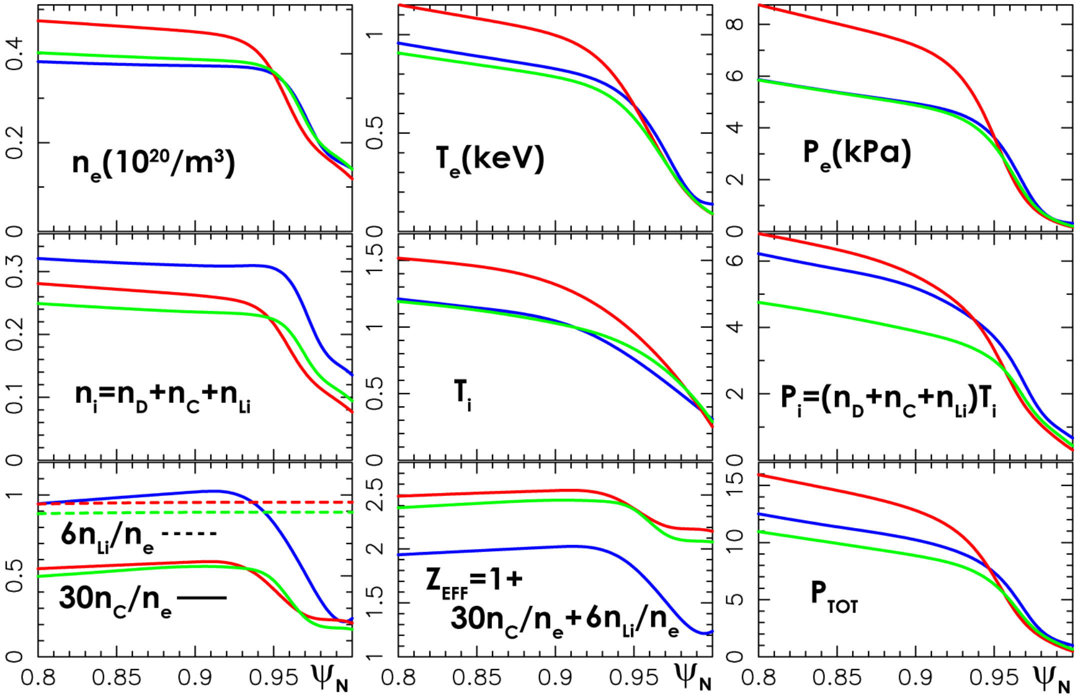
T. Osborne, Nucl. Fusion **55** (2015) 063018

In addition to affecting BCM, Li may extend enhanced pedestal phase by reducing ion pressure through dilution

- At similar times following an ELM with enhanced pedestal, discharge with Li has lower ion pressure and higher Z_{eff}
  - Reduced p′,j ⇒ Li case stable to PBM for much longer







Summary and Open Questions: Effect of Lithium aerosol injection in DIII-D

- Microscopic Li particles penetrate into the core
  - Low injection rates: recycling unaffected, but there is an immediate reduction of higher-Z impurities, as well as a measurable reduction in ELM frequency
  - Pedestal unaffected at low Li injection rates; suggests no intrinsic stability benefit to main ion dilution

- In presence of BCM, Li injection causes long ELM-free periods with increased confinement and H-factor
  - How does Li interact with BCM to make it more likely to occur between ELM cycles?
  - Would C, B, or Be dust work as well?
  - Can the BCM or other mode be destabilized in reference discharges where it is not observed?

Lithium aerosol injection in EAST (in-depth presentation of the research)

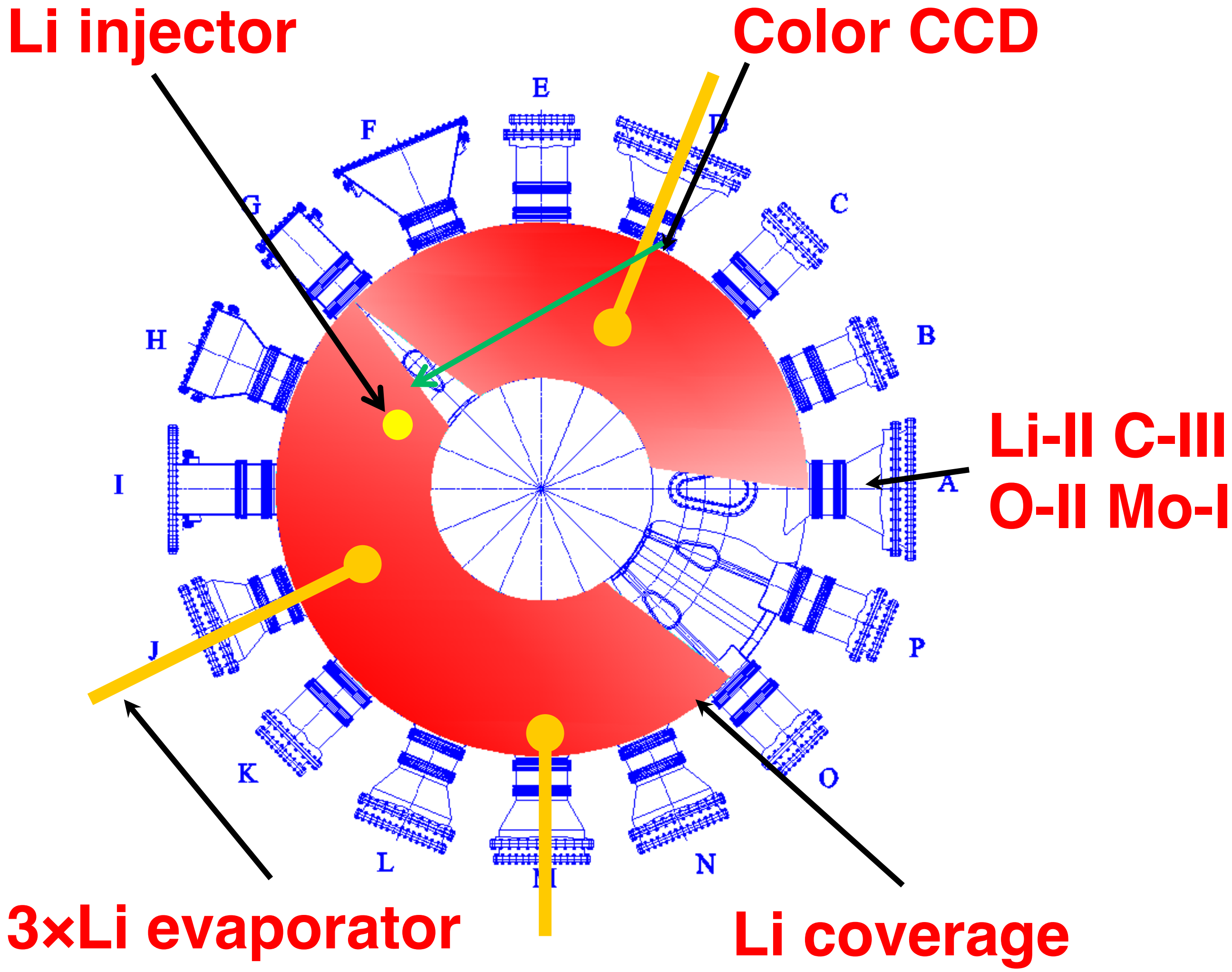
Real-time conditioning with Li injector eliminated ELMs in 24 sec long H-mode discharges in EAST

- 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
  - Profile measurements and stability analysis are needed

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



Li injector

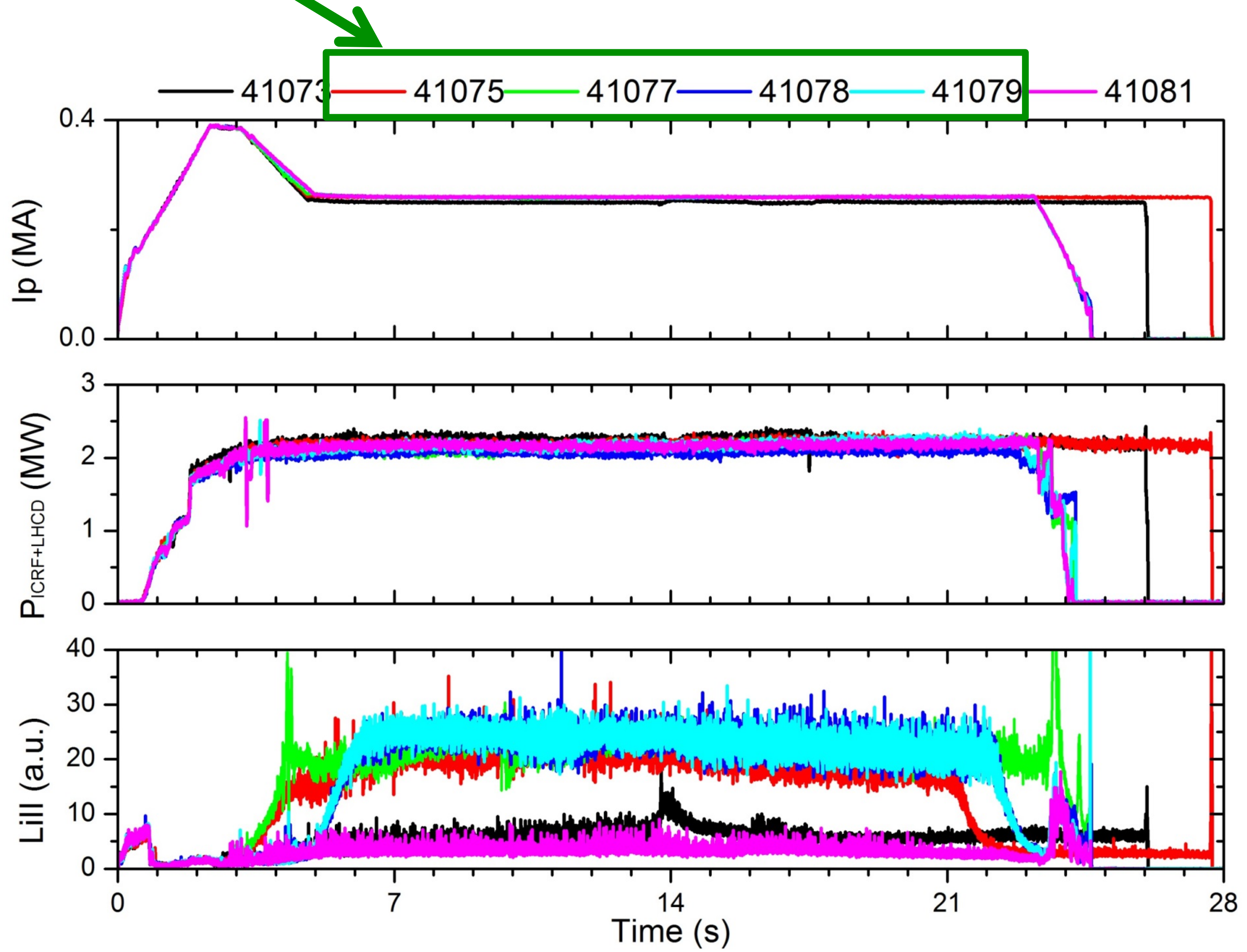
Color CCD

Li-II C-III
O-II Mo-I

3×Li evaporator

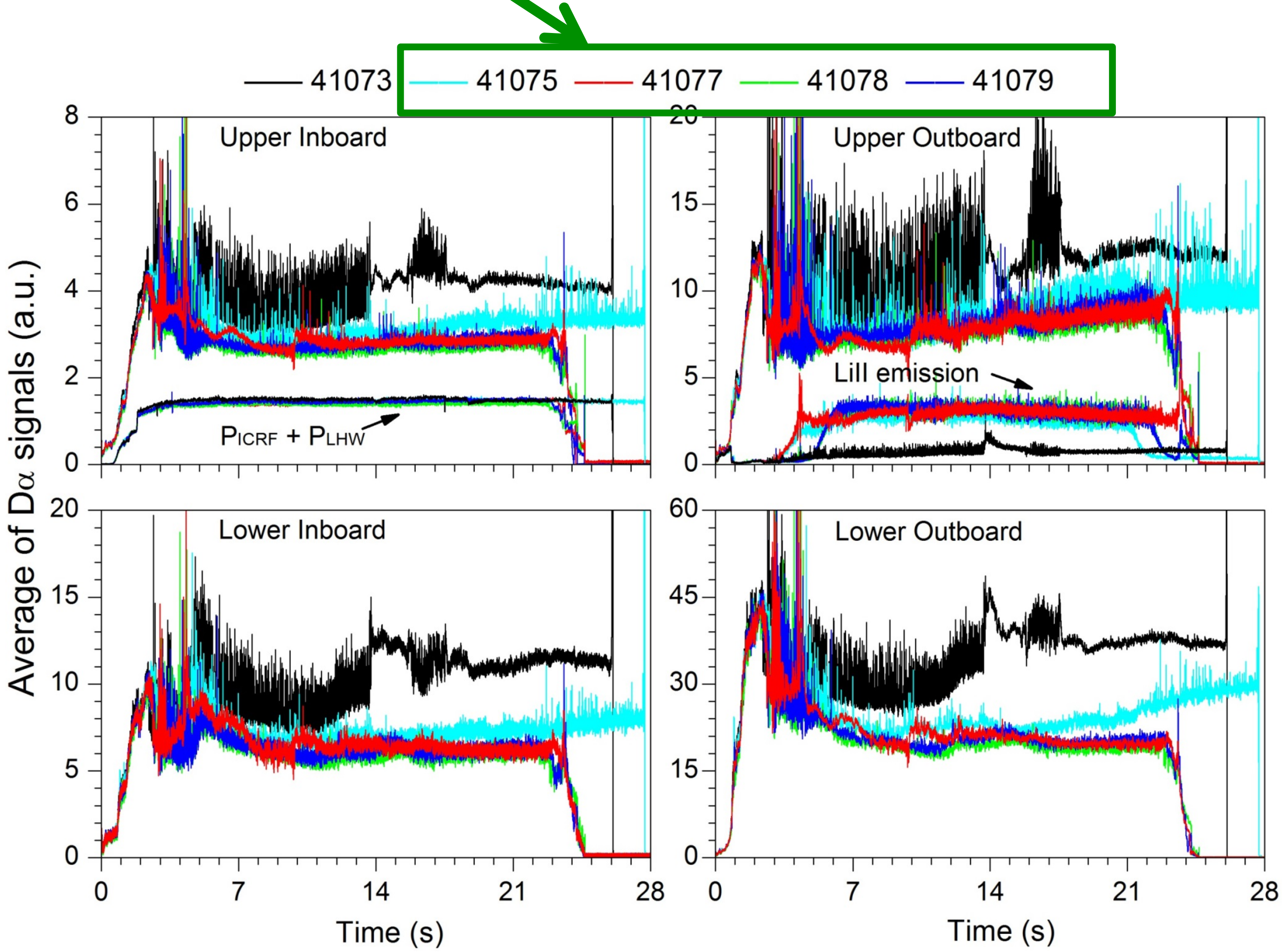
Li coverage

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



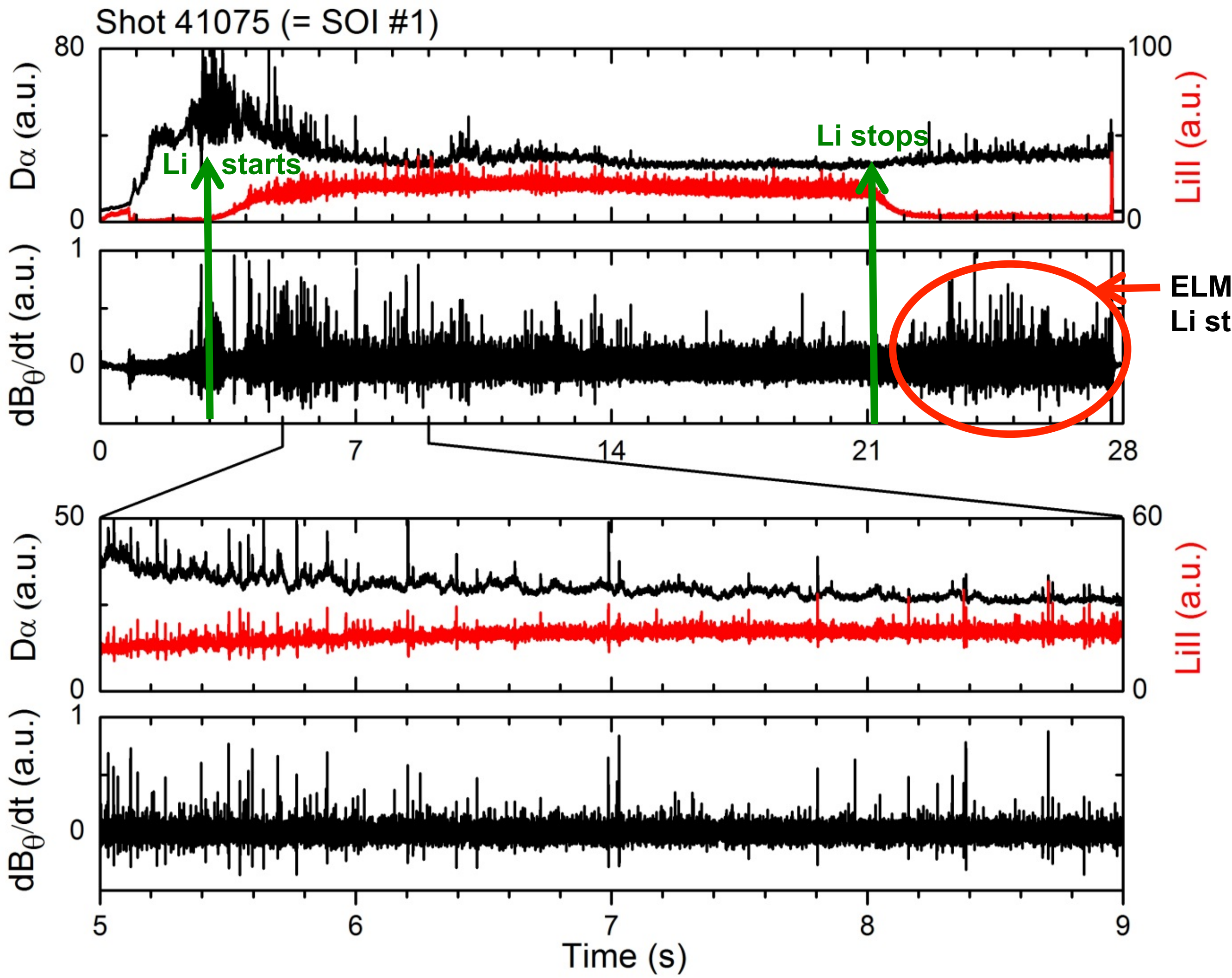
J.S. Hu, PRL **114** (2015) 055001

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



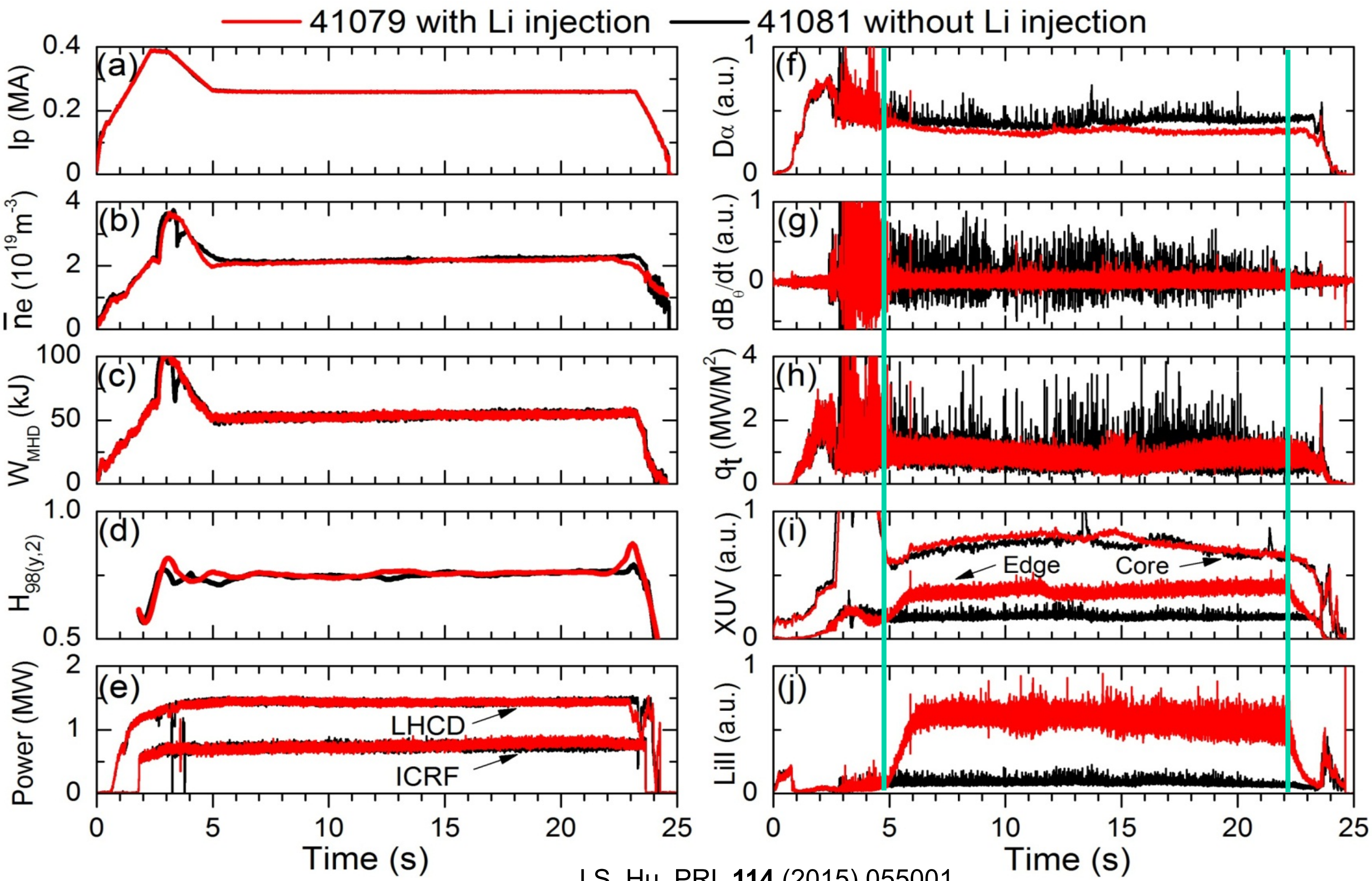
R. Maingi, IAEA 2014 paper EX/P6-54

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



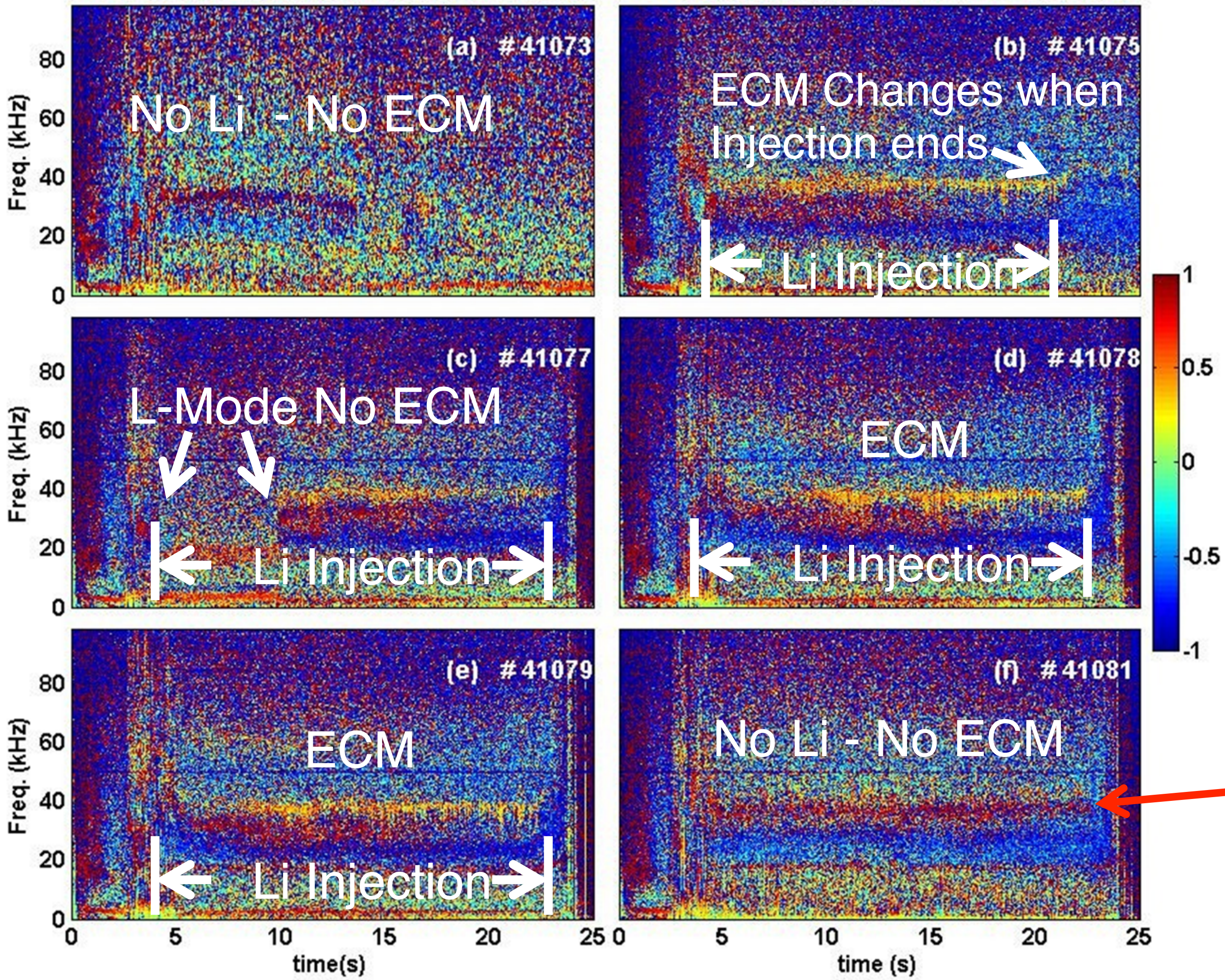
ELMS return when Li stopped!

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



J.S. Hu, PRL **114** (2015) 055001

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.S. Hu, PRL **114** (2015) 055001

Summary and Open Questions: Effect of Lithium aerosol injection in EAST

- Li injection into EAST eliminates ELMs
  - Does the Li injection shift the n_e profile inward?
  - Is the underlying physics consistent with ideal MHD stability?
  - How does the Li injection modify the existing ECM (or destabilize a new one)?
  - Does this work with higher heating power, NBI heating instead of ICRF?
  - Does this work in USN discharges where the main strike points would be on the W PFCs?

Outline

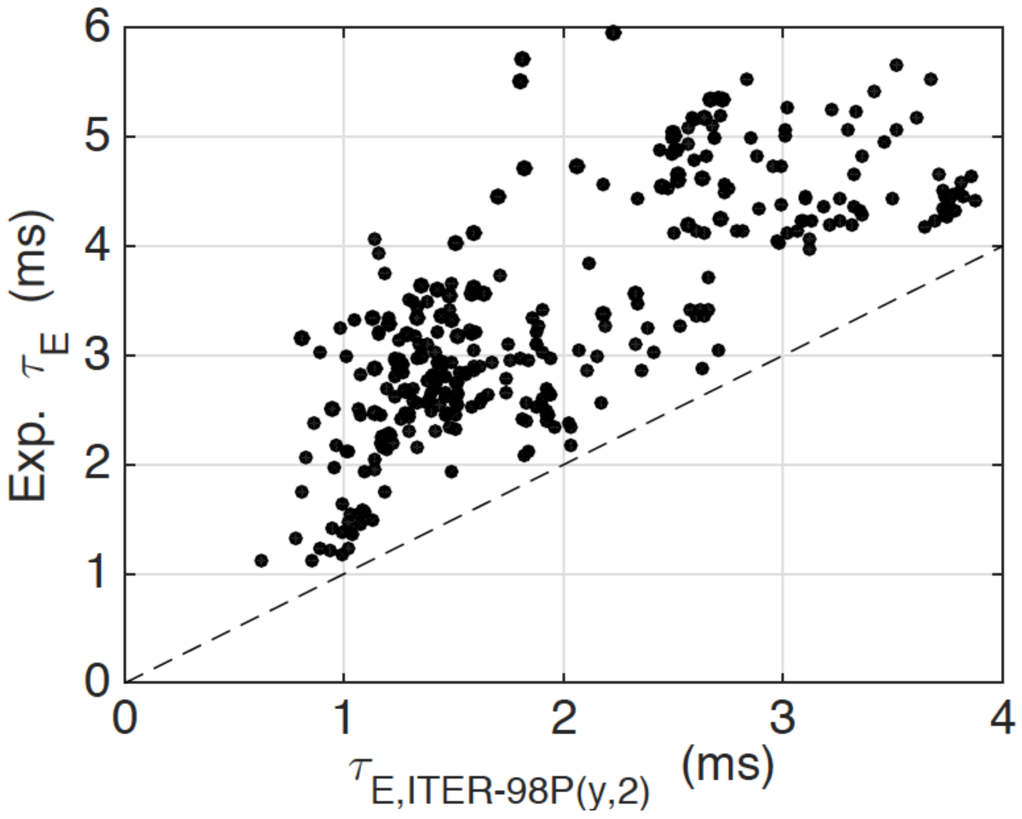
- Pedestals with carbon walls and high-Z walls
  - Brief history of PFC materials in fusion devices

- Purposeful introduction of low-Z
  - Real time injection with gas/aerosol [JET, AUG, DIII-D, EAST]
  - ➢ **Inter-discharge Coatings (lithium, (boron)) [NSTX, (LTX, C-Mod, EAST)]**
  - Real-time injection with pellets [DIII-D, (EAST)]
  - Low-Z liquid metal PFCs: static, flowing [(LTX, FTU), EAST]

- Prospects and open questions

Lithium (solid and liquid) PFCs can double H-factor

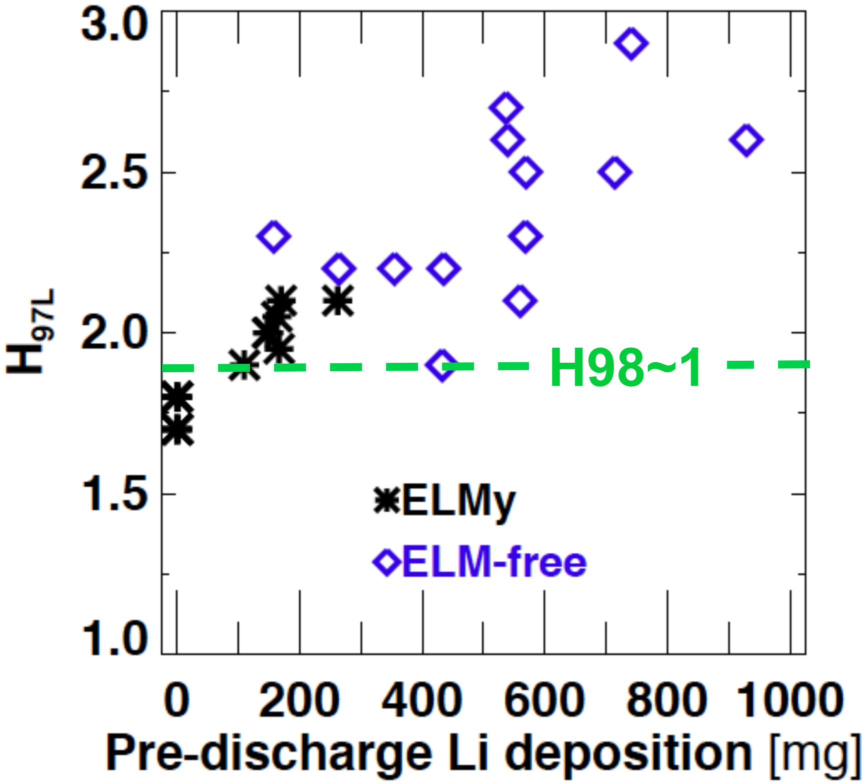
LTX



- 2-3x improvement over ITER98P(y,2) (H-mode scaling)

J.C. Schmitt, Phys. Plasmas **22** (2015) 056112

NSTX



- H98y2 increased from 0.8 -> 1.4 (H-mode scaling)

D.P. Boyle, J. Nucl. Mater. **438** (2013) S979

Lithium pre-discharge coatings in NSTX (in-depth presentation of the research)

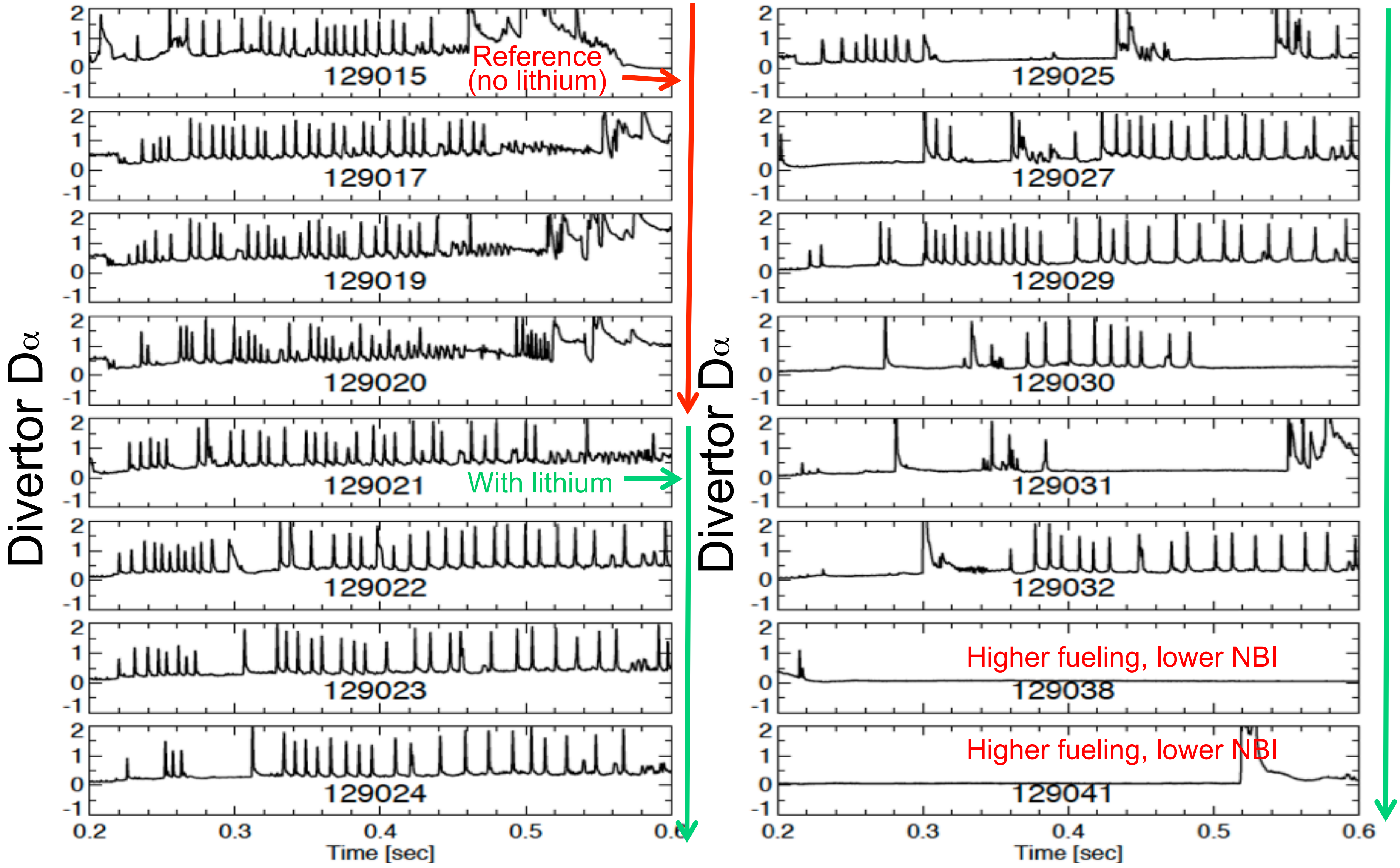
Plasma characteristics and edge stability improved nearly continuously with increasing lithium coatings in NSTX

- Lithium evaporated before discharge; amount scanned
  - Core Li concentration very low, typically < 0.1%

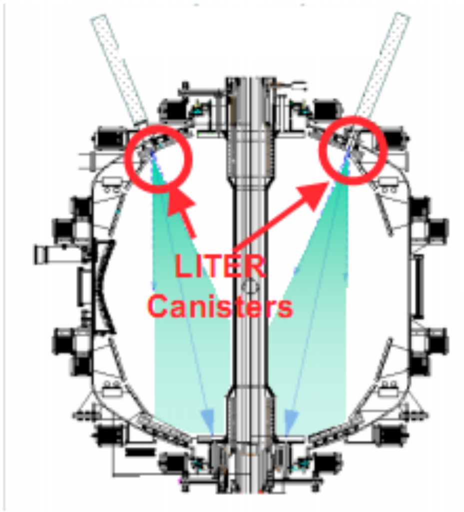
- Global characteristics changed
  - Recycling: D_α declined in all measured views
  - Energy confinement (τ_E, H-factor) improved, consistent with reduced transport at lower ν^*
  - *When discharges were ELM-free, radiated power increased with time (we tested several techniques to ameliorate this problem)*

- Edge particle and thermal transport declined
- ELM frequency decreased before going to 0
  - Profiles shifted away from separatrix – improving stability to kink/ peeling modes
  - Edge stability gradually improved

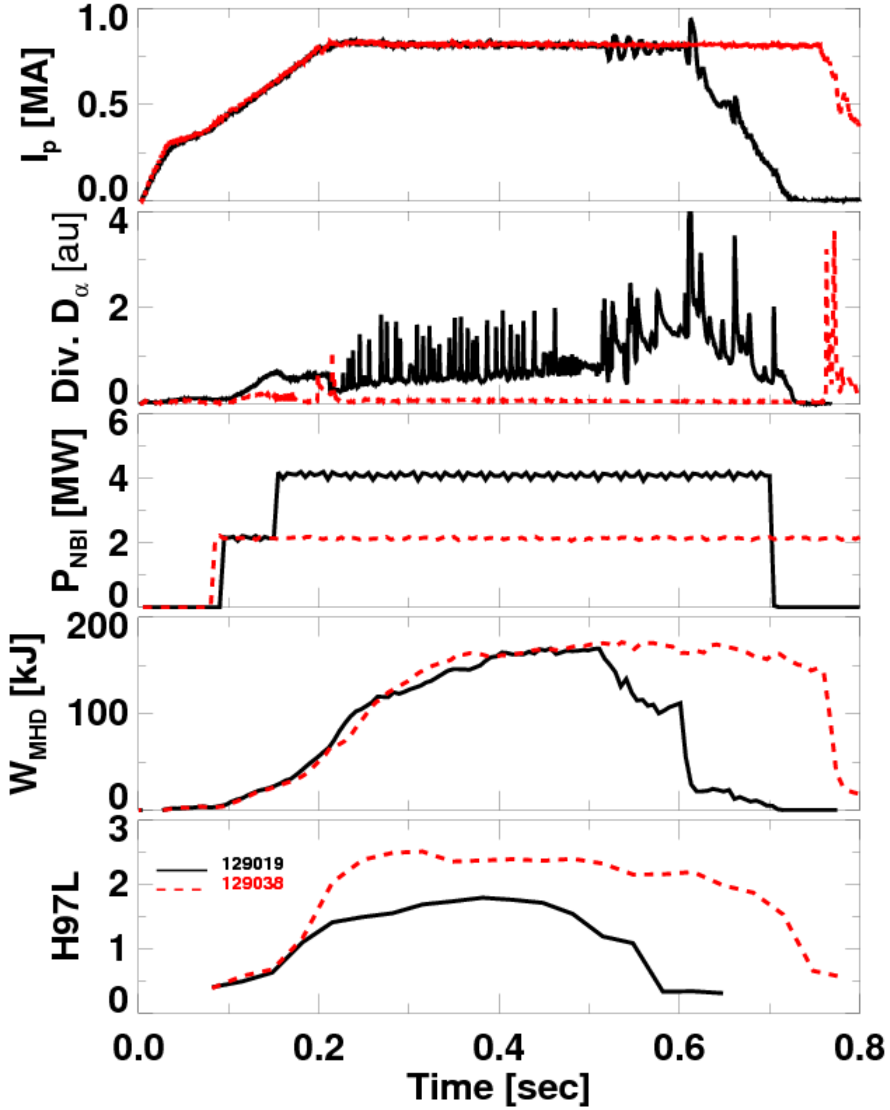
ELMs eliminated gradually during systematic introduction of lithium evaporation into NSTX



Type I ELMs eliminated, energy confinement improved with lithium wall coatings

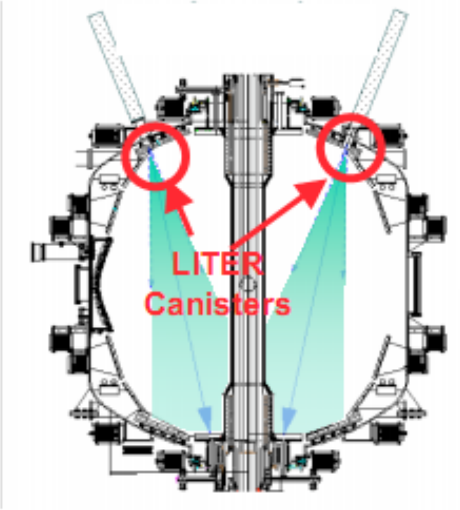


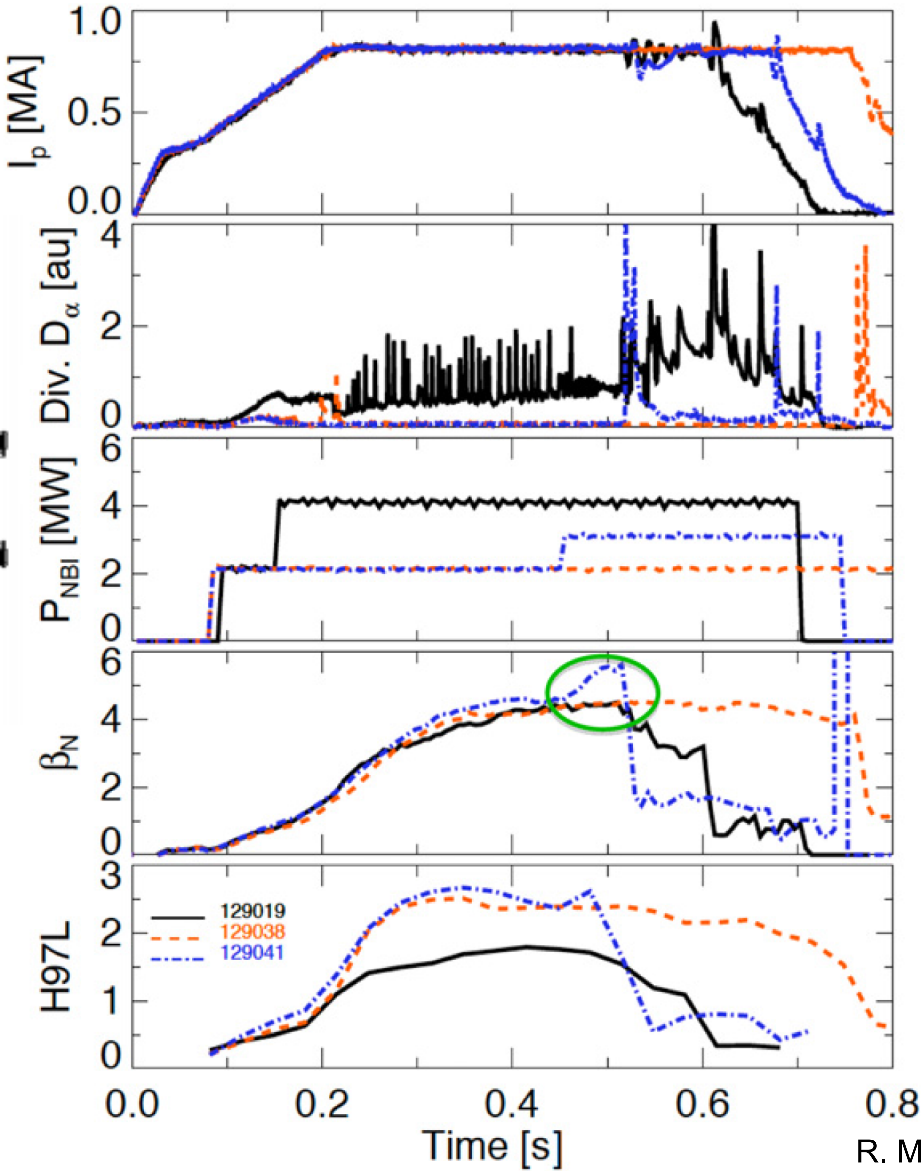
~ 700mg Li
between 129037
and 129038



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

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

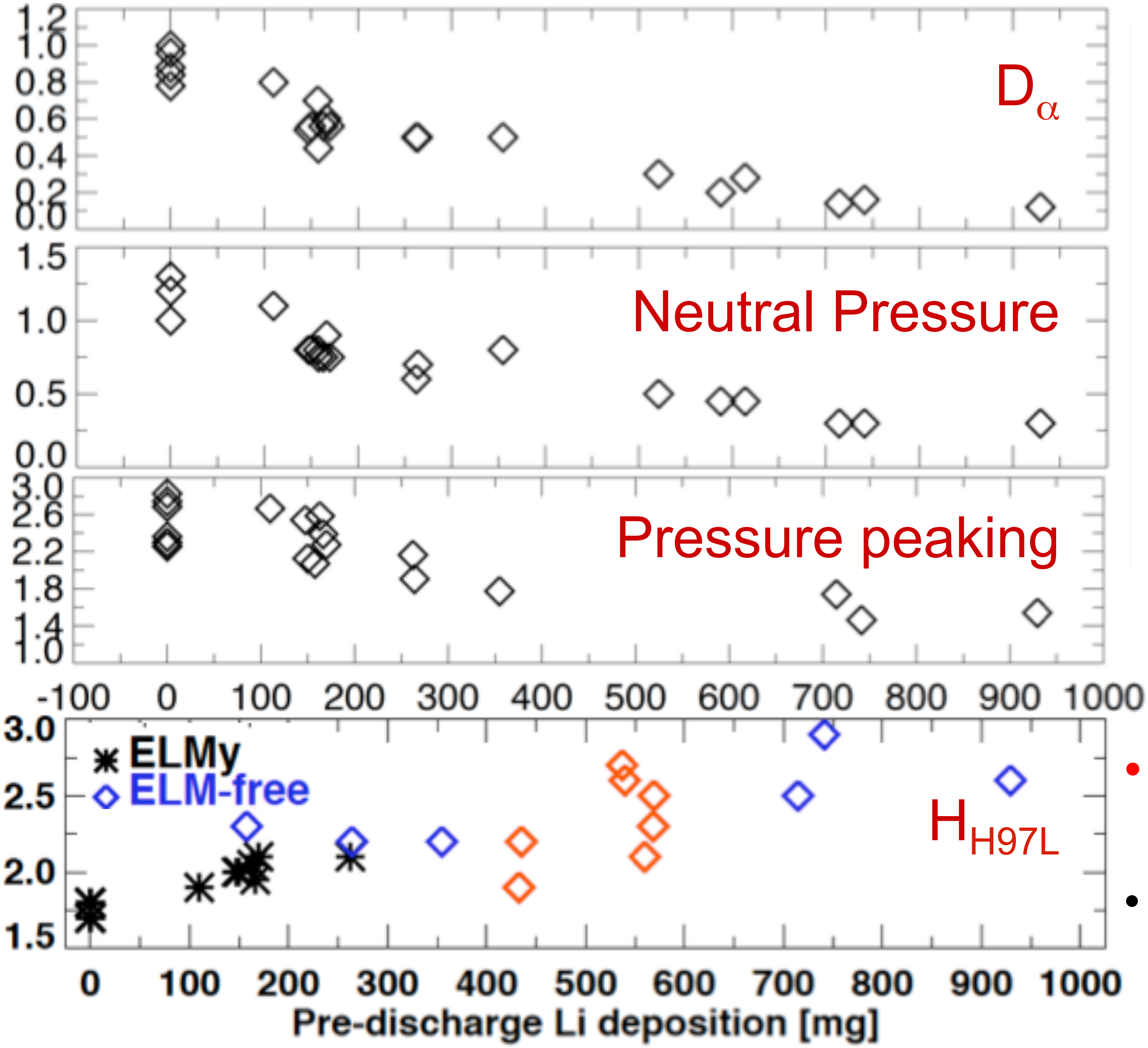


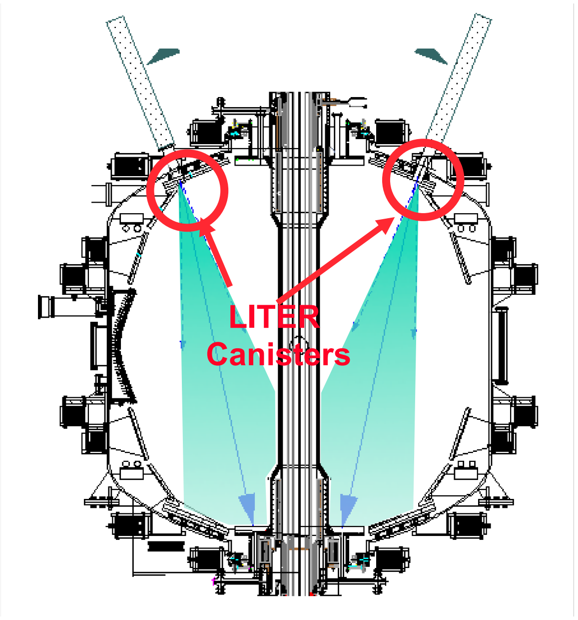


- Without Li, With Li, With Li
- ELM-free, reduced divertor recycling
- Power scan to identify β limit
- Core β limit observed, but no ELMs

R. Maingi, Nuc. Fusion **52** (2012) 083001

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

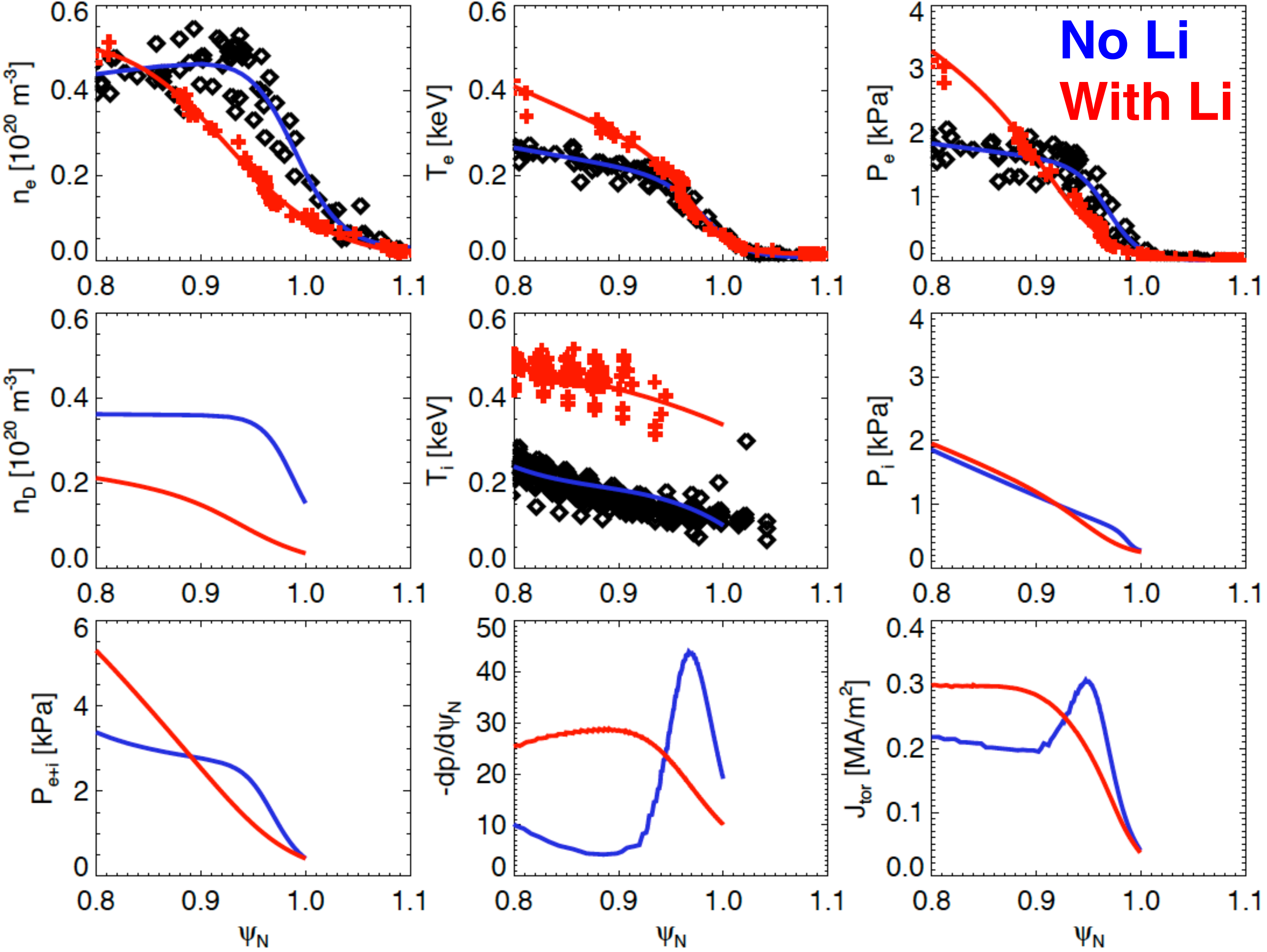




- **H_{H98y2} range from 0.8-1.4**
- Data in orange from other experiment

R. Maingi, PRL **107** (2011) 145004

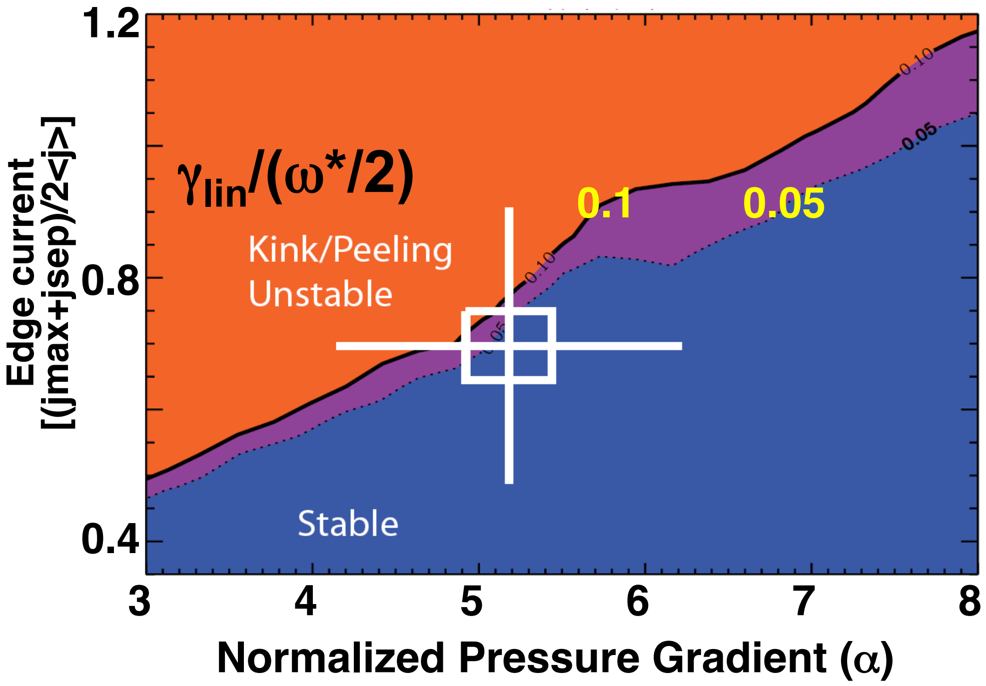
Edge profiles modified with lithium

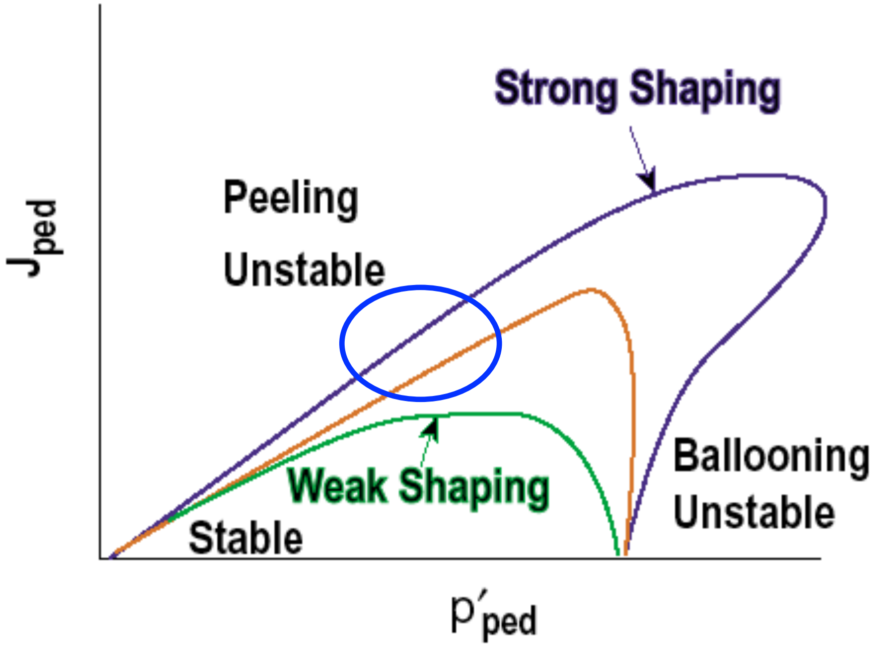


R. Maingi, Nucl. Fusion **52** (2012) 083001

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

No lithium

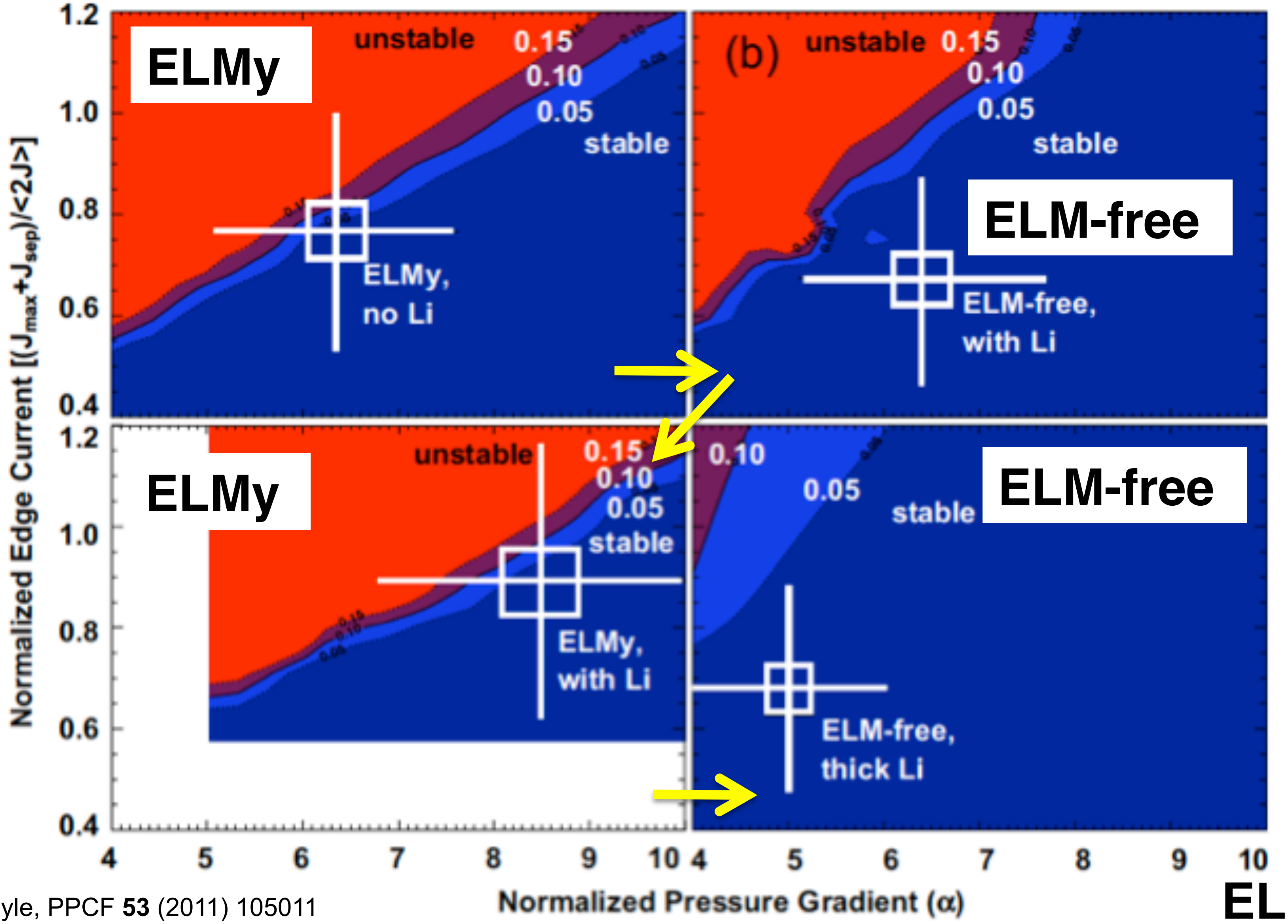




- Low n=1-5 pre-cursor oscillations observed before ELM crash
- Mode growth rates low

R. Maingi, PRL **103** (2009) 075001

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

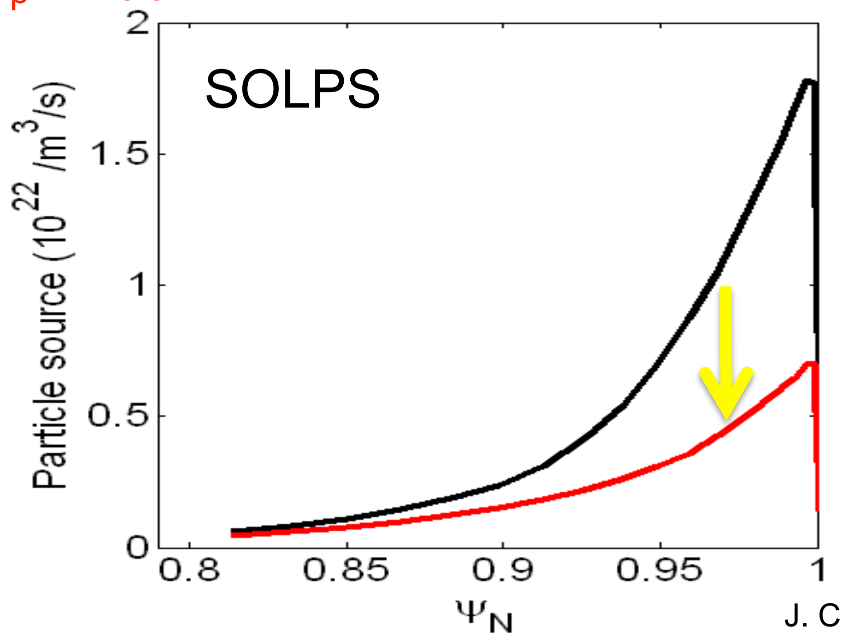


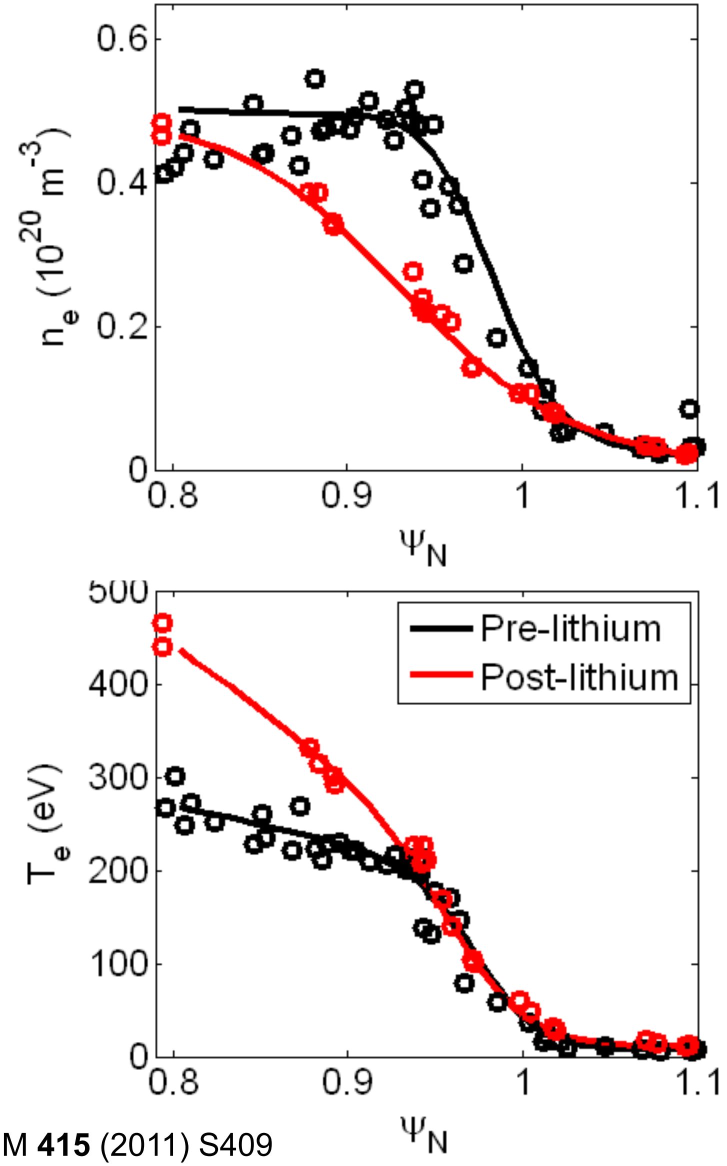
D. Boyle, PPCF **53** (2011) 105011

ELITE

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



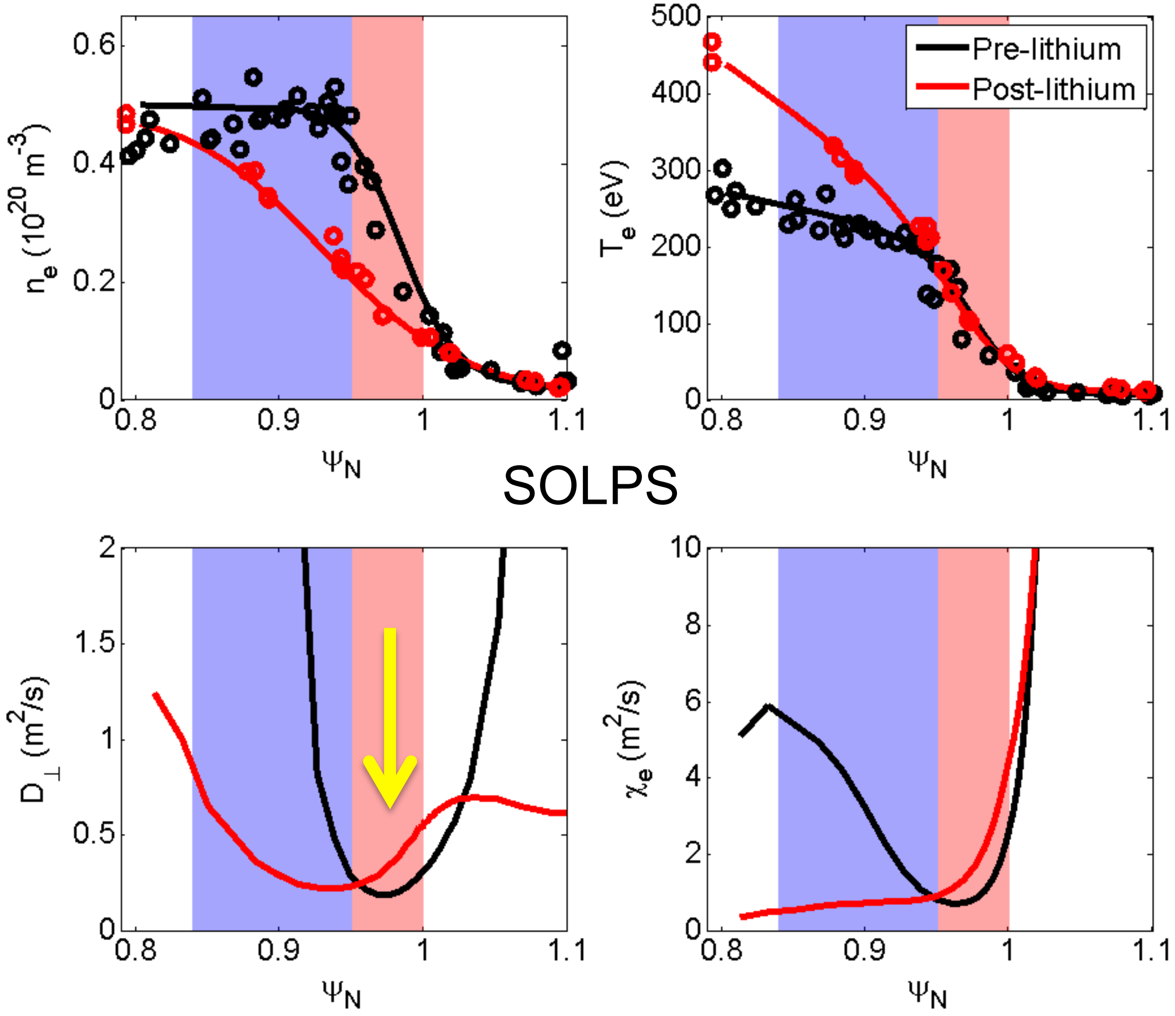


J. Canik, JNM **415** (2011) S409

Recycling and edge transport changes interpreted with SOLPS simulations

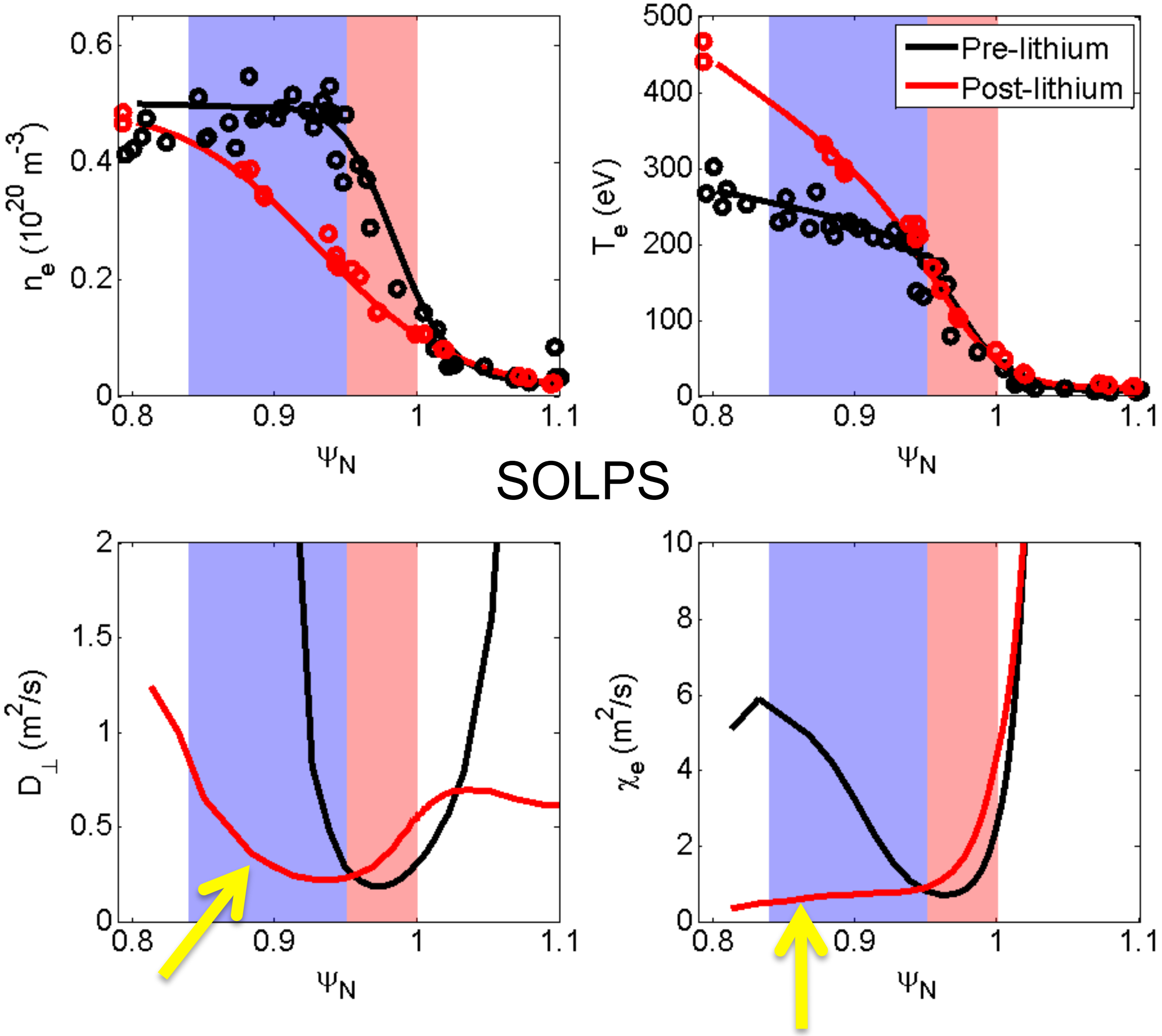
- Pre-lithium case shows typical barrier region inside separatrix
- Change in n_e profile with lithium from $0.95<\psi_N<1$ consistent with drop in fueling at ~ constant transport

(red shaded region)



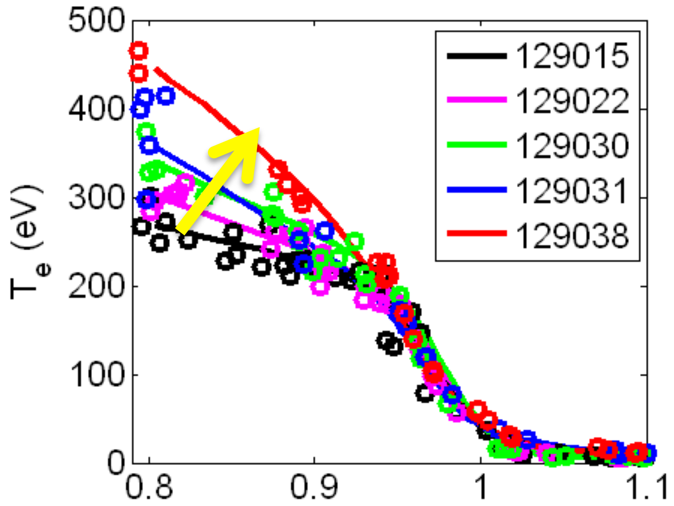
Recycling and edge transport changes interpreted with SOLPS simulations

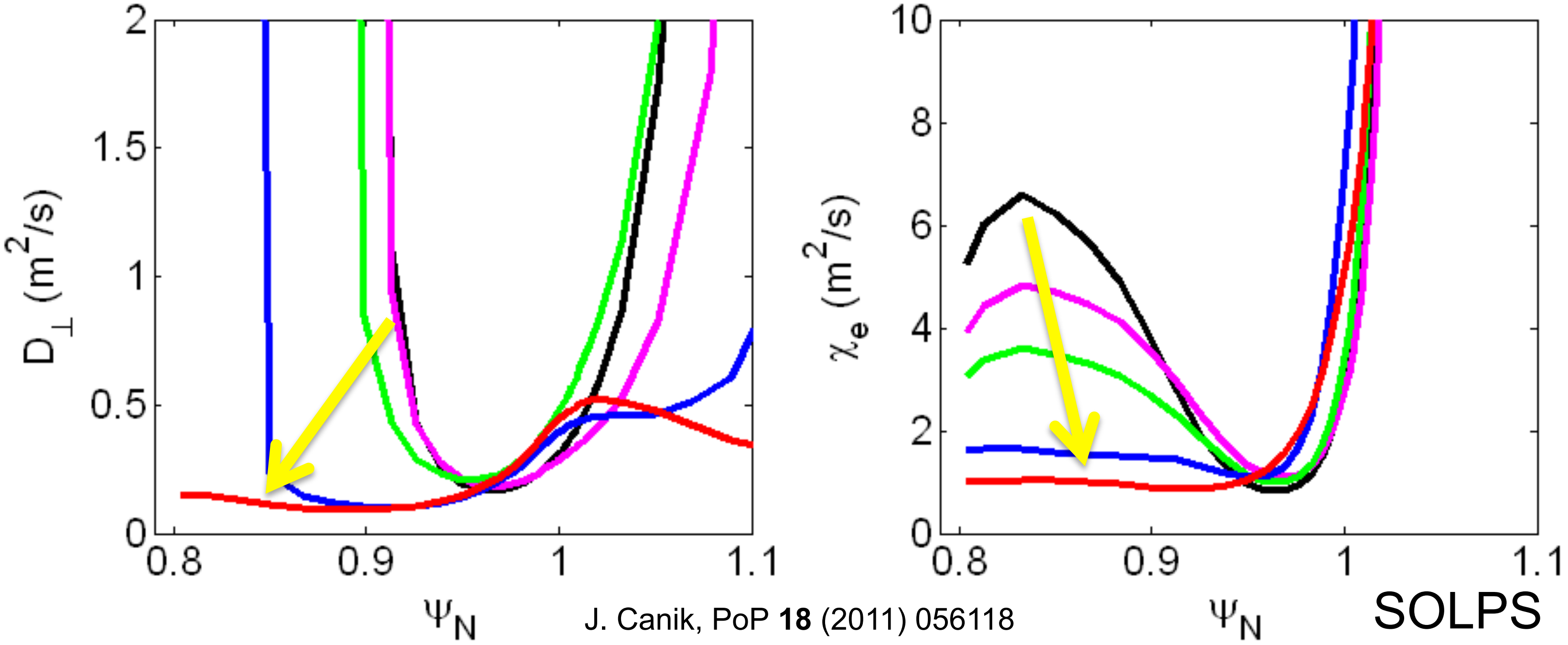
- Pre-lithium case shows typical barrier region inside separatrix
- Change in n_e profile with lithium from $0.95<\psi_N<1$ consistent with drop in fueling at ~ constant transport
- Spatial region of low transport expanded with lithium
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)



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



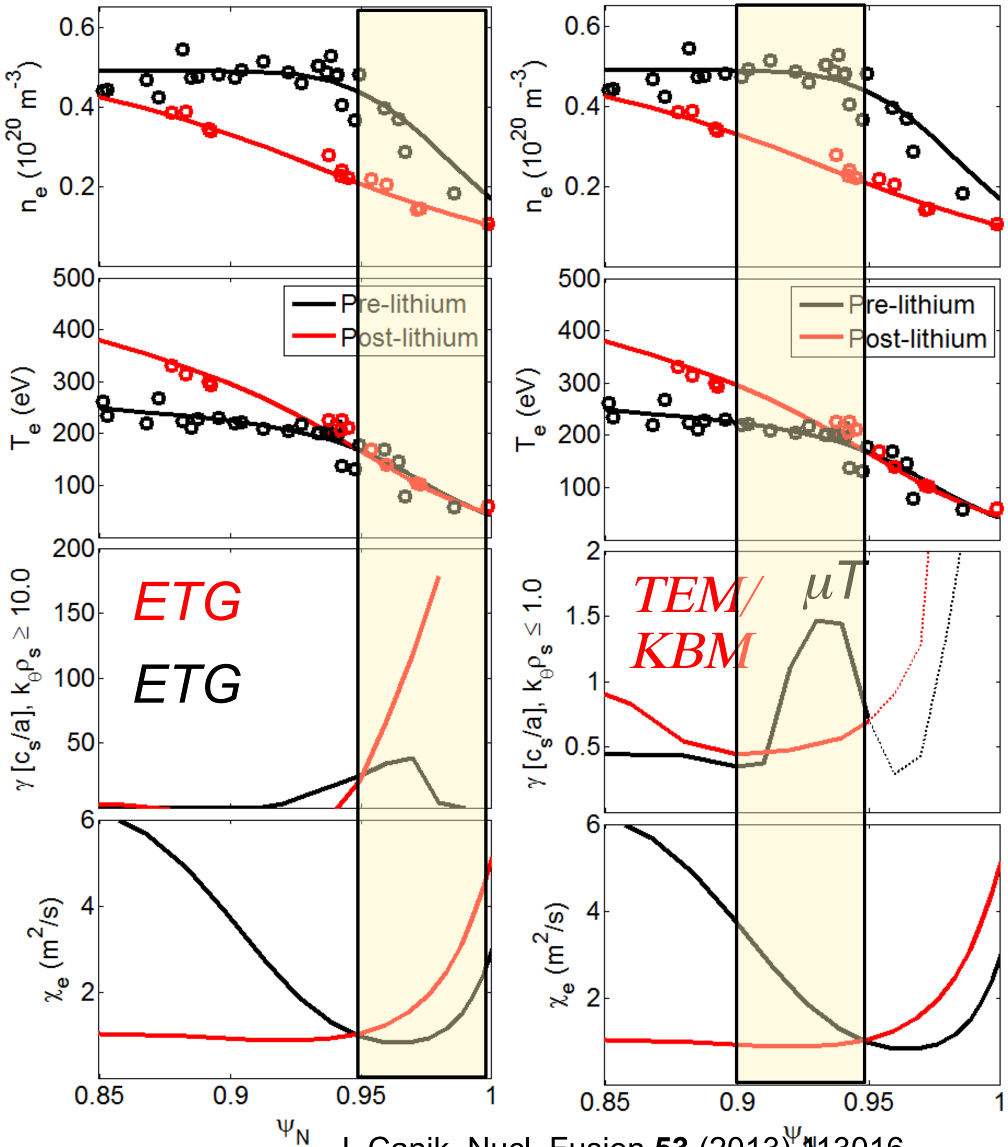


J. Canik, PoP **18** (2011) 056118

SOLPS

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
- Linear GS2 calcs only: (need non-linear calcs for actual heat flux)
- E x B shear rate higher w/Li



J. Canik, Nucl. Fusion **53** (2013) 113016

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

First key step is recycling reduction with lithium

ψ_N from 0.95-1 (recycling region)

Li coatings reduce recycling and core fueling (SOLPS)

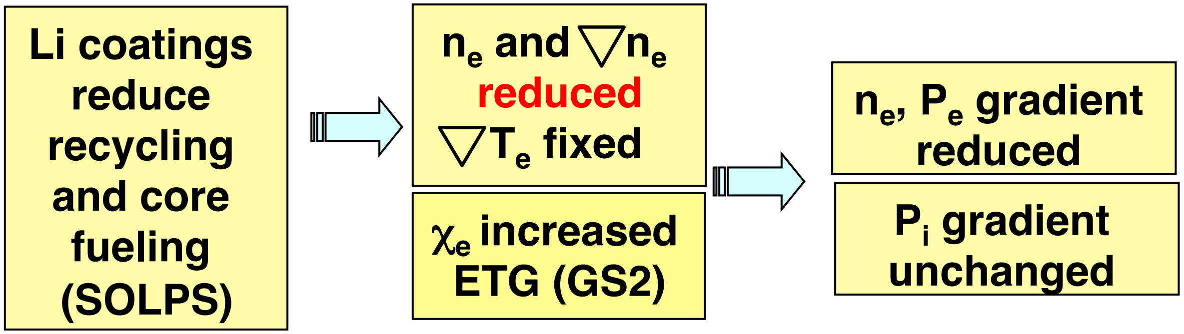
n_e and ∇n_e reduced
∇T_e fixed

χ_e increased
ETG (GS2)

ψ_N from 0.8-0.94

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 fixed

χ_e increased ETG (GS2)

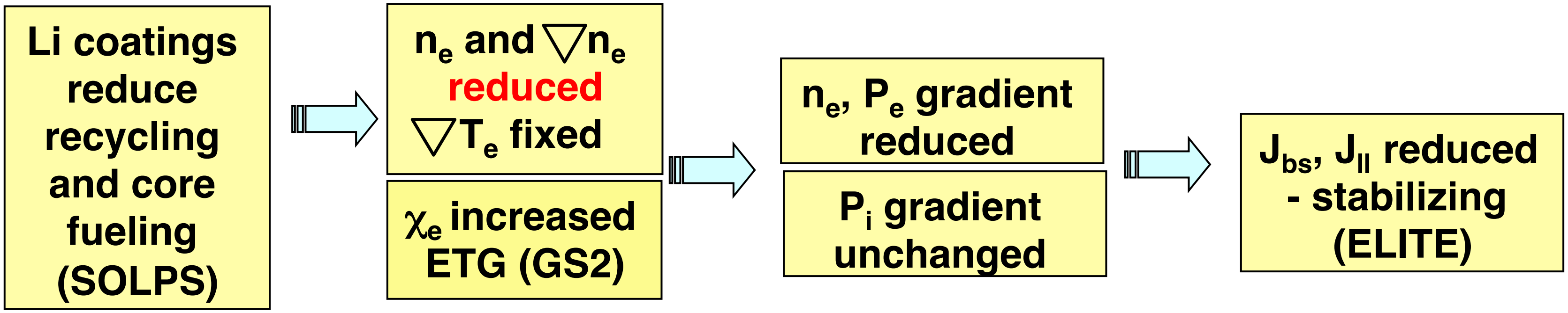
n_e, P_e gradient reduced

P_i gradient unchanged

ψ_N from 0.8-0.94

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 fixed

χ_e increased
ETG (GS2)

n_e, P_e gradient reduced

P_i gradient unchanged

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

ψ_N from 0.8-0.94

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 fixed

χ_e increased ETG (GS2)

→

n_e, P_e gradient reduced

P_i gradient unchanged

→

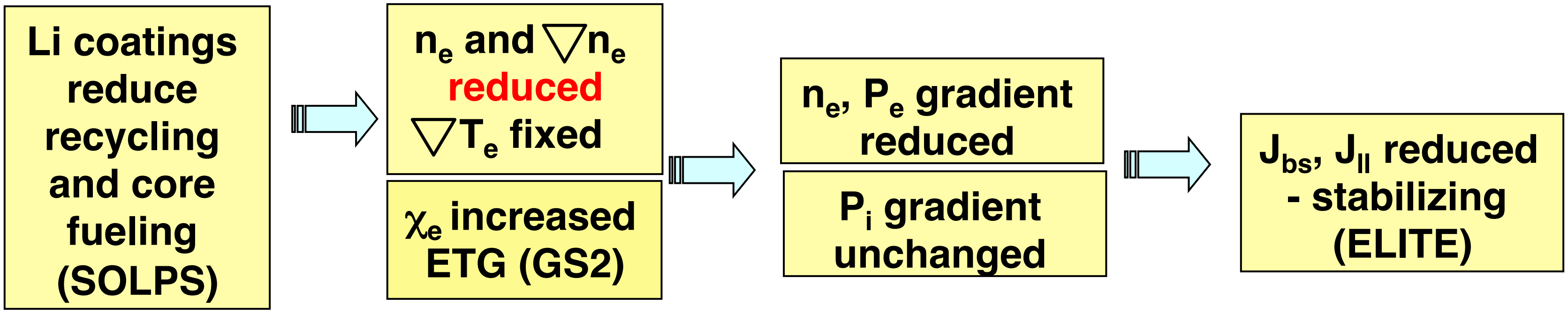
J_{bs}, $J_{\parallel}$ reduced - stabilizing (ELITE)

ψ_N from 0.8-0.94

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

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 fixed

χ_e increased ETG (GS2)

n_e, P_e gradient reduced

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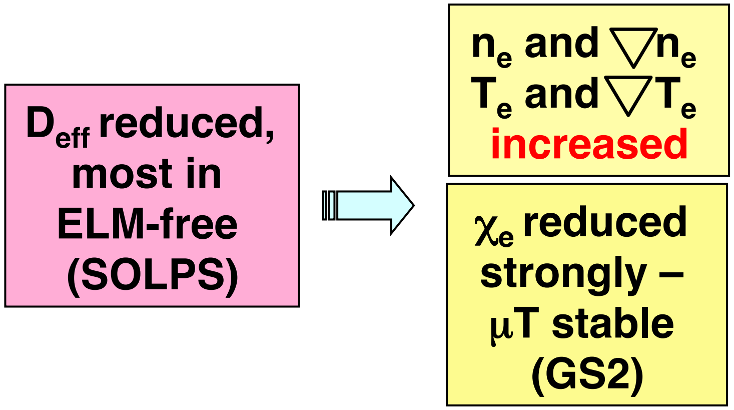
ψ_N from 0.8-0.94



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)

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 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

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 fixed

χ_e increased ETG (GS2)

n_e, P_e gradient reduced

P_i gradient unchanged

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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

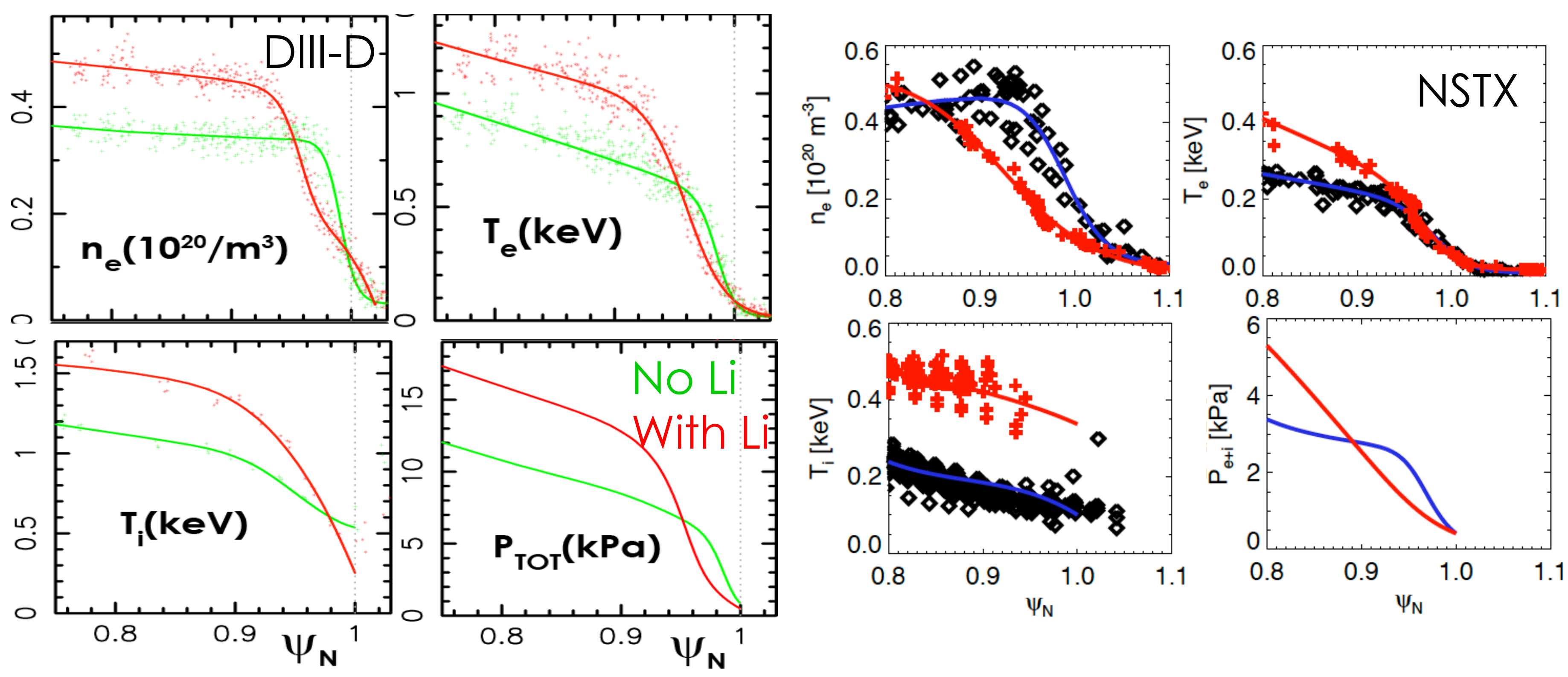
χ_e reduced strongly – μT stable (GS2)

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

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

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

- Gradients shifted inward more in NSTX than in DIII-D



Summary and Open Questions: Effect of Lithium pre-discharge coatings in NSTX

- Pre-discharge Li coatings result in improved pressure and confinement, increasing with Li dose
  - n_e profile shifts inward, T_e profile stays constant, pressure shifts away from separatrix
  - n_e shift consistent with reduced recycling and constant transport in last 3% of ψ_N (source region)
  - T_e invariance consistent with ETG destabilization
  - Confinement improvement consistent with μT stabilization

- Why does particle transport go down inside of pedestal?

- Why is there no evidence of a fluctuation increase in the far edge, near the SOL?

Outline

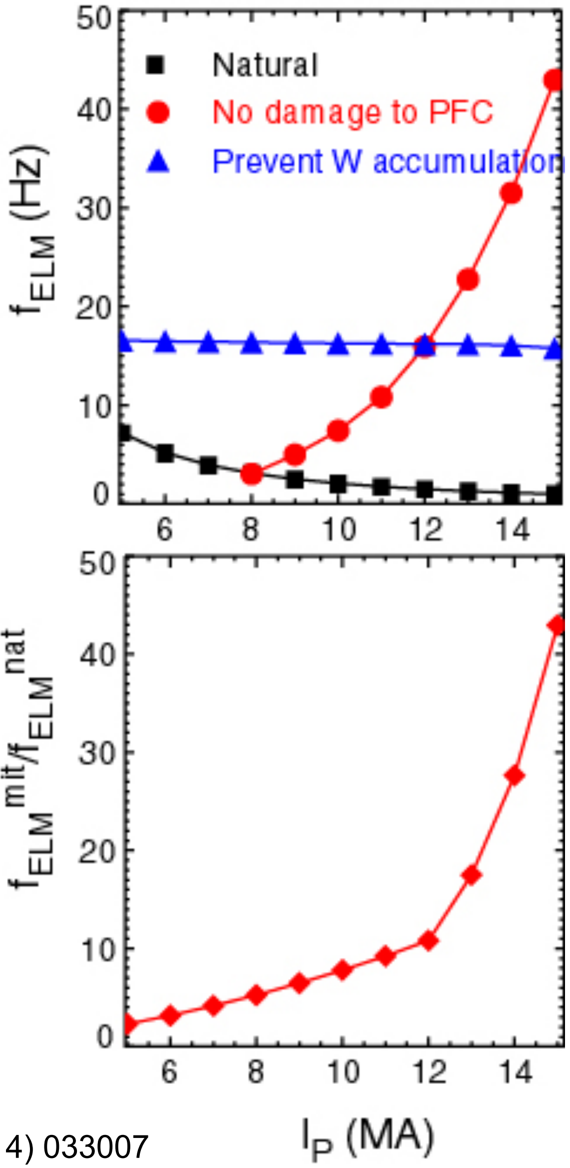
- Pedestals with carbon walls and high-Z walls
  - Brief history of PFC materials in fusion devices

- Purposeful introduction of low-Z
  - Real time injection with gas/aerosol [JET, AUG, DIII-D, EAST]
  - Inter-discharge Coatings (lithium, (boron)) [NSTX, (LTX, C-Mod, EAST)]
  - ➢ **Real-time injection with pellets [DIII-D, EAST]**
  - Low-Z liquid metal PFCs: static, flowing [(LTX, FTU), EAST]

- Prospects and open questions

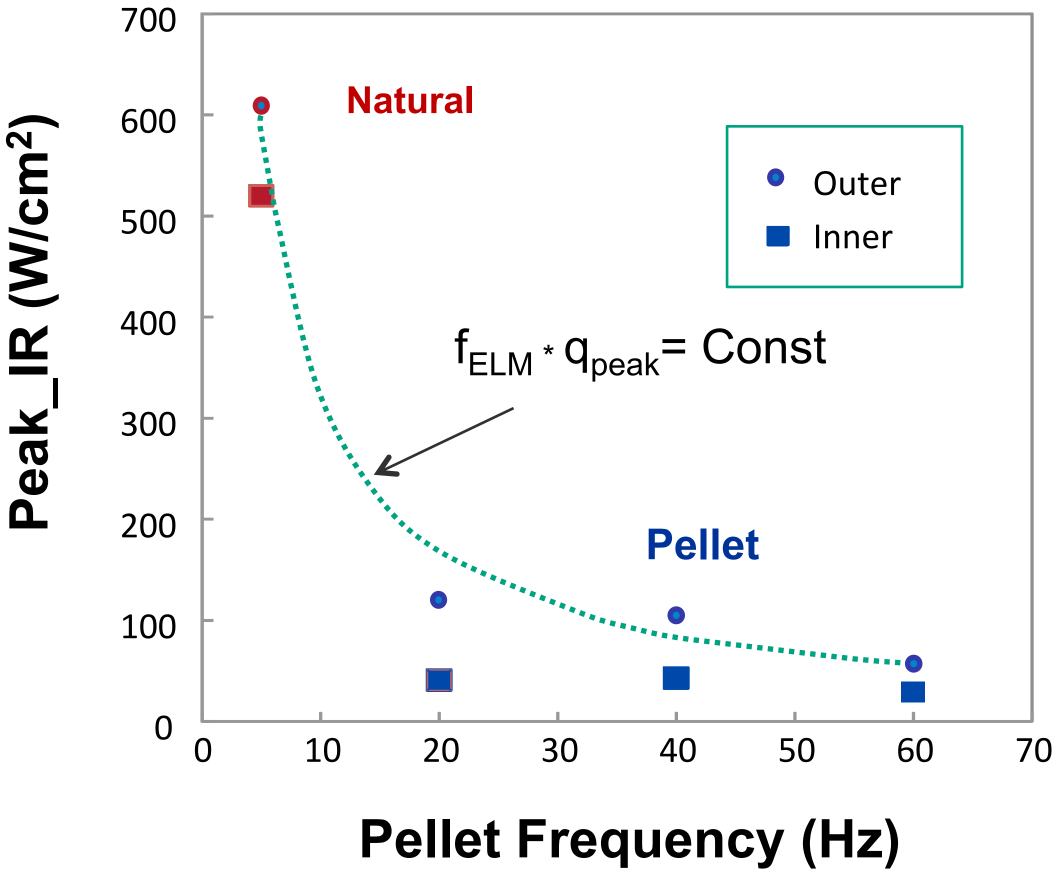
Required ELM frequency for acceptable ELM size in ITER increases with I_p

- $\Delta W_{ELM} < 0.7$ MJ (0.2% W_p)
  - 50% of damage limit, not including fatigue
- Inter-ELM heat flux width $\lambda_q \sim 1/I_p$
  - ELM wetted area critical
- $\Delta W_{ELM} f_{ELM} = (0.2\text{-}0.4)\ P_{SOL}$
- Minimum required f_{ELM} for acceptable heat flux increases with I_P
  - (Including Be/W PFCs)

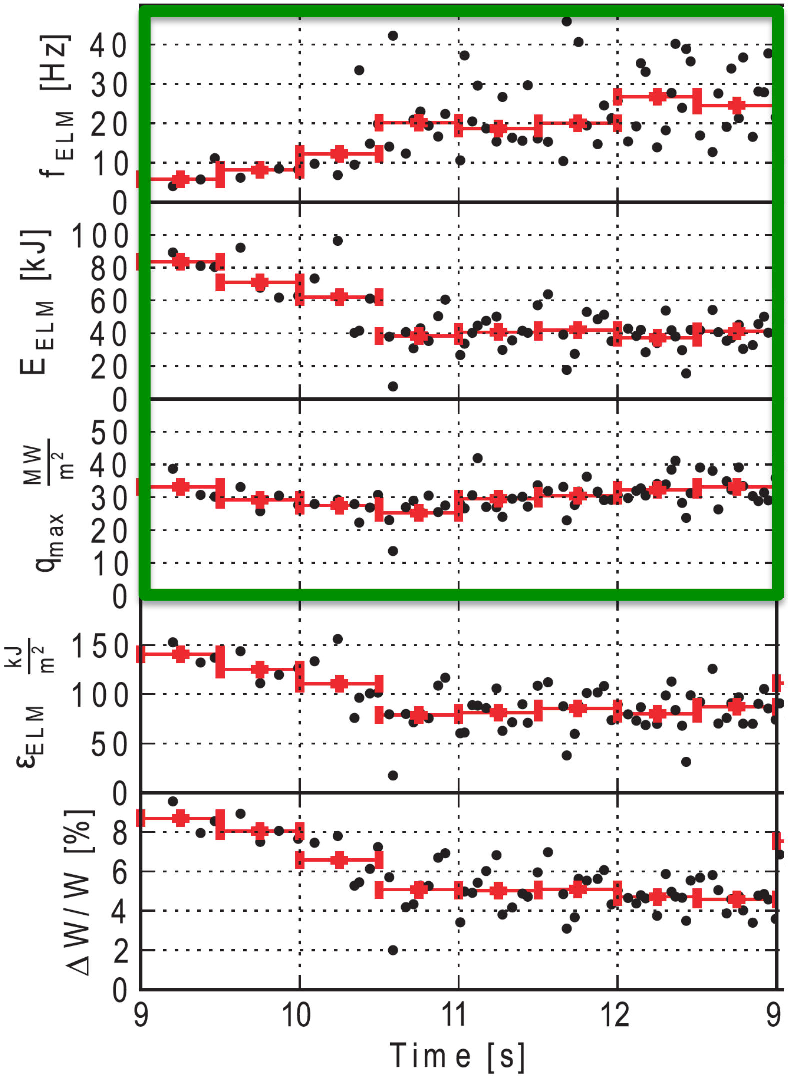


A. Loarte, Nucl. Fusion **54** (2014) 033007

Peak heat flux decreased in DIII-D with D_2 pellet pacing, but not in JET with the ILW

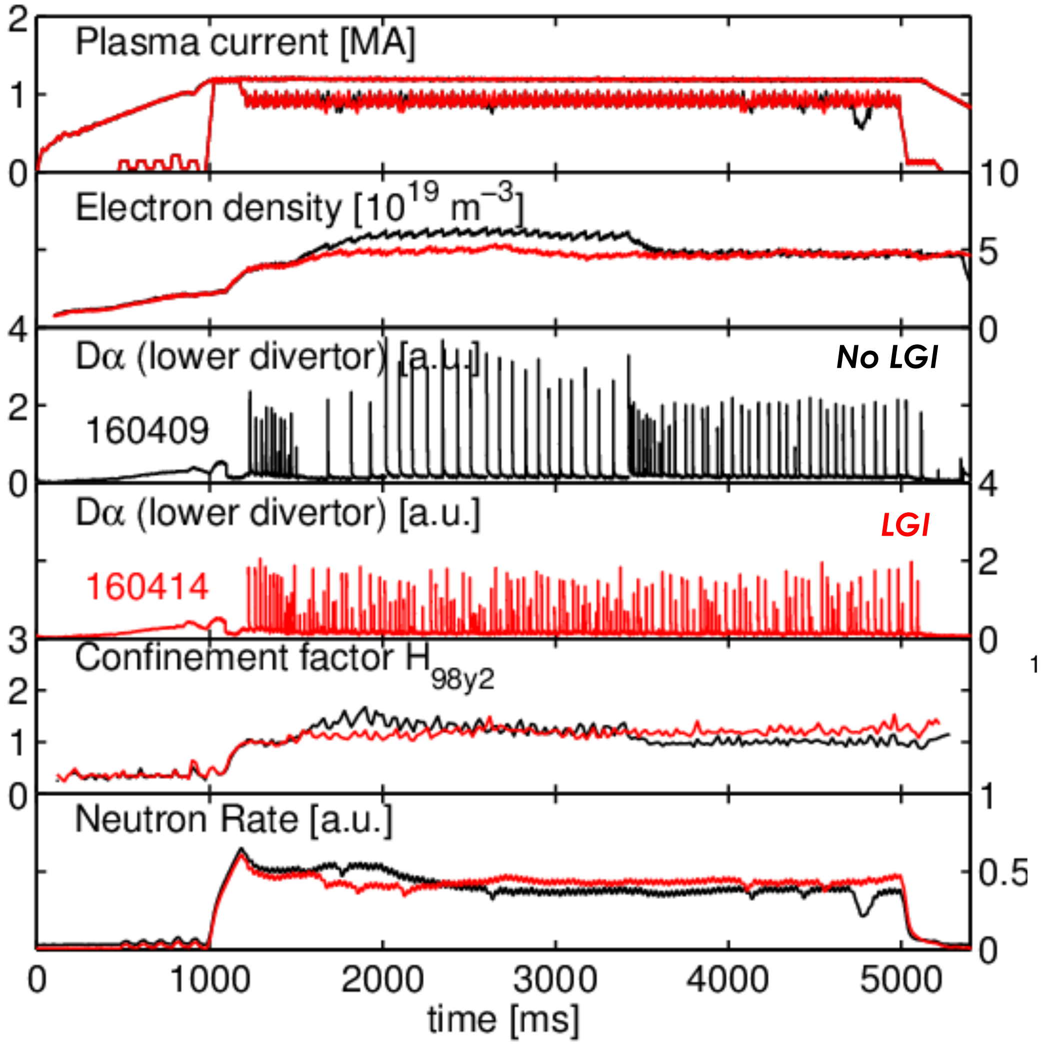


L. Baylor, PRL **110** (2013) 245001

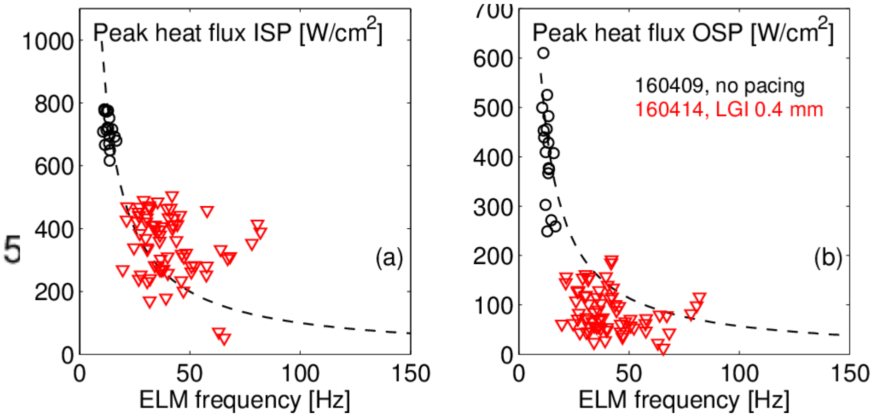


P. Lang, Nucl. Fusion **53** (2013) 073010

Multiplication of natural ELM frequency and heat flux reduction obtained with lithium granule injection in DIII-D

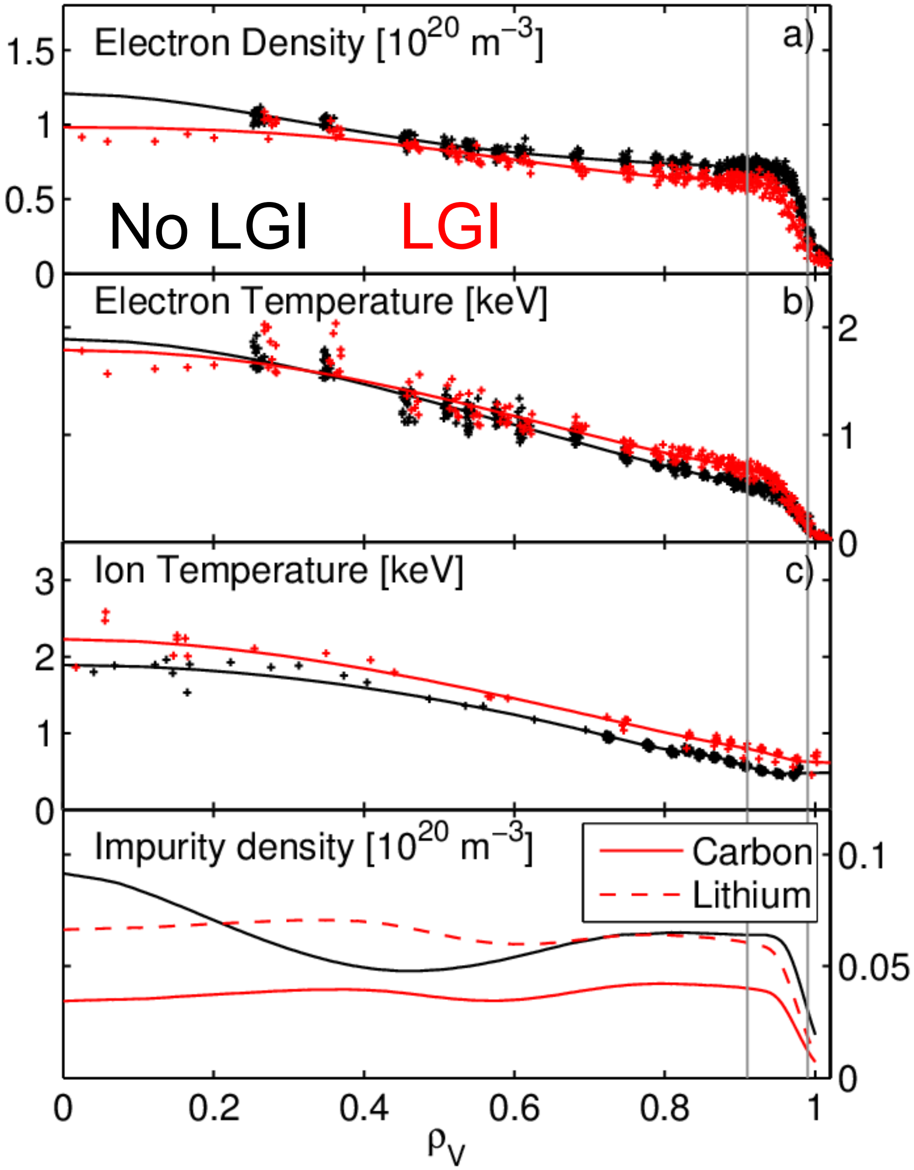


- Reference ELMy H-mode
  - 1.2 MA, $\beta_N = 1.4$,
  - P_{NBI}=2.3 MW, **T_{NBI}=2.9 N m**
  - "Natural" **f_{ELM} = 12 Hz**
- LGI pacing (1.5 < t < 5 s)
  - Granule diam. **0.4 mm**
  - Granule velocity **105m/s**
  - Average f_{LGI} =140 Hz
  - **f_{ELM} = 38 Hz** (3X)



A. Bortolon, Nucl. Fusion (2015) to be submitted

Substantial Li concentration in core with LGI, but carbon density reduced so Z_{eff} changes modestly

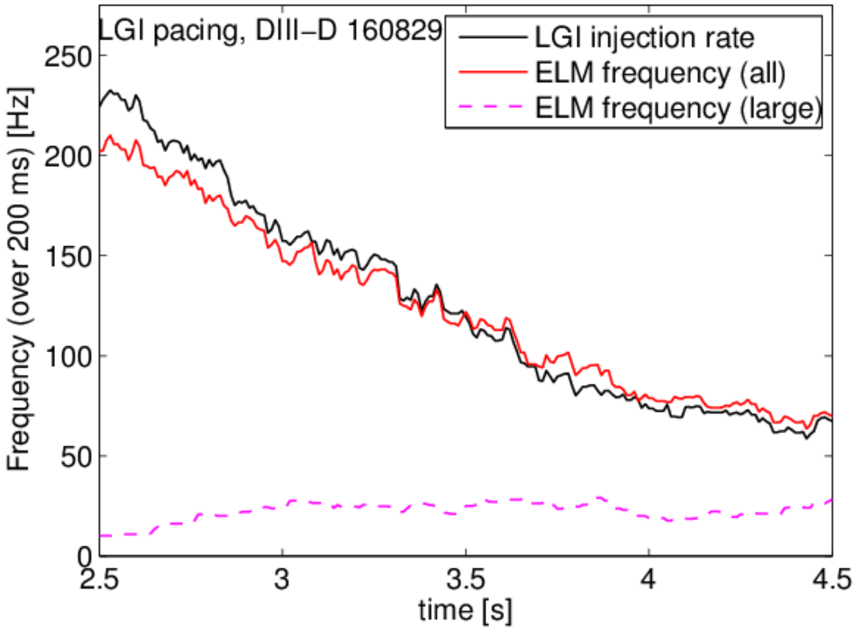


- Rapid ELMs with LGI reduced edge n_e
- T_e increased at constant pressure
- T_i increased
- Carbon was reduced

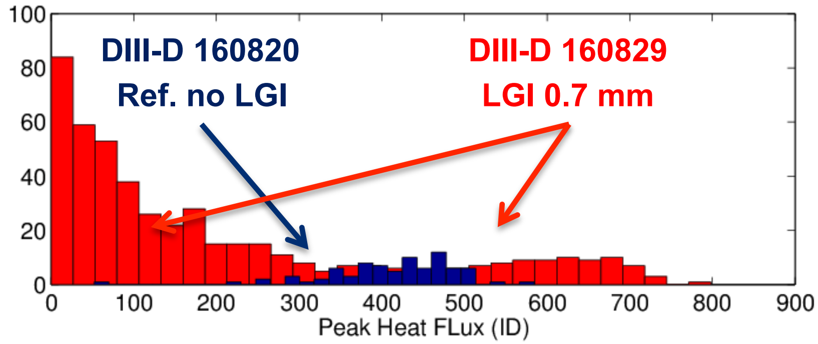
➢ No intrinsic effect of high edge Li on edge stability!

A. Bortolon, Nucl. Fusion (2015) to be submitted

Two classes of ELMs observed In low torque DIII-D discharges



- ELM pacing by LGI shown in ITER-like, low-torque (T~0.6 N m)
  - 0.7 mm granules, 110m/s
  - Pacing efficiency ~100%
- LGI injection frequency reduced dynamically during the shot
  - From 240 Hz to 60 Hz (4X)
- Frequency of ELMs follows the evolution of frequency of Li ablations



- Two classes of paced ELMs
  - Small and frequent
  - Large and rare
- Frequency of large ELMs does not change substantially from reference
  - Amplitude is larger!

A. Bortolon, H-mode workshop 2015

Outline

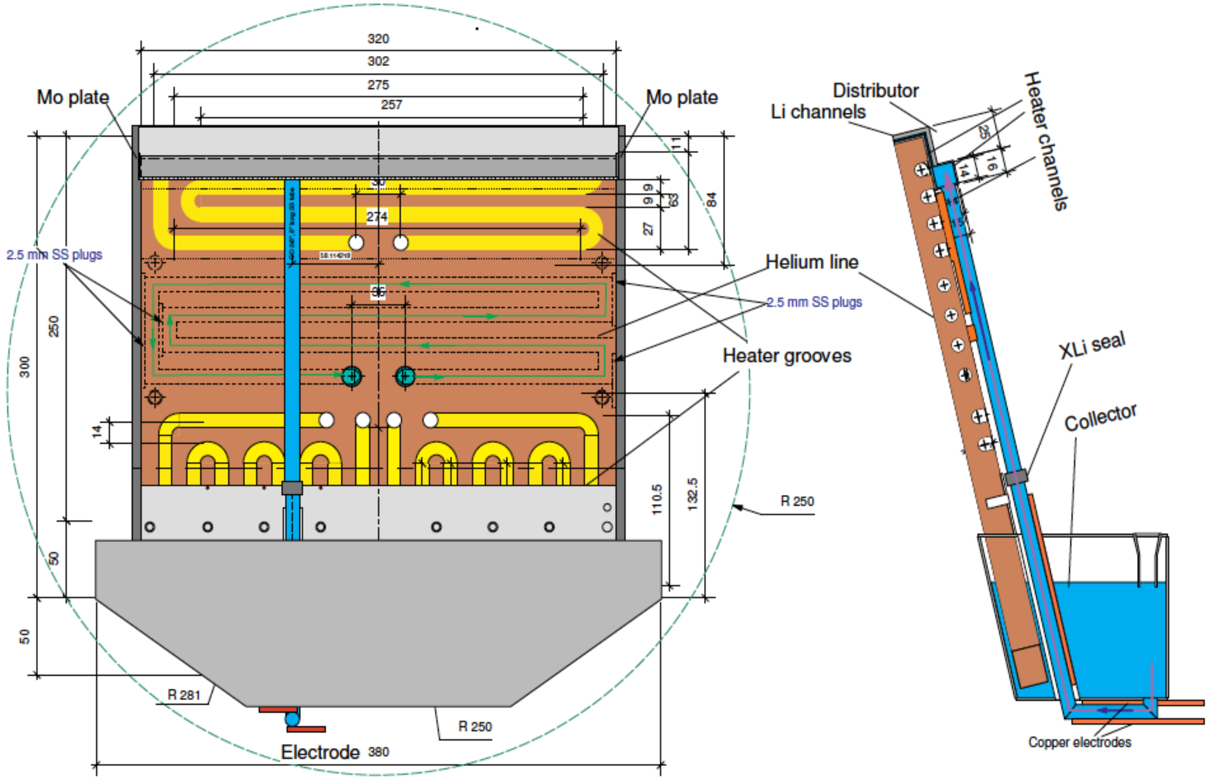
- Pedestals with carbon walls and high-Z walls
  - Brief history of PFC materials in fusion devices

- Purposeful introduction of low-Z
  - Real time injection with gas/aerosol [JET, AUG, DIII-D, EAST]
  - Inter-discharge Coatings (lithium, (boron)) [NSTX, (LTX, C-Mod, EAST)]
  - Real-time injection with pellets [DIII-D, EAST]
  - ➢ **Low-Z liquid metal PFCs: static, flowing [(LTX, FTU), EAST]**

- Prospects and open questions

Liquid lithium limiter delivered to EAST was evaluated as a primary outer midplane PFC in Oct. 2014

- Liquid Li thin film viscous flow system tested on HT-7 and EAST
  - To confirm that liquid Li flow can be maintained for long periods
- H-mode discharges maintained with liquid Li PFC!!
  - Wetting sub-optimal
  - Next test with new plate in FY16



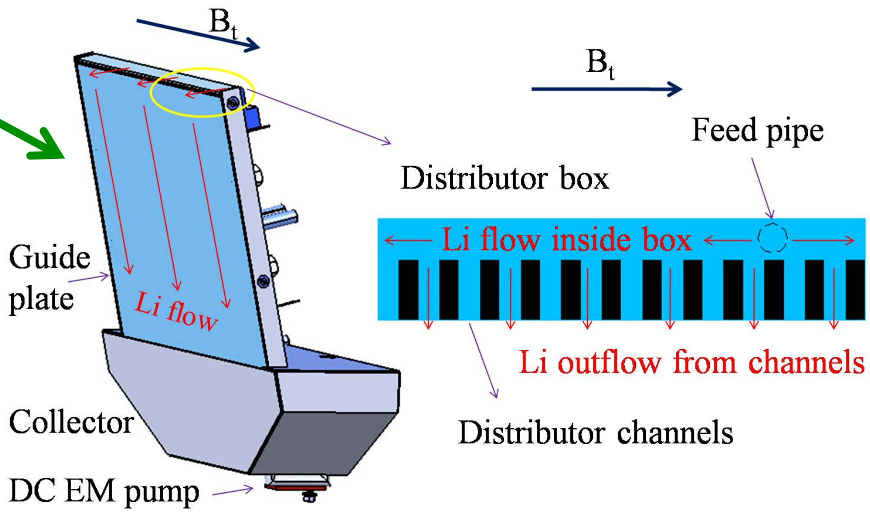
Copper coupon and collector

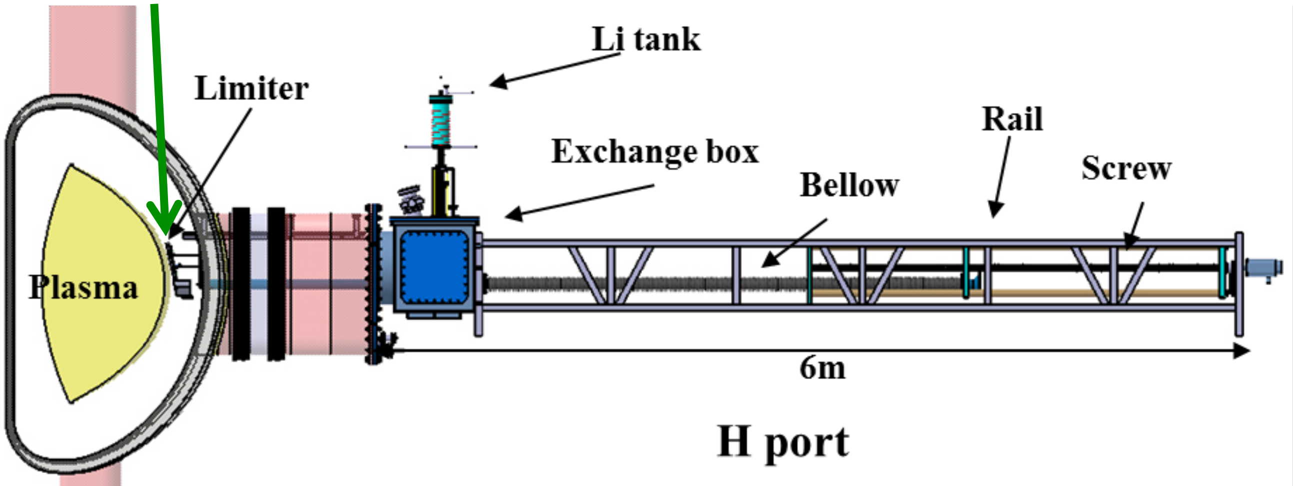
Schematic of heated copper plate and small liquid lithium reservoir, to be mounted on an insertable probe for testing in EAST during the 2014 campaign

J.S. Hu, Nucl. Fusion (2015) submitted

EAST: Liquid lithium limiter concept developed and fabricated at PPPL, and inserted via midplane port

- Designed and fabricated at PPPL
- Used a DC EM pump, with B_T of EAST, for steady-state recirculation
- Implemented 10/14
- Eventual goal: LL divertor

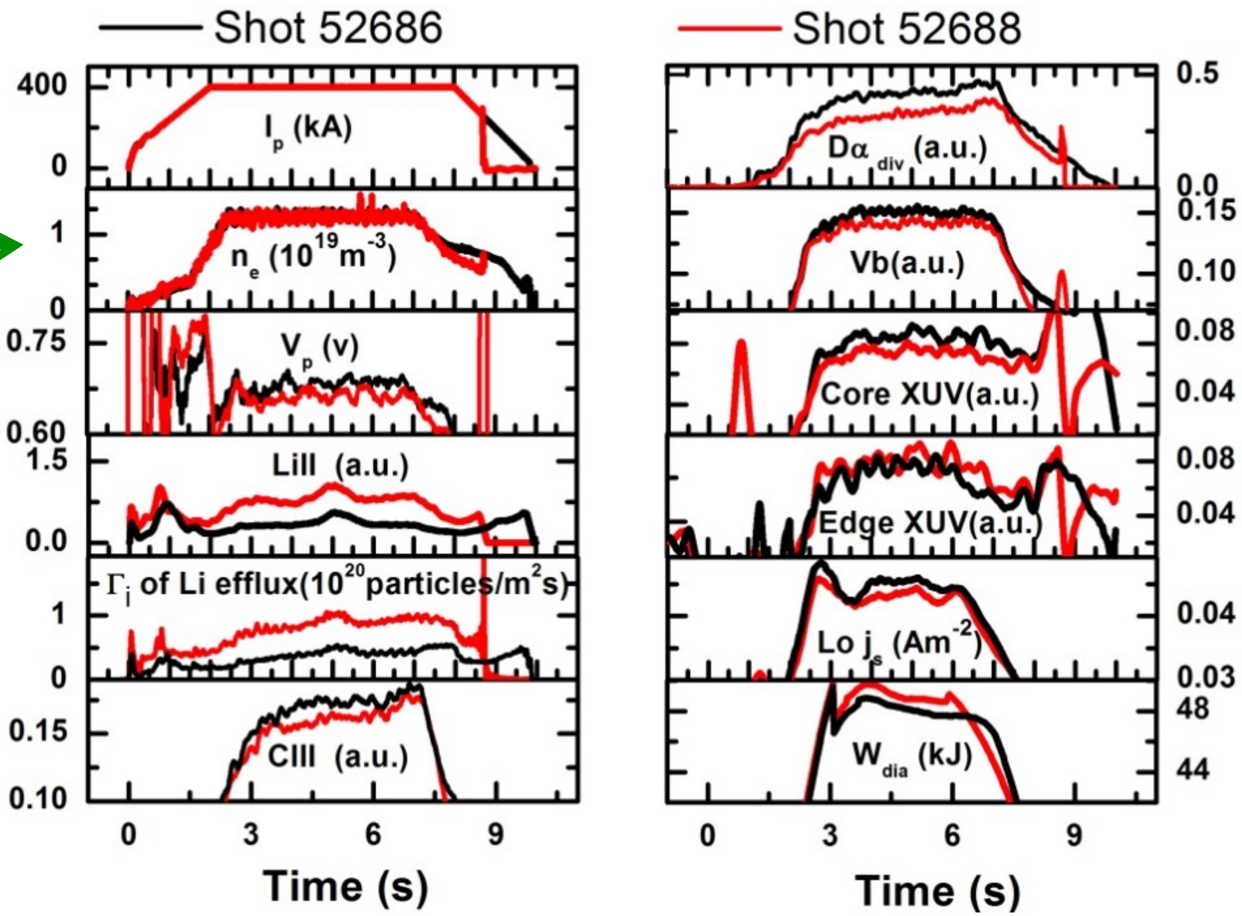




J. Ren, Rev. Sci. Instrum. **86** (2015) 023504

EAST: Liquid lithium limiter compatible with EAST scenarios, including H-mode

- Lithium light increased when current driven in limiter system
- Performance improved in ohmic discharges
- D_α and impurities decreased in both divertors
- Damage to limiter observed; design upgrade started



J.S. Hu et al., *Nucl. Fusion* (2015) submitted

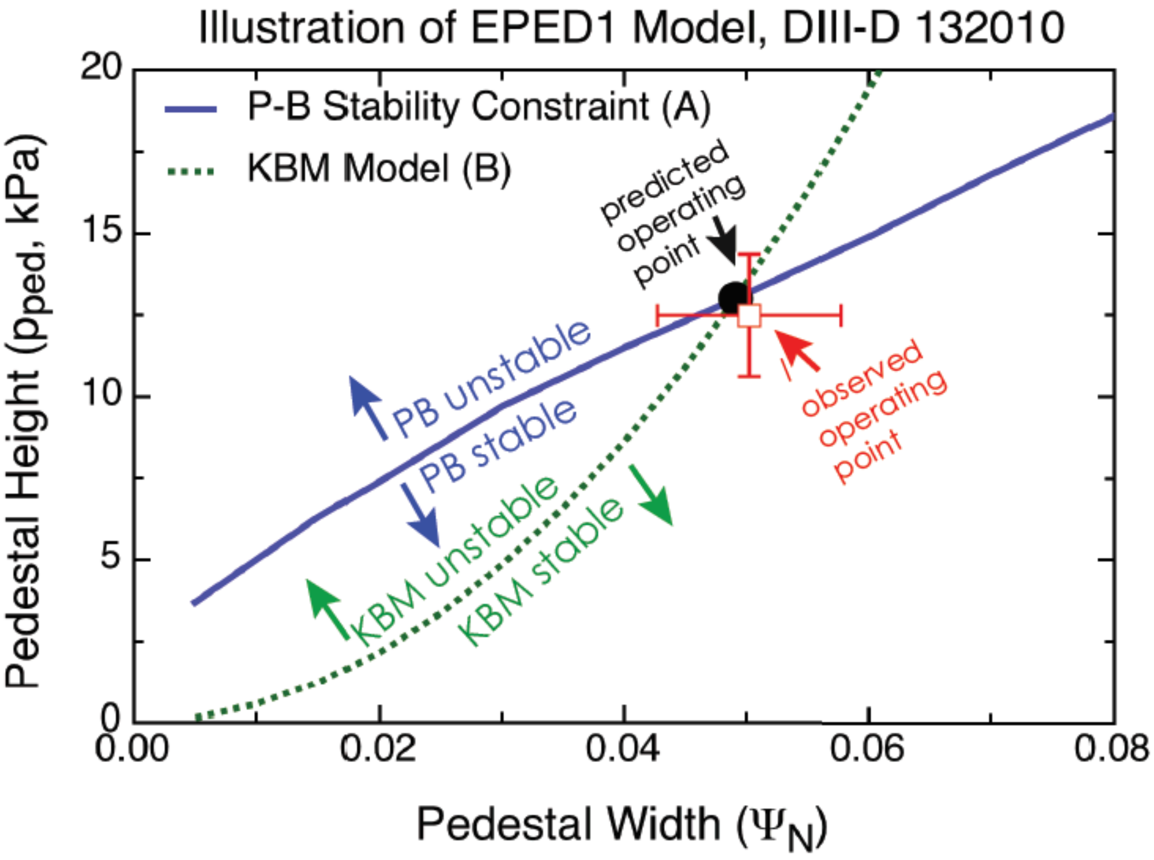
Summary and Open Questions

- Low-Z impurities can improve pedestal performance
  - Combination of profile shift, higher Z_{eff}, and maybe main ion dilution all contribute
  - Is it simply necessary to have lower-Z than the wall material, or Z<10 (Neon) required?
  - Why don't noble gases enhance performance like N_2 or Li?
  - Does the magnitude of the improvement increase with the density profile shift, independent of species?
  - Is there evidence for what clamps the T_e profile?
  - What kind of mode is the BCM? Can we excite modes, e.g. the BCM or ECM, for a controllable profile shift?
  - Will the low-Z injections generate hydrogen-rich dust?
- Li seems to give the highest performance boost
  - Is there an upper P_{SOL} limit on use of lithium?
  - Can a flowing liquid lithium system be designed to capitalize on this increase, while also removing tritium?

BACKUP

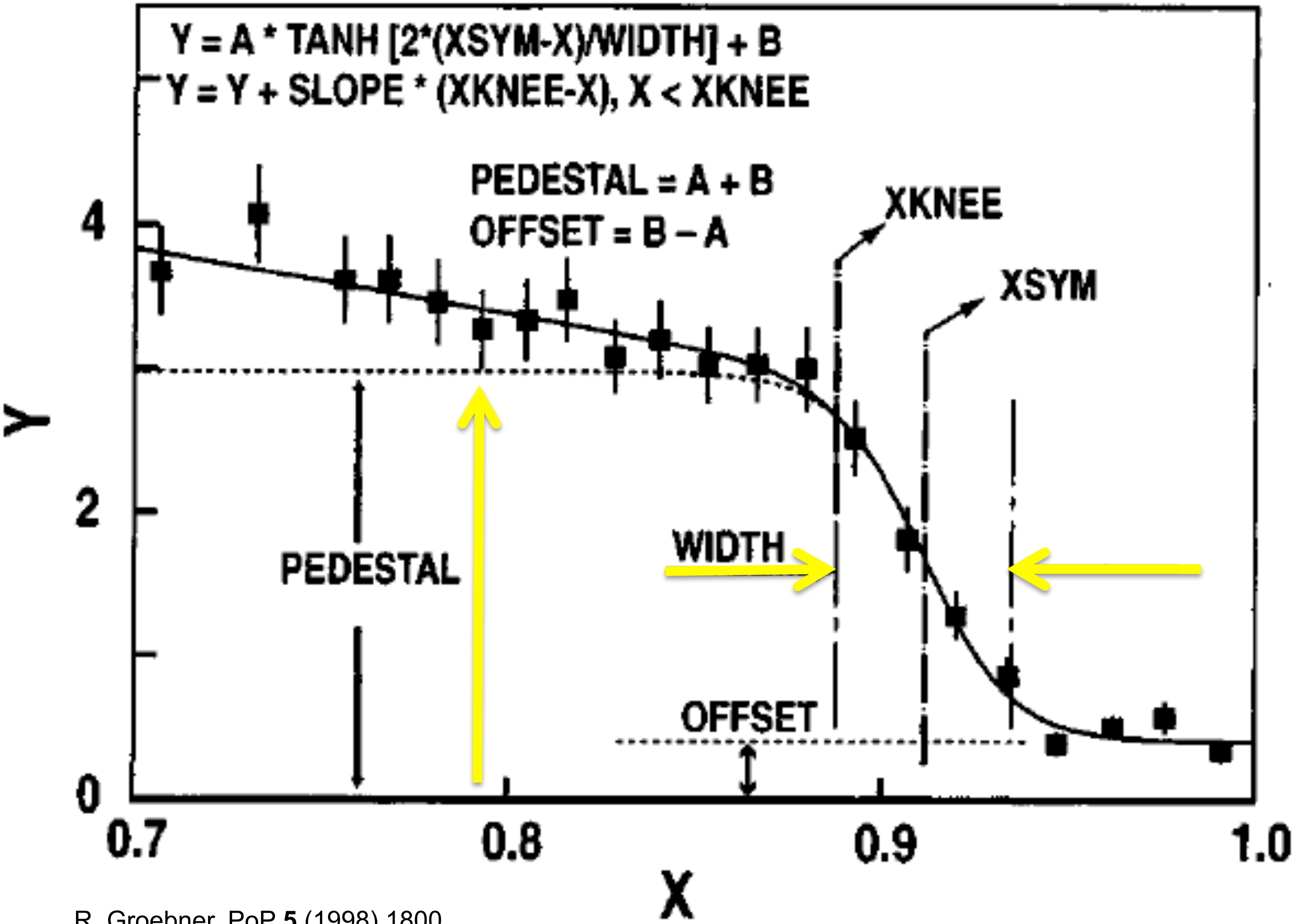
A model for pedestal height has been developed and tested

- **EPED model combines peeling-ballooning (PB) stability and a model for limit on pressure gradient**
- **Limit on Grad P from model of kinetic ballooning modes (KBM)**
  - Proposed to provide hard limit to pressure gradient
- **Combined models for PB and KBM predict a unique operating point**



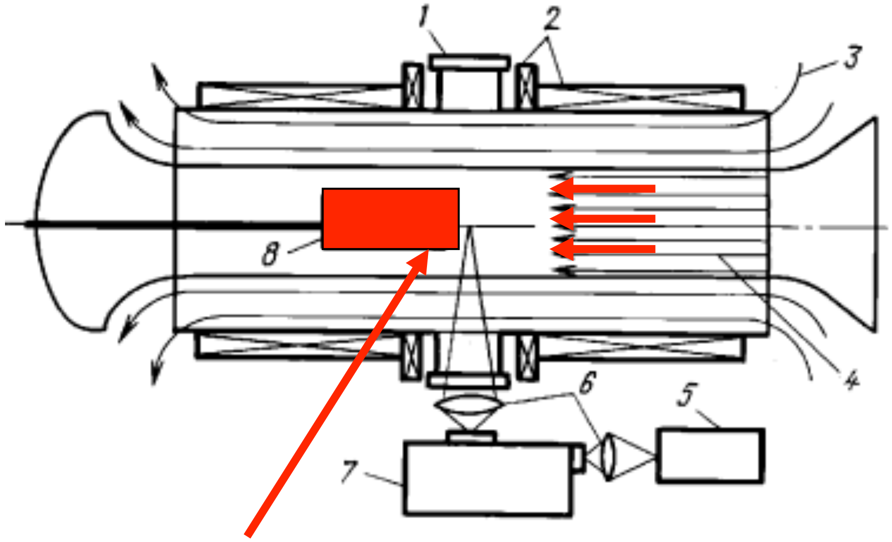
P. Snyder, PoP **16** (2009) 056118

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



R. Groebner, PoP **5** (1998) 1800

Lithium loaded targets withstood high steady and transient heat loads in plasma gun experiments



Lithium Capillary Porous System (CPS) targets

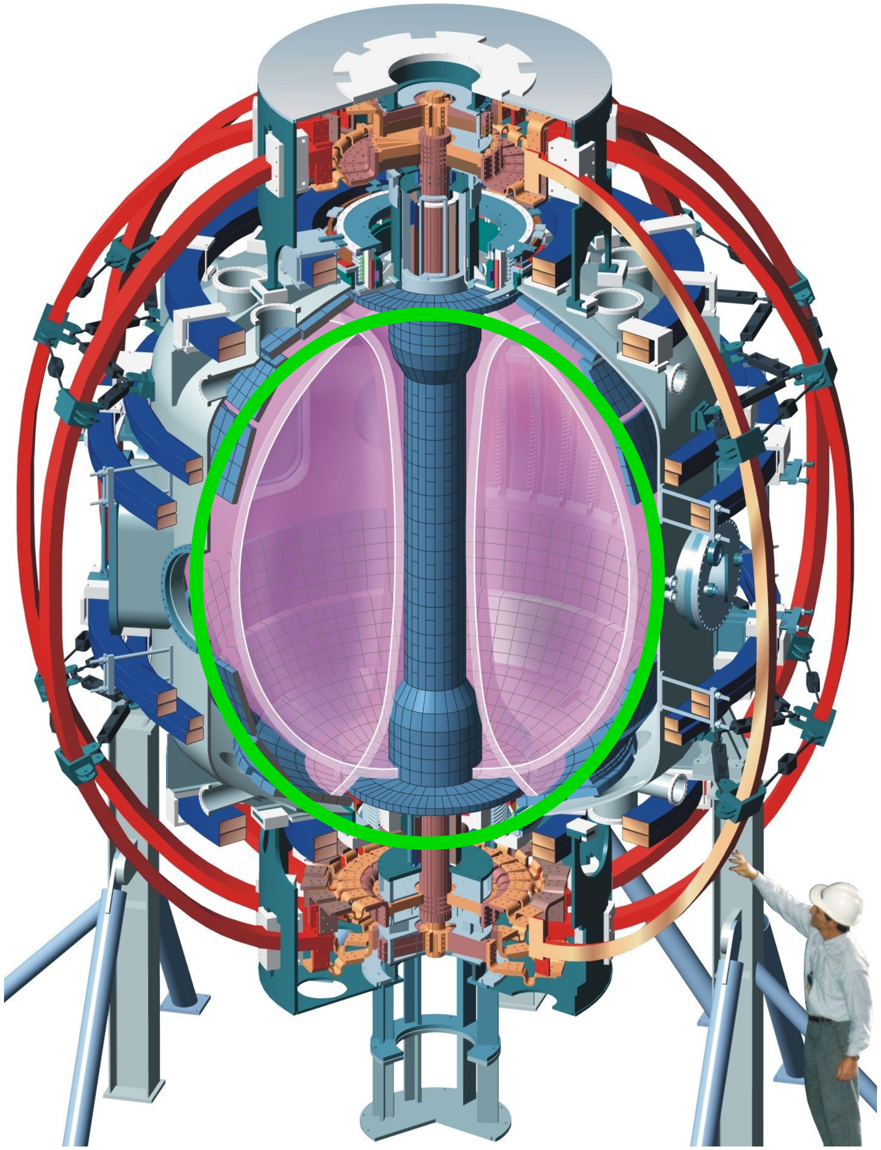
- Steady operation with heat loads from 1-11 MW/m^2 withstood for 3 hours
- Heat loads $\leq$ 25 MW/m^2 withstood with Li targets (5-10 minutes, limited by Li inventory)
- Transient loads $\leq$ 50 MW/m^2 withstood with Li targets without cooling (up to 15 sec)

Liquid metal PFCs are an option to solid PFCs, but have substantial R&D needs to assess viability

- Advantages
  - Erosion tolerable from PFC view: self-healing surface
  - No dust; main chamber material and tritium transported to divertor could be removed via flow outside of tokamak
  - Liquid metal is neutron tolerant; protects substrate from PMI
  - Liquid (and solid) lithium offer access to low recycling, high confinement regimes under proper conditions
  - Very high steady, and transient heat exhaust, in principle (50 MW/m^2 from electron beam exhausted; also 60 MJ/m^2 in 1 μsec)
- Disadvantages and R&D needs
  - Liquid metal surfaces and flows need to be stable
  - Liquid metal chemistry needs to be controlled
  - Temperature windows need optimization

* *Most of experience in fusion is with Li, but Sn and eutectics (e.g. Sn-Li) offer some promise in terms of broader temperature windows*

NSTX-U will commence research operations in Dec. 2015



NSTX-U Facility Parameters

Major Radius 0.90 m

Minor Radius ≤ 0.55 m

Plasma Current ≤ 2.0 MA

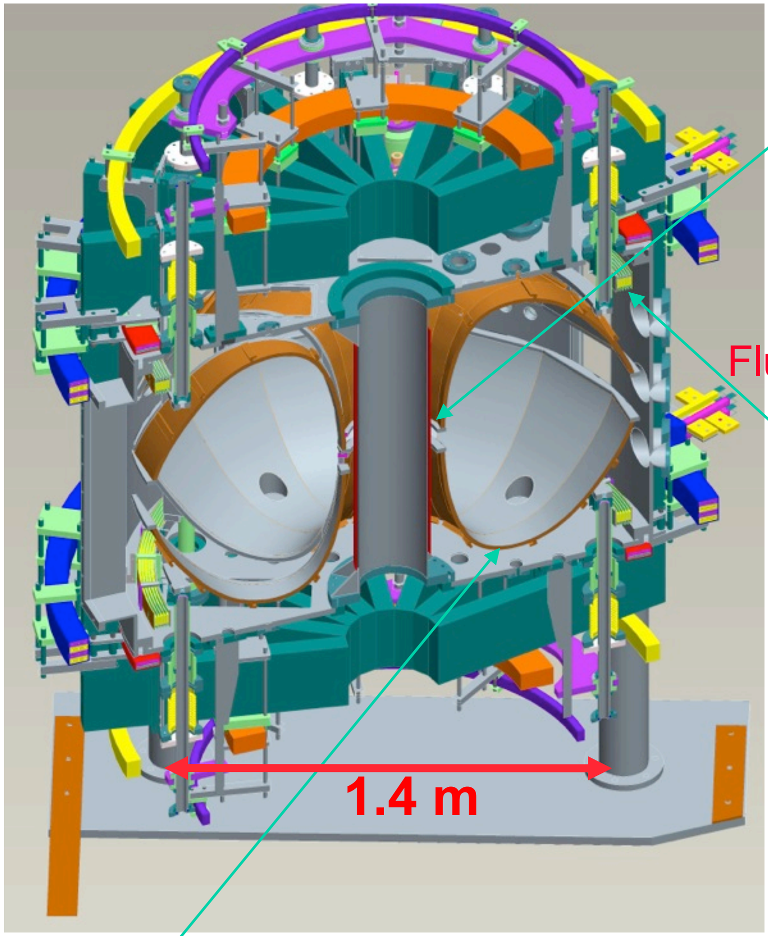
Toroidal Field ≤ 1.0 T

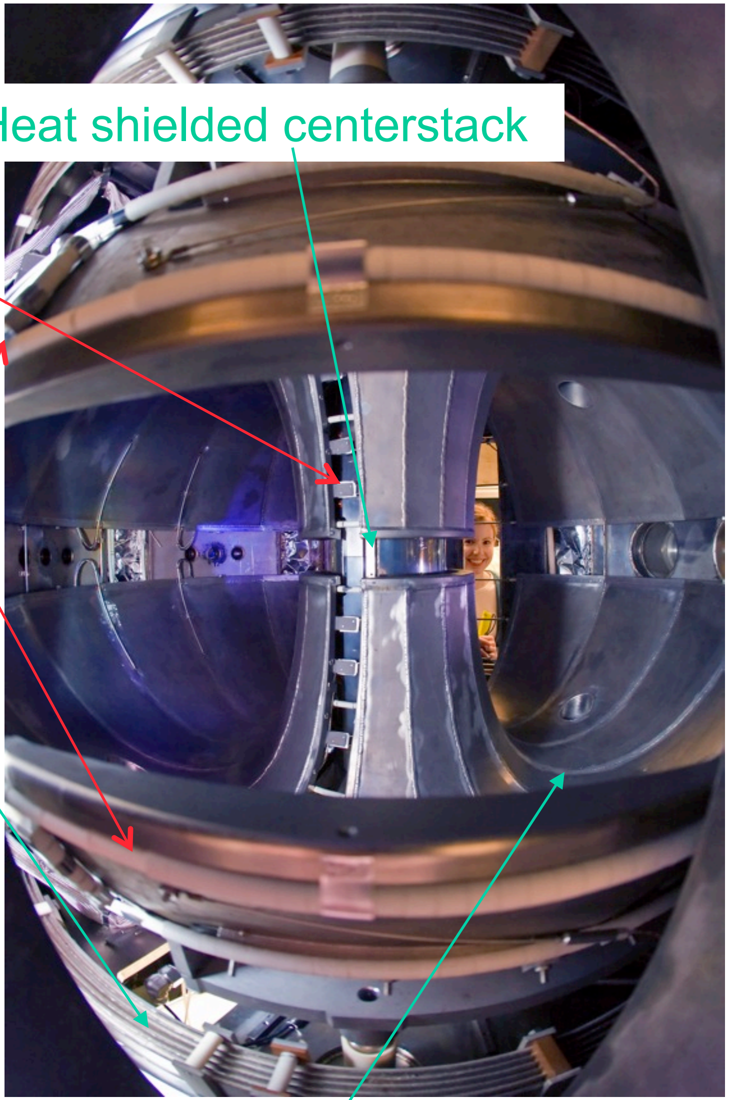
Neutral Beam Power ≤ 12 MW

RF Heating ≤ 6 MW

Pulse Length ≤ 10 sec

LTX remains the only tokamak with a hot, high Z, lithium compatible wall





Heat shielded centerstack

2-axis Mirnov coils

Flux loops

Fast, uncased internal coil