Type-I ELM mitigation by continuous lithium granule gravitational injection into the upper tungsten divertor in EAST

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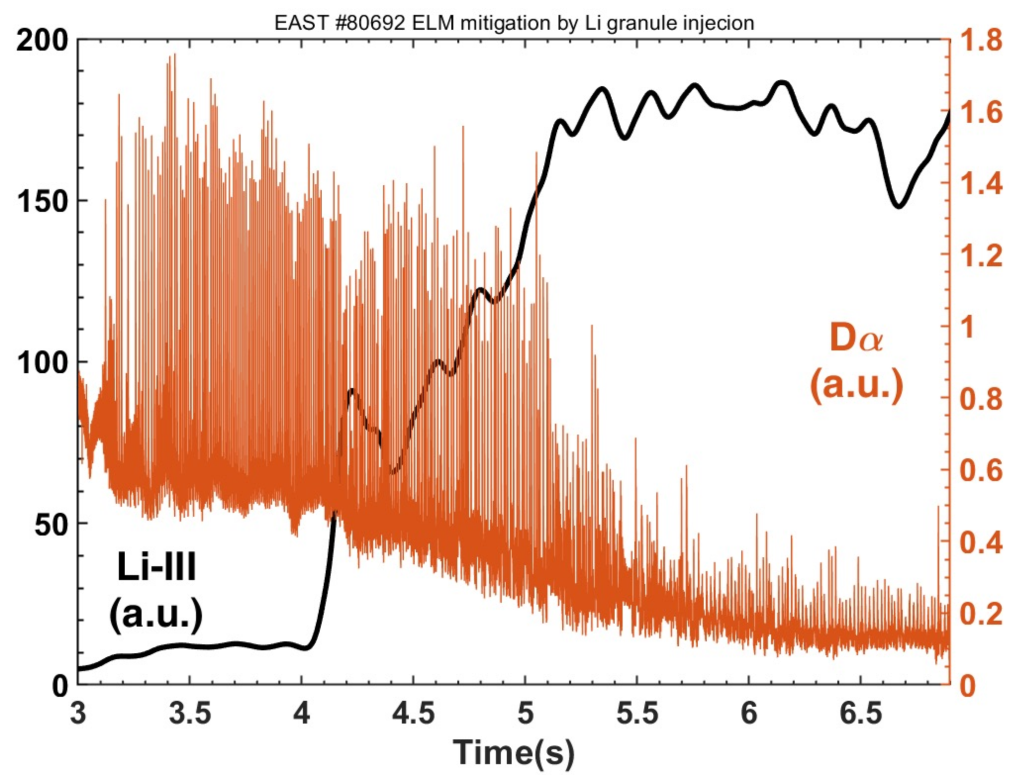
NSTX-U Monday meeting

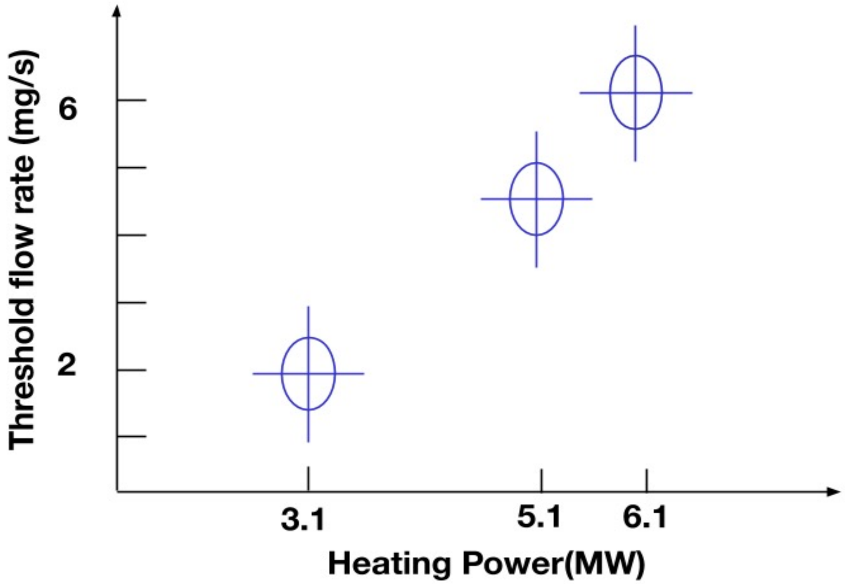
May 24, 2021



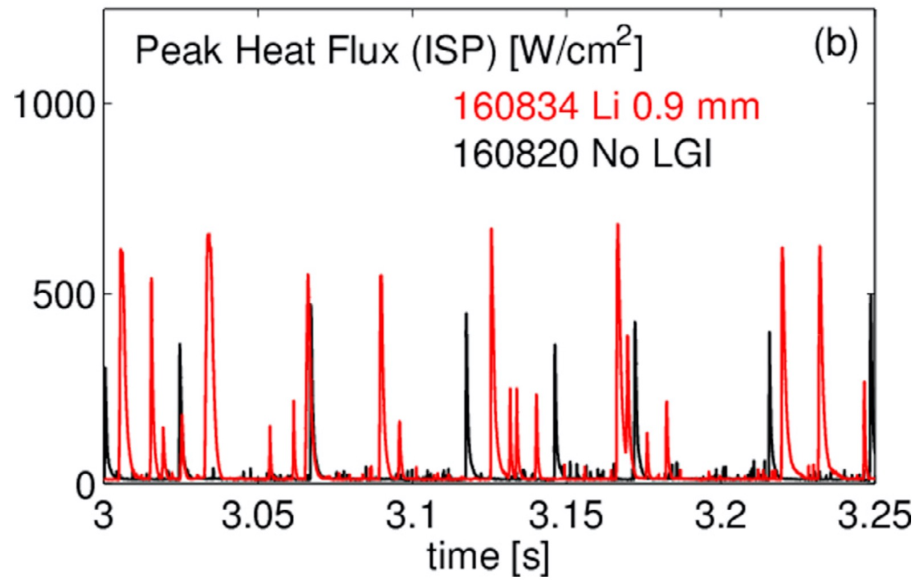
Challenges in ELM control by injecting dust-size impurity powder

- **Dust-size(<100μm) Li/B powder gravitational injection(<10m/s) in NSTX, EAST, DIII-D→ ELM suppression**
  D. Mansfield JNM 2009; J. Hu PRL 2015; T. Osborne NF 2015; R. Maingi NF 2018; Z. Sun NF 2021
  – Fast ablation through SOL at high heating power→ limited perturbation inside separatrix
  – Energetic dust→ damage PFCs; suspending air→ safety hazard for hardware operation

- **ELM pacing by D/Li pellet injection with high-speed(>~50m/s)**
  – not all triggered ELMs have reduced amplitude; complicated hardware



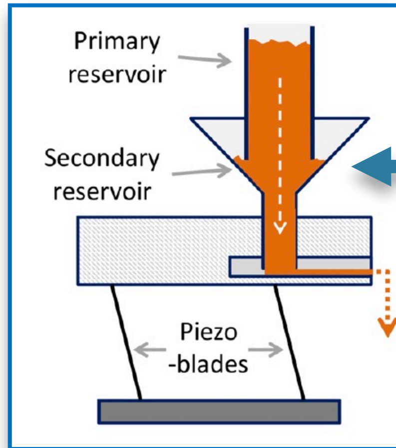
R. Maingi IAEA-FEC 2021



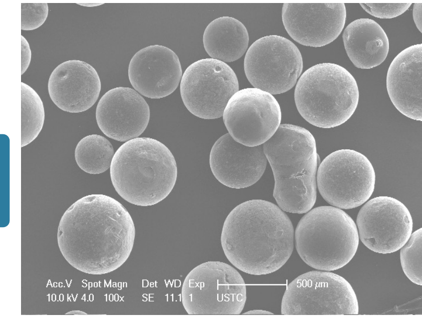
A. Bortolon NME 2017

Impurity Powder Dropper enables injection of Li granules on EAST with ITER-like W divertor

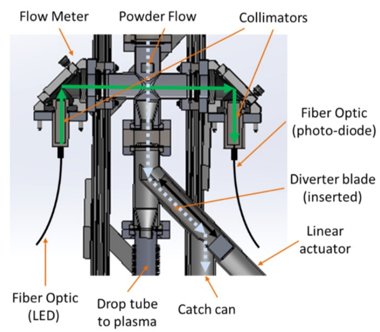
- EAST has a mix of PFC material
  - Upper Div.~ W Monoblock PFCs
  - Center stack ~ Mo tiles
  - Lower Div. ~C tiles



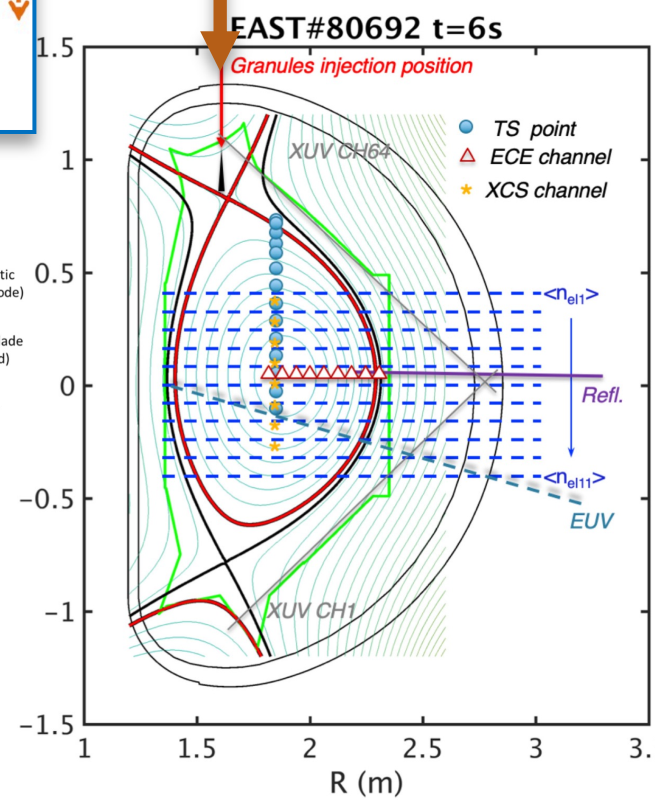
IPD



- Multi-impurity injection system based on linear piezoelectric powder feeder
  - Li, Be, B, BN, Si, SiC, Sn…
  - Particle size 5-1000? μm
  - Continuous/burst, controllable flow rate 2-250mg/s, calibratable
- 700 ±100μm spherical granule
- Driven by gravity, ~10m/s
- Near the upper X-point

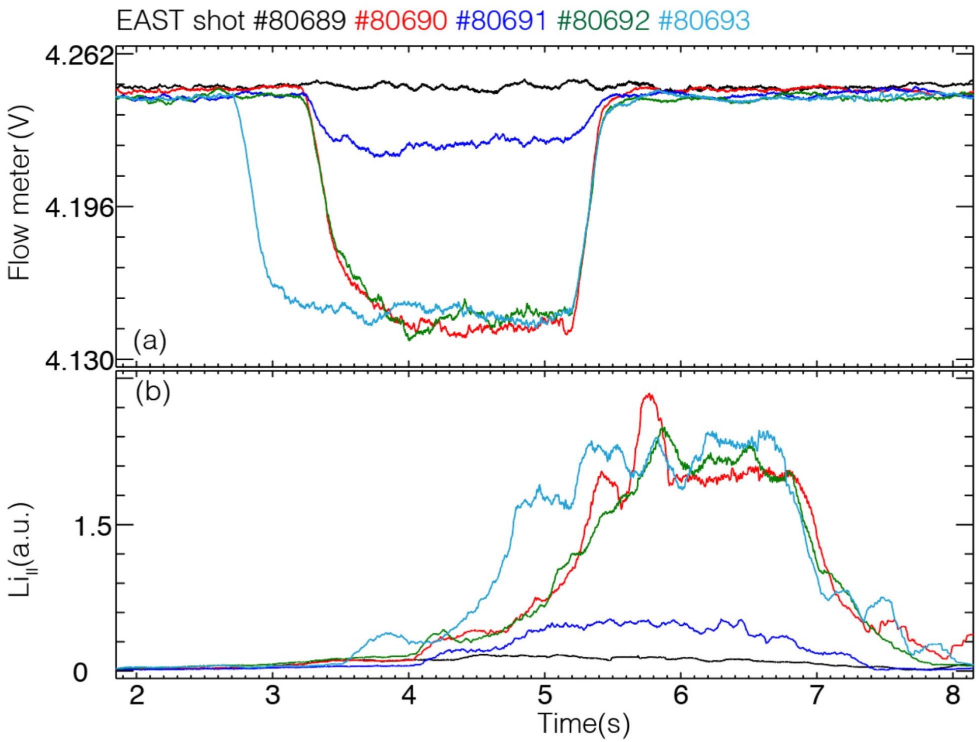


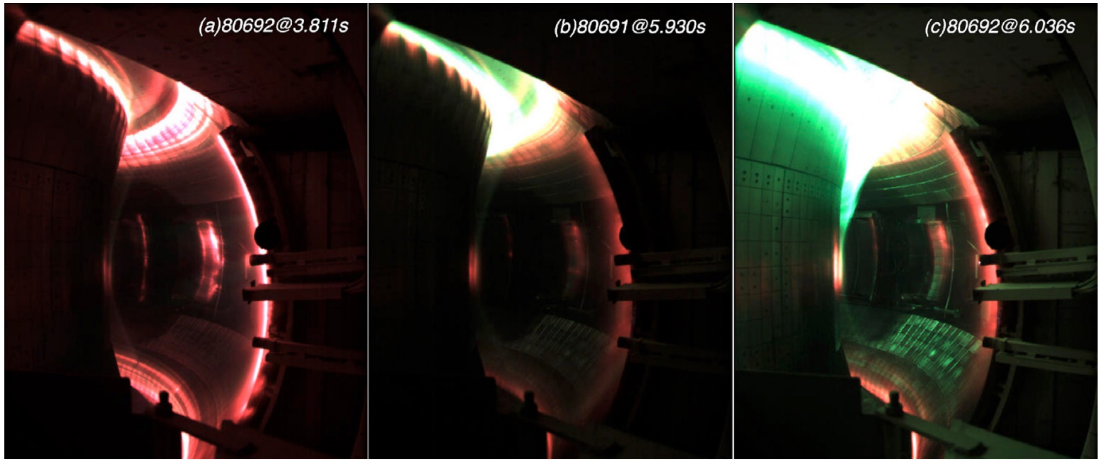
A. Nagy RSI 2018



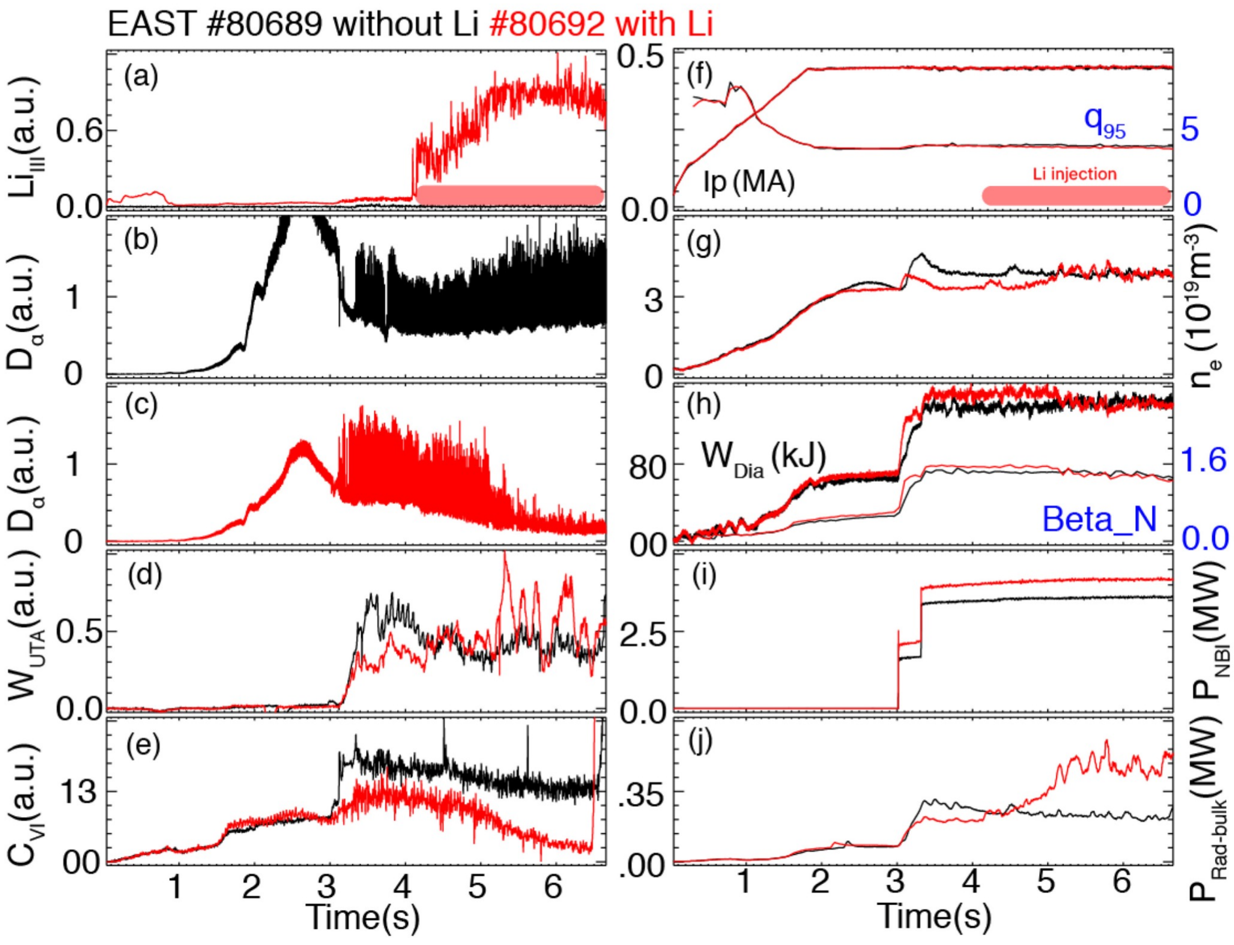
Gravity assisted Li granule injection into plasma

- Li-II (548.6nm) emission correlates with the flowmeter voltage drop
- Two timings and two flow rates in four shots
  - High rate: 194mg/s ± 10, ~2000Hz
  - Low rate: 32mg/s ± 2, ~680Hz
- True color video shows Li granules go into upper divertor plasma, wider green region with higher flowrate



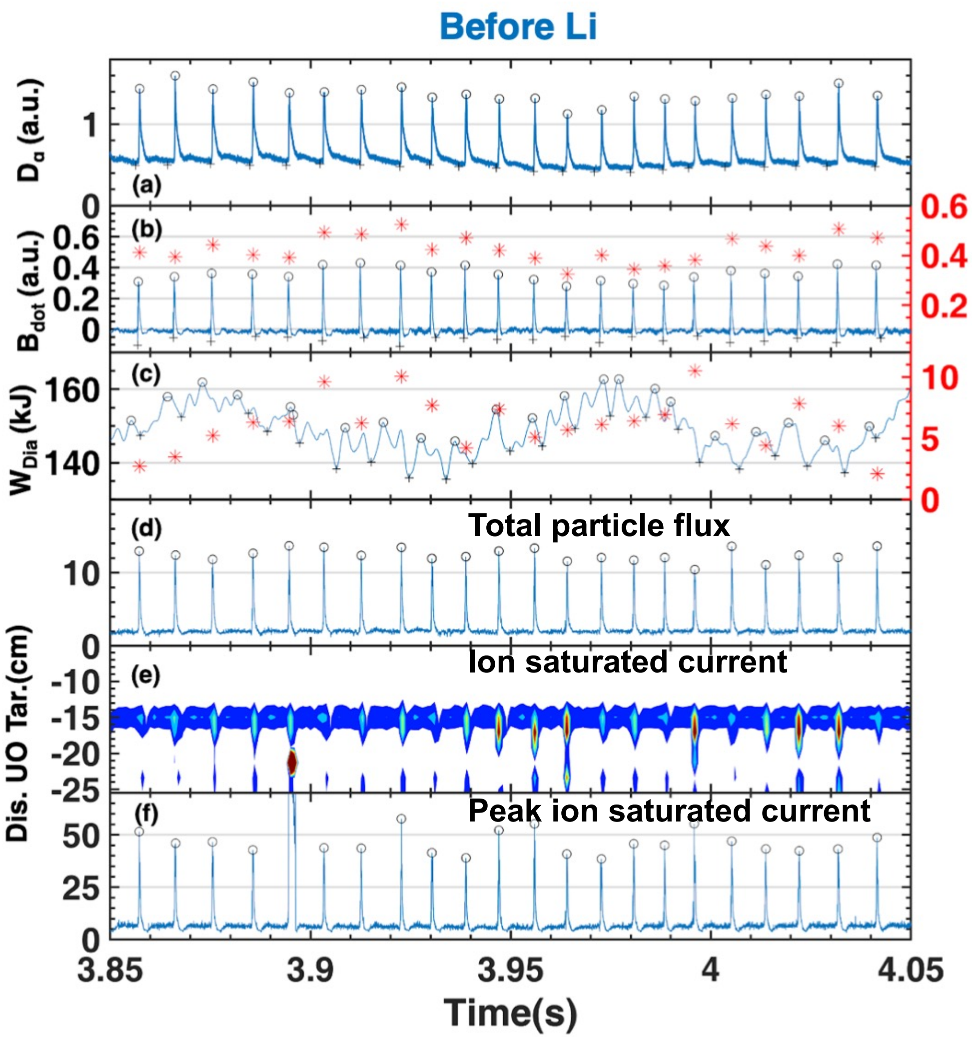


ELM mitigation sustained 2.8s (40Xτ_e) without core impurity accumulation



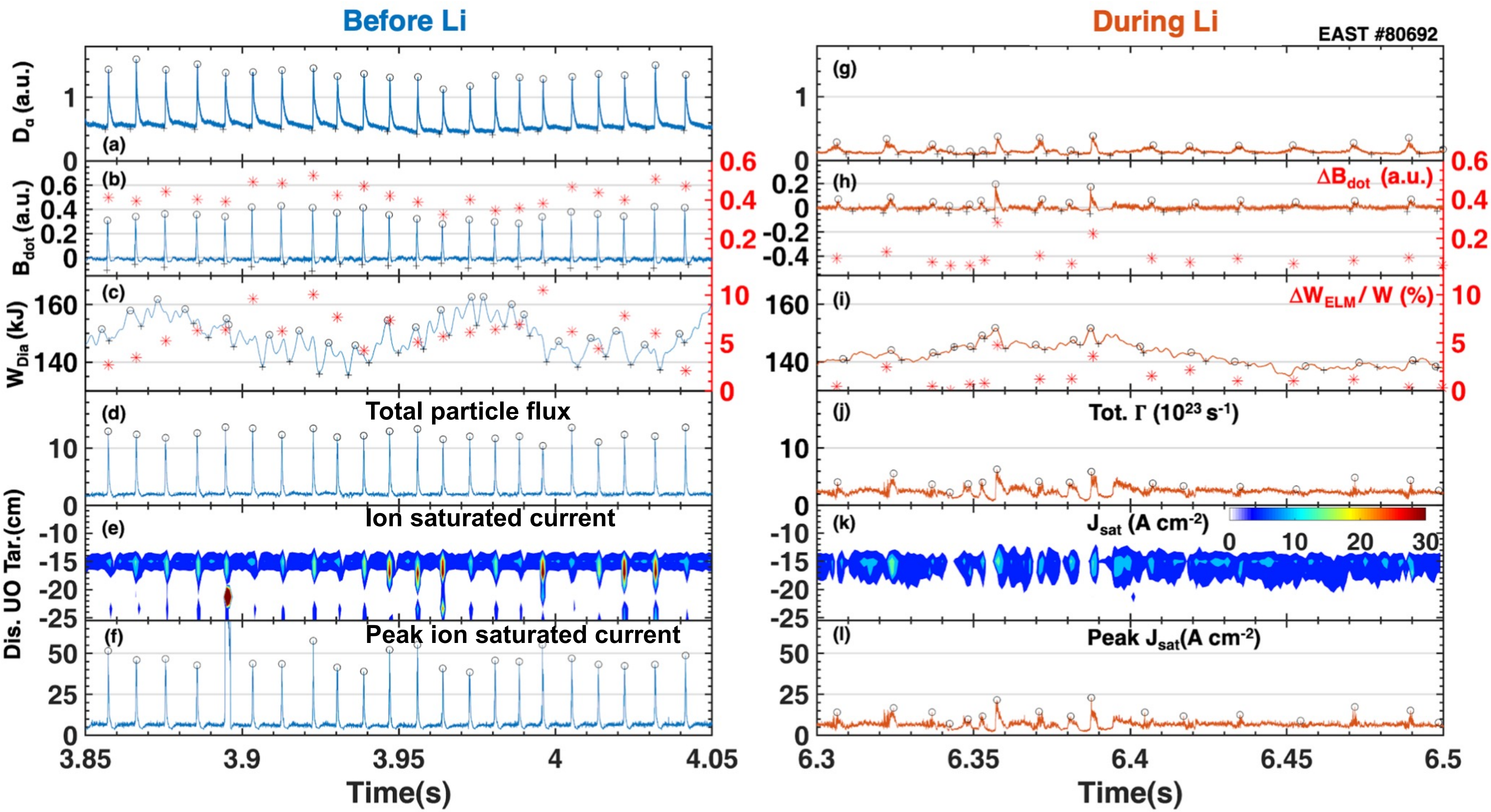
- q_{95}~3.9, B_t=1.6T, USN, W divertor, δ=0.36, Co-NBI+LHW heating~5 MW, β_N~1.5, Type-I ELM
- Same gas fueling
- P_{NBI} 3.5→4.1MW
- ~194mg/s(~5.1e10^{22} ele./s, plasma inventory ~2e10^{22} ele.)
- ne 3.3→3.9, 47%→55%
- Eng. 152→141kJ, 7%
- Radiation 0.2→0.5MW
- C-VI decays gradually, no core W ramp-up
- Dα spike size reduced by 85%, not full ELM suppression

Significant ELM mitigation, ~70%

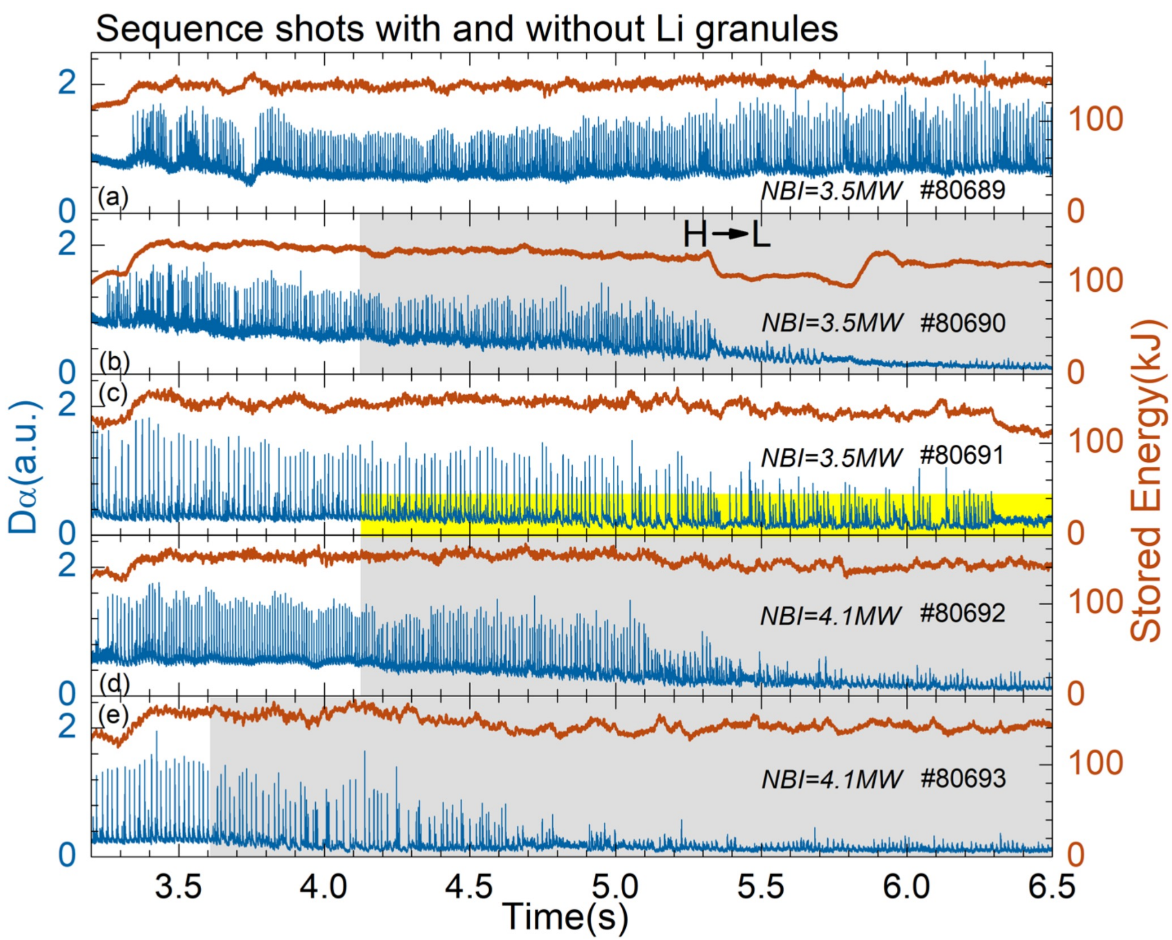


Significant ELM mitigation, ~70%

Dα peak-valley ~85%, dB/dt peak-valley ~80%, $\triangle W_{ELM}/W$ 6%→1%, maximum total particle flux ~70%, peak Jsat~70%



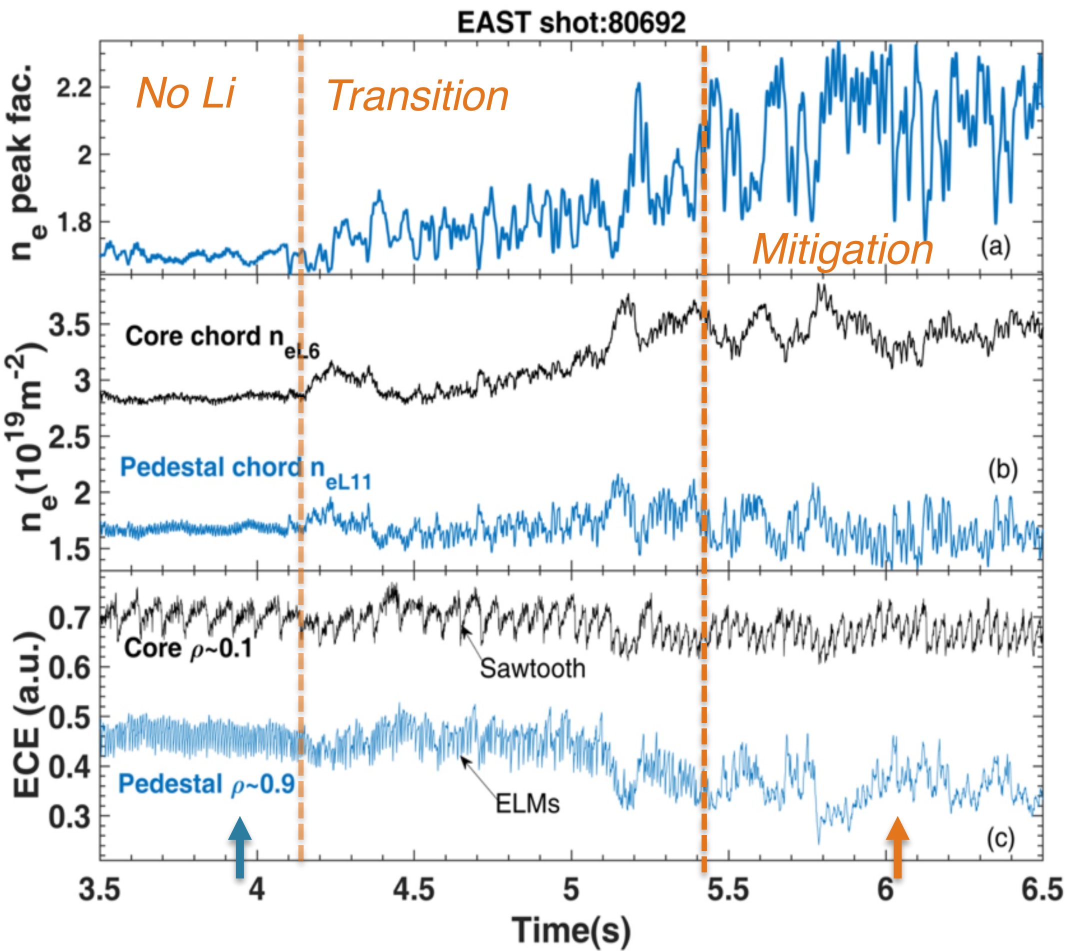
Reproducible ELM mitigation with modest stored energy reduction

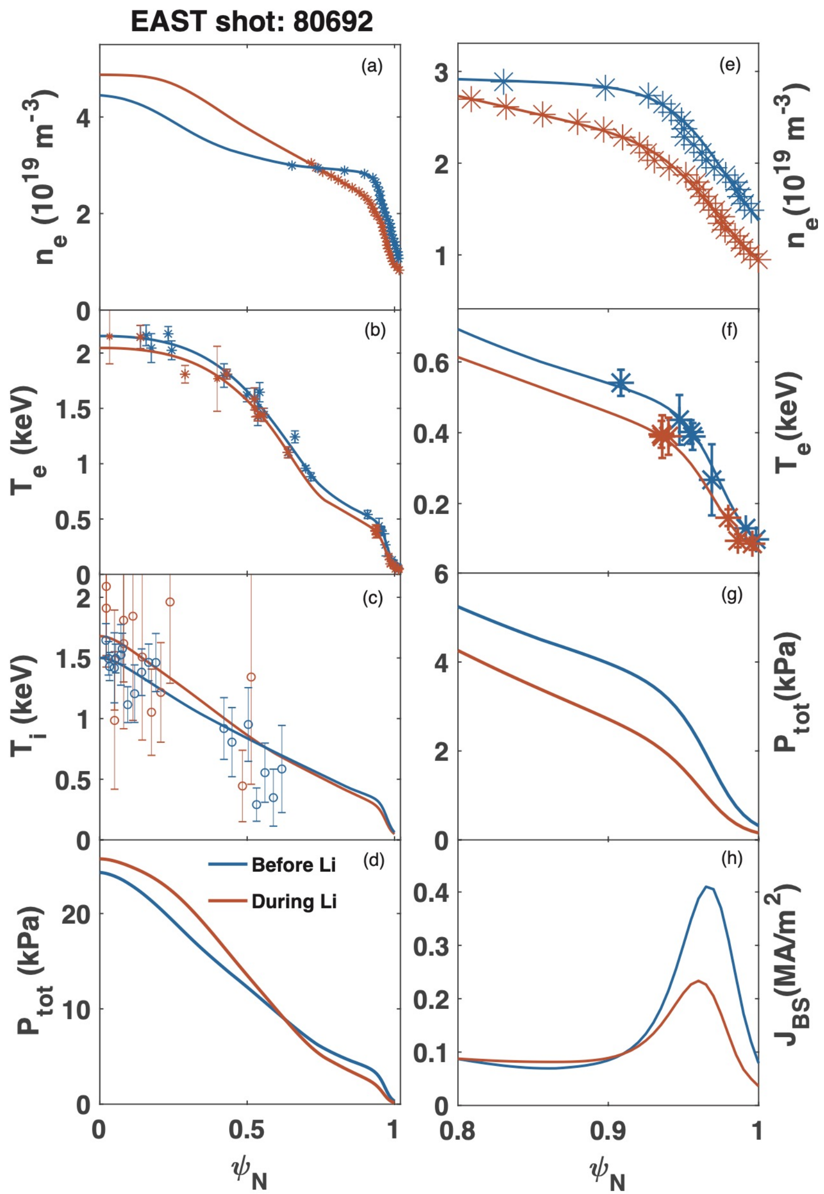


- No Li, No mitigation
- Too much Li, H→L transition
- Too little Li, the effect discounted
- No H→L transition with higher heating power
- Earlier contacting plasma, earlier ELM mitigation, reproducible
- ELM mitigation accompanied with W_{Dia} reduction, <10%
- Comparing with Li power, less granule flowrate needed？ Minimum Li deliver rate increase with heating power increase？

Pedestal top pressure decrease by 25% but core increase 10%

- Core： ne↑~10%, Te↓<5%, Ti↑ slightly
- Pedestal: ne↓~10%, Te↓~20%, J_{BS}↓50%
- Hypothesis: ne peaking→ ITG↓→ improve core confinement

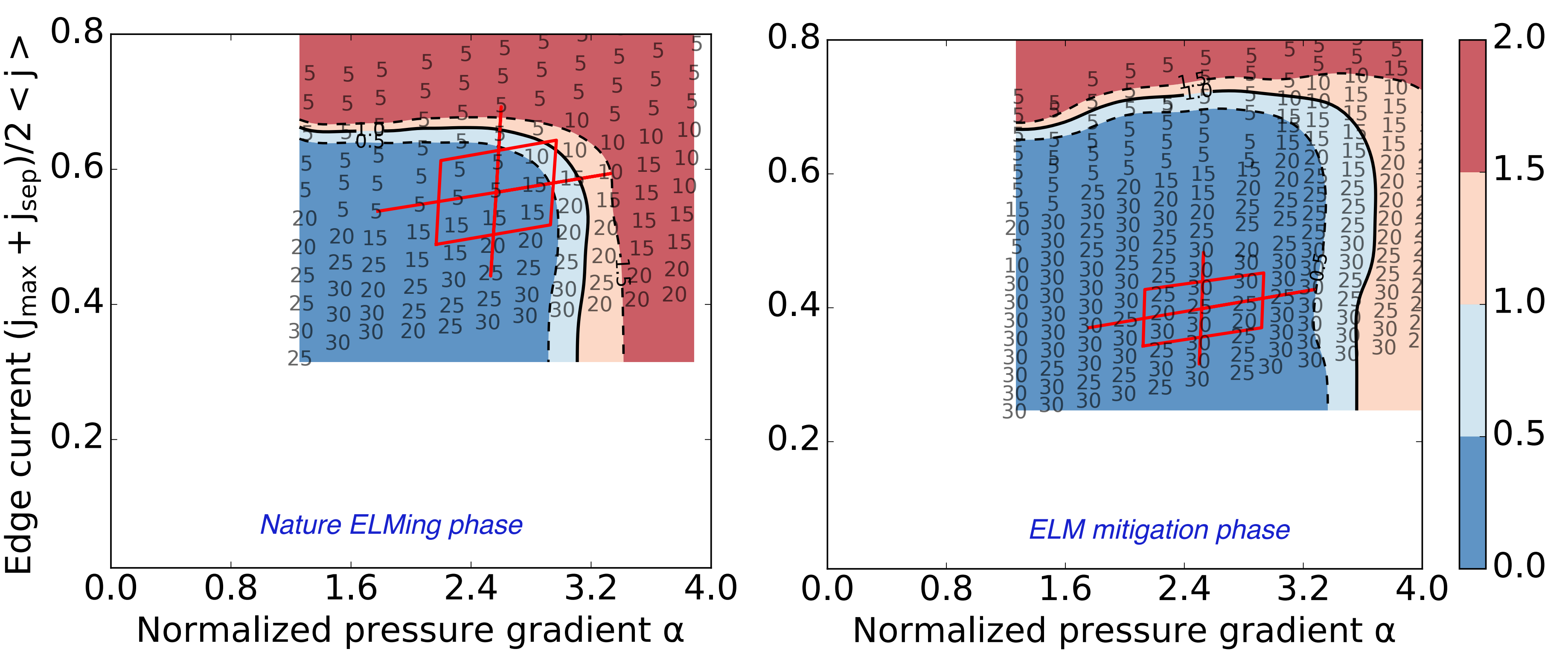




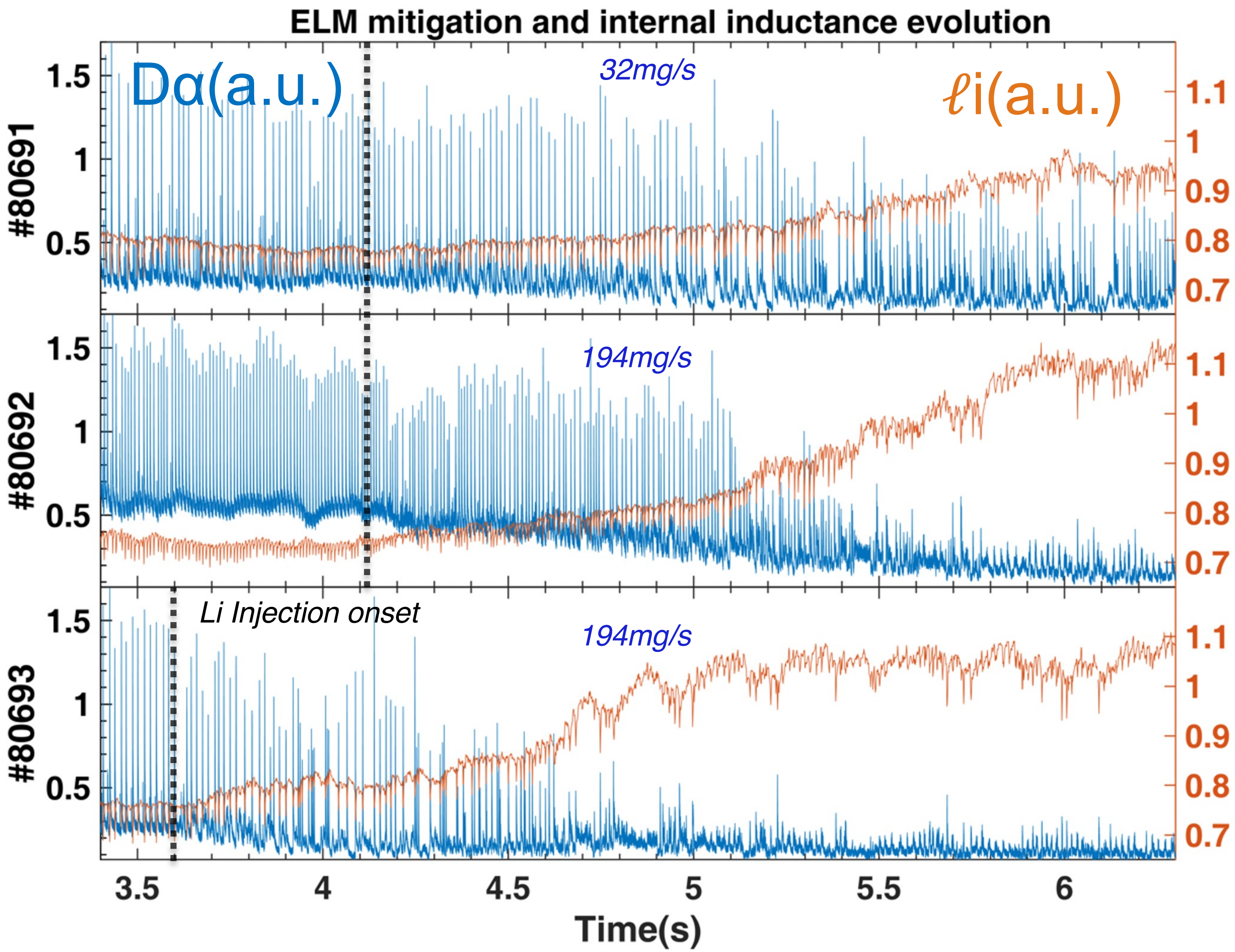
Pedestal stable in peeling-ballooning instability by ELITE analysis

- **Nature ELM occupying PBM stability boundary conner, intermediate-n (n=5-15) destabilized**
- **Li case in stable region, high-n (n=25-30) narrow-radial-width ballooning modes moderately close to the PBM boundary**
  - Small ELMs likely triggered by local effect, clustered granules, similar as D pellet

Futatani NF 2014



Edge current loss consistent with internal inductance increase

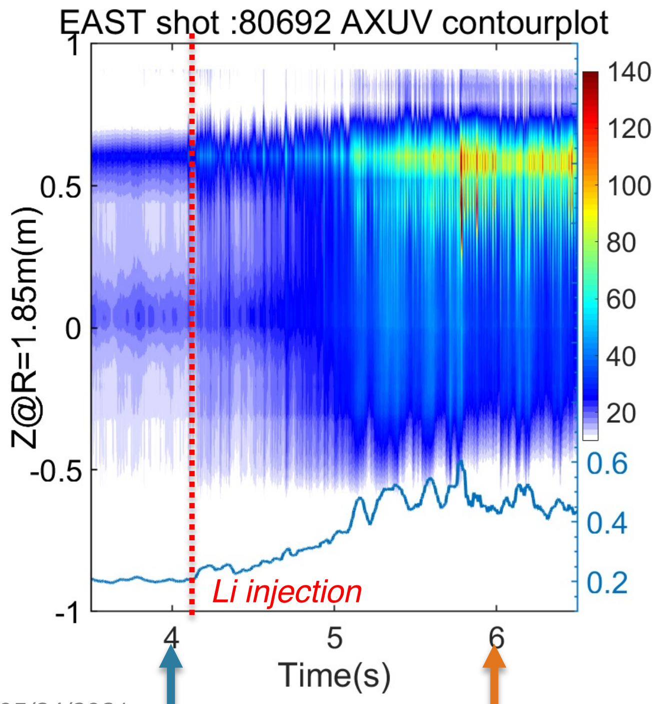


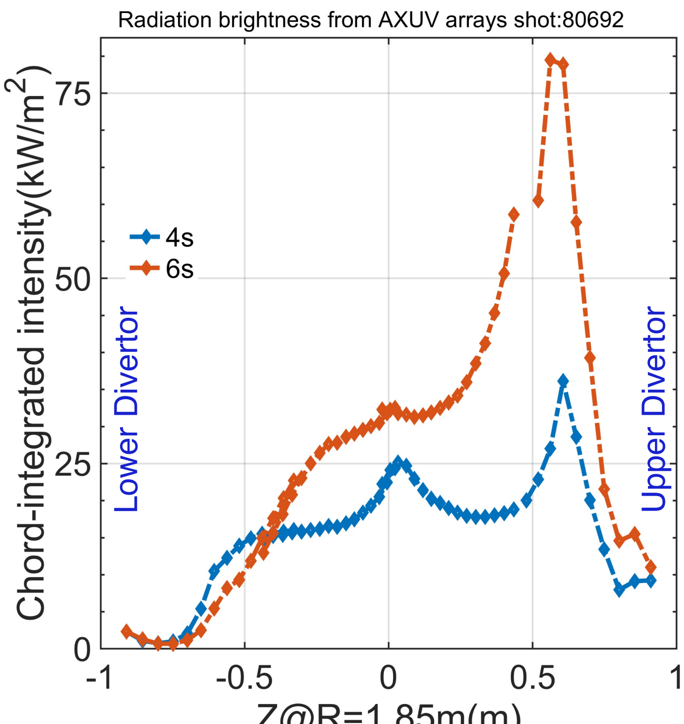
- **ELM mitigation correlates with the li value and time evolution**

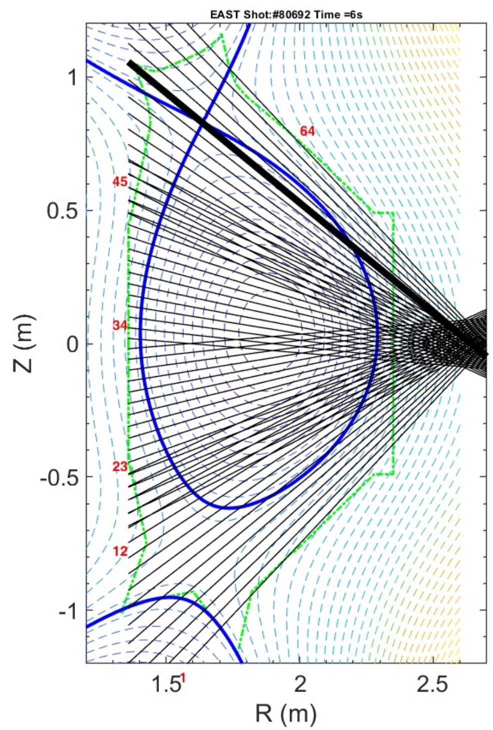
- **Edge bootstrap current reduction**
  - Max. P’ ↓ 10%
  - $\upsilon_e^* \propto Z_{eff}\, T_e^{-2}$ ↑
    - Z_{eff} ↑ 1.5→2.1
    - Edge T_e↓

Edge cooling is likely responsible for the depressed pedestal Te

- **Total radiated power grows by 2.5x, dominated by the upper divertor region**

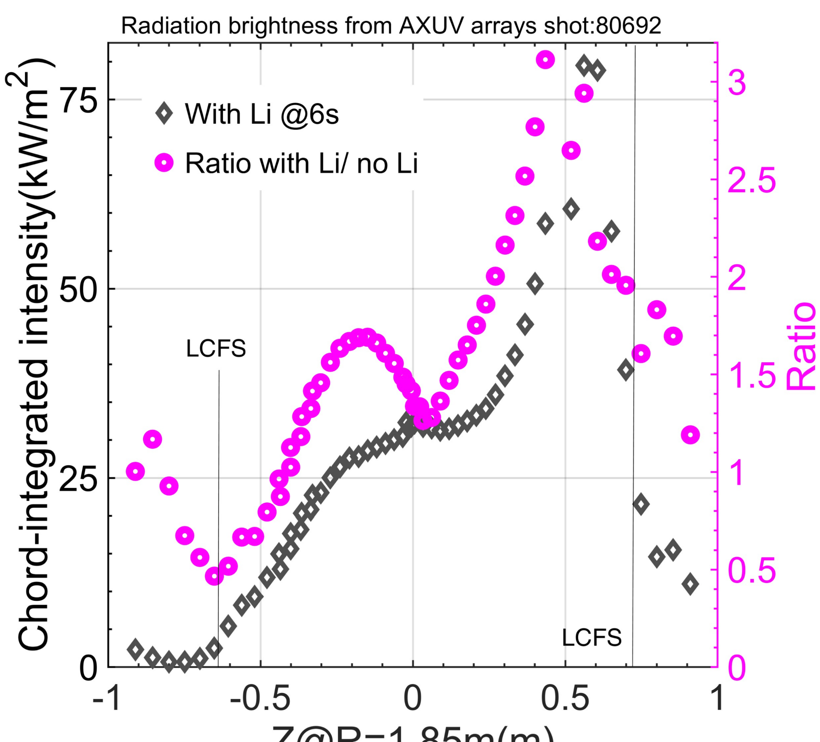


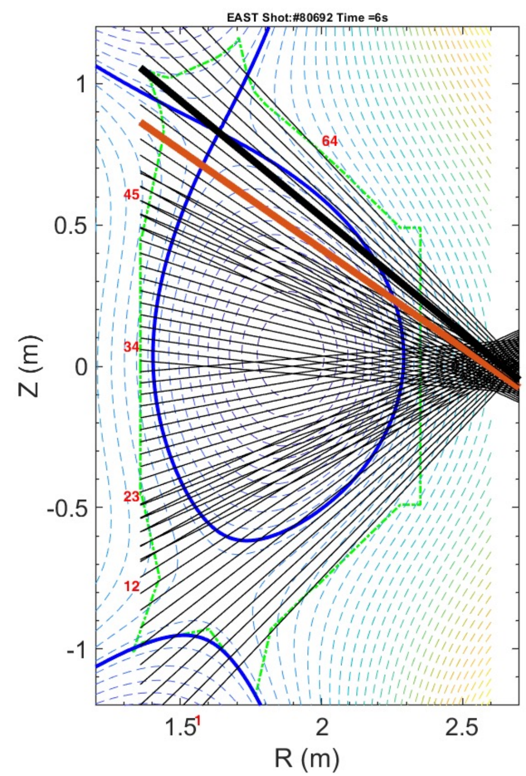




Edge cooling is likely responsible for the depressed pedestal Te

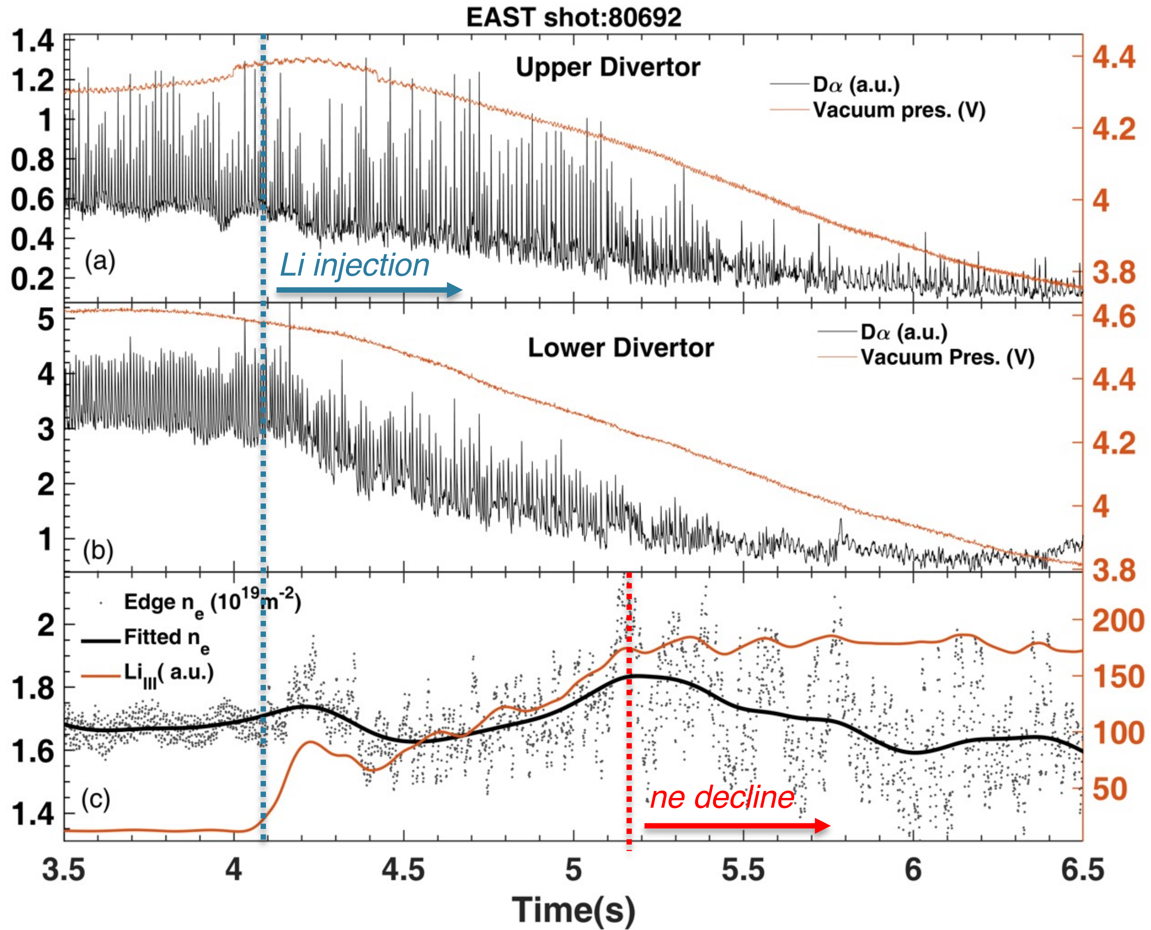
- **Total radiated power grows by 2.5x, dominated by the upper divertor region**
- **Maximum XUV signal increase of 3.2x occurred in the channel below the maximum radiation channel**
- **Imply the granule penetration across X-point? NGS model showed maximum ablation can go into deeper with depressed pedestal**





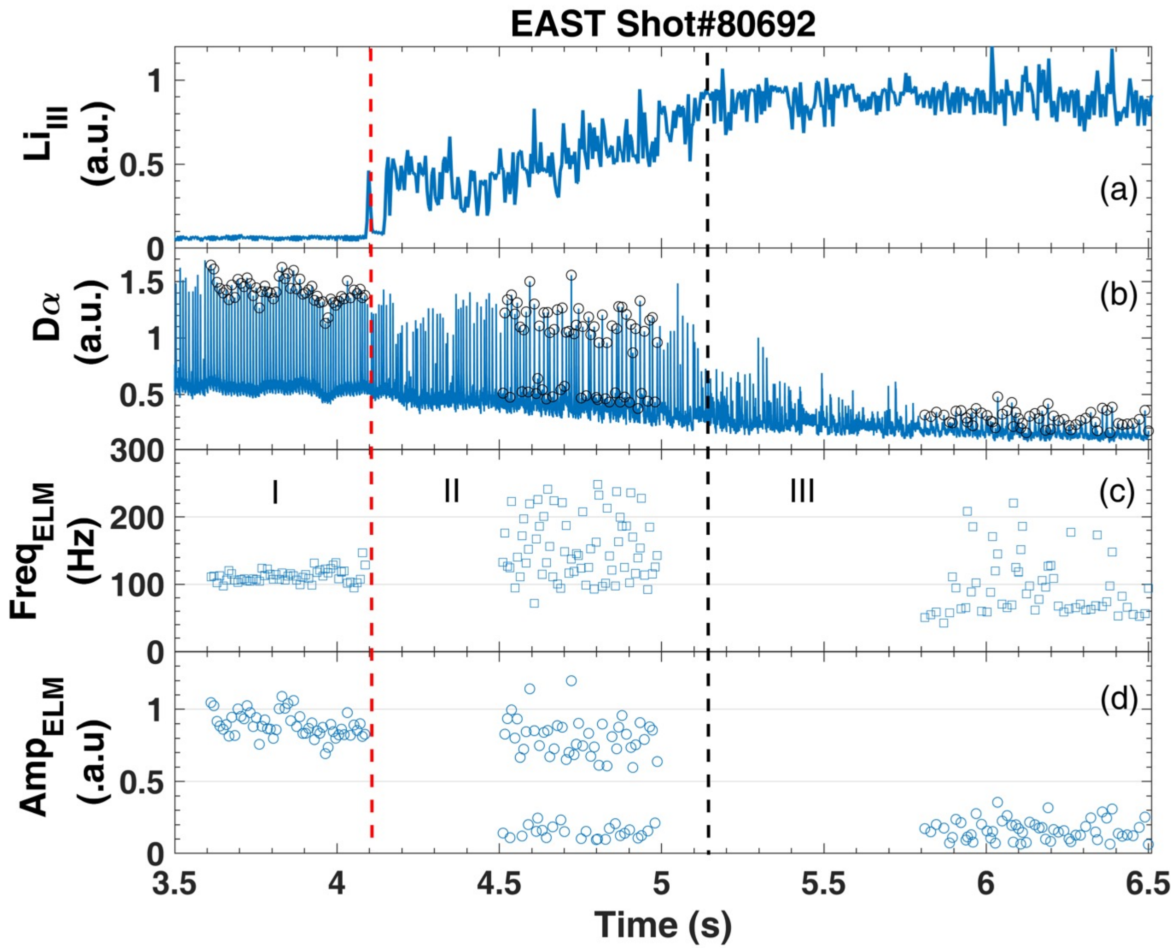
Pedestal ne reduction possibly stems from D recycling control with sufficient Li on the wall

- **Real-time recycling control and pedestal ne increase occurred just after Li injection**
  - undergoes ablation and ionization near separatrix, flows into the SOL to the target, and recombines on the wall; Li ionization introduces electrons
- **Pedestal ne starts to decline as the Li accumulates more on the wall and D recycling control becomes more effective**



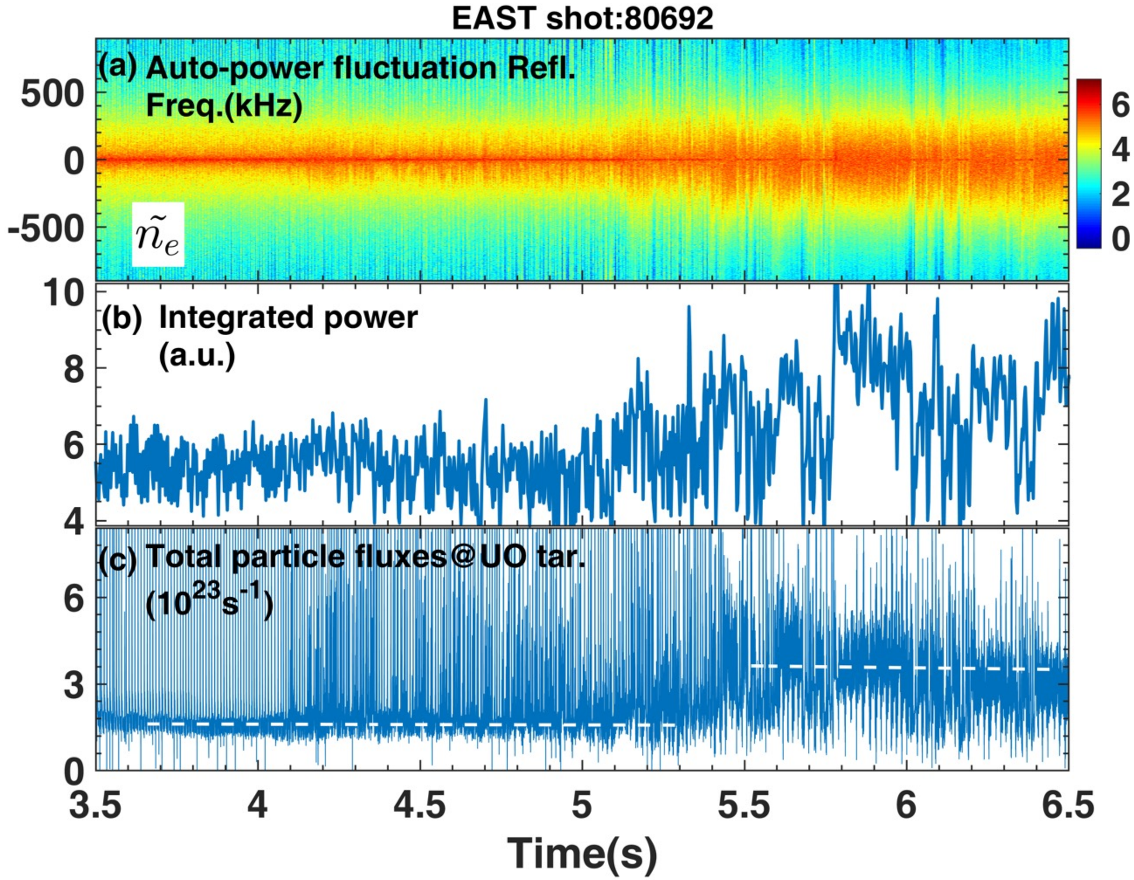
No ELM frequency increases with large ELM size reduction

- **~1s transition phase: mixed small and large-amplitude ELMs, averaged ELM frequency slightly larger than Phase I, ~110Hz**
- **ELM mitigation phase III: variable frequency, ~80Hz<110Hz<< 2kHz**



Enhanced background turbulence and transport

- **Pedestal density fluctuations ↑~50-100%**
- **Particle flux between ELMs in ELM mitigation phase elevated ~2X , beneficial for impurity outward transport**
- **Increased turbulence and reduced pedestal were concomitant in time**



- O-mode reflectometer
- Around the pedestal top
- No obvious increase in pedestal foot and steep region

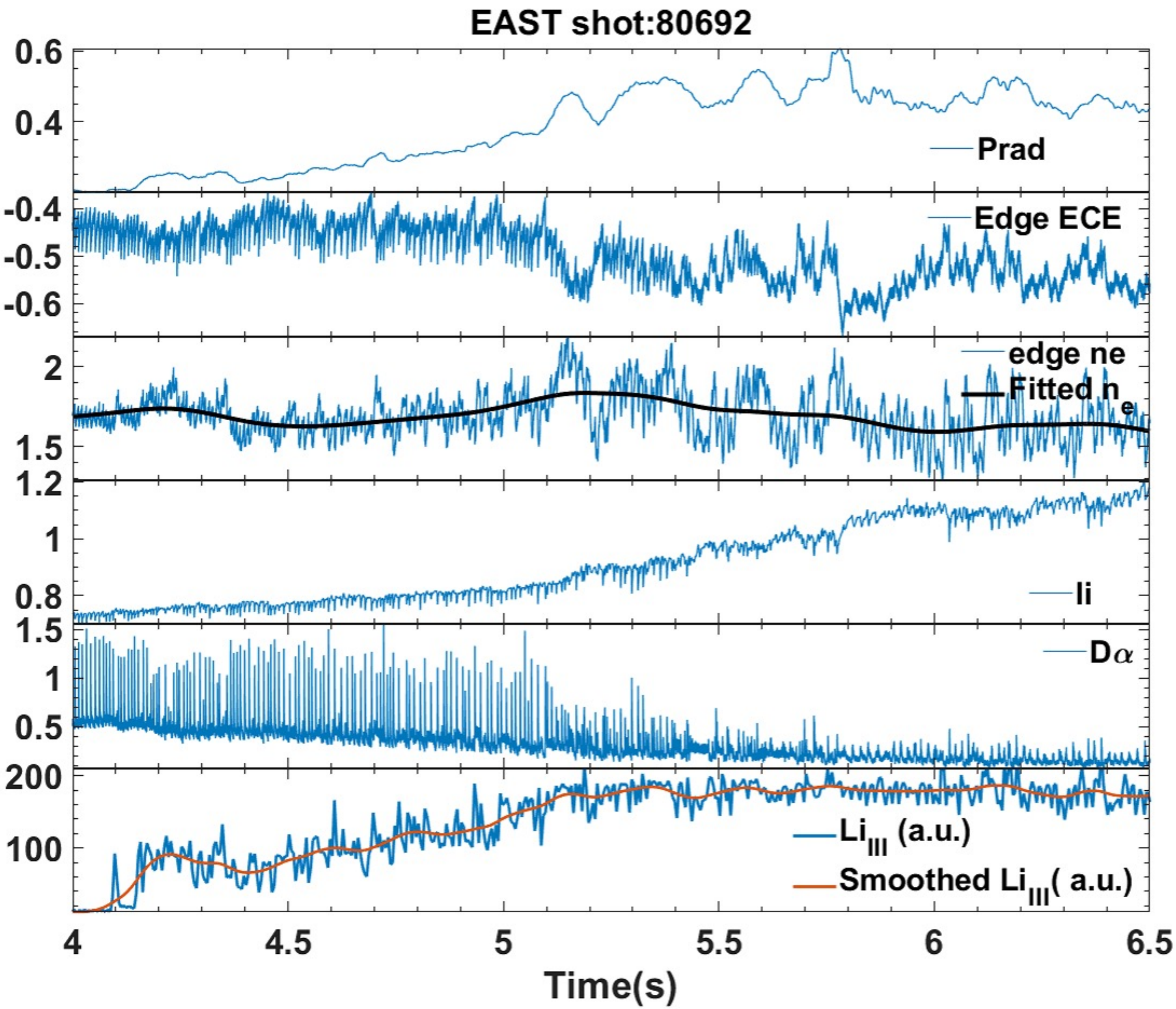
Summary and future work

- **A reproducible high β_N H-mode regime devoid of large ELMs has been achieved by gravitational injection of Li granules with 700um diameter from upper X-point in EAST with a W divertor**
- **ELM amplitudes were reduced by 70% and sustained stably without impurity accumulation in the plasma core**
- **The remaining small ELMs and enhanced density fluctuation facilitated particle outward transport**
- **Depressed pedestal pressure and improved core pressure were observed, < 10% reduction of stored energy is a modest cost for obtaining ELM mitigation.**
- **Low-Z large-size Li granule injection can effectively modify pedestal profiles possibly due to edge cooling and recycling control**
- **The ELITE code has confirmed that mitigated ELM phase is more stable to the PBM than reference ELMy H-mode, due principally to reduced edge current.**
- **Open questions for future work**
  - Assess ion dilution effect
  - Is X-point injection a key ingredient?
  - Test other materials, Be, B, etc, with and without recycling effect
  - Synergy effect with liquid lithium divertor

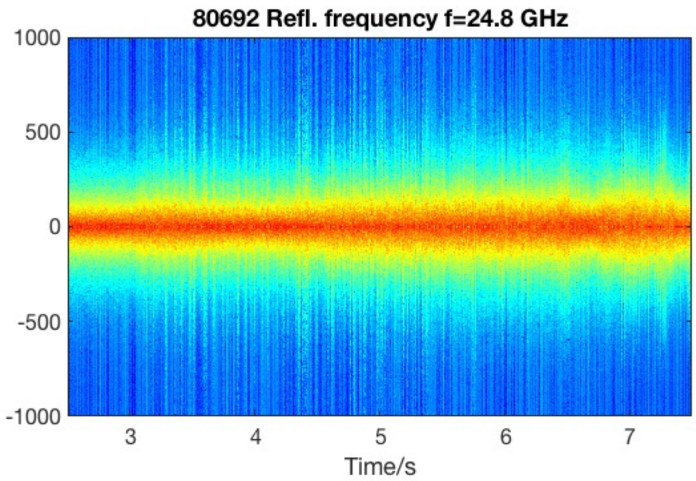
Thank you for your attention

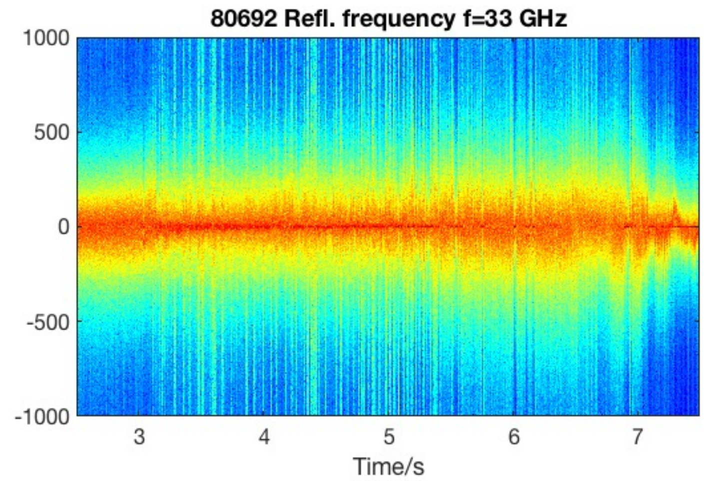
More information:
Zhen Sun et al 2021 Nucl. Fusion in press
https://doi.org/10.1088/1741-4326/abf85

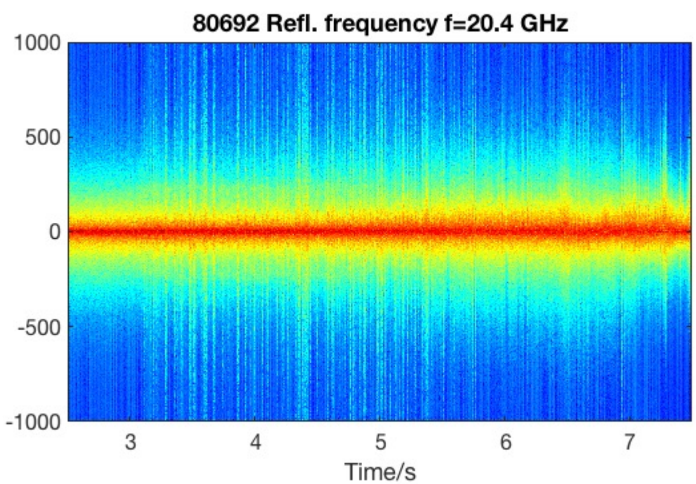
Evolution Radiation, ne, Te, and li

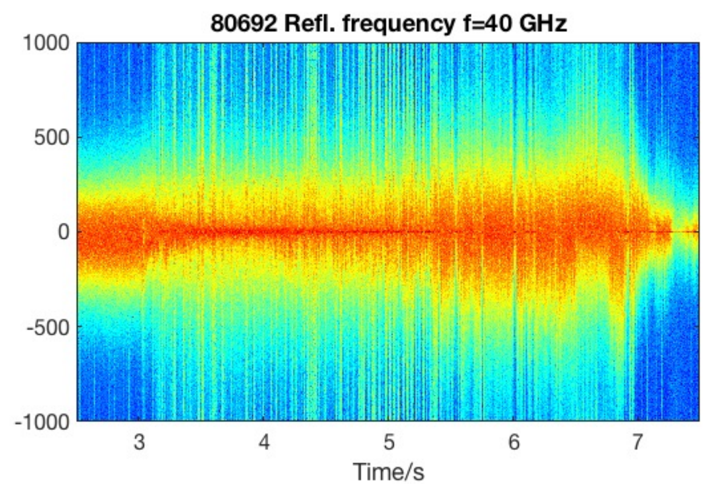


Density fluctuation by reflectometer

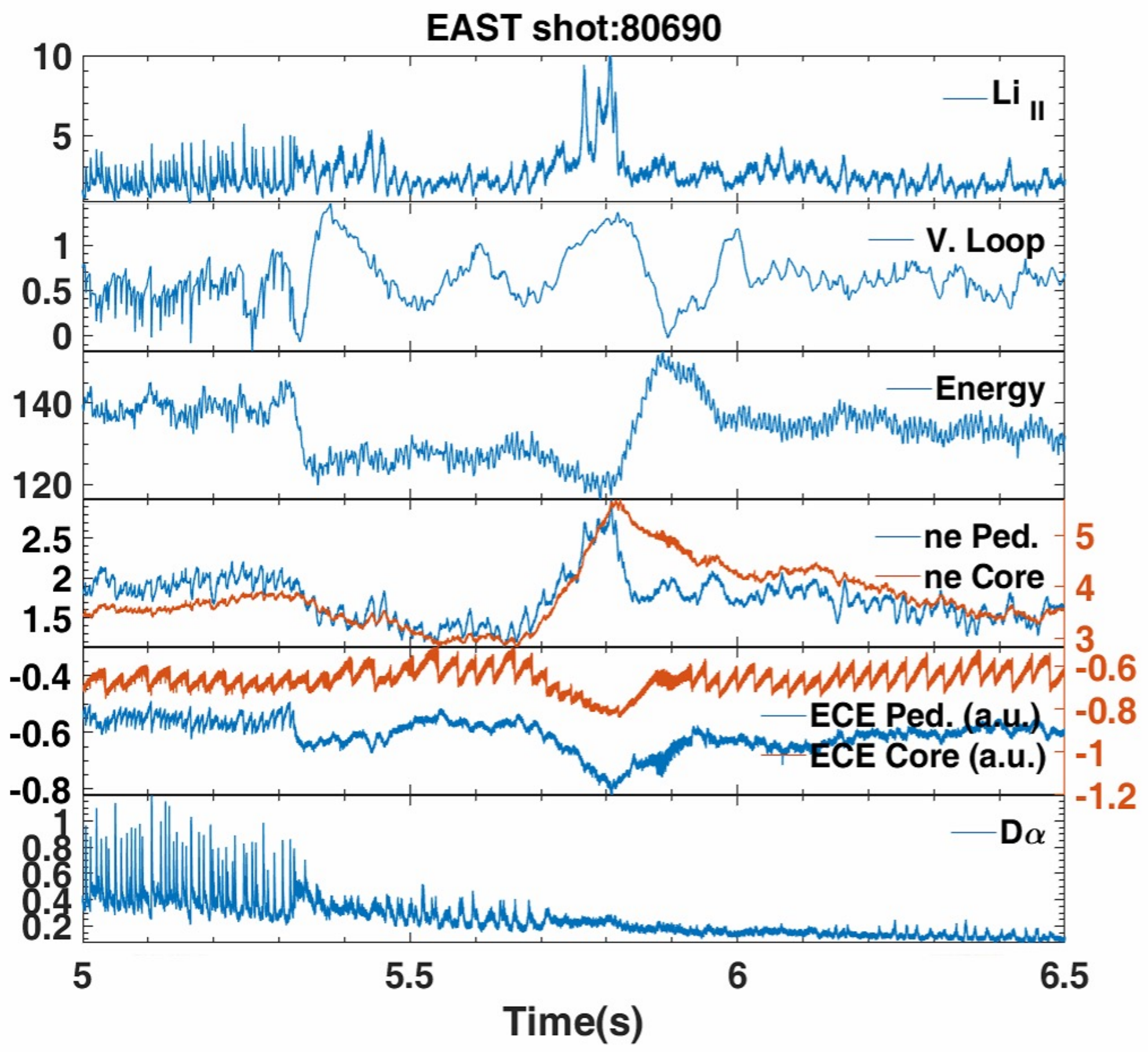






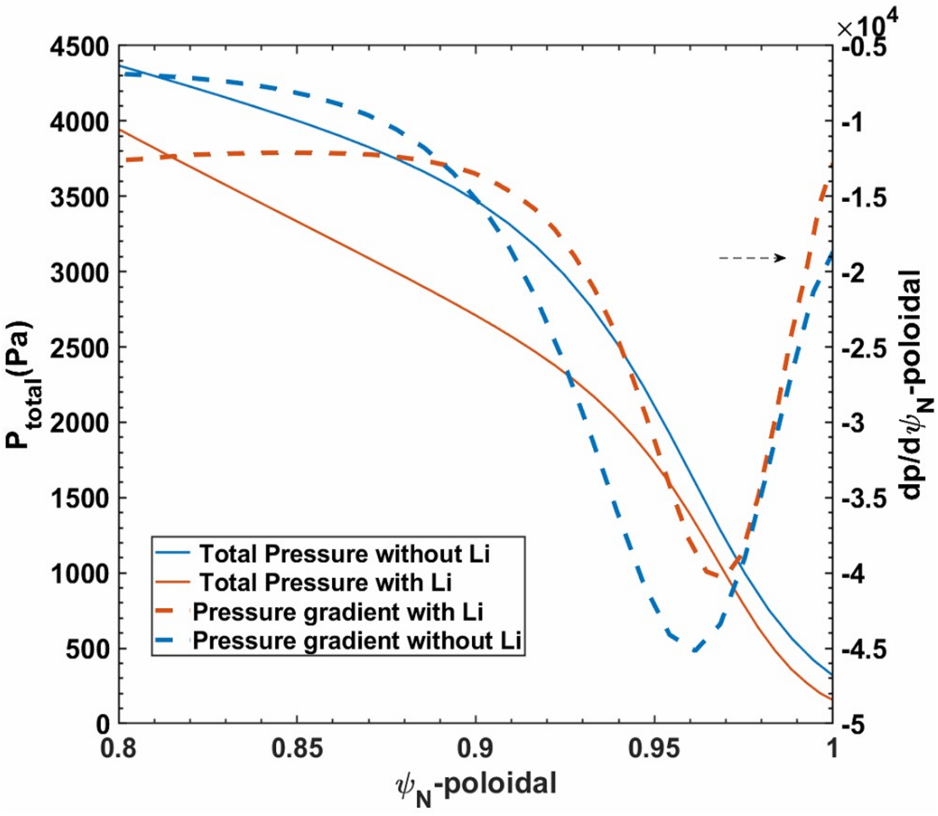


H-L-H transition

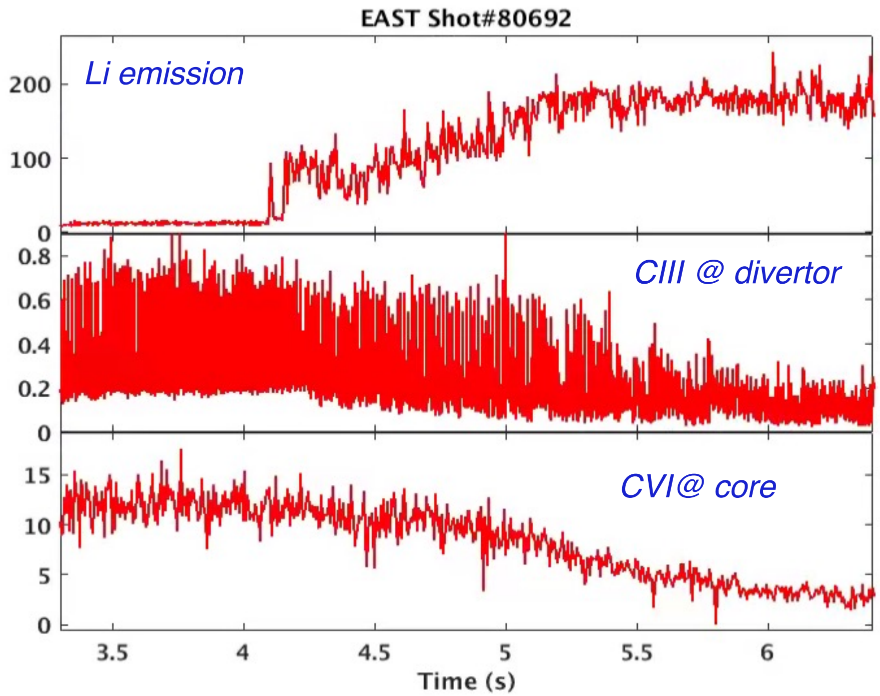


P’ and normalized P’

- $\alpha = -2\mu_0 R B^{-2} q^2 p'$

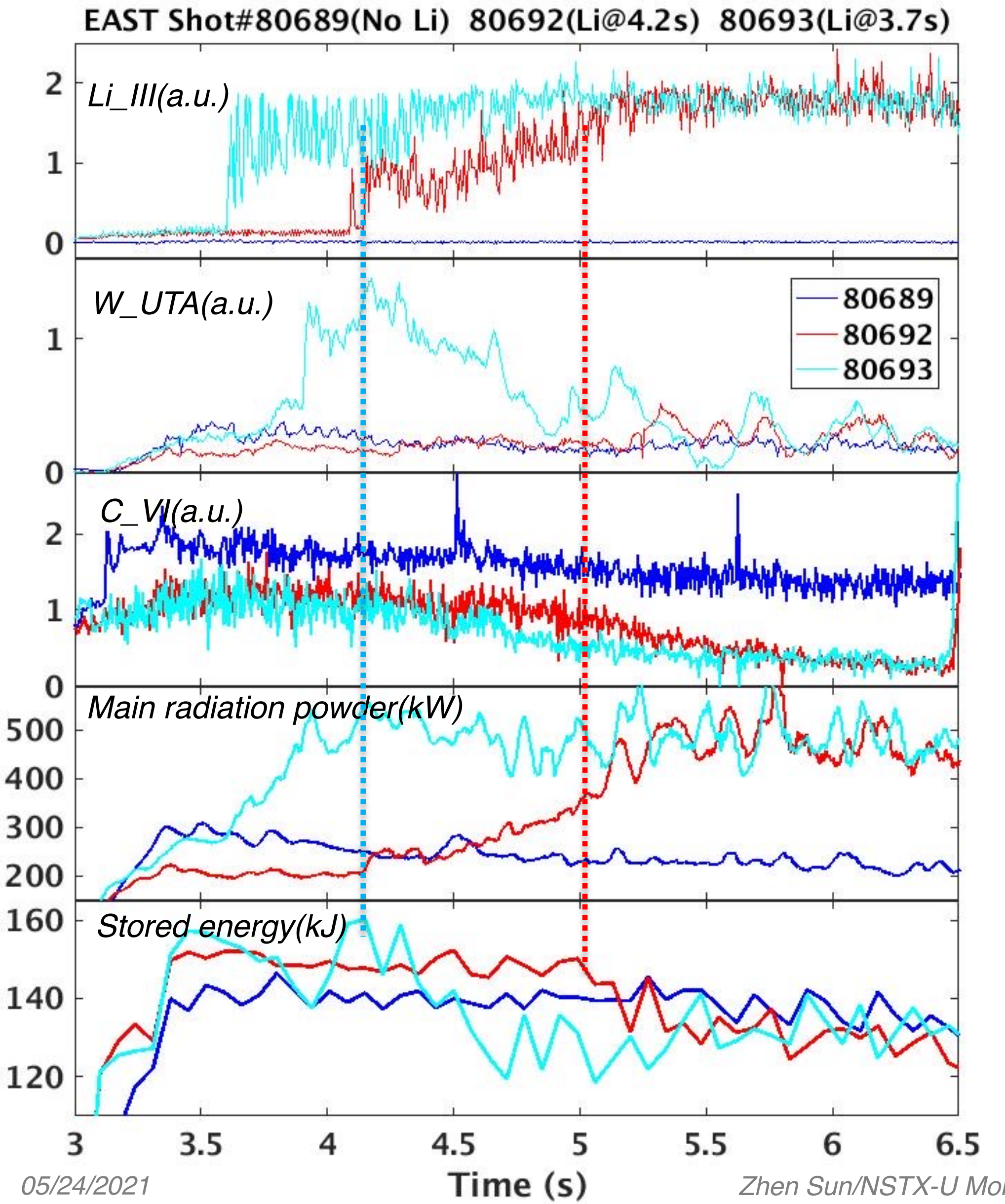


C impurity control

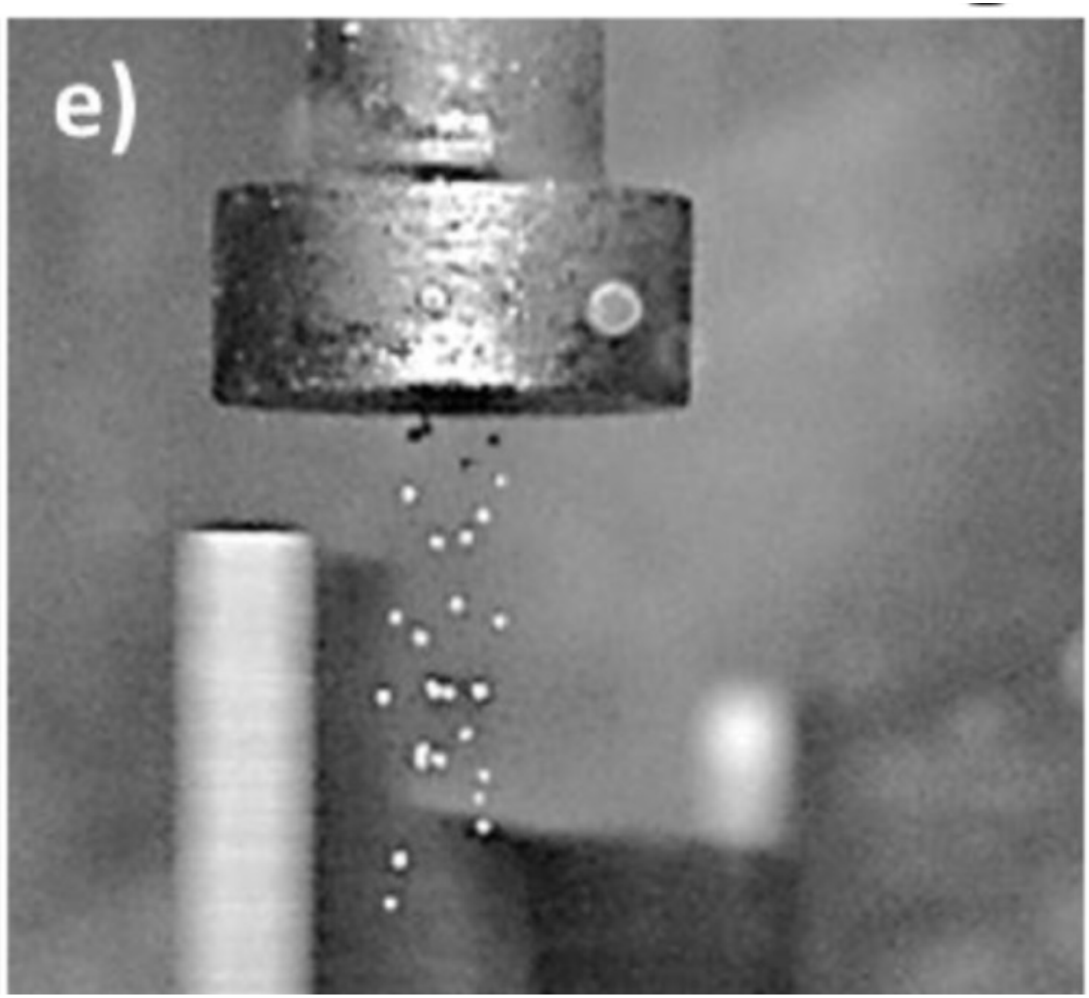


- Carbon in the core reduce gradually following the accumulative Li
- Possibly due to the reduction of C sputter by ELM and Li conditioning effect

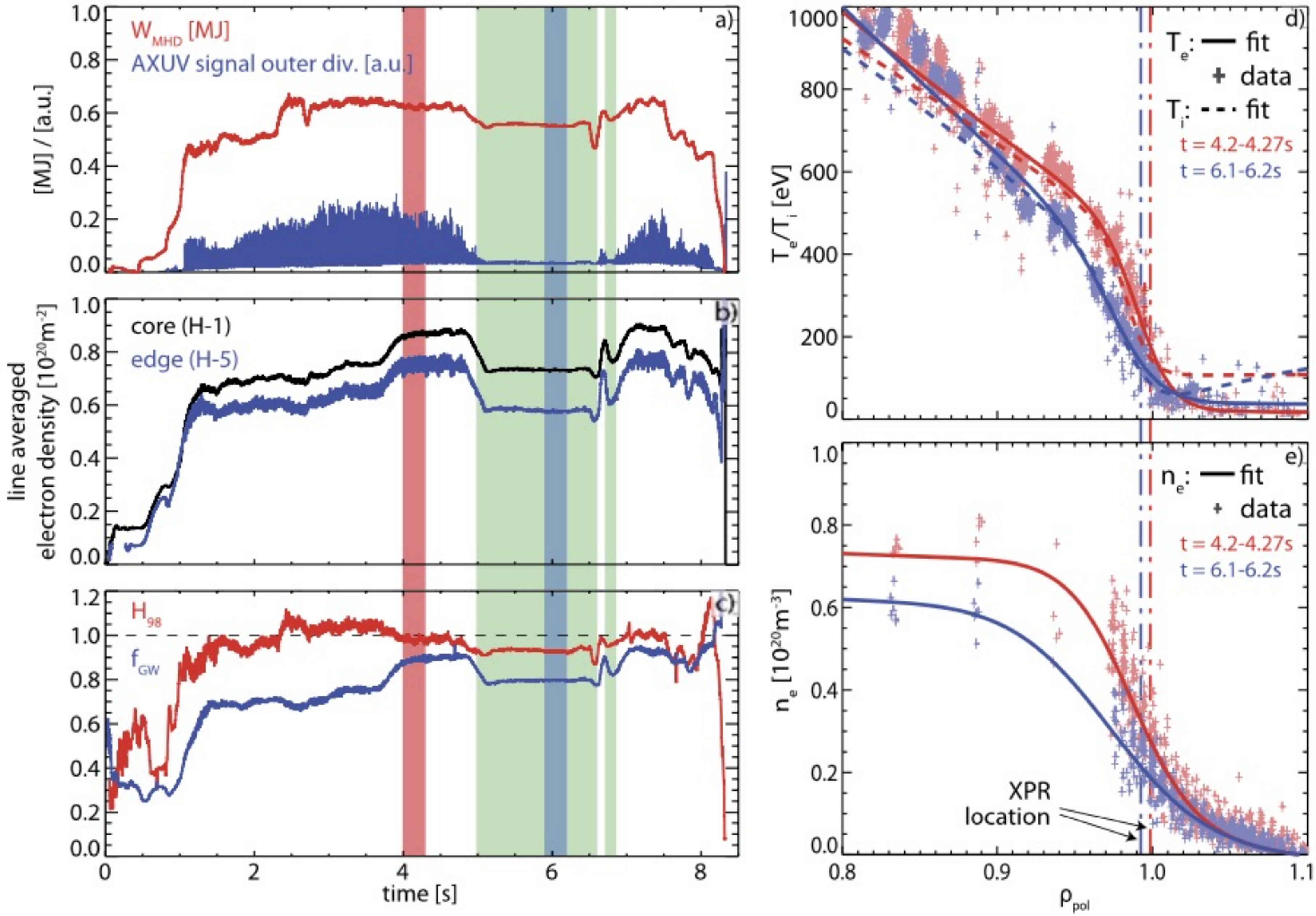
Impurity and radiation power



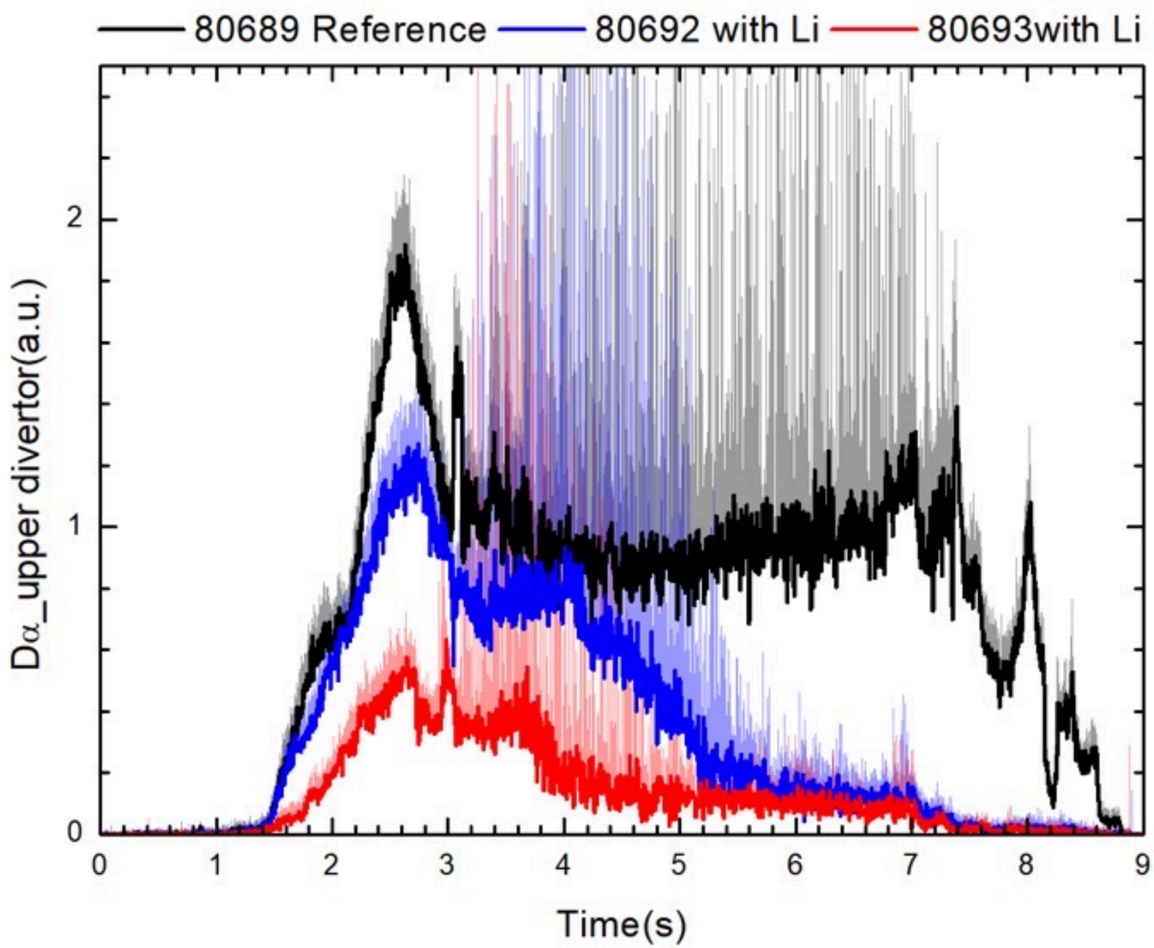
Clustered granules



AUG X-point Radiator



Remarkable real-time recycling control



- Dα pointing upper target plate reduces to very lower level, similar trend on lower target plate; recycling globally reduce
- Ablated Li deposited on the plate affects next shot
- Similar as Li powder injection , SLOPS indicating ΔR ~20%↓