ELM suppression with B powder injection and ELM triggering with Li and C granule injection in EAST

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NSTX-U Physics Meeting
30 May 2019

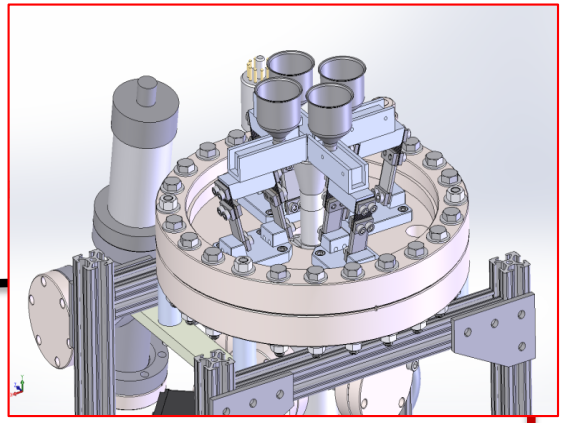
PPPL PRINCETON PLASMA PHYSICS LABORATORY

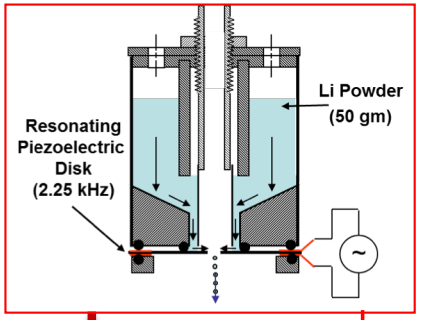
ASIPP

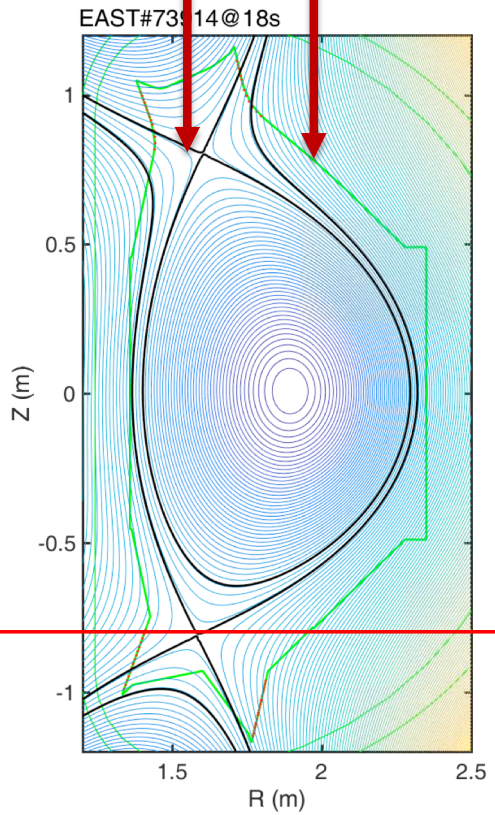
Summary and preliminary conclusions

- B suppresses ELMs over wide range of conditions
  - Constant or increased W_{MHD}, works with SMBI gas feedback, no wall hysteresis as seen with Li
  - Edge modes observed in XUV, Mirnovs when ELMs suppressed
  - ELM suppression with B also works with pure RF heating
  - ELM suppression with B works at reduced density and collisionality, i.e. over a range of ν^*
- ELM triggering and pacing with Li granule at 0.9mm in ELM-suppressed discharges works; obtained a spread in triggered ELM frequency
- ELM triggering with low speed Li granule dropping works at low power (good penetration), but probably not at high power (this is expected)
- ELM triggering with C granule: good data obtained with a velocity scan; maybe trigger ELMs at lower velocity, since granules penetrate too deeply at high velocity?

Impurity Powder Dropper (Nagy, Bortolon) drops material from one of four reservoirs above upper X-point







~50μm Li powder
Classical Li powder dropper
Mansfield, Roquemore

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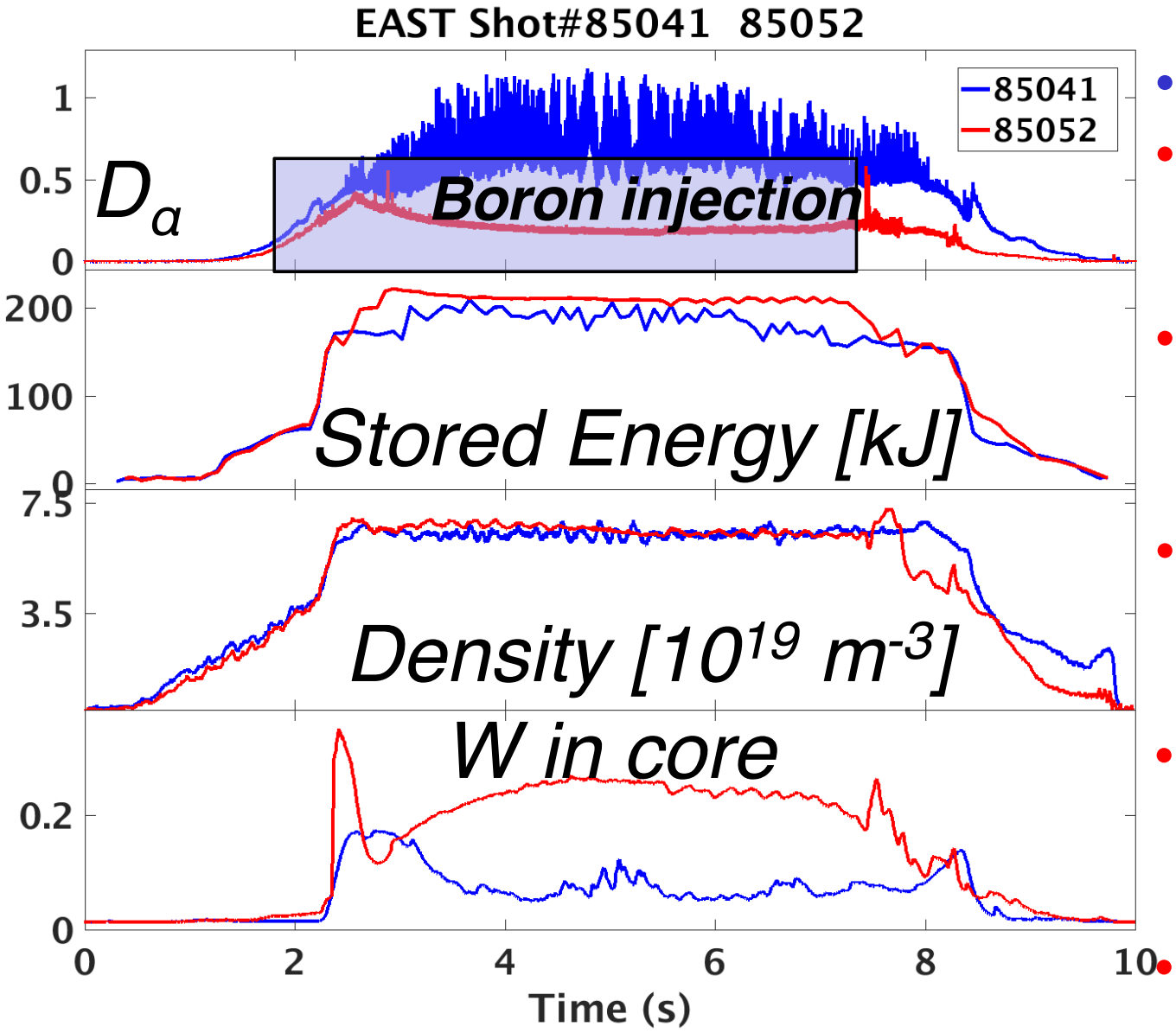
ELM suppression with B powder injection achieved
Edge mode w/harmonics observed during ELM suppression

- **Wide range of operation conditions at 0.5 MA, 2.5T**
  - RF only heating: 2.8 MW – 3.7 MW
  - RF + 1-2 co-NB: 4.1 MW – 6.2 MW
  - RF + 2 co-NB + 1 ctr-NB: 7.1 MW
  - Density range: 3.8e19 – 6e19
- **Mode on AXUV diodes near upper X-point**
  - Multiple harmonics ~ 3-5 kHZ fundamental; only with Boron
  - Only appears on channels close to upper X-point (where B injected)
  - Mode brighter with increasing B injection rate
  - No mode when Li is injected for ELM suppression
  - No mode in reference ELMy shots
- **Mode in magnetic probes on center stack and OMP**
  - Multiple harmonics ~ 3-5 kHZ fundamental; only with Boron
  - Mode stronger with increasing B injection rate
  - Mode slightly different frequency than the one in AXUV

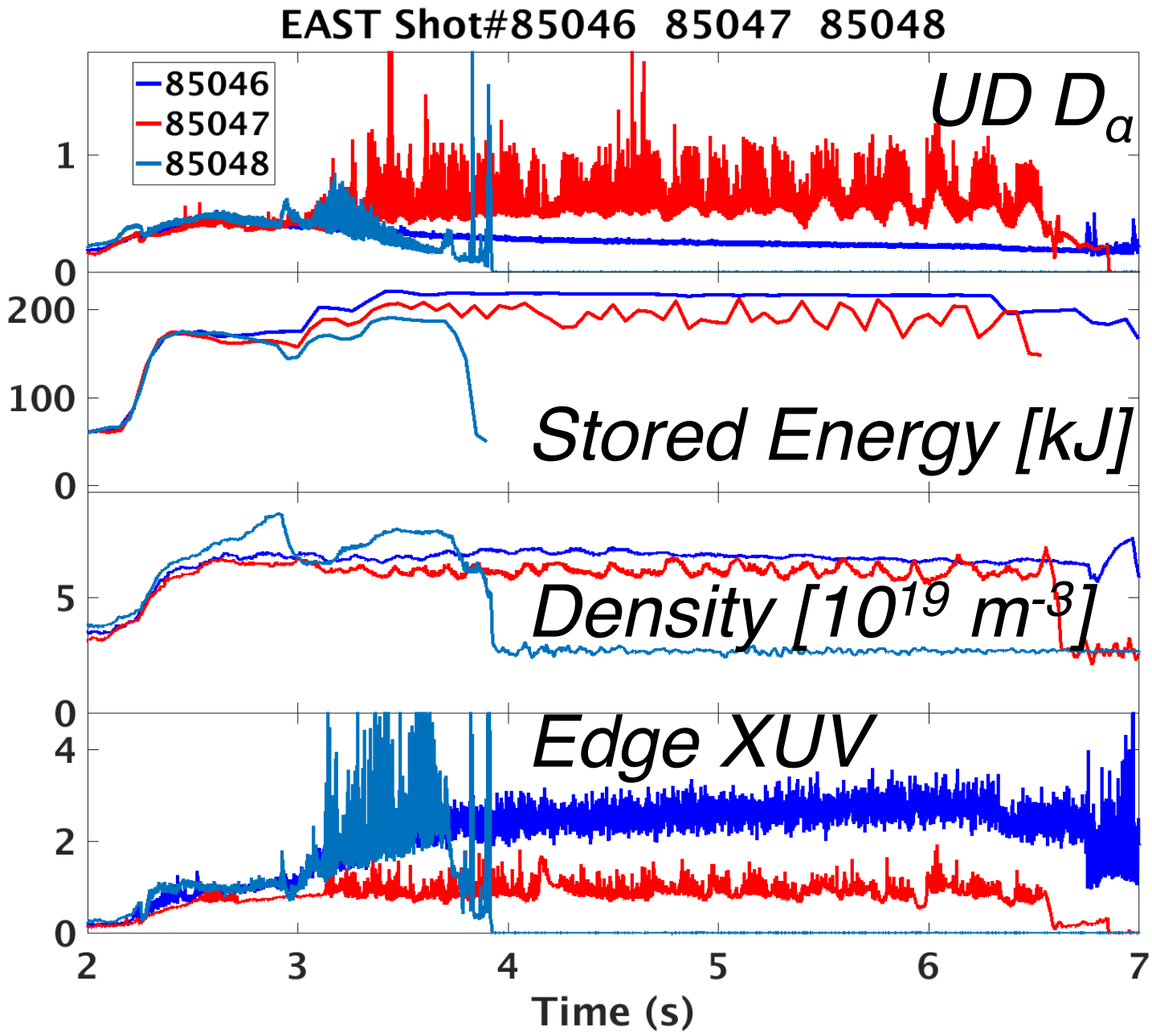
B injection suppressed ELMs with constant stored energy and density



- No Boron
- Boron injection above a threshold
- Stored energy increased slightly
- Density matched
- W higher in core, but holds steady at a low level
- W actually reduced in other cases

- I_p=0.5 MA, B_t=2.5 T, P_{heat}~6 MW, USN

Optimal flow rate found for B injection to suppress ELMs in the range of 20 mg/s under all tested conditions

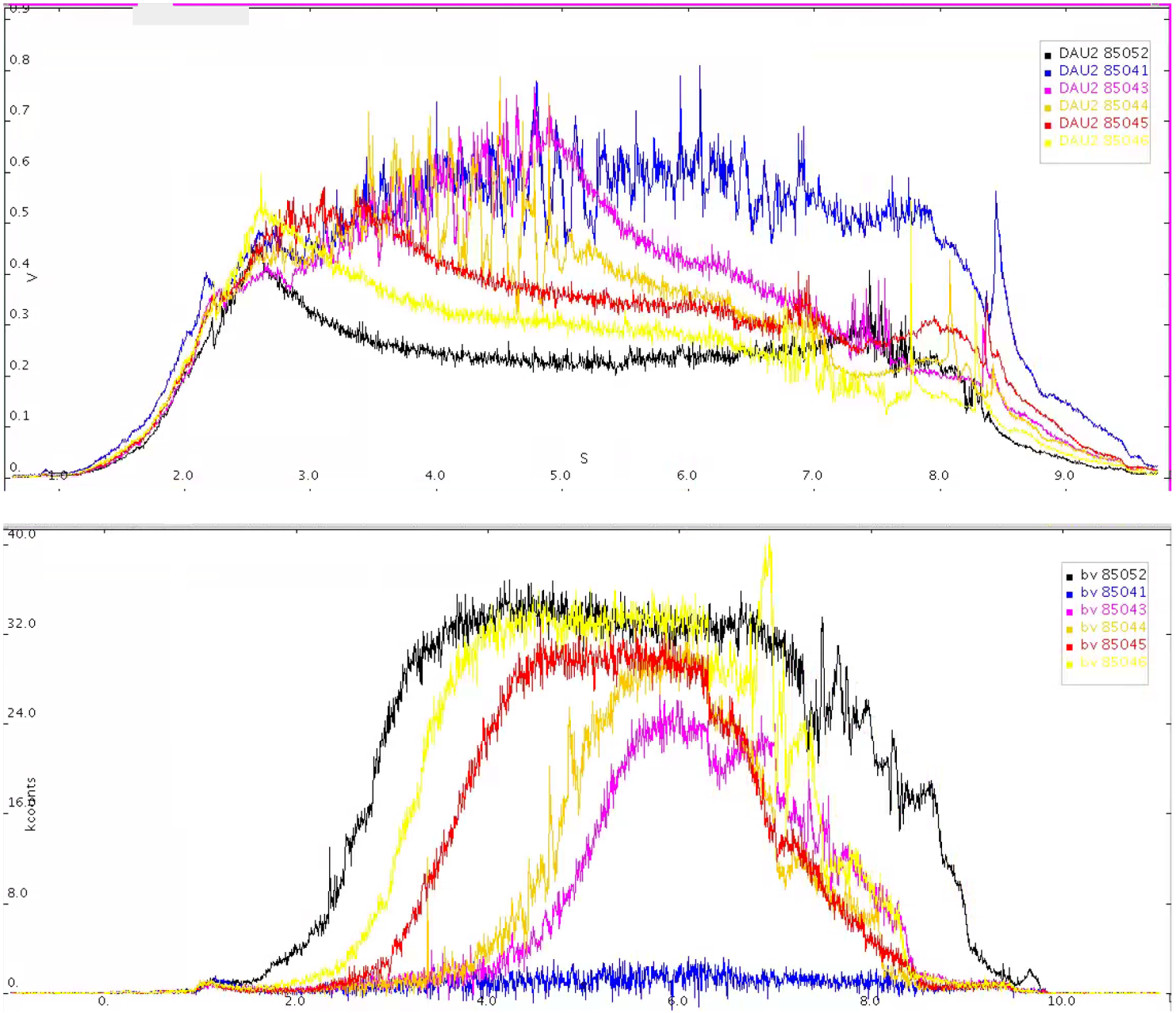


~ 5 mg/s

~ 20 mg/s

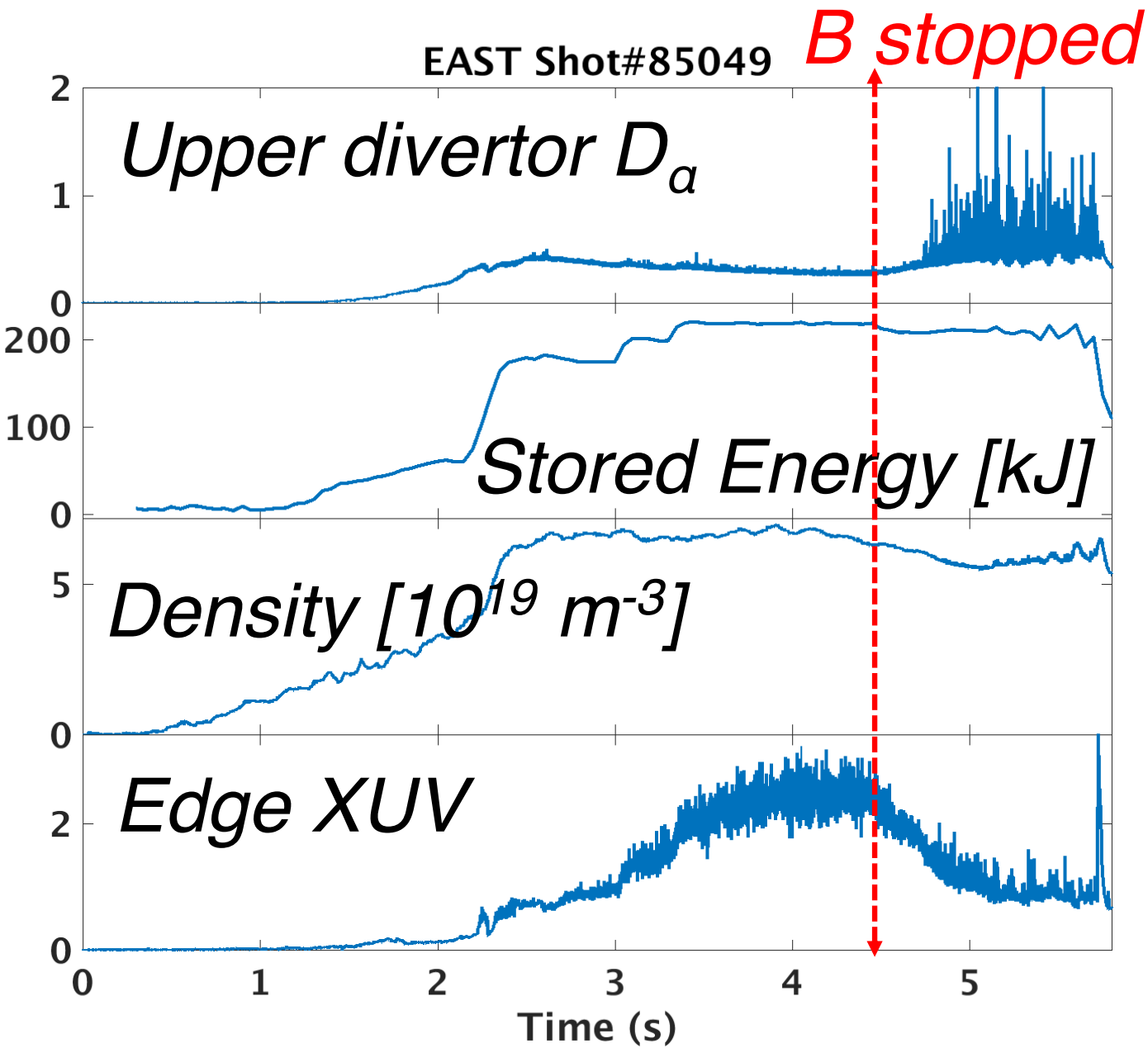
~ 250mg/s

B timing scan confirmed causality for ELM suppression

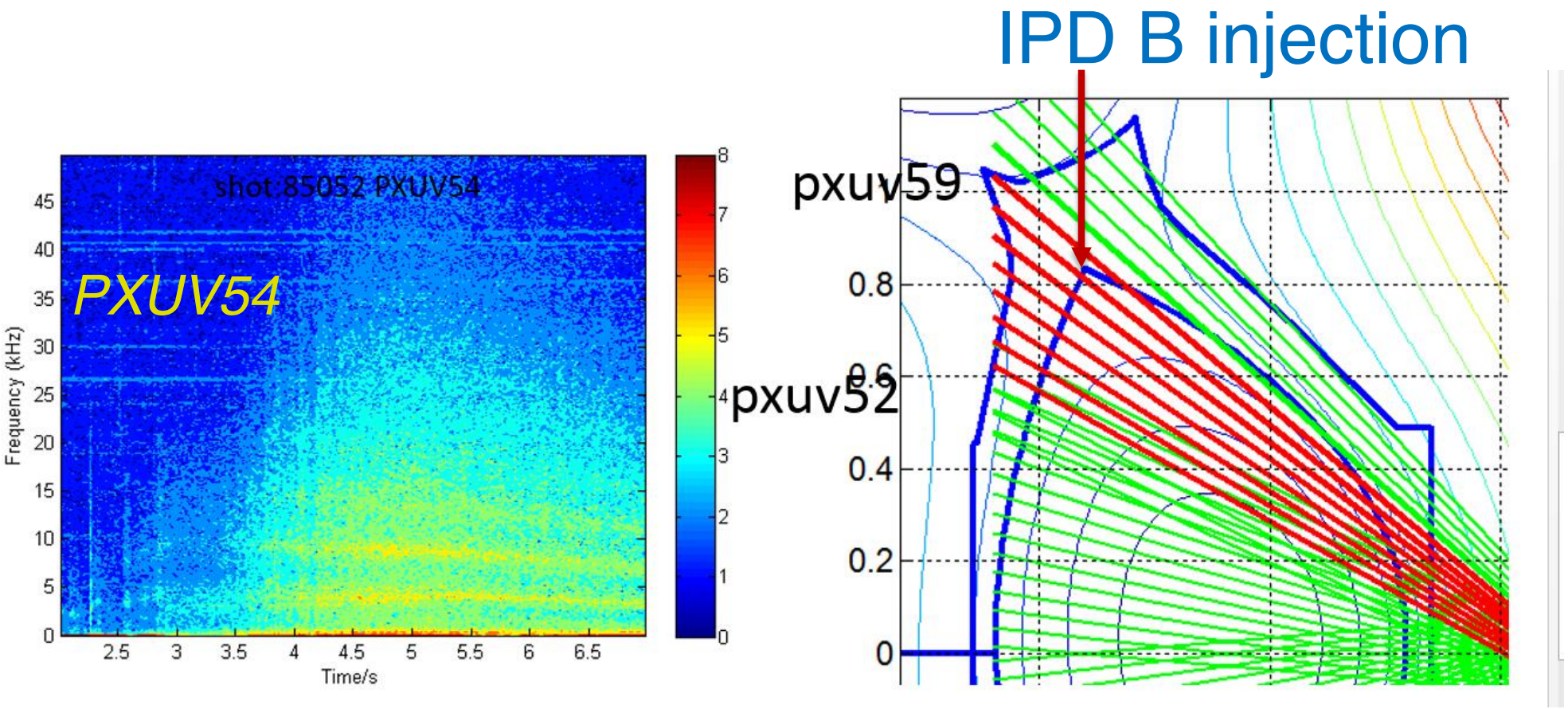


- Reference ELMy (No B)
- All others at B ~ 20 mg/s
- All shots with B injection have ELM suppression when B-V in edge was ~ 8-12 kcounts

ELMs return in ~ 0.5 sec when boron injection is terminated

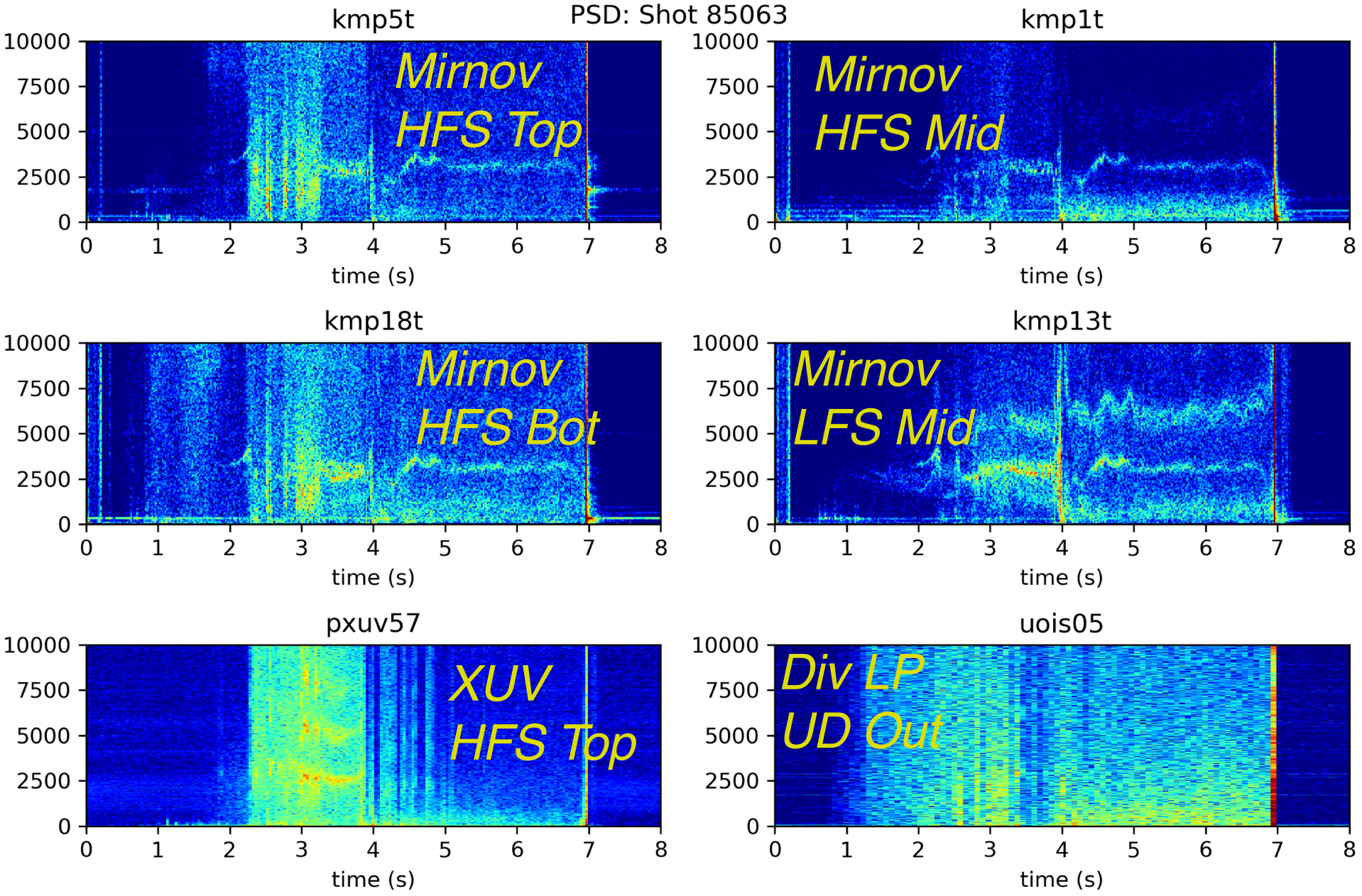


Edge Harmonic Oscillation observed during ELM suppressed H-mode with B injection

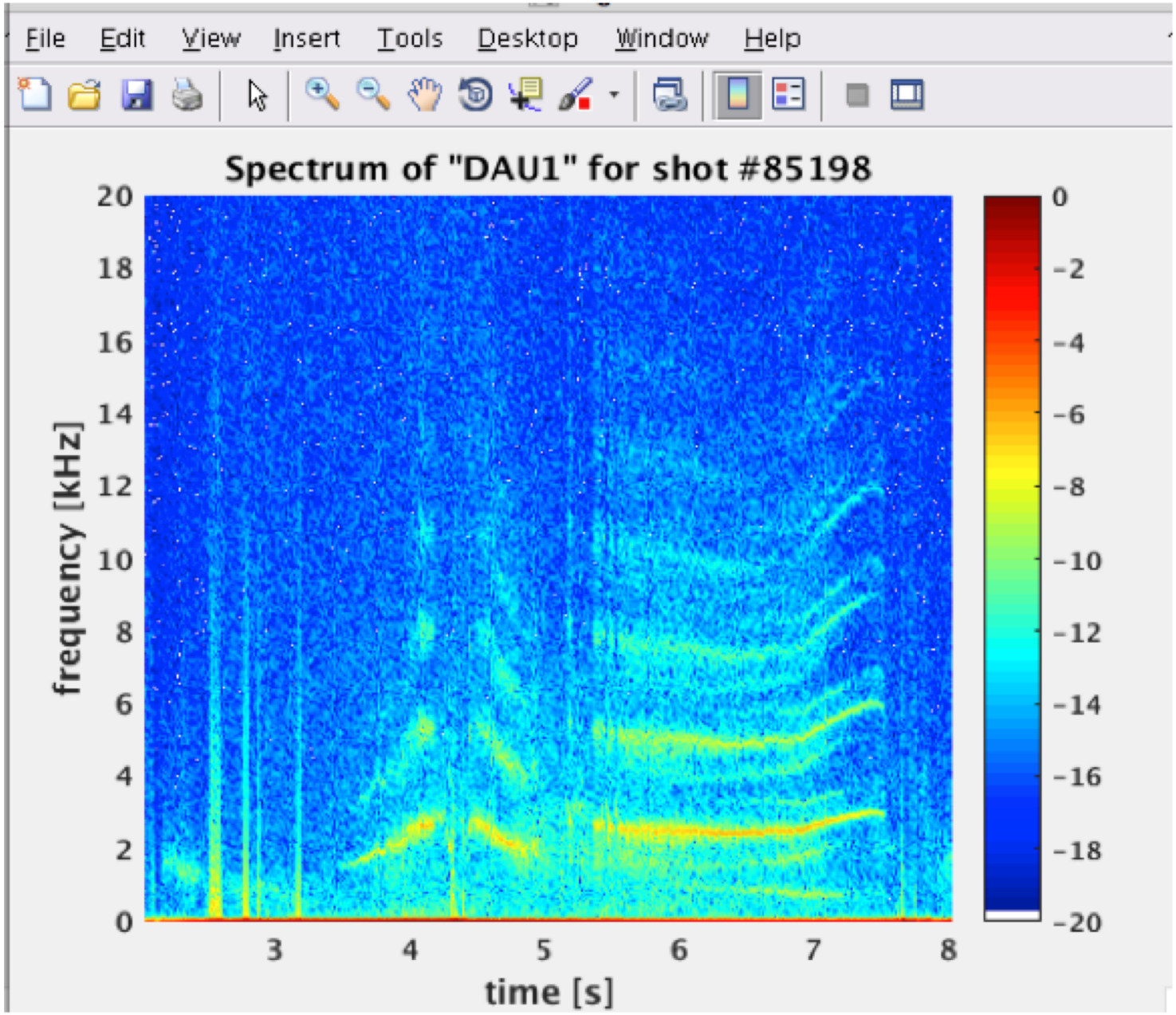


- Mode shows up in PXUV52-59, near B injection point: enhanced n_e?
- Brighter at higher B injection rates: more light?
- Not observed if B injection rate too low for ELM suppression

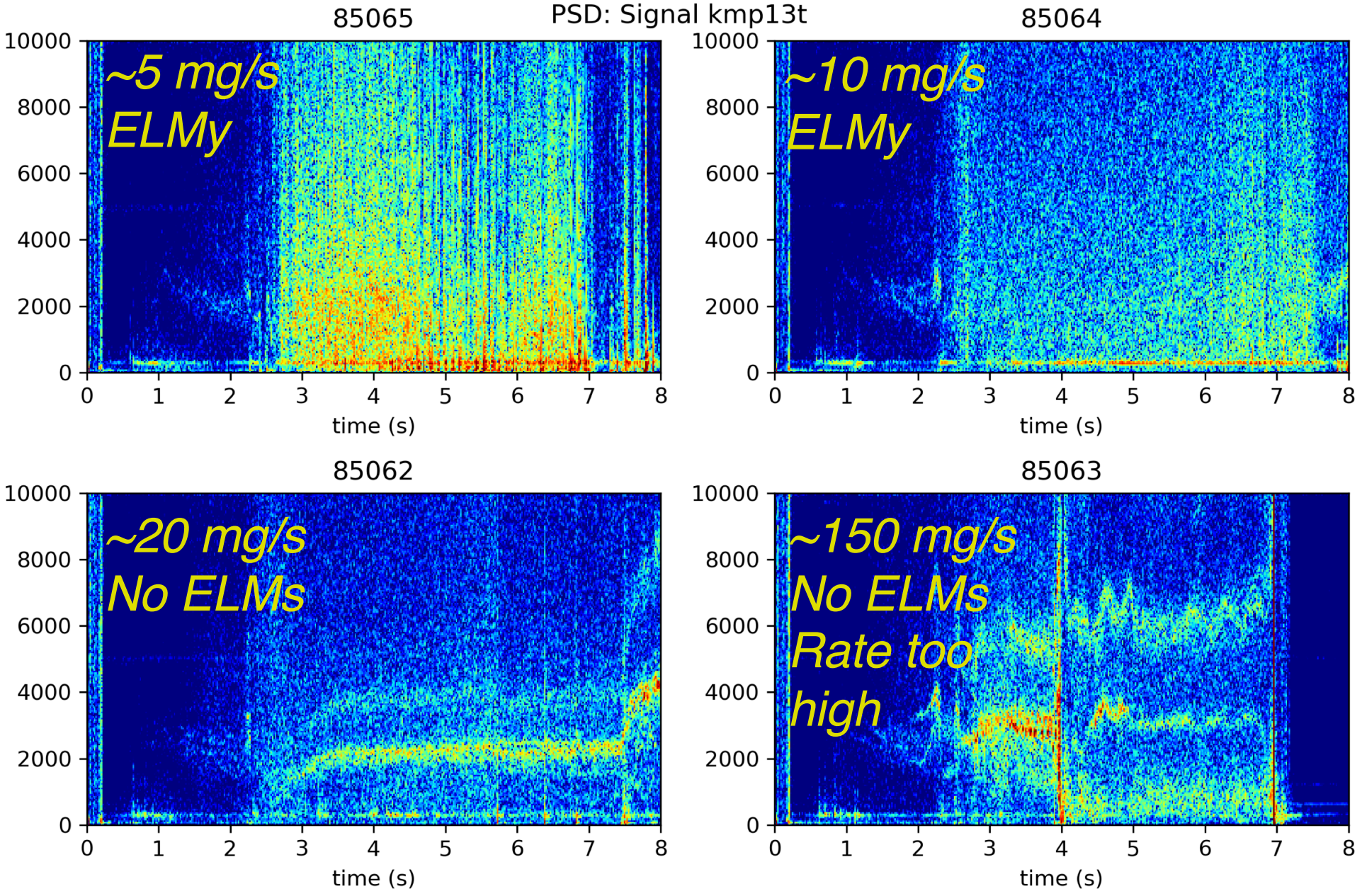
Modes show up clearly in magnetics and AXUV, but at slightly different frequencies, but not in divertor LP



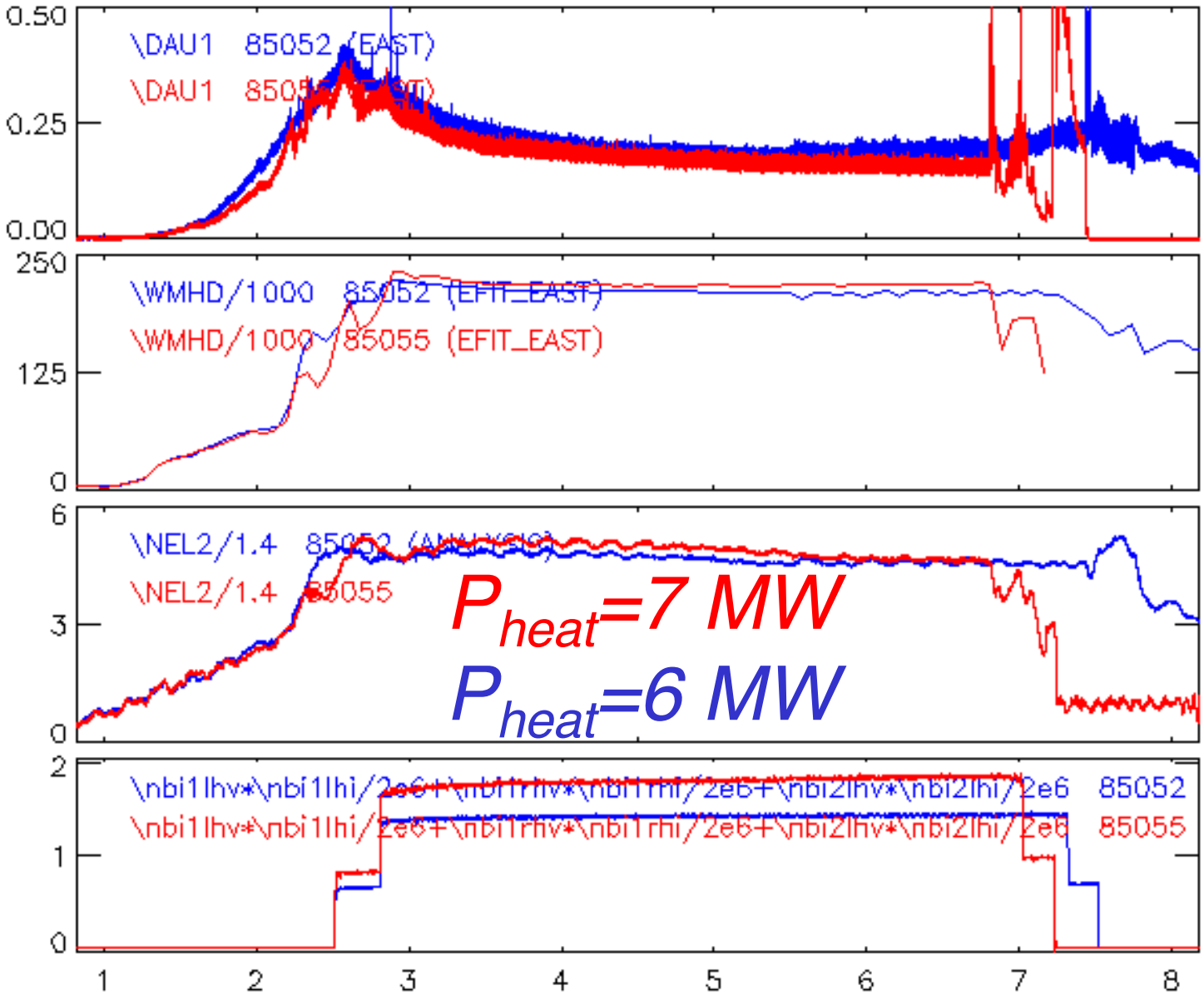
Multiple harmonics also observed in Upper Divertor D_α emission when B injected and ELMs suppressed



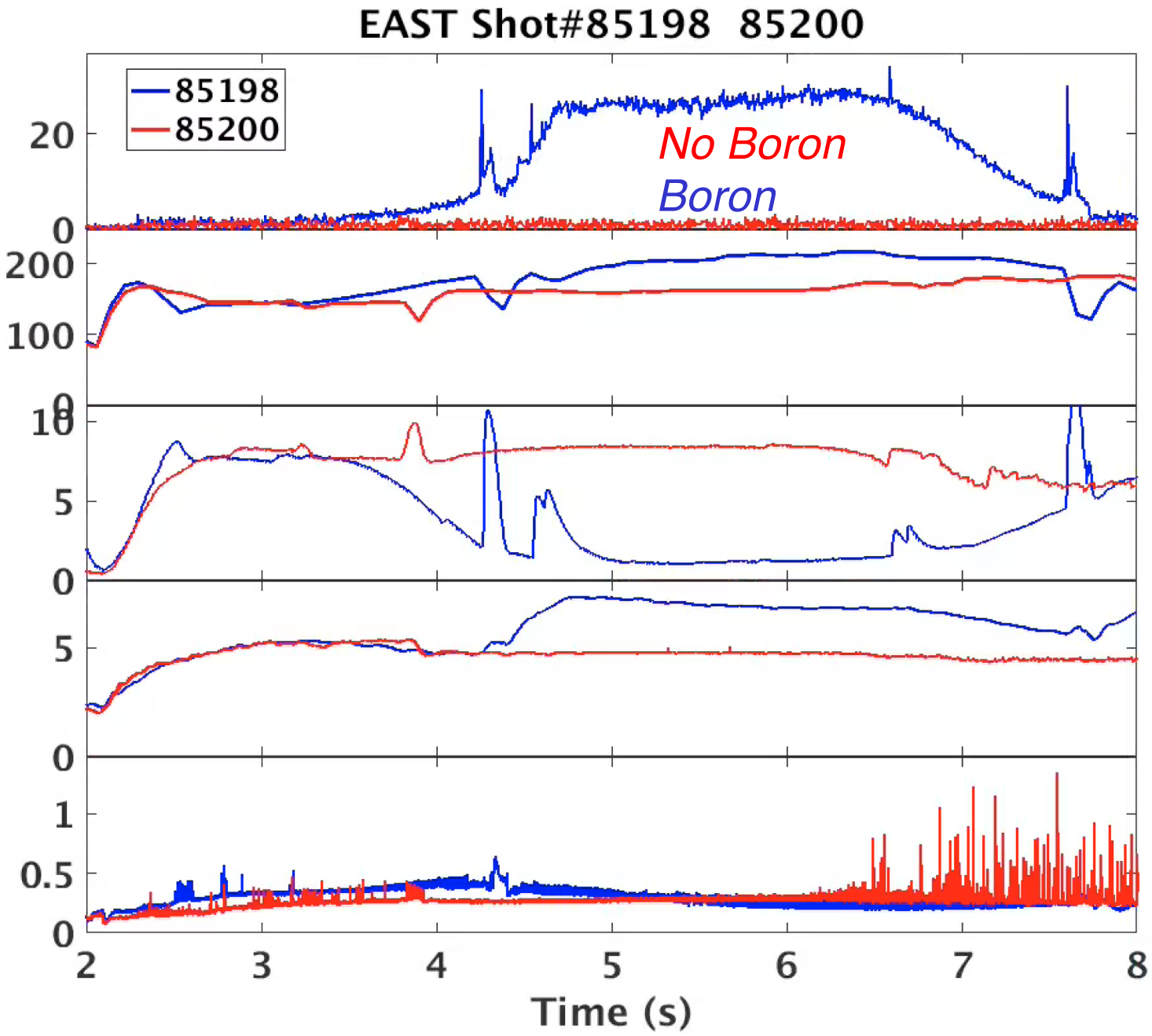
Mode amplitude increases with increasing B injection rate (Mirnov LFS mid)



B injection suppressed ELMs over a range of input power (highest input powers with NBI shown)



ELM suppression demonstrated in RF only discharges (P_{RF} ~ 2.8 MW), paving the way for future long pulse demonstration



B-V edge

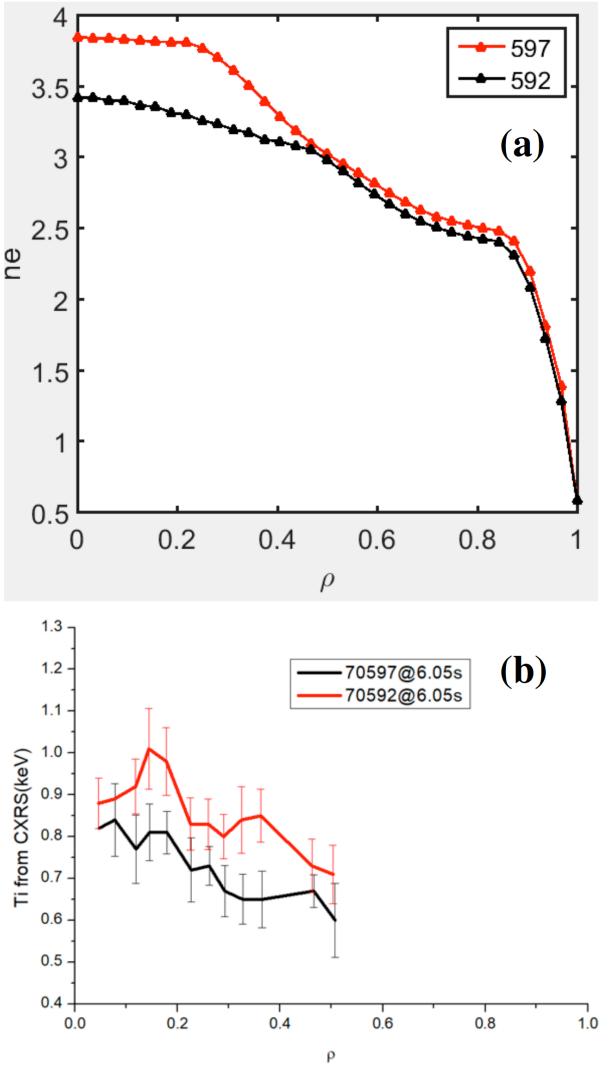
W_{MHD} [kJ]

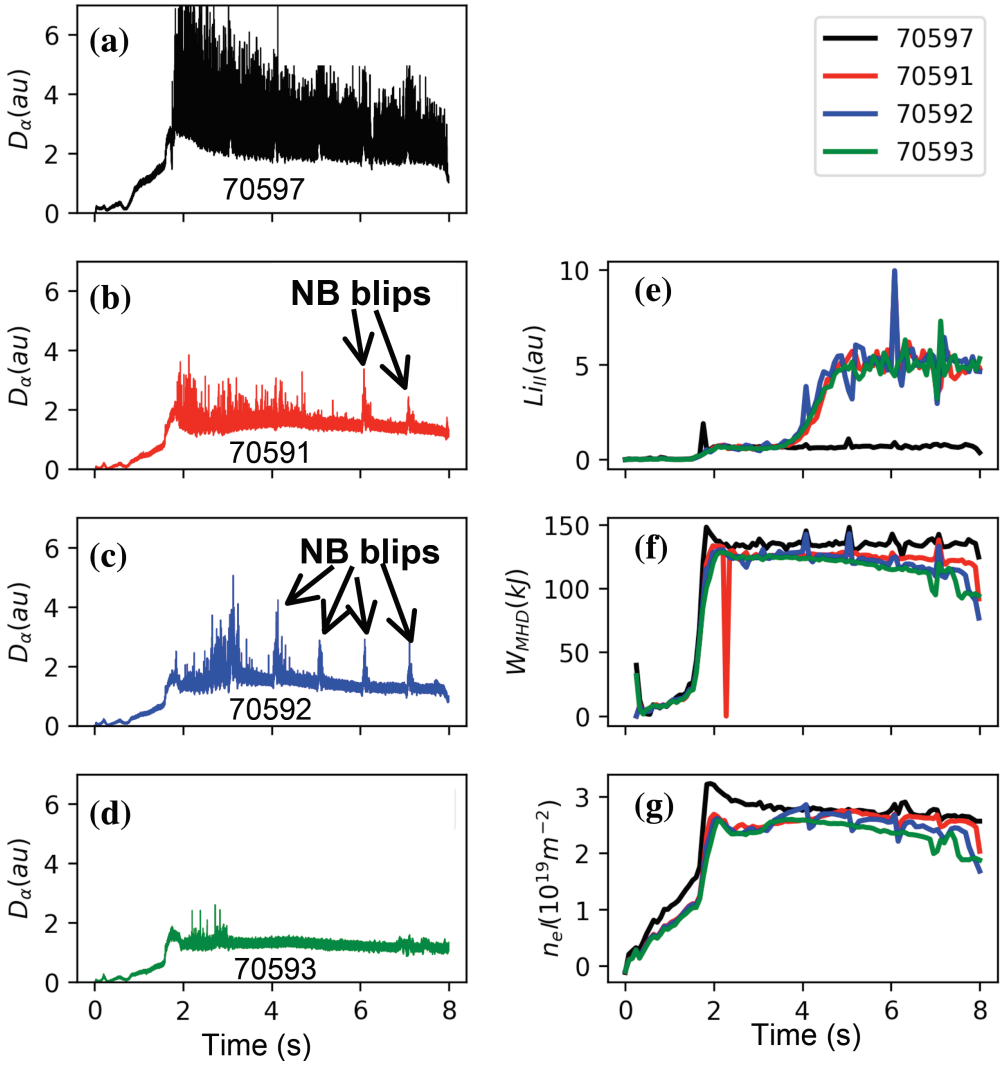
W in core goes down

Density 10^{19} m^{-3}

Upper Div. D_α

Background: Recycling and ELMs progressively reduced with constant Li injection rate in EAST

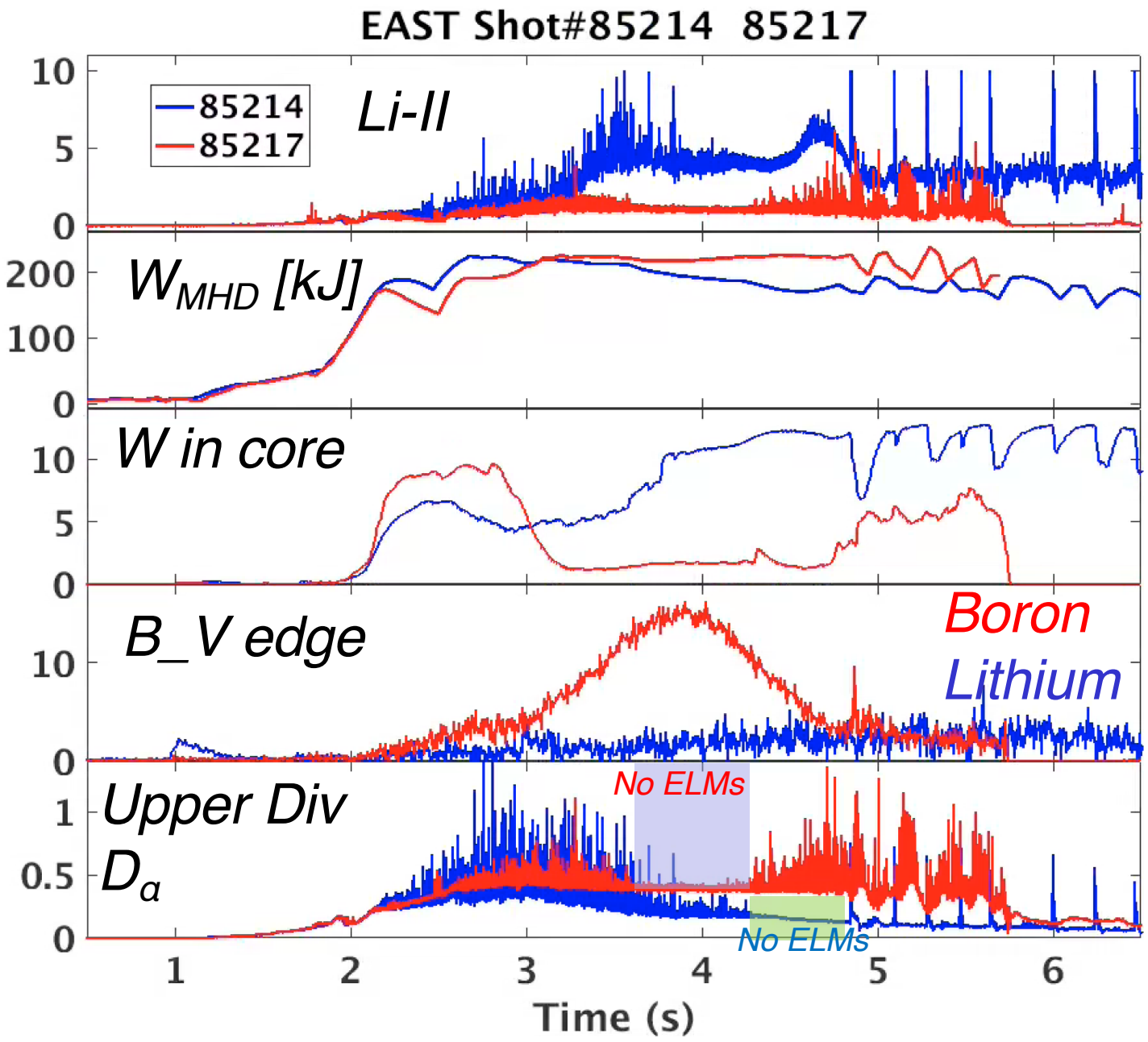




R. Maingi, Nucl. Fusion **58** (2018) 024003; builds on R. Maingi, *Phys. Rev. Letts.* **107** (2011) 145004

- SOLPS analysis shows local divertor recycling coefficient drops by 20%
- J. Canik, *IEEE Trans. Plasma Sci.* **46** (2018) 1081; builds on J. Canik, *Phys. Plasmas* **18** (2011) 056118

ELM suppression with B powder easier than with Li powder: constant or increased W_{MHD}, no apparent wall hysteresis



Li flow rate continuous

B flow for short duration

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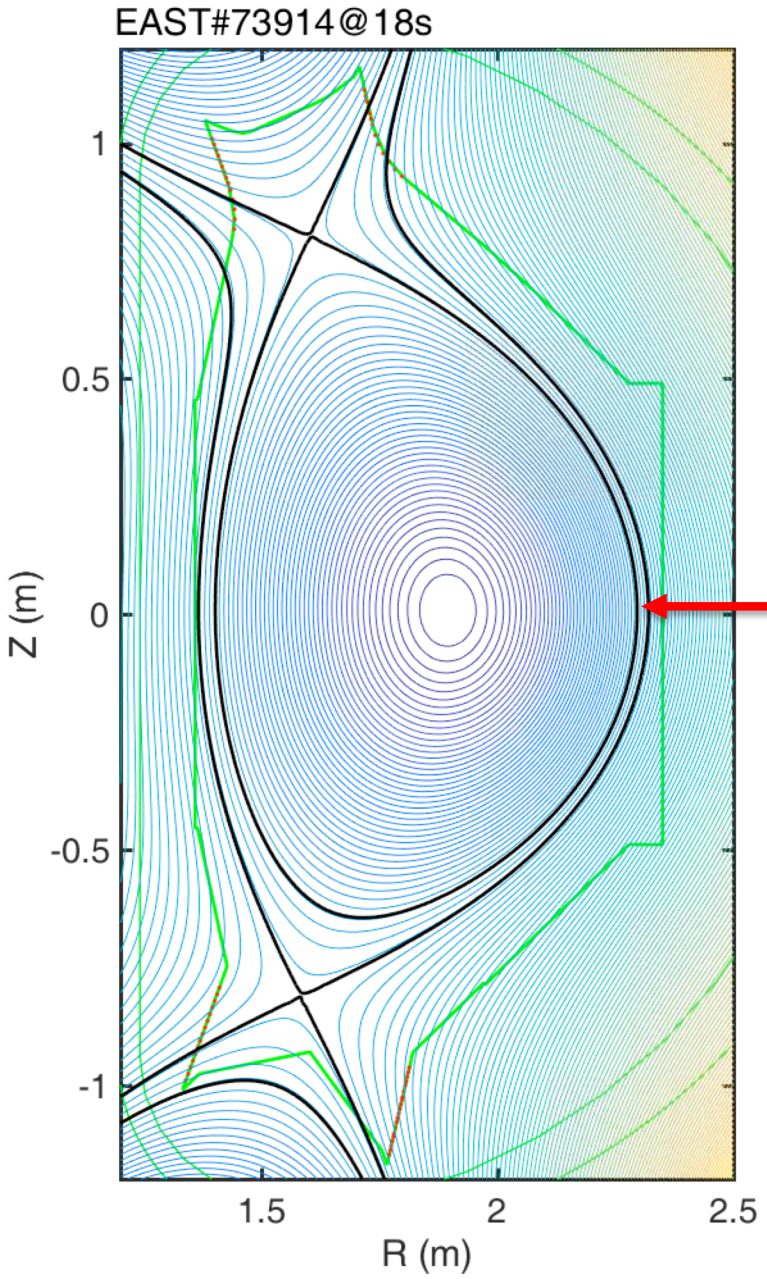
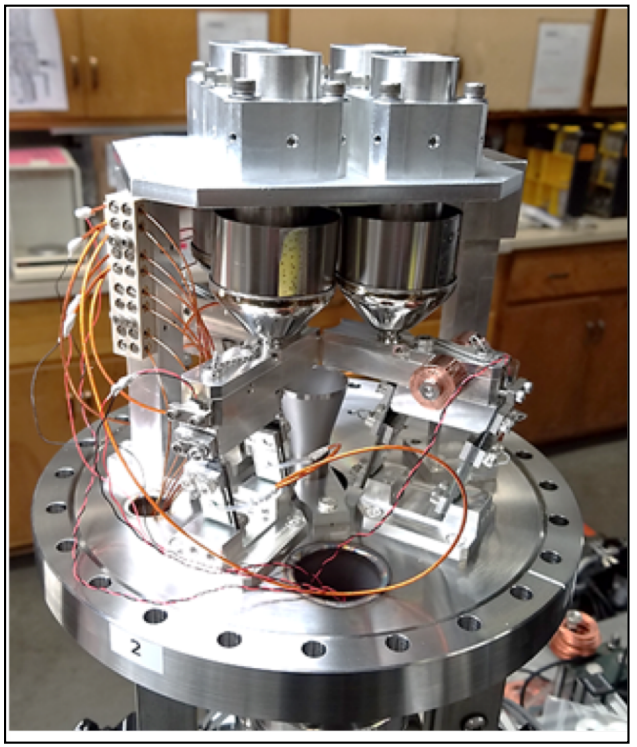
New impurity granule injector capable of injecting multiple impurity sizes and materials



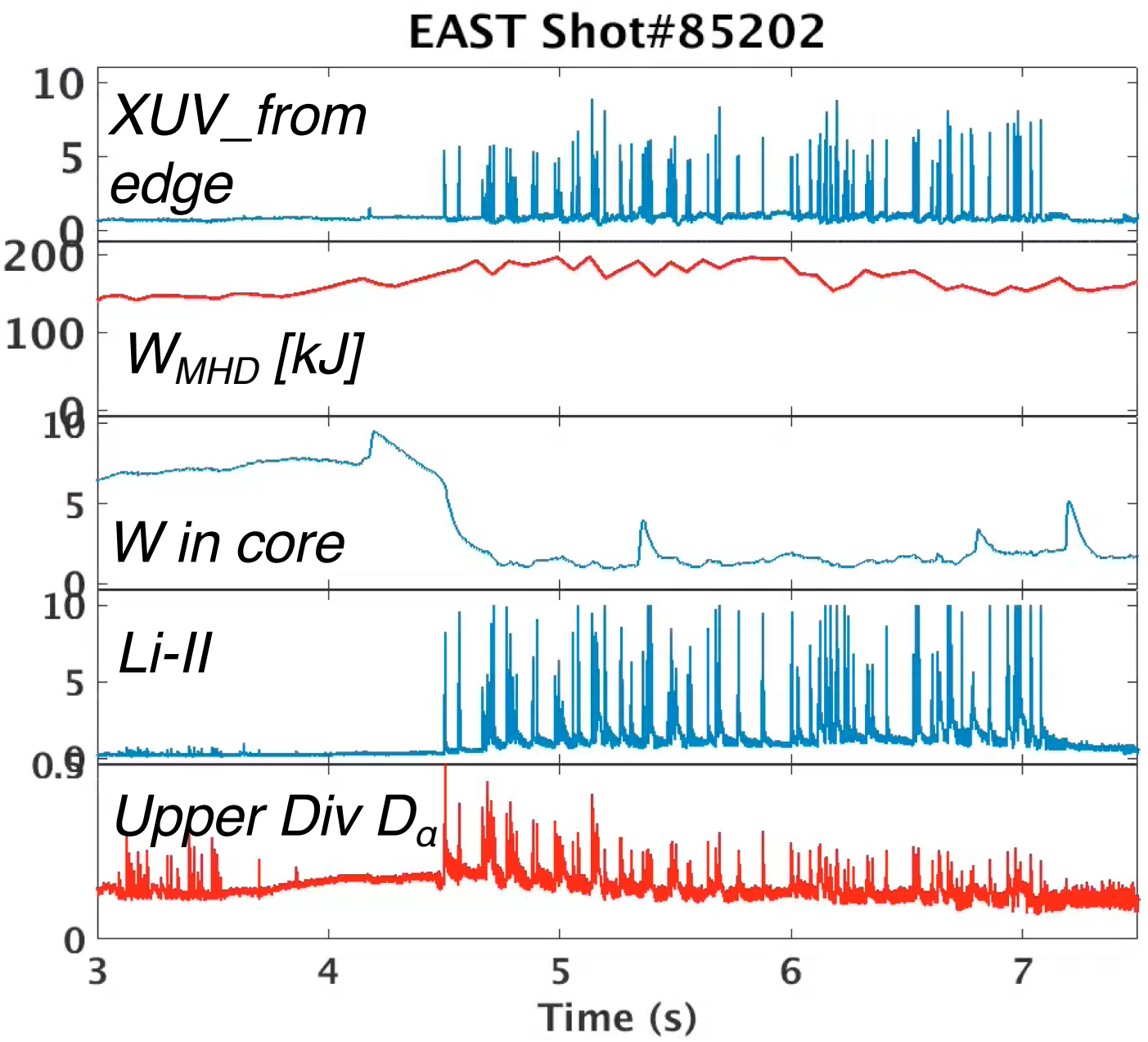


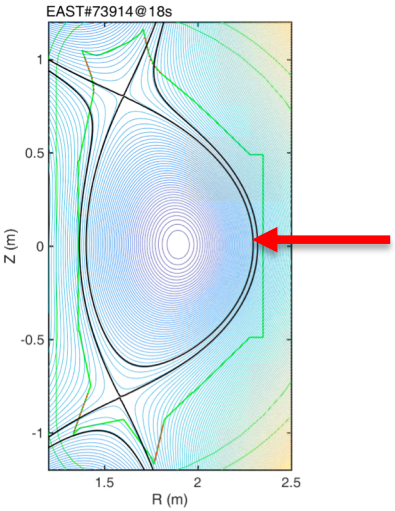
- 0.9, 0.7, 0.5 mm Li granules
- 0.7 mm C granules
- Injection speed: 50-150 m/s
- Used the B powder ELM suppressed discharges as the reference

ELM triggering and pacing experiments with the new impurity granule injector

- **Physics principles to be tested with ELM pacing**
  - Dependence of ELM size on triggered ELM frequency in a discharge with suppressed ELMs; *expect* $\Delta W \sim 1/\nu_{ELM}$
    - *Gravitationally dropped C granules also trigger ELMS!*
  - Dependence of ELM triggering efficiency on Li granule size; *expect clear size threshold that increases with heating power*
    - *This segment was postponed till July run*
  - Dependence of pellet ablation on injected material; *expect carbon to penetrate much more deeply than Li; don't know if C granule will trigger ELMs*
    - *Penetration too deep, i.e. not enough mass in pedestal?*

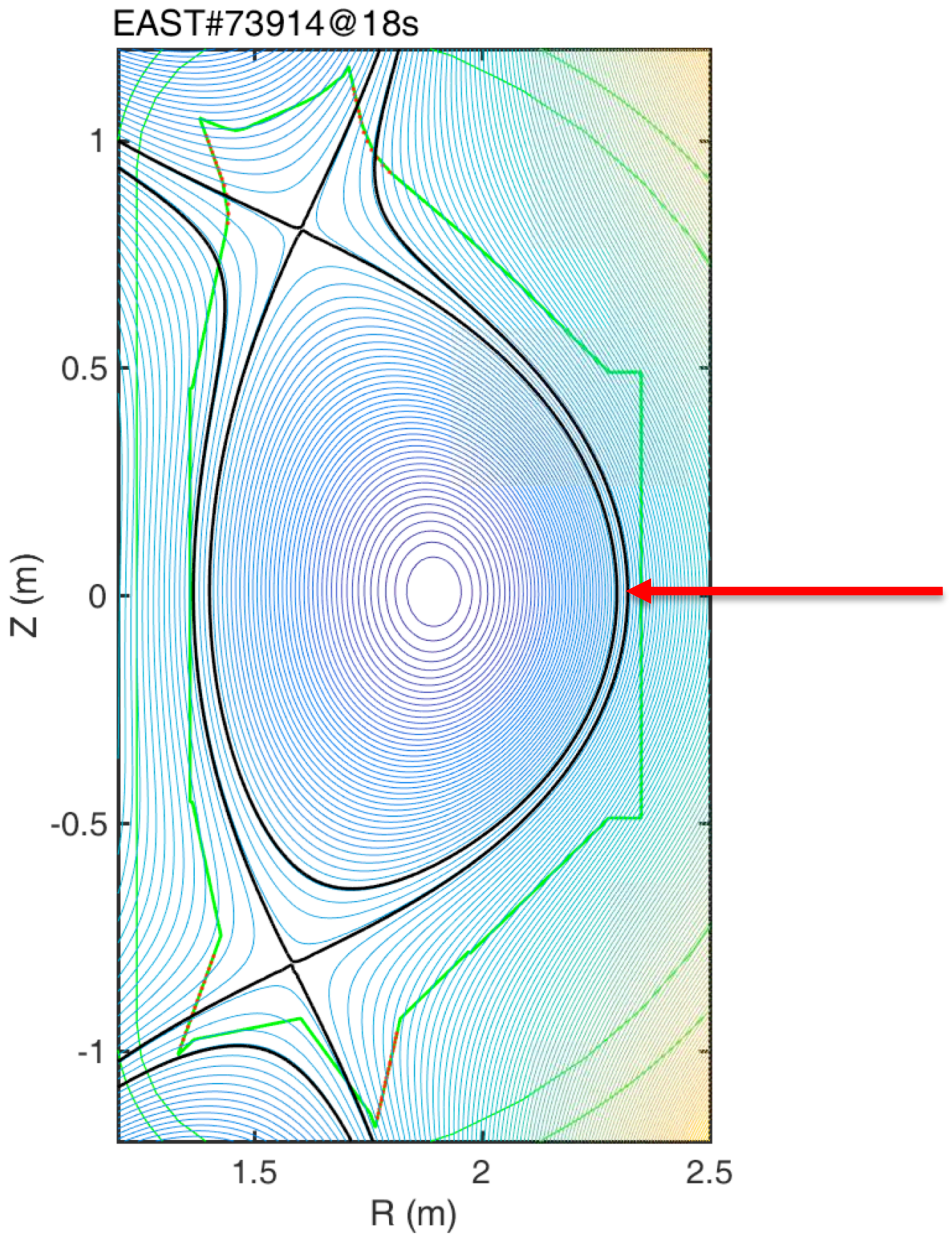
Li granules trigger ELMs in ELM suppressed discharges with B injection; triggered ELM frequency scan from 5-100 Hz





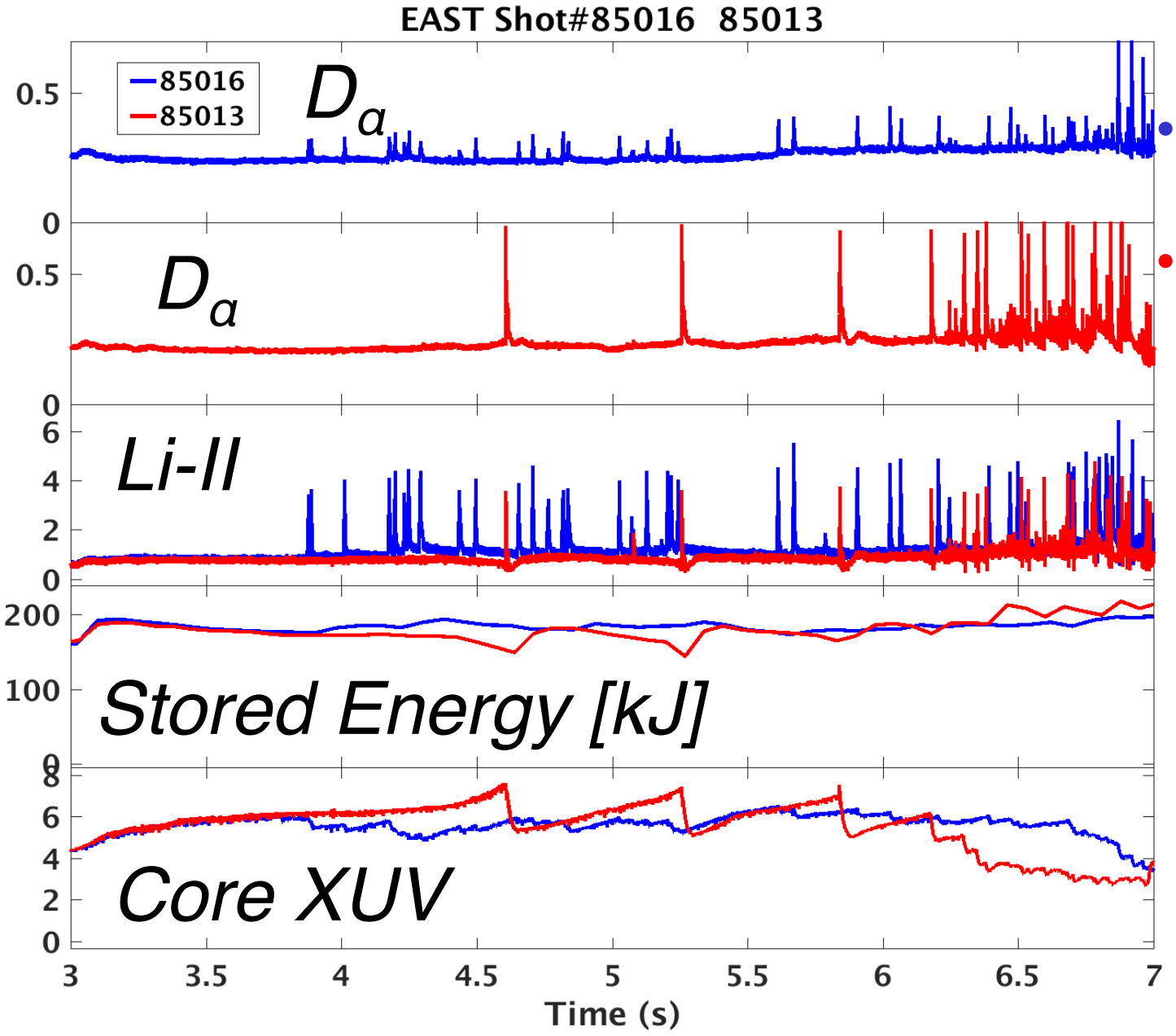
Li granules injected by the IGI ~ 100 m/s

C granules (0.7mm) injected into ELM suppressed discharges with B injection; ELM triggering being assessed

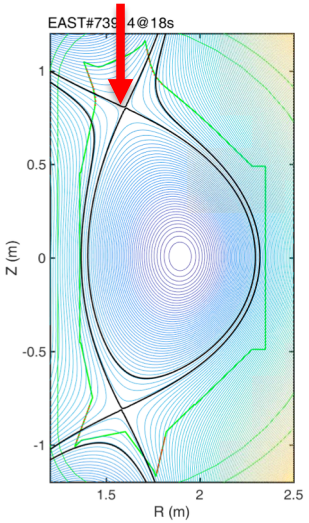


- C granules injected by the IGI at 2 different speeds ~ 50 & 100 m/s
- C granules penetrate much more deeply than Li granules, looking at ablation light
- Preliminary analysis suggests that slower granules trigger ELMs; faster granules may not deposit enough material in pedestal

Li granules dropped into X-point mitigated giant ELMs
Each granule triggered an ELM



- Li granules
- No granules



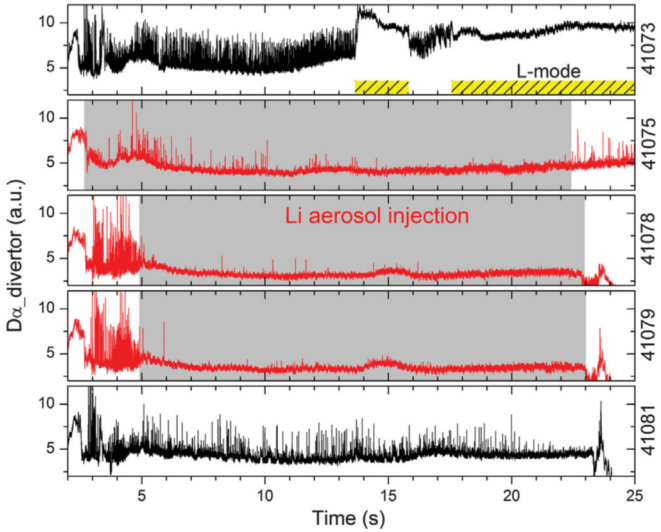
Summary and Next Steps

- ✓ B suppresses ELMs much more easily than Li powder!
  - Constant or increased WMHD, works with SMBI density feedback, no wall hysteresis, over a range of P_{NBI}, density, ν^*
  - Want to follow-up under what conditions B increases energy confinement (transport vs edge) in EAST
  - Want to follow-up on DIII-D, KSTAR, AUG
  - Need to investigate where B mass ends up!
  - Need a fine B injection rate scan!
- ✓ ELM suppression with B works with pure RF heating
  - Paves the way for long pulse ELM suppression with B
- ✓ ELM pacing with Li granule injection in ELM-suppressed discharges works (0.9mm tested)
  - There is a range in the triggered ELM frequency, so we should be able to check if $\Delta W \sim 1/\nu_{ELM}$
- ✓ ELM triggering with low speed Li granule dropping works at low power (good penetration)
  - Not expected to trigger ELMs at high power; need to test

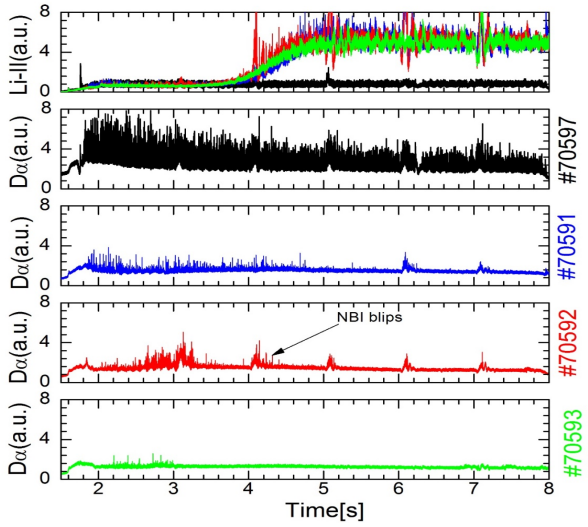
Thank you
Backup slide follow

Goal: determine if effective ELM control can be enabled by Li or B injection in high-power, H-mode plasmas

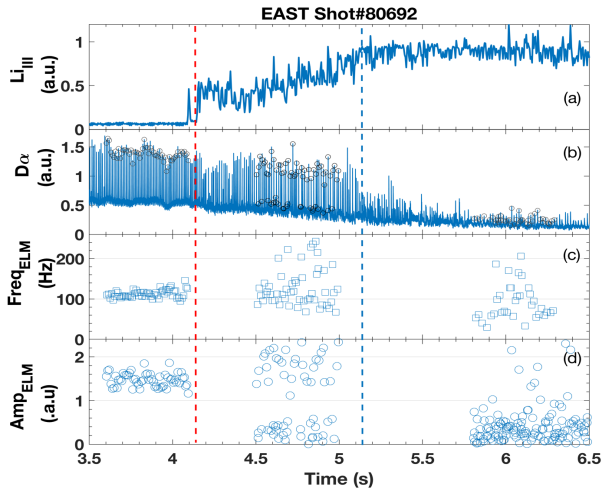
- ***Transient heat flux induced by ELM is key issue for future device, also for EAST with high heating power***
- ***The effect on ELM of Li powder/granule injection were observed on EAST, but with 2-6MW heating, low current ≤ 0.45 MA.***
- ***It is necessary to explore the window of ELM elimination by impurity particles injection, toward higher heating power, low ν^* with W divertor for CFETR, and possibly ITER***



C wall
2.5MW
250kA
Li powder
J.S. Hu, PRL 2015

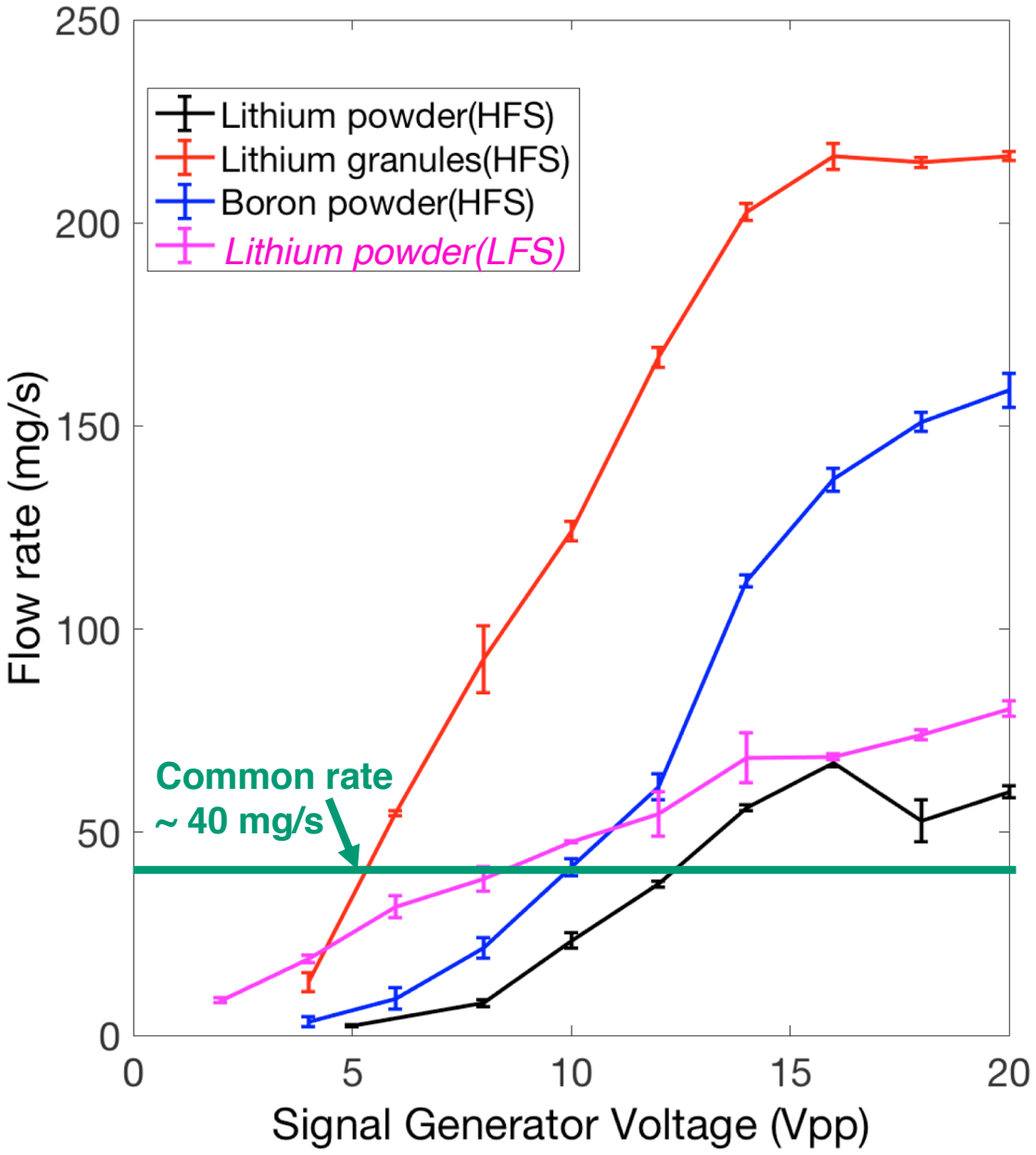


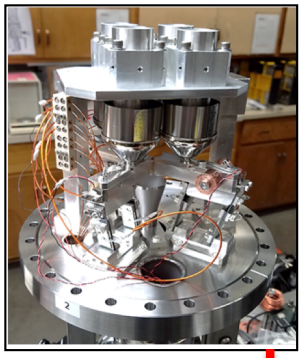
W wall
3MW
400kA
Li powder
R. Maingi, NF 2018

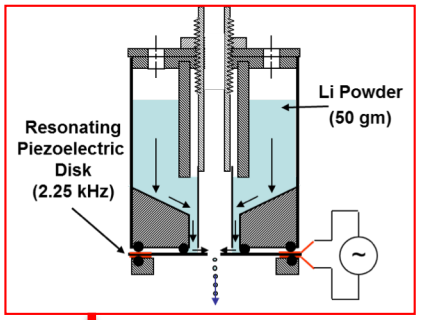


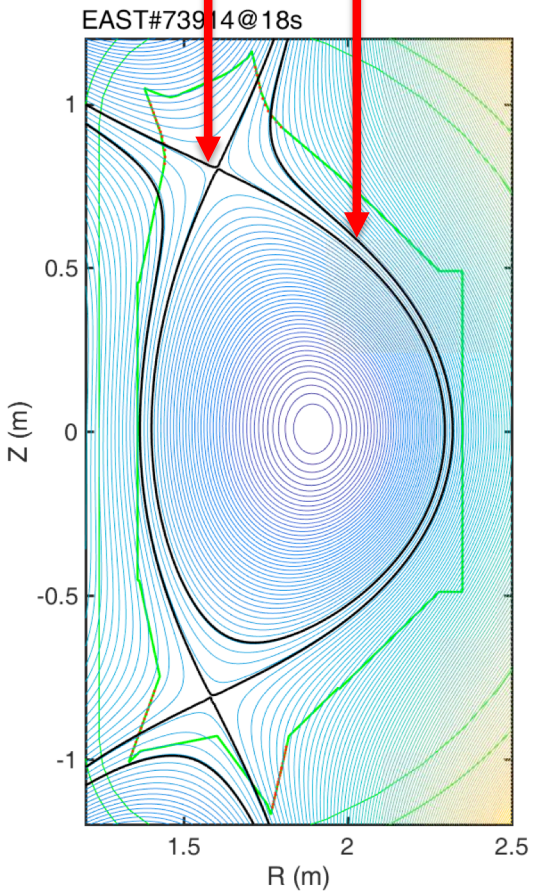
W wall
5.5MW
450kA
Li granule
Z. Sun, NF 2019 in prep

Calibrated flow rate demonstrated with the new impurity powder dropper



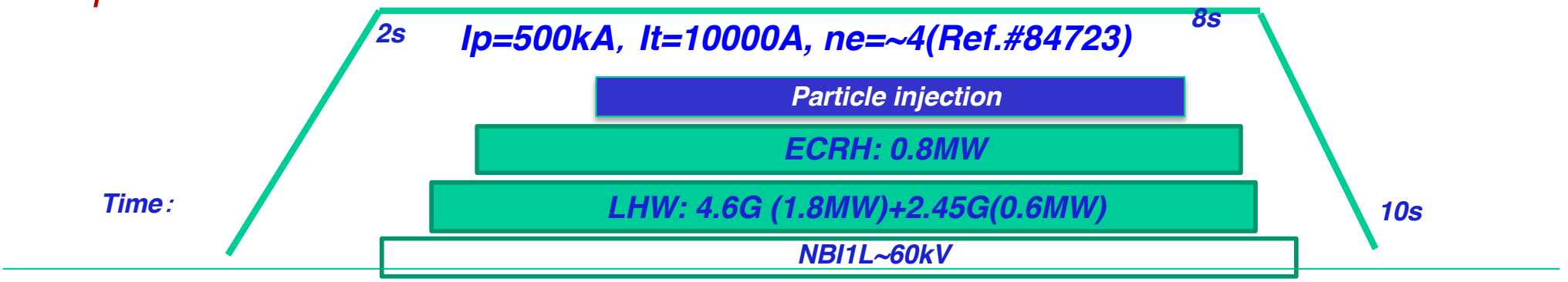






Plasma waveforms

Step 1



Step 2