ELM elimination with impurity powder injection in EAST and MHD effect on liquid metal flow

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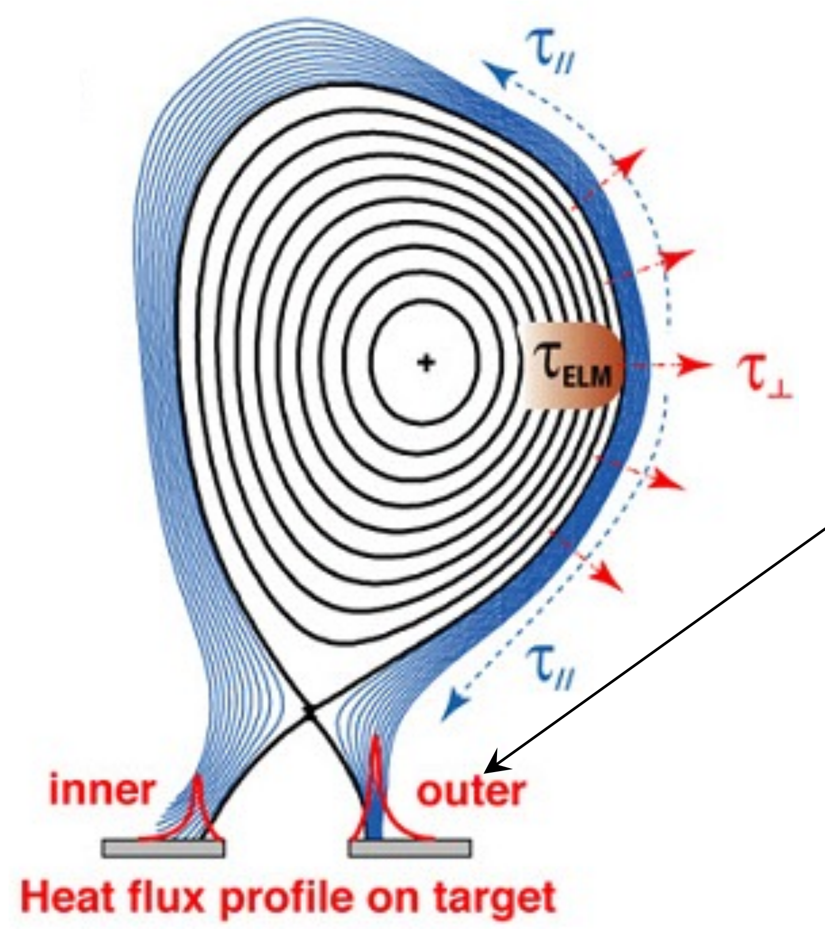
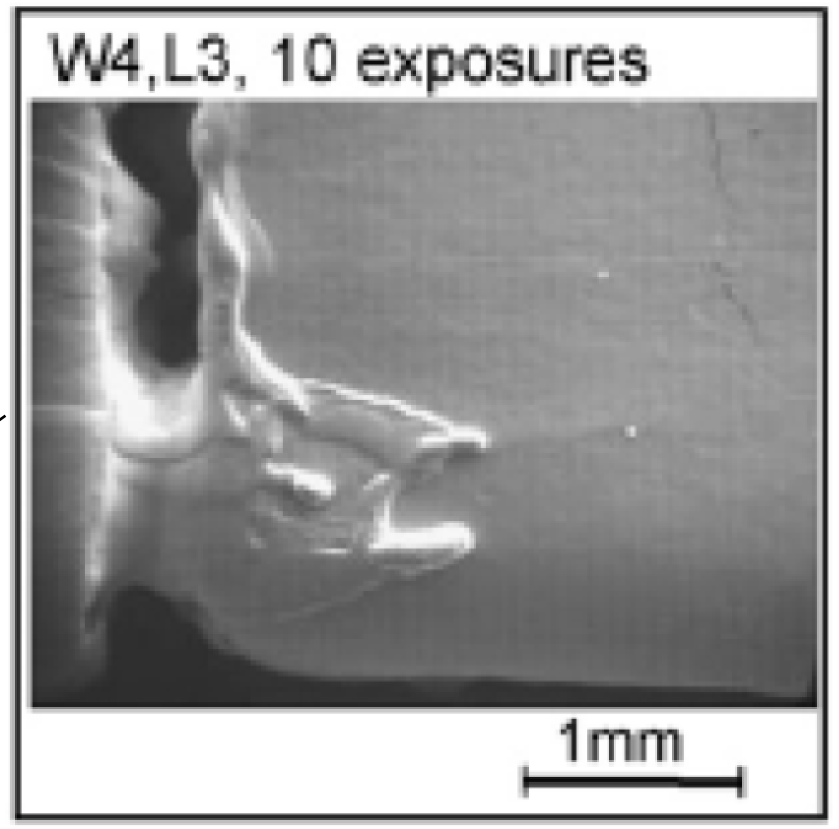
NSTX-U / Magnetic Fusion Science Meetings
Dec. 8, 2021

Professional experience

- **2015 obtain PhD in ASIPP**
- **2015-2018 staff researcher in ASIPP**
  - Build and develop Li coating as the most effective wall conditioning technology and study its impact on plasma performance on EAST
  - PI for lithium powder/granule injection programs on EAST
    - ELM trigger by Li granule injection
    - Firstly achieve 18s ELM-free H-mode by Li powder injection
    - Real-time wall conditioning for 100s H-mode using Li powder
  - Support for building liquid Li limiter/circuit and conduct experiments of liquid Li limiter on HT-7 and EAST
- **2018-Present post-doc in PPPL**
  - Lead impurity powder/granule injection programs on EAST
  - Participate in impurity powder injection experiments on LHD and AUG
  - Study MHD effect on LM flow in LMX

PFCs need to withstand steady and transient heat fluxes





Zhitlukhin JNM 2007

Steady-state heat fluxes & neutron fluxes

Transient heat fluxes e.g. Giant ELM

- **Solid/W wall: erosion, dust formation, high-Z impurity accumulation…**
- **ELMs, <1ms, resulting in 10x or larger increases in the peak divertor heat flux**
  - RMP, pellet pacing, etc
  - Limitations

P. Lang, NF, 2013

- **Alternative ELM control methods are desired**
- **Liquid metal flow: very high steady and transient heat exhaust**
- **Liquid metal flow in magnetic needs more investigations**

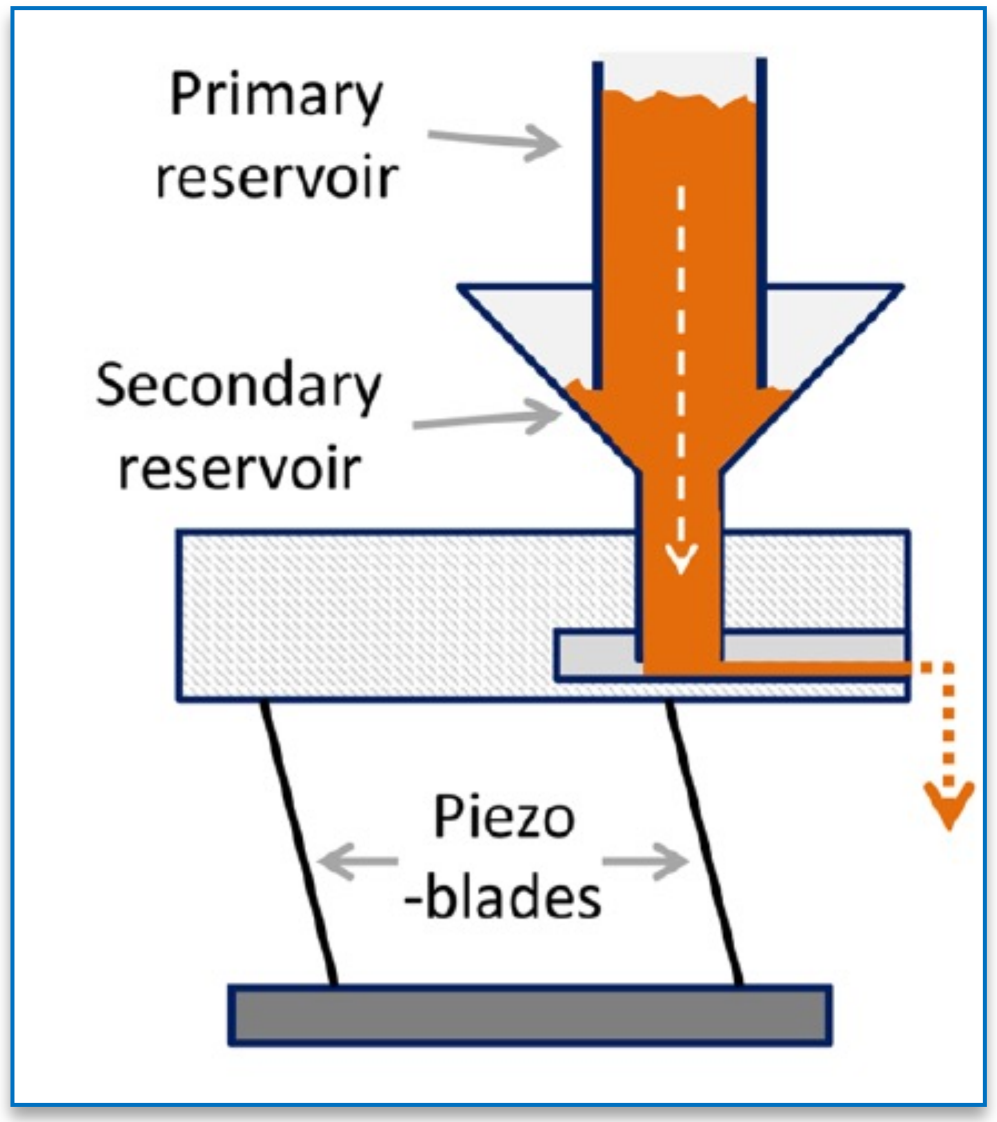
C. Kessel, FST, 2019

Outline

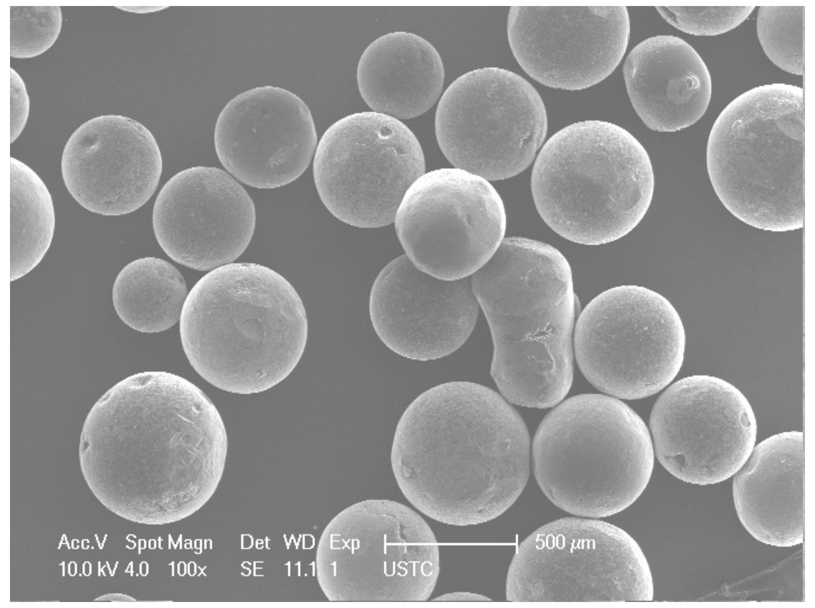
- ELM mitigation by Lithium granule injection
- ELM suppression by Boron powder injection
- MHD effect on liquid metal flow
- Summary

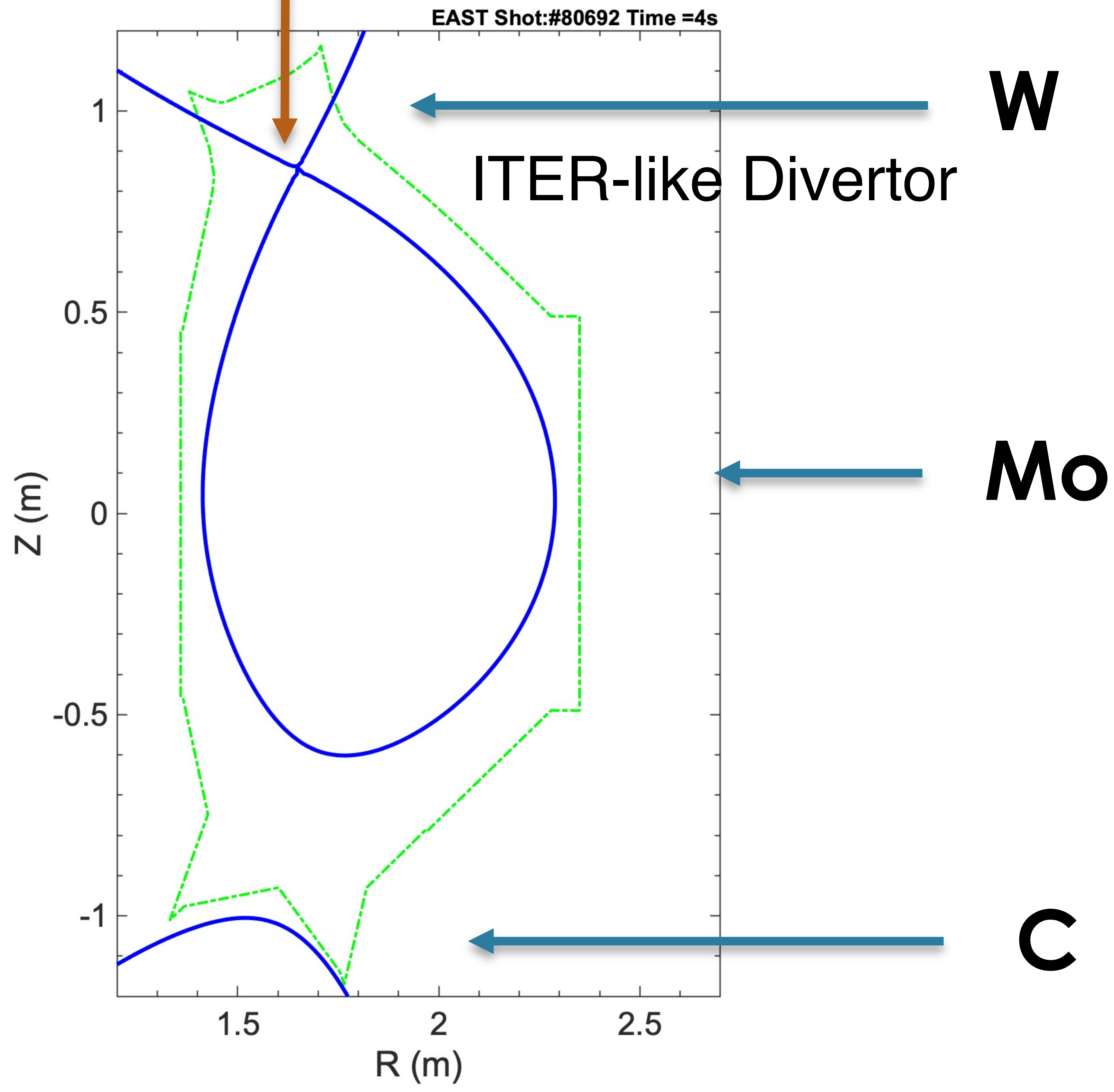
Impurity Powder Dropper enables injection of Li granules on EAST with ITER-like W divertor

- EAST has a mix of PFC material
  - Upper Div.~ W Monoblock PFCs
  - Center stack ~ Mo tiles
  - Lower Div. ~C tiles→ W(2021)



IPD

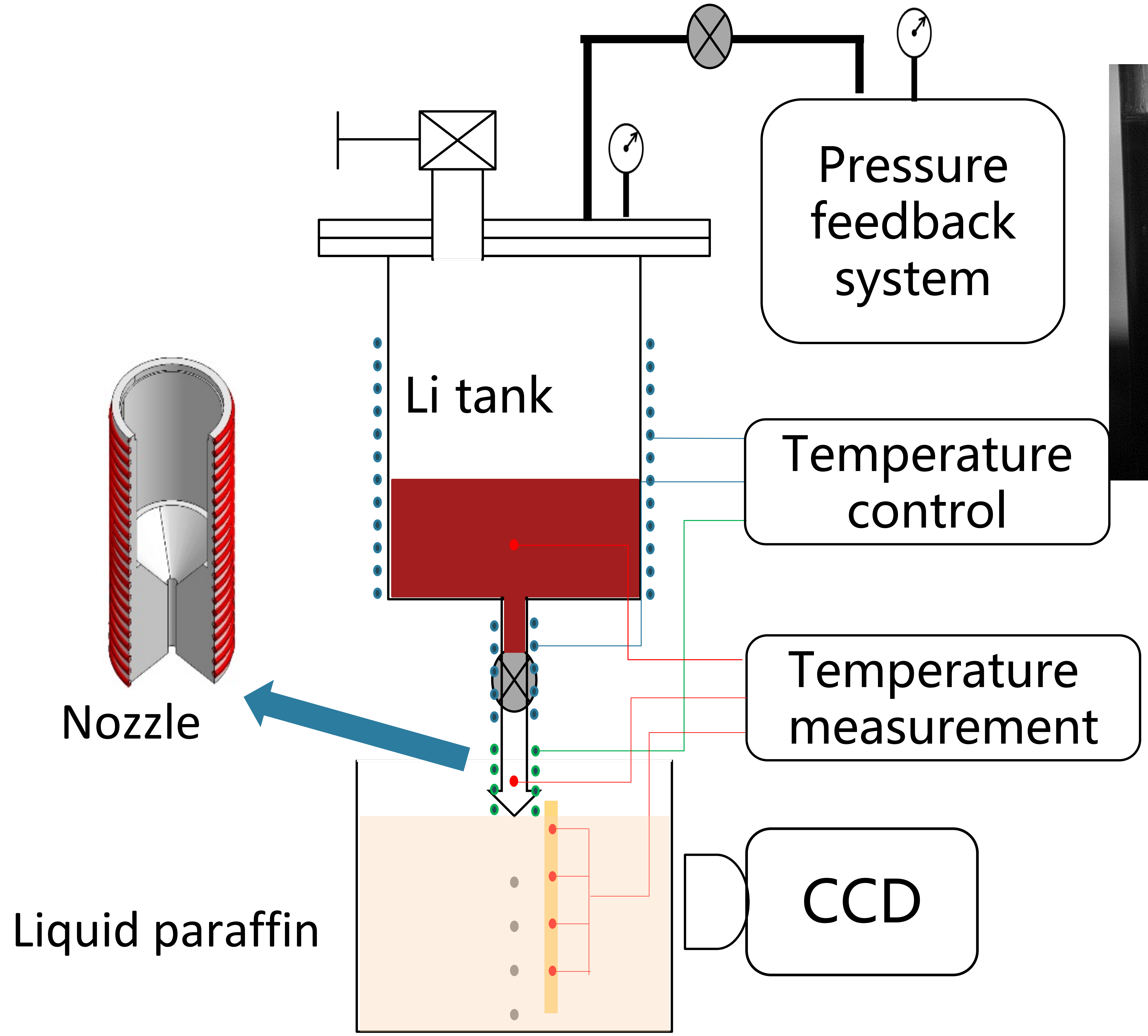


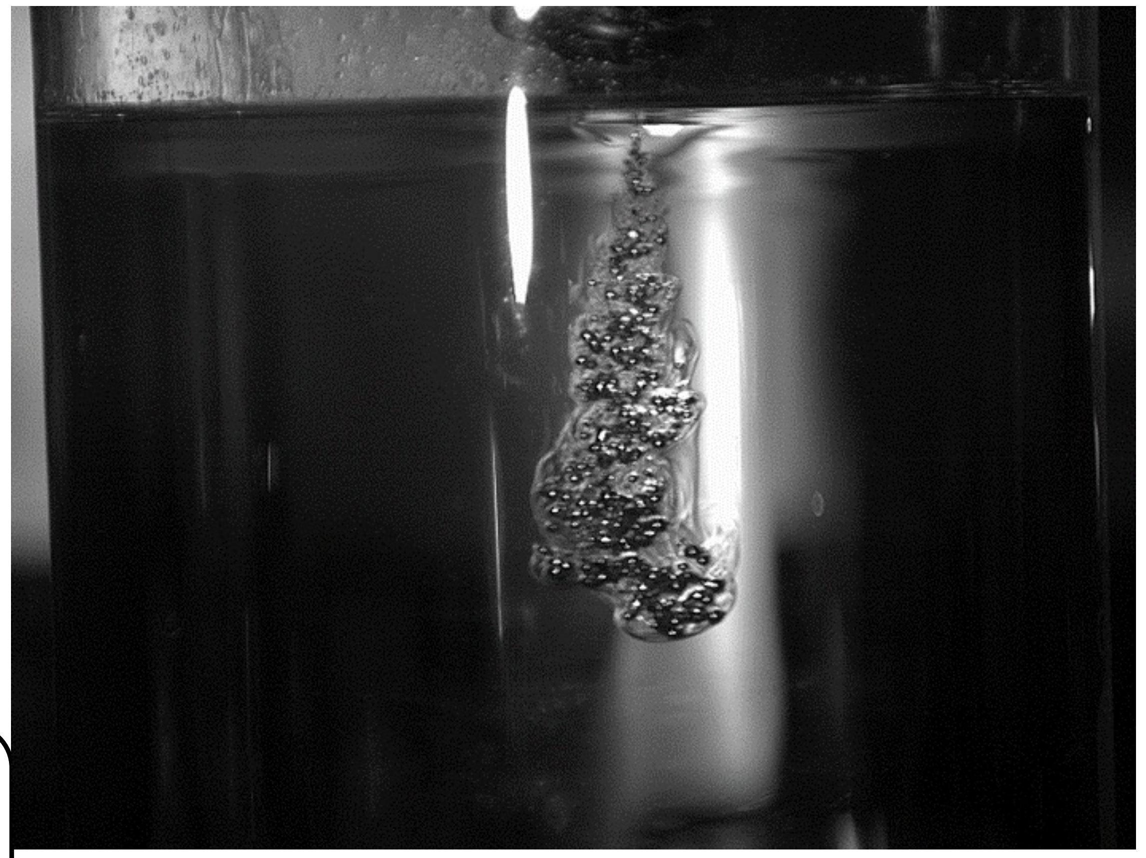


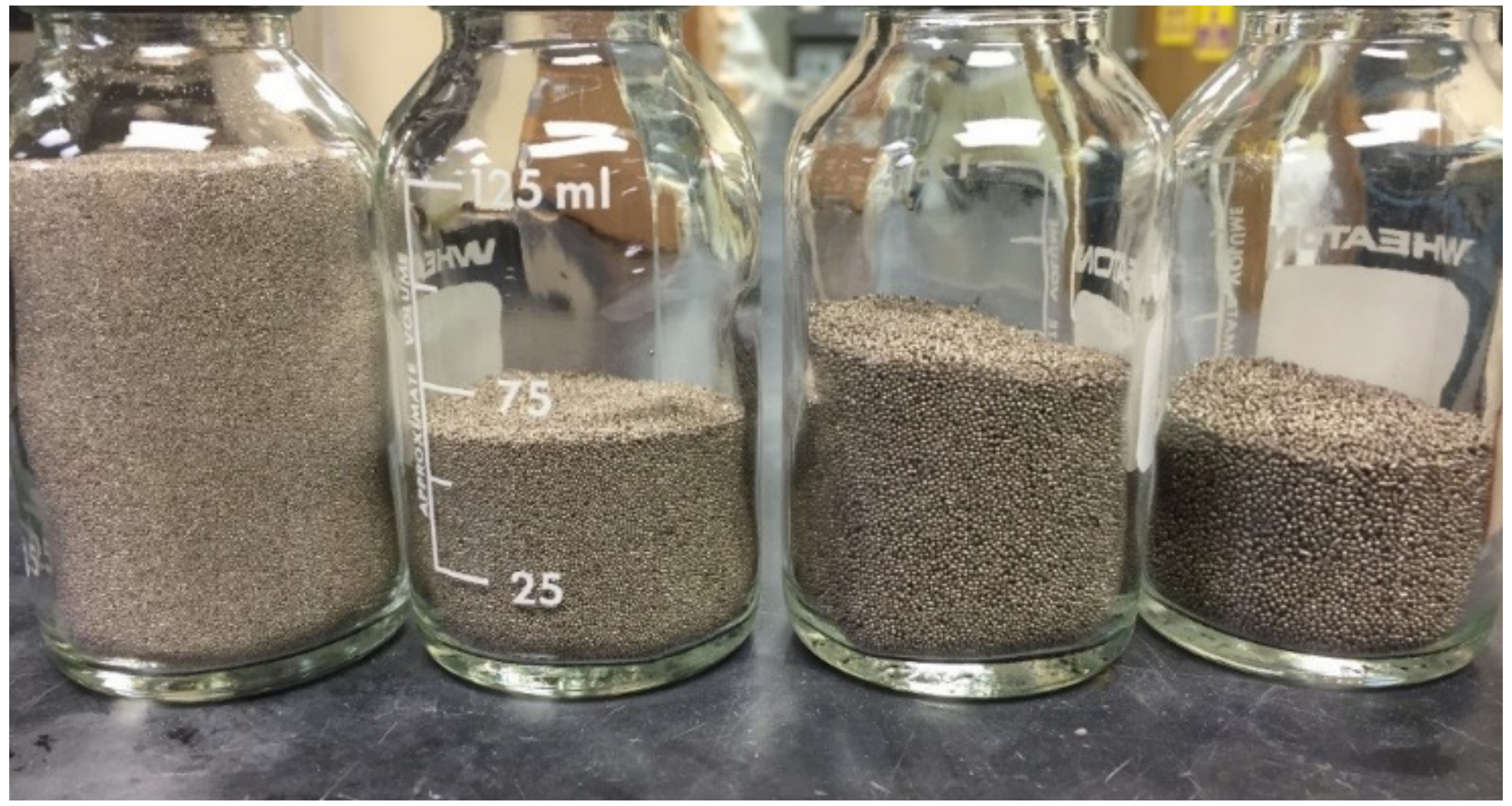
- Multi-impurity injection system based on linear piezoelectric powder feeder
  - –Li, B, Be, BN, Si, SiC, Sn…
  - –Particle size 5-1000? μm
  - –Continuous/burst, controllable flow rate 2-250mg/s, calibratable
- Driven by gravity, ~10m/s
- Near the upper X-point
- 700 ±100μm spherical granule

A. Nagy, RSI, 2018

Li granule production



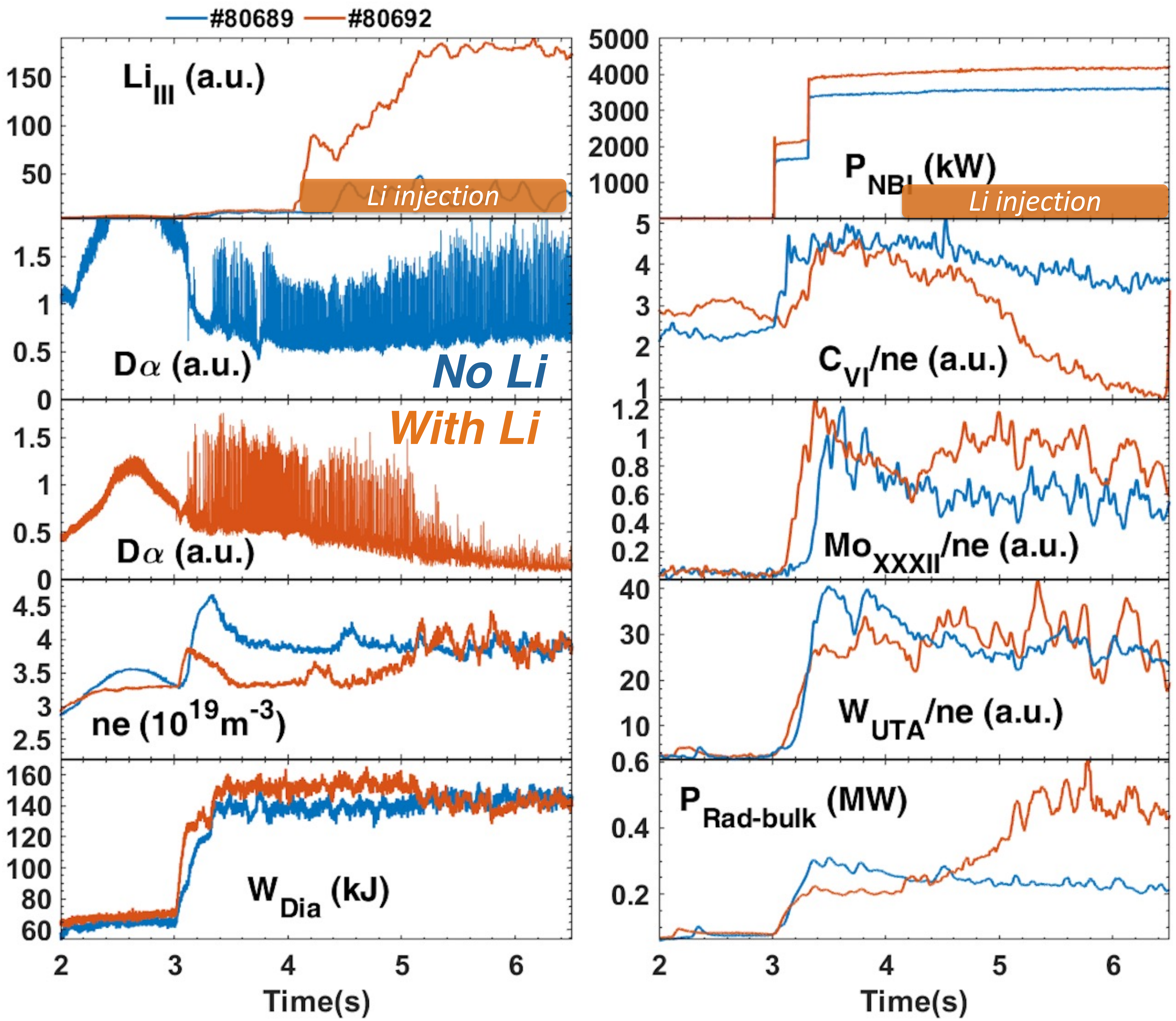




- The size of granules decided by diameter of nozzle and pressure
- Granules with different diameter of were selected ($300\mu m$,$500\mu m$,$700\mu m$,$900\mu m$)

Z. Sun et.al. 17th IUMRS, 2016

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

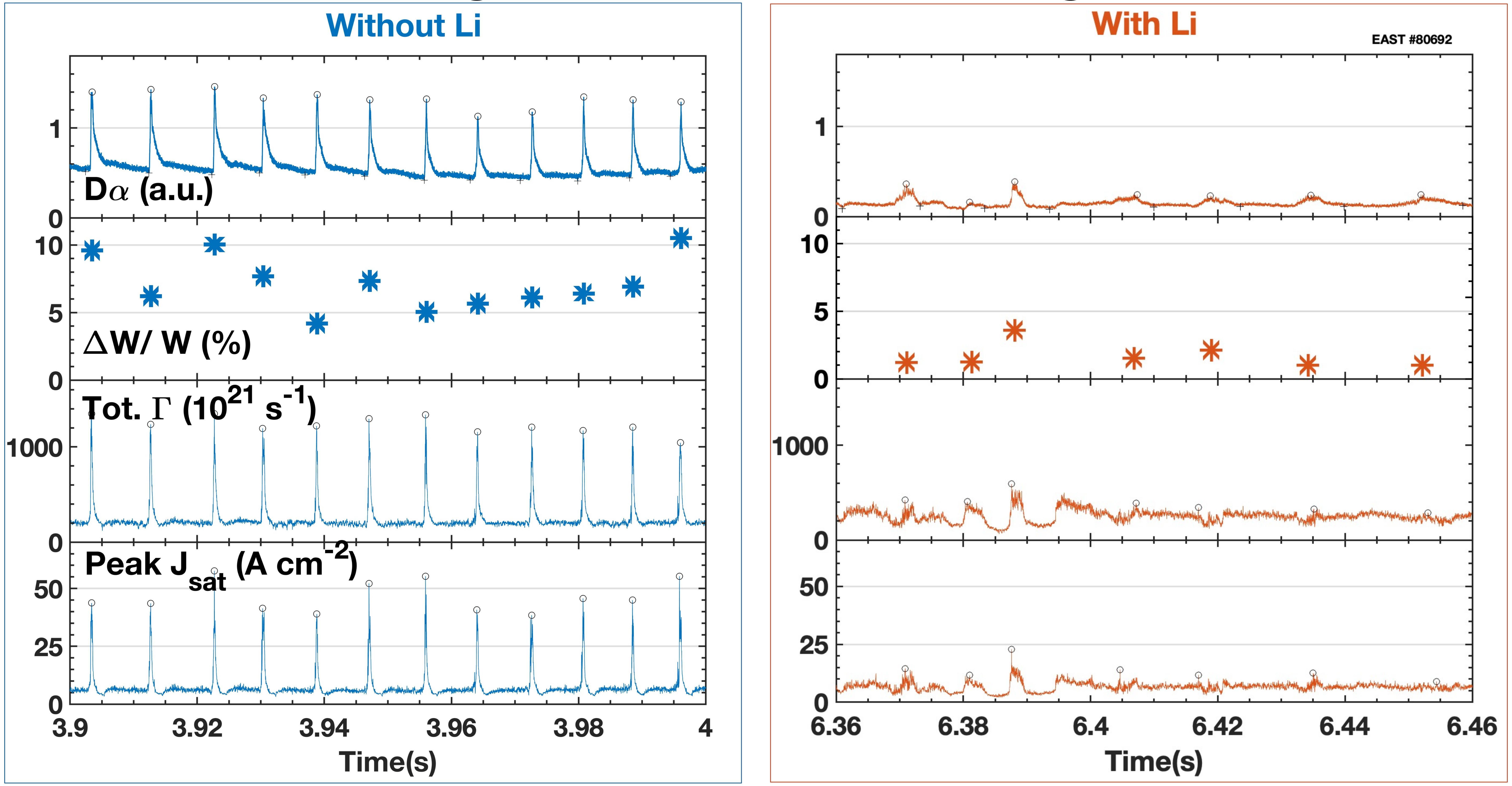


Z. Sun, NF, 2021

- q_{95}~3.9, B_t=1.6T, USN, W divertor, δ=0.36, Co-NBI+LHW heating~4.5-5.1 MW, β_N~1.5, Type-I ELM, same gas fueling
- P_{NBI} 3.5/4.1MW
- ~194mg/s, ~2000Hz (~5.1e10^{22} ele./s, plasma inventory ~2e10^{22} ele.)
- Da spike size reduced obviously
- Density and sored energy same as reference shot, reduced by ~7%
- C-VI decays gradually, no core W ramp-up
- Radiation 0.2→0.5MW, saturated

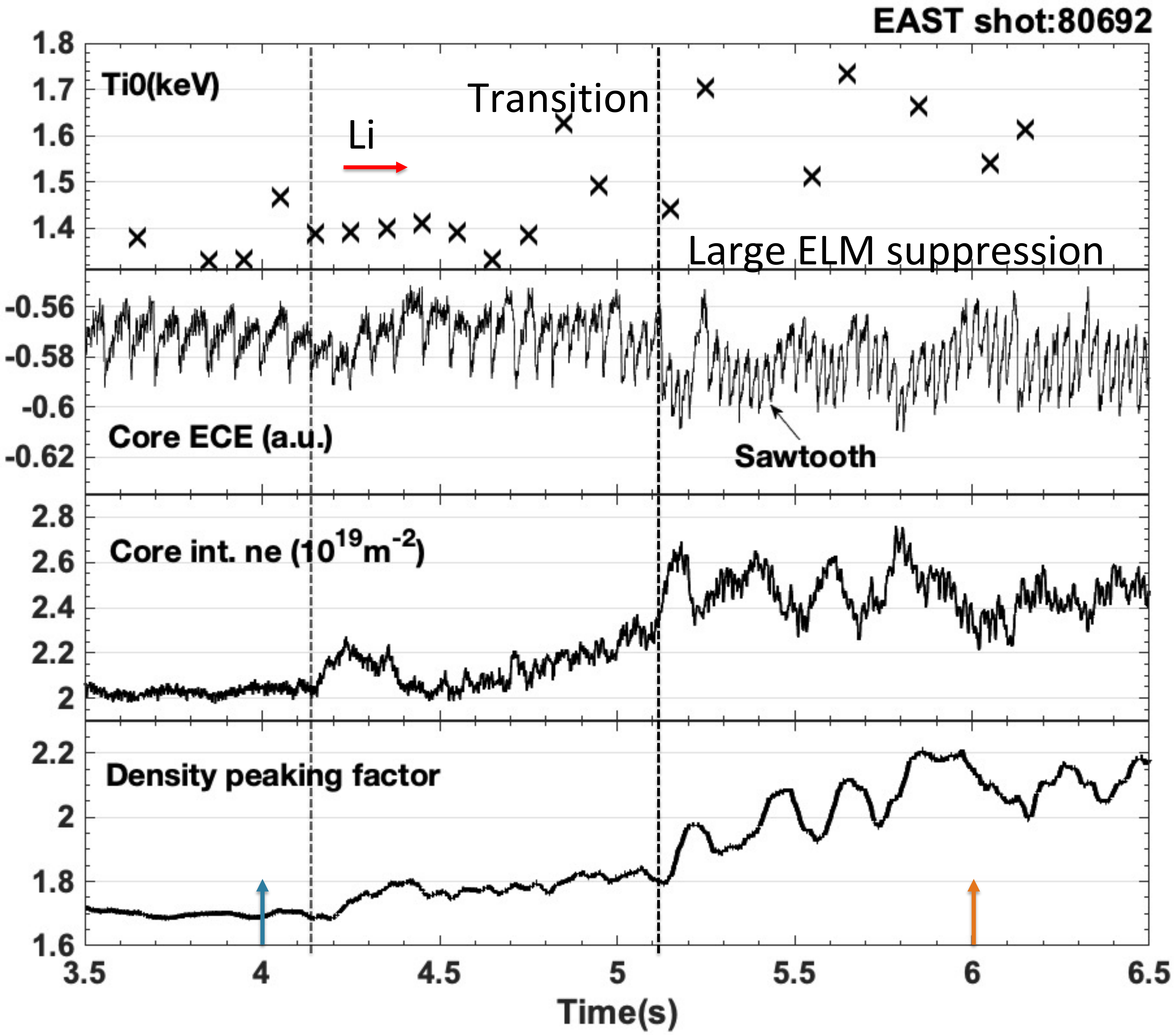
Significant ELM mitigation, ~70%

- Da peak-valley by ~85%, $\Delta W_{ELM}/W$ ~6%→~1%, by 82%
- Maximum total particle flux ~70%, peak ion saturated current ~70%
- ELM frequency: regular, ~110 Hz→ less regular, ~85Hz

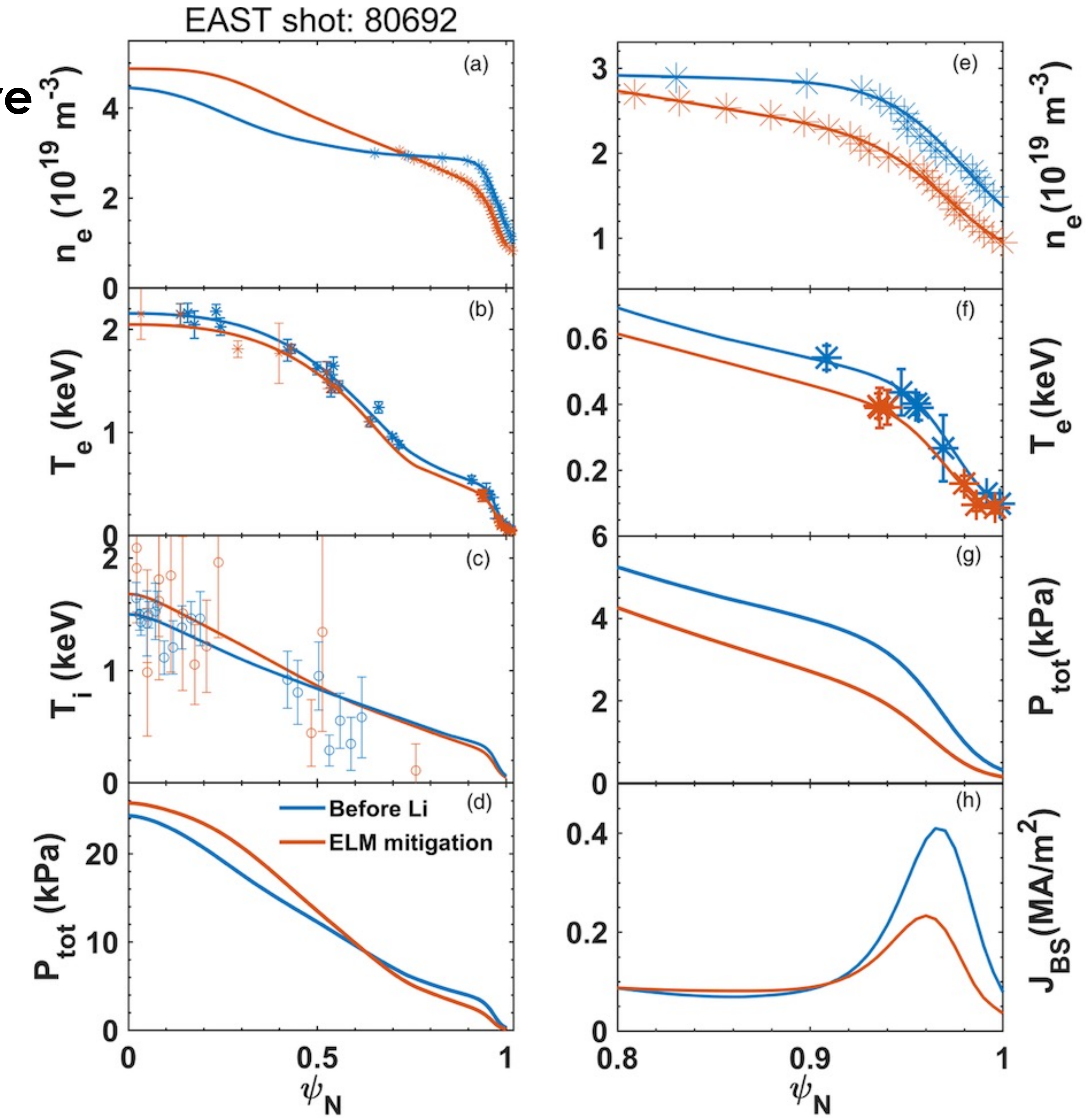


Pedestal top pressure decreases by 25% but core increases 10%

- **Core：Ti(0)↑~15-30%, ne0↑~10-20%, Te(0)↓<5%, P↑**
- **Pedestal: ne↓~10%, Te↓~20%, J_{BS}↓50%, P and P'↓**
- **Hypothesis: ne peaking / ion dilution→ ITG↓→ improve core confinement**



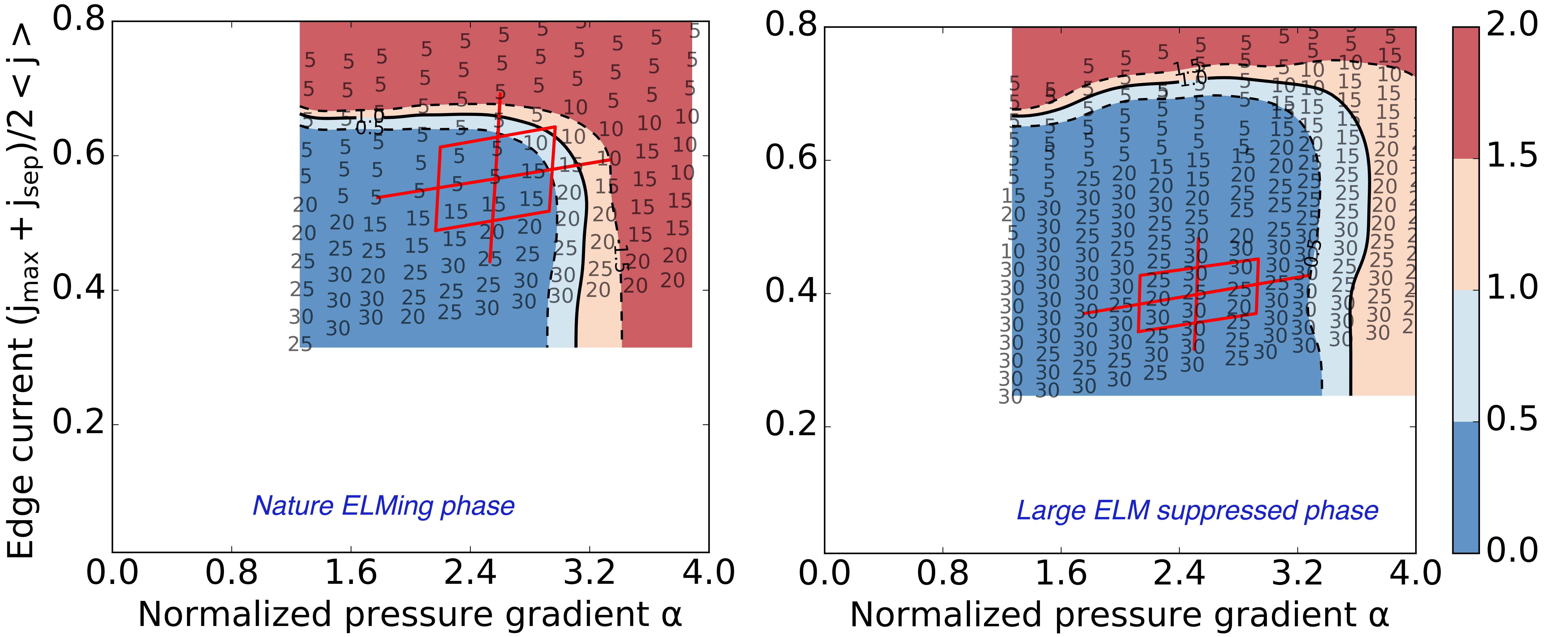
Without Li With Li



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 of clustered granules, similar as D pellet

Futatani NF 2014



Outline

- ELM mitigation by Lithium granule injection
- ELM suppression by Boron powder injection
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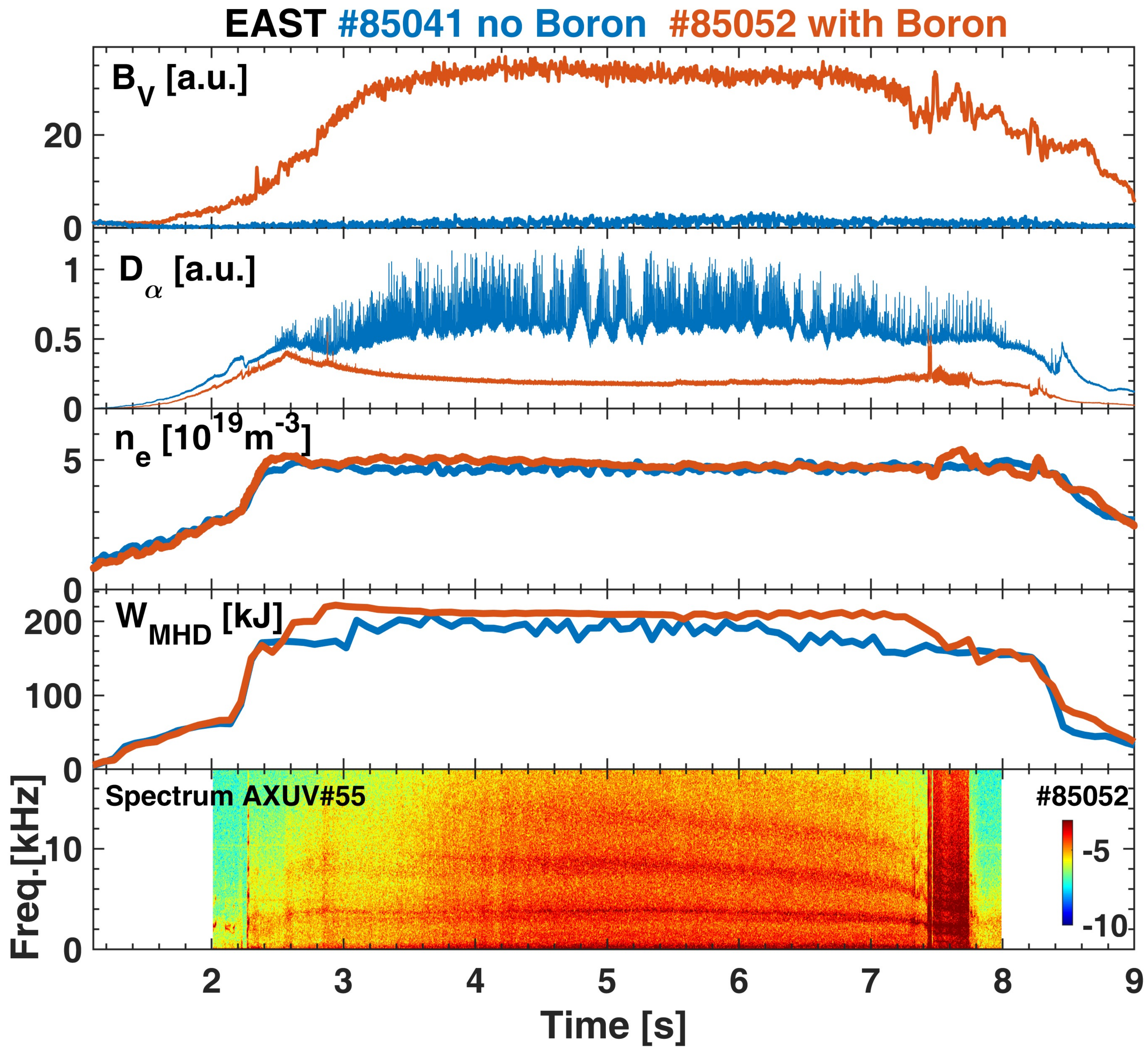
Highlights

- **ELM elimination enabled by real-time B power injection**
  - Modest energy confinement *improvement*
  - Constant density
  - Causality demonstrated
  - B flow rate threshold observed for ELM elimination observed
- **Edge harmonic modes associate with B injection and ELM elimination**
  - Destabilized or intensified
  - Provide ample particle transport to avoid impurity accumulation in ELM stable plasmas
- **ELM elimination over a wide operating window of heating power, electron density, collisionality, main ion species, plasma shape**

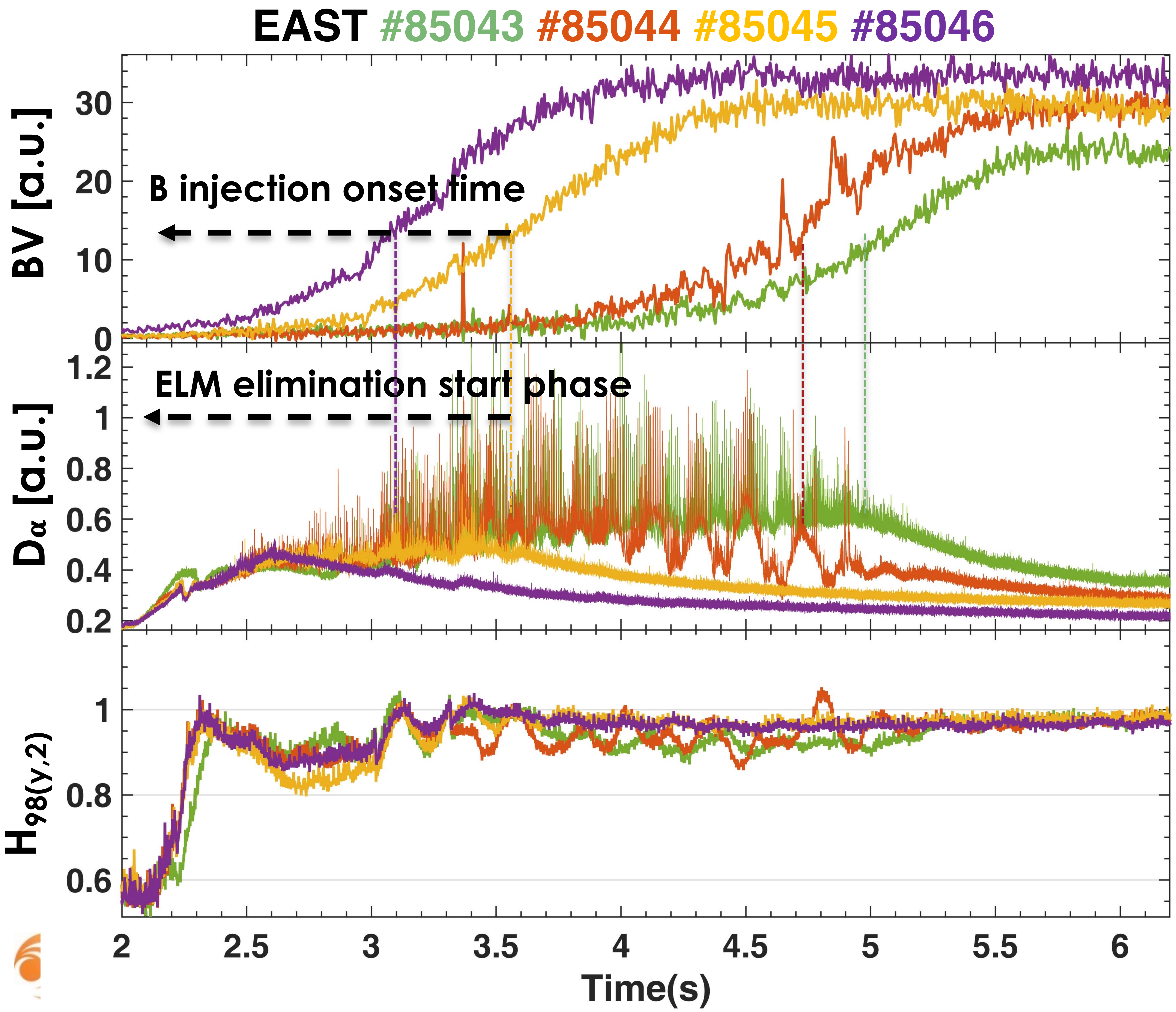
R. Maingi, JoFE, 2020 Z. Sun, NF letter, 2021 Z. Sun, PoP, 2021 A. Diallo, IAEA-FEC, 2021 R. Maingi, IAEA-FEC, 2021

Boron powder injection suppressed ELMs with constant density and slightly increased stored energy in EAST



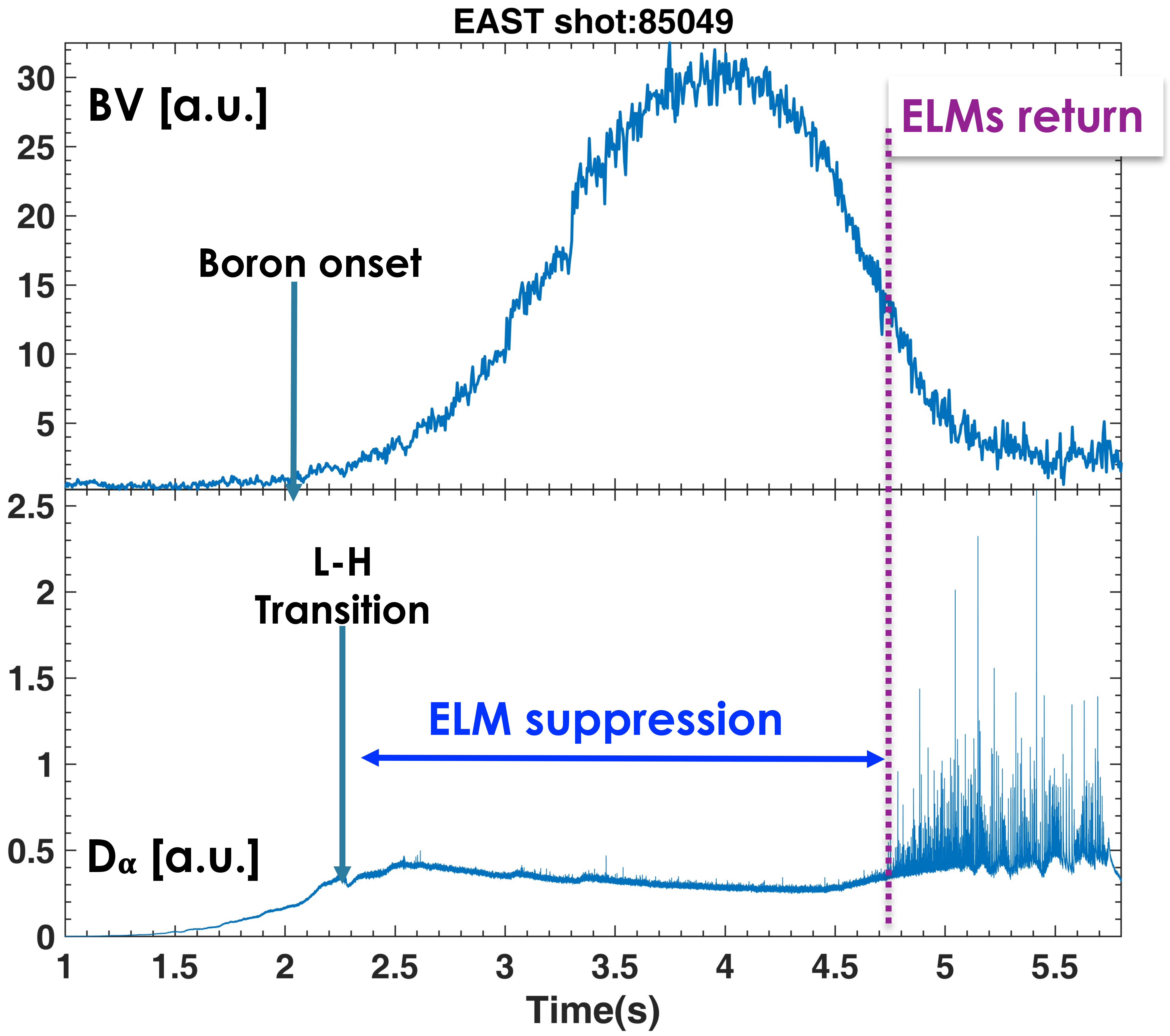
- **Same plasma condition**
  - I_p = 0.5 MA, B_t = 2.5 T, P_{heat}~ 6 MW, USN, δ^u~0.57, δ^l~0.27, ϵ~1.65, grad-B drift ↑, toward upper X-point
  - Type-I ELMs, τ_E ~ 64 ms, $H_{98(y,2)}$ ~ 1
- **Edge B-V emission when B injected (from T_e ~ 150 eV)**
- **Stored energy increased slightly**
- **Density stable and matched**
- **Harmonic mode destabilized**
  - Fundamental mode n=1

Injection time of B tracks well the ELM suppression phase



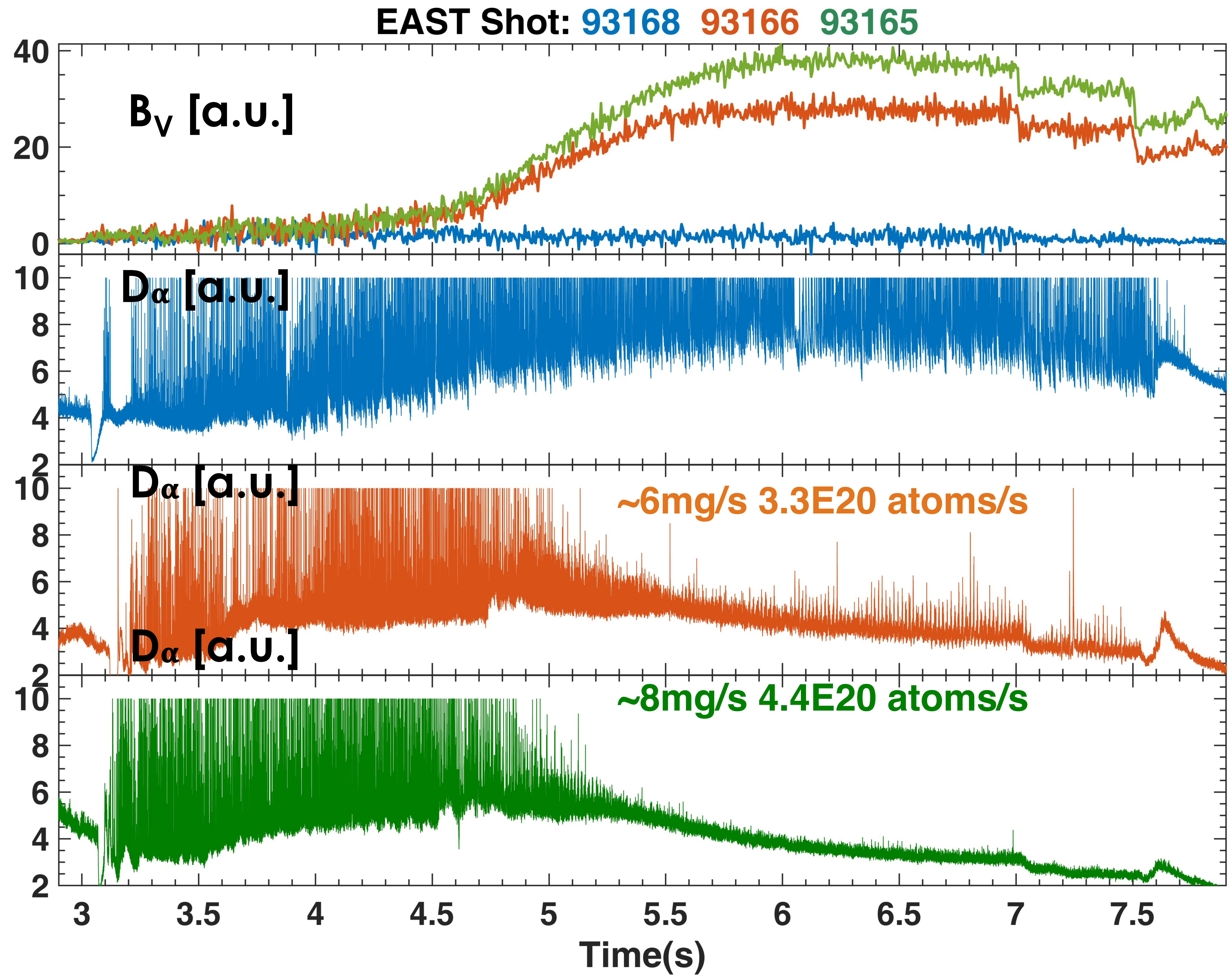
- **Same plasma condition**
- **Reproduceable ELM suppression**
  - ELM suppression begins when B emission reaches to a threshold
- **ELM suppression phase strongly correlated with B injection time**
- **Energy confinement improves slightly**

ELMs reappear after the B injection interrupted



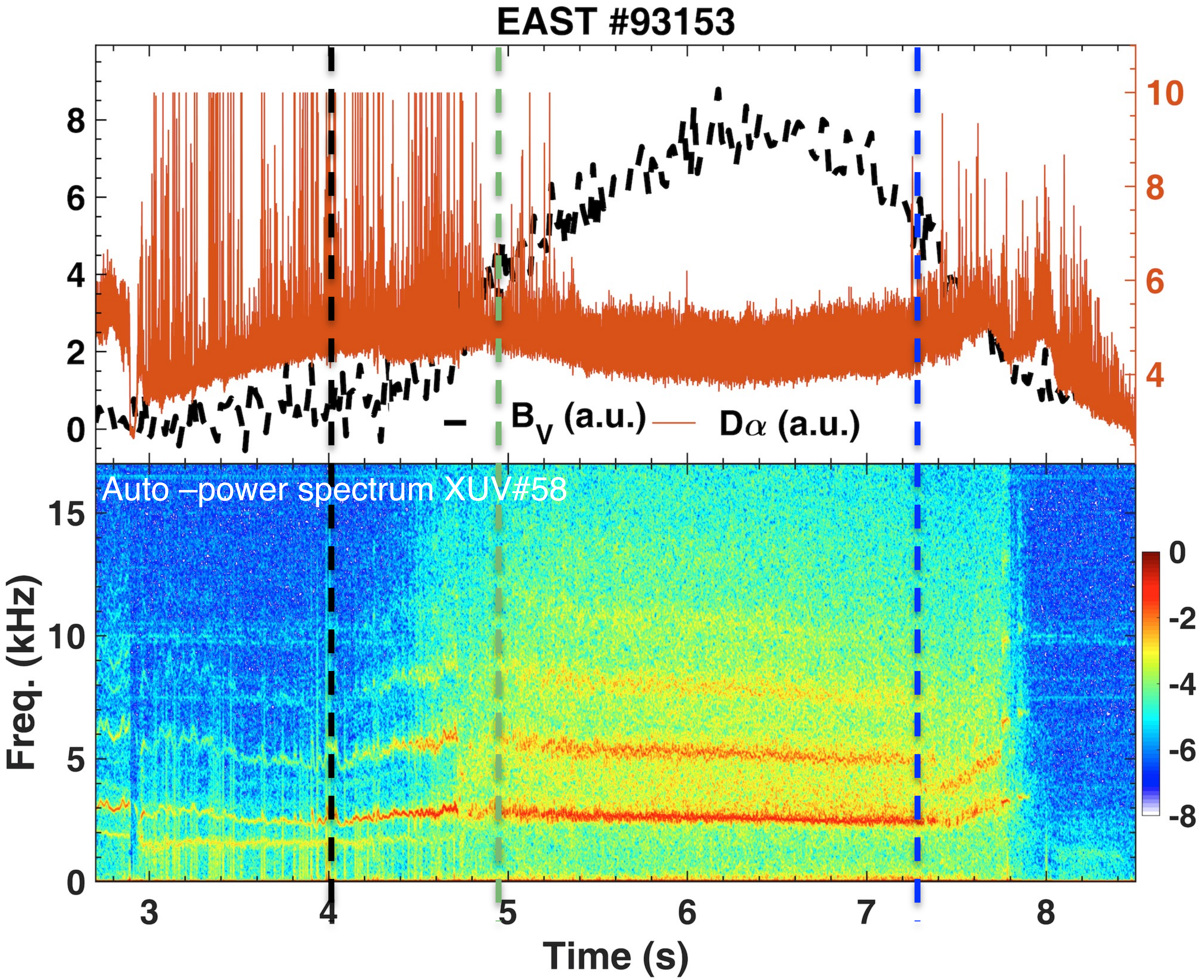
- **ELM suppression during the B injection**
- **ELMs reappear during the B_V declining after B injection interrupted**
- **Clearly no wall hysteresis → adequate for including in the plasma control system**
  - ~ 0.5 sec when boron injection is terminated

Flow rate range found for B injection to completely suppress ELMs



- **Observed lower threshold**
  - Too little, no effect on ELM
  - ~6mg/s ELM mitigation
  - ~8mg/s ELM elimination
  - Marginal rate: ~20% below→ small ELMs reappear
- **Wide range of B injection flow rate compatible with plasma performance**
  - Upper limit ~10-20 times lower threshold flow rate for ELM elimination
  - Too much cause collapse

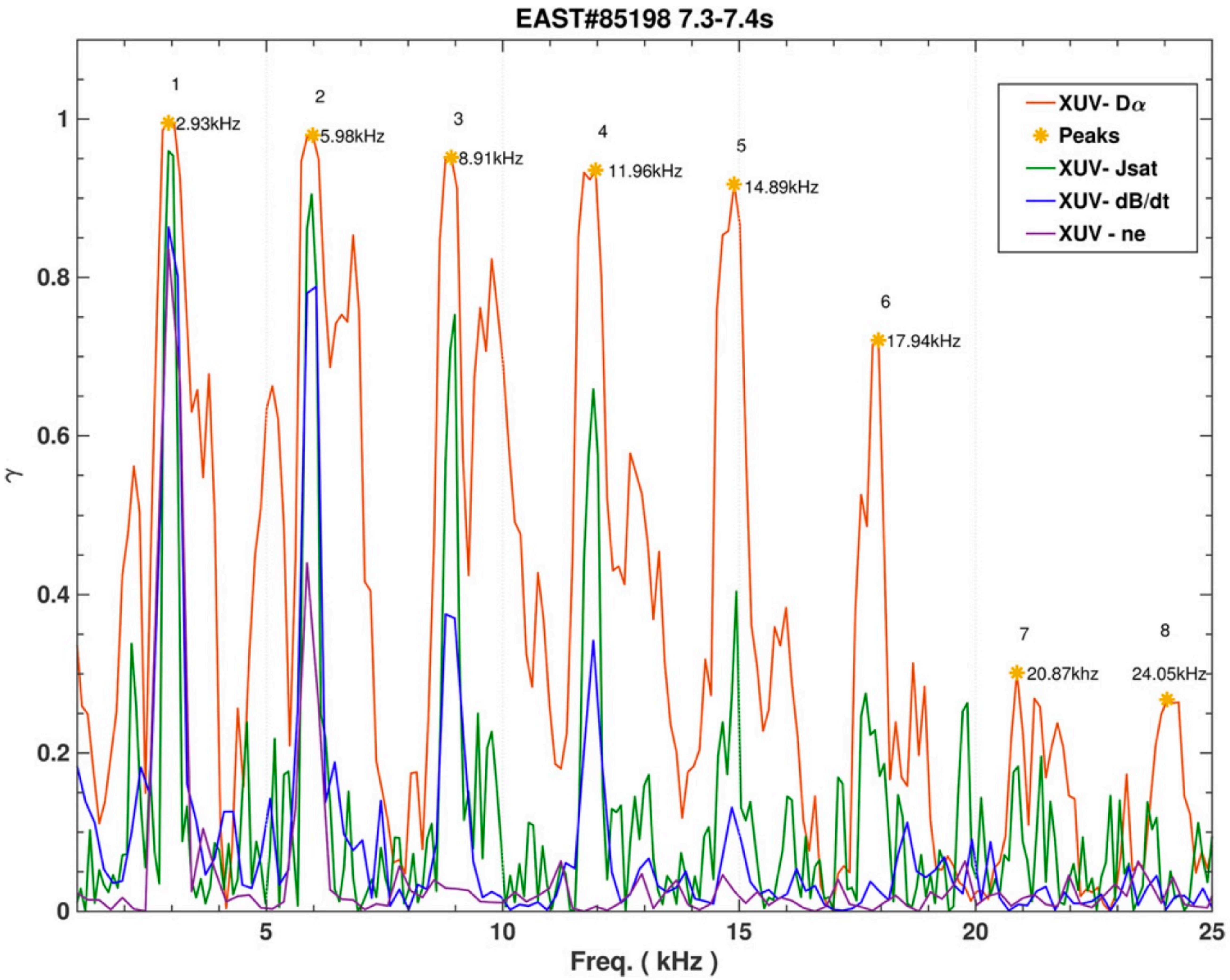
Harmonic oscillation modes associated with ELM suppression by B injection



- **Week harmonic mode observed before B injection**
- **ELMs become less when the harmonics become stronger**
- **ELM suppression begins when the BV emission reaches a threshold and the harmonic mode intensity saturate**
- **ELMs reappear when the B_V ramps down and the mode intensity reduces**

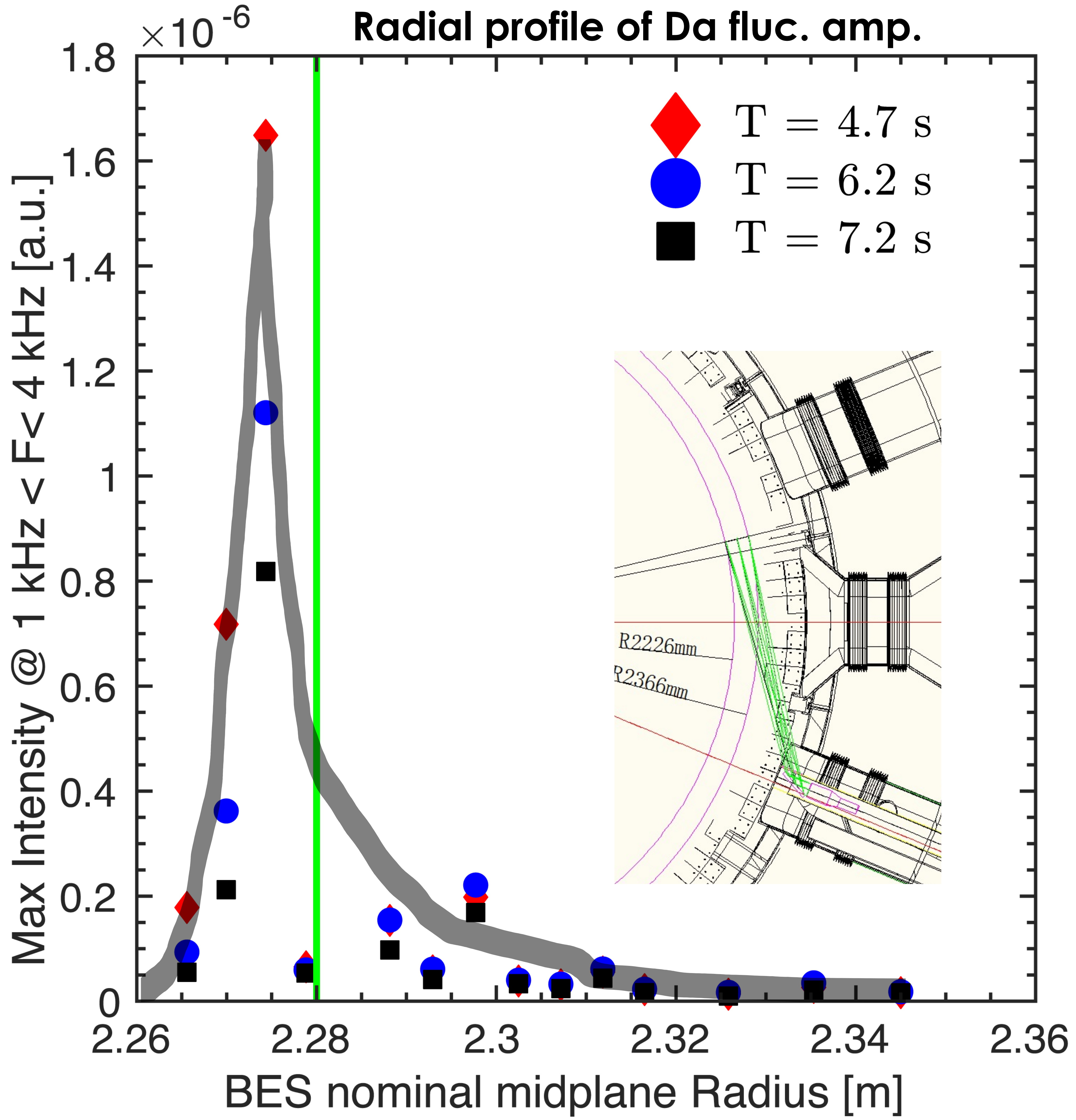
Role of the harmonic fluctuations

Identification of coherent fluctuations with harmonics in many diagnostics



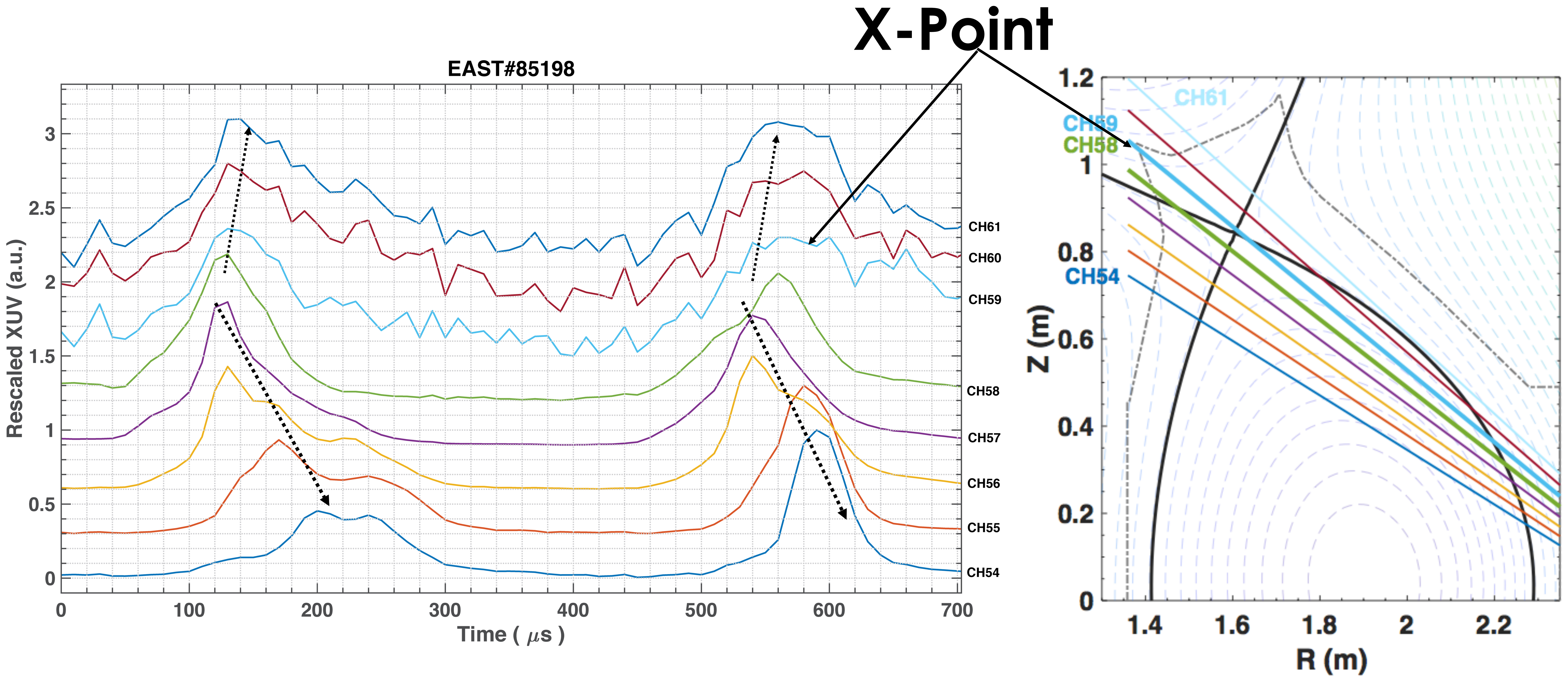
- Harmonic mode observed on magnetic probes, ne, Te, XUV, Dalpha, Jsat
- Multiple harmonics strongly correlated among different diagnostics

The mode exists in the pedestal region and SOL

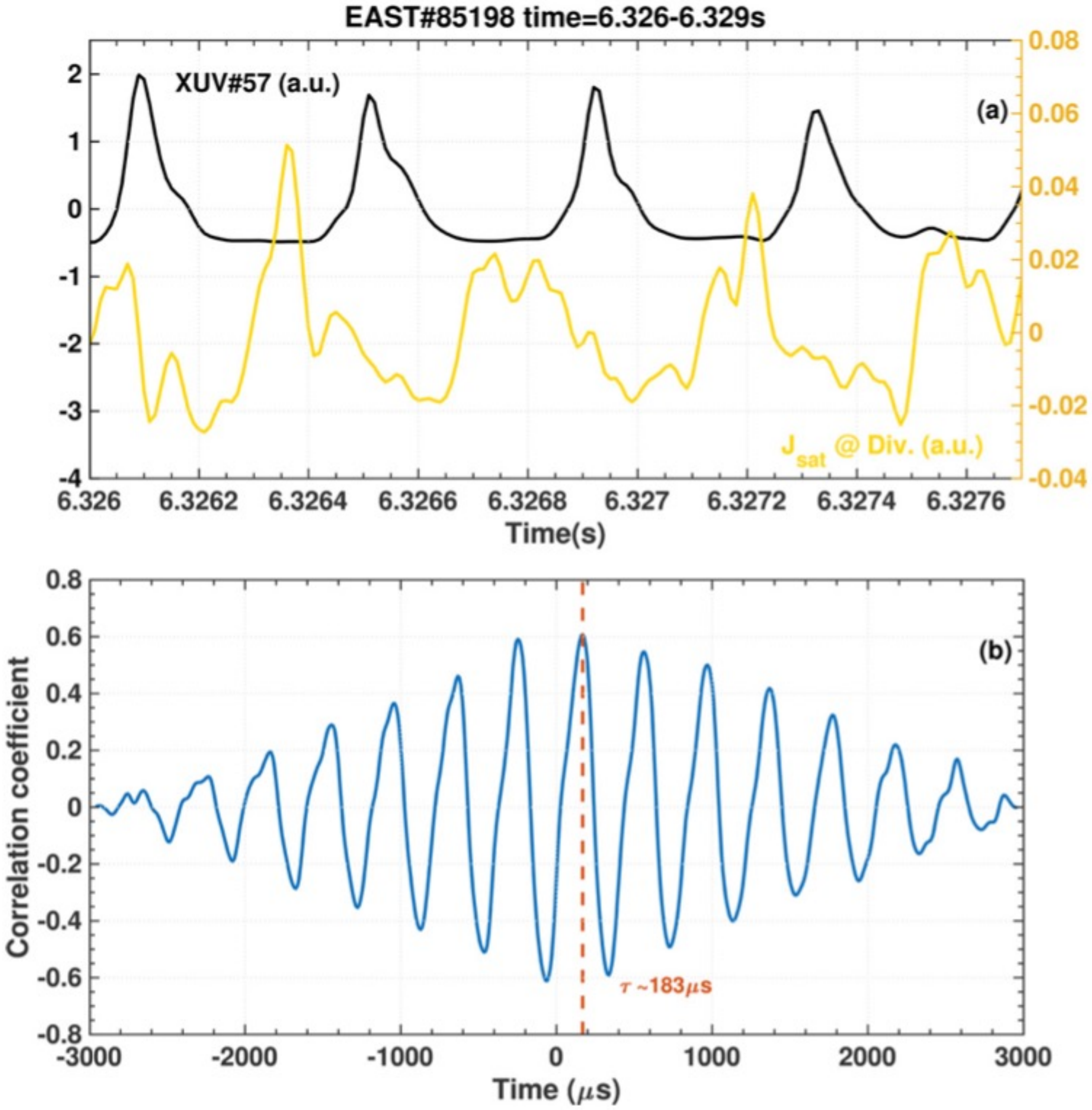


- **Fundamental modes observed in multi-channel Da, tangentially viewing midplane**
- **Appear inside and outside of separatrix, peaked fluctuation amplitude profile**

Mode propagates poloidally away from the X-point

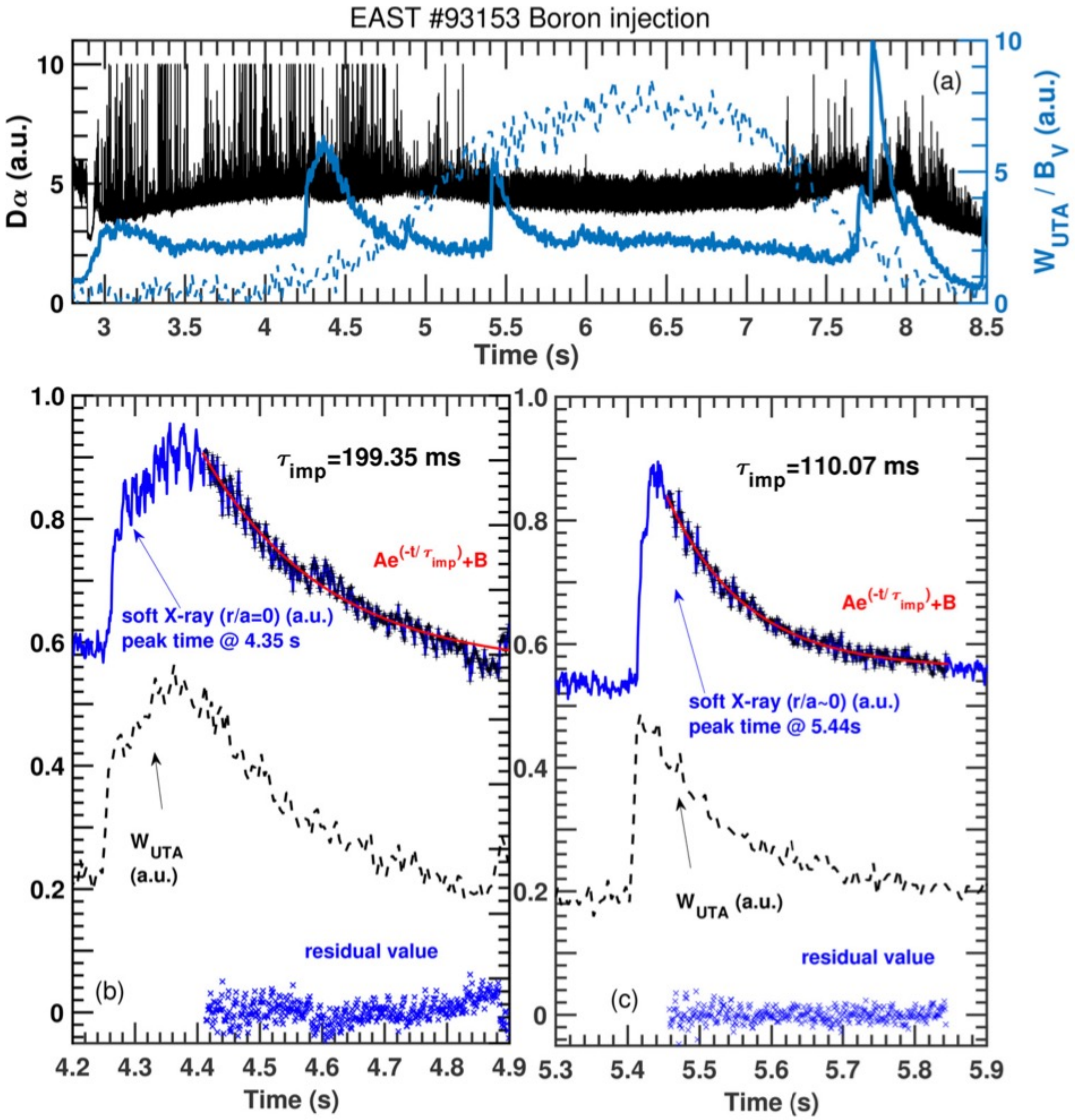


B-induced mode related with particle transport



- A time delay between the mode in the upstream plasma measured by the XUV and the modulation of the ion saturation current
- Time delay, ~180μs, close to the ion transit time (τ||~200μs)

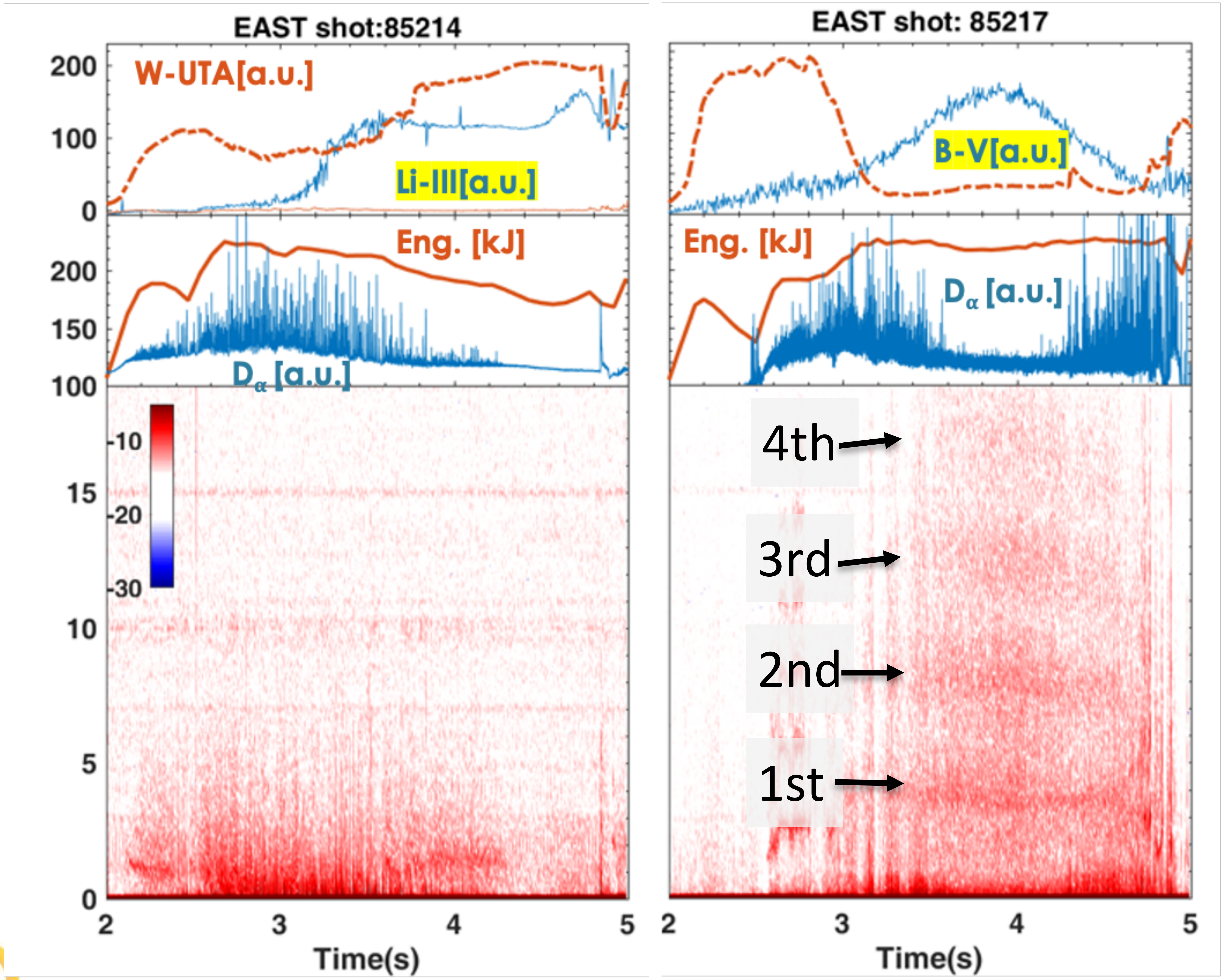
Enhanced impurity transport to prevent core impurity accumulation



The mode excitation time: 5-7.5s.

- **Impurity confinement time calculated during mode effect on the particle transport τ_{imp}^{mode}~110ms**
- **Comparable with normal ELMy H-mode τ_{imp}~200ms; significantly shorter than τ_{imp}~ > 650ms in the classic ELM-free H mode**

Edge harmonic mode not observed for Li powder



Same plasma parameters

Li case:

- **No mode observed**
- **ELM suppression**

Boron case:

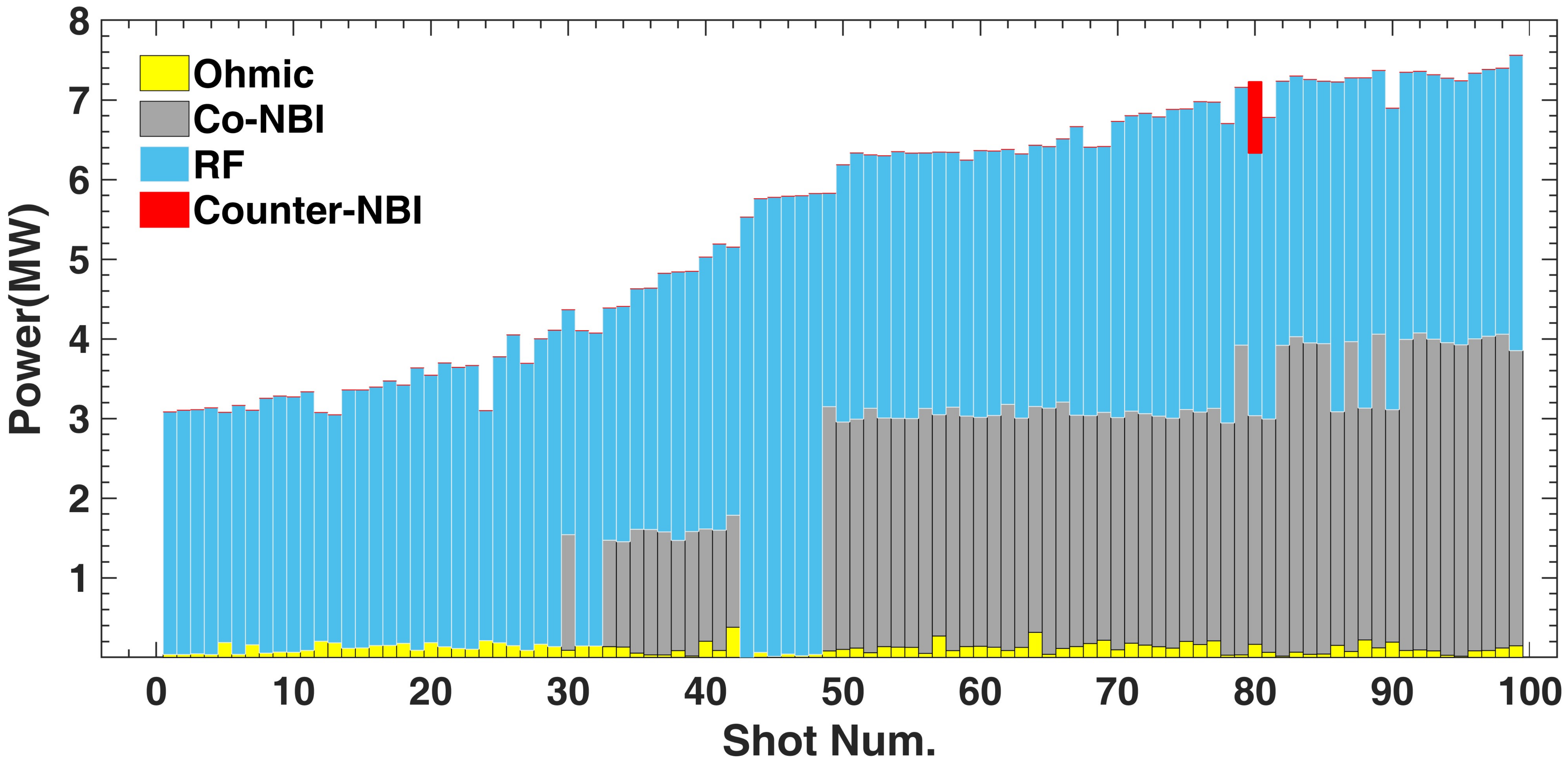
- **Mode appears and remains active**
- **Core W reduces significantly**

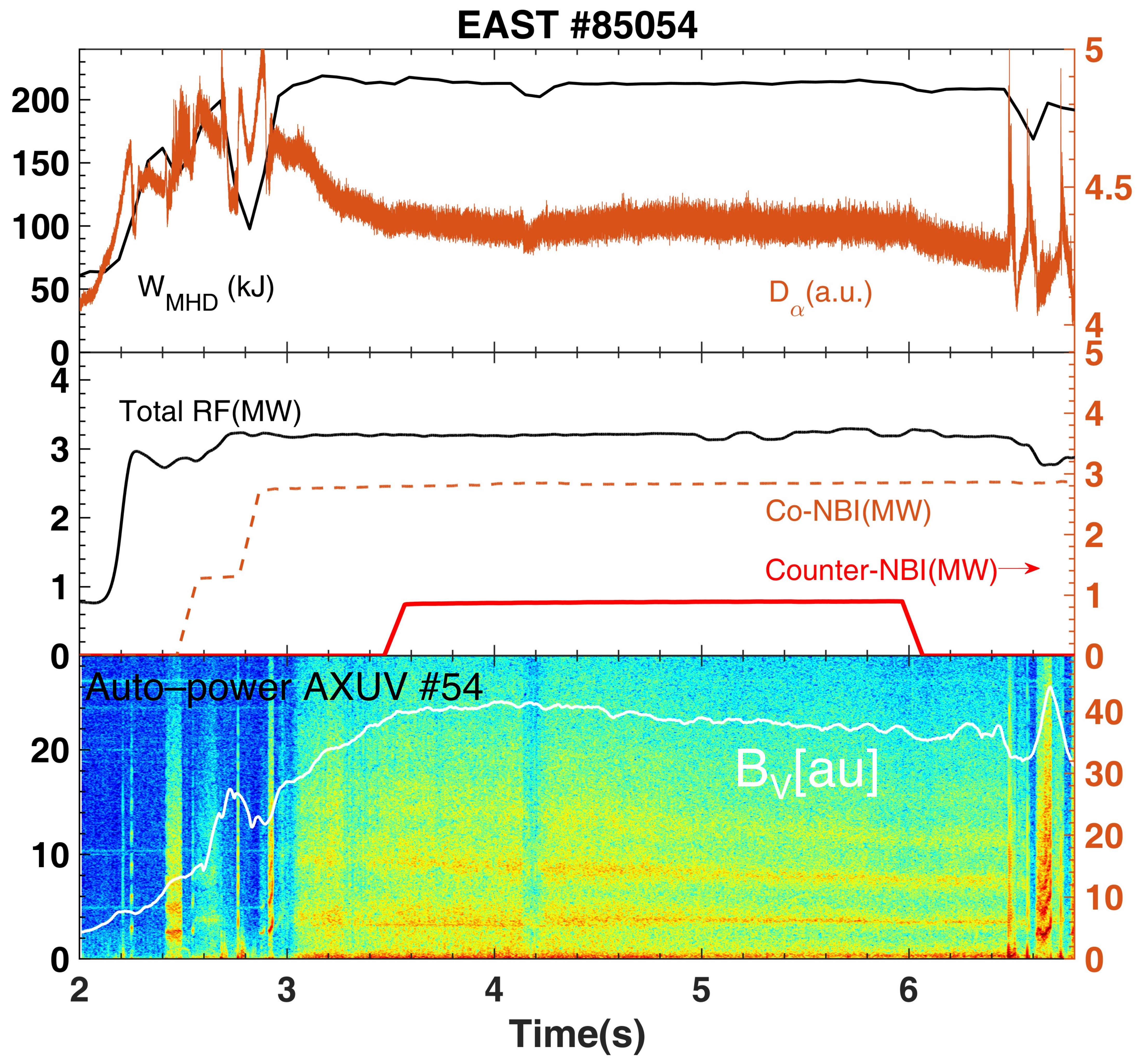
Robust ELM suppression over a wide range of conditions

Noted: succeeded in suppressing ELMs in every attempted condition

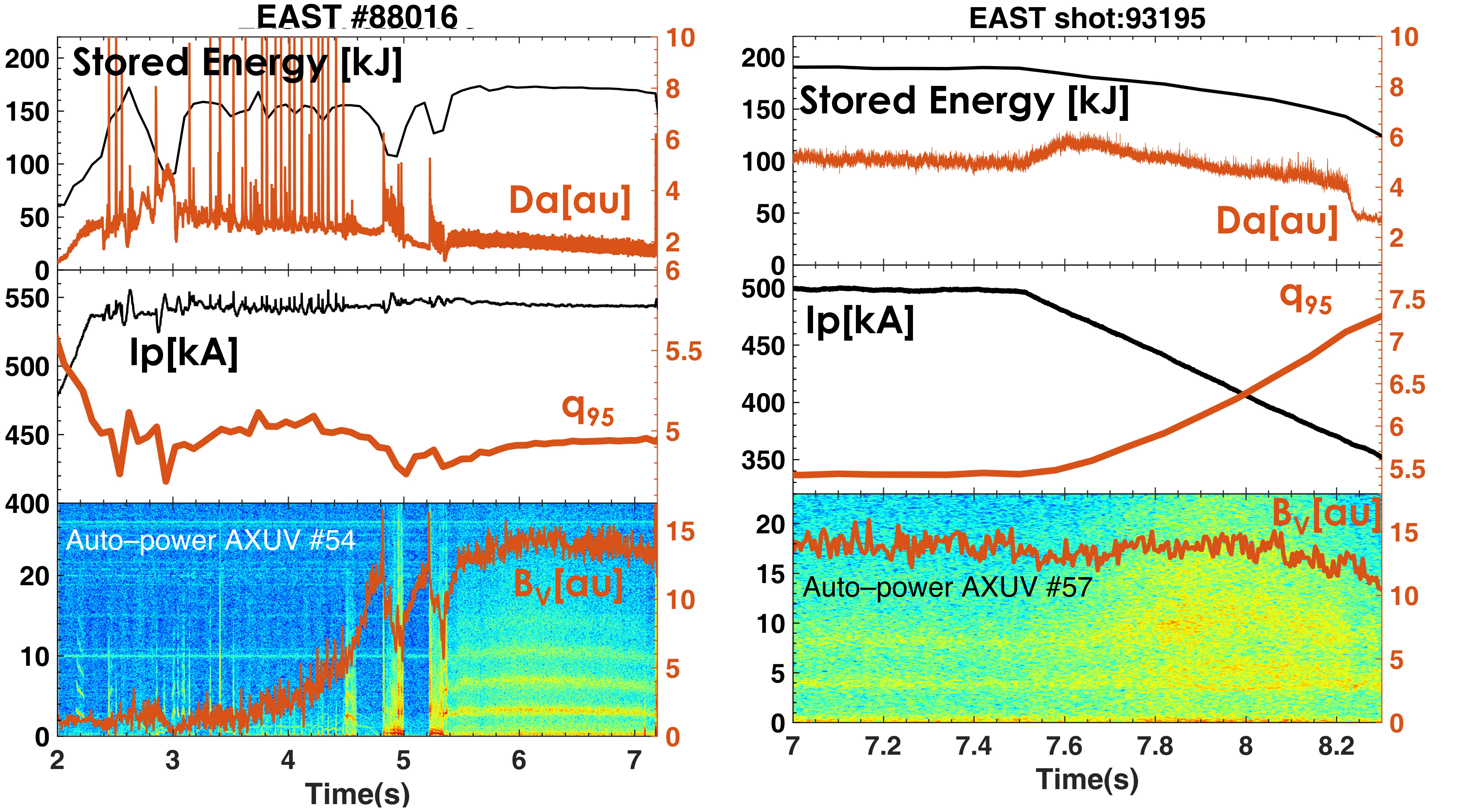
Not sensitive to heating scheme and power

- **Wide range of input powder with different schemes**
  - **RF only heating: 2.8 MW – 5.8 MW**
  - **RF + 1-2 co-NB: 4.1 MW – 7.5MW**
  - **RF + 2 co-NB + 1 ctr-NB: 7.1 MW**
  - **Appears to be insensitive to the toroidal rotation**
- $\nu^{*}_{e,ped}$ **~0.7-6**



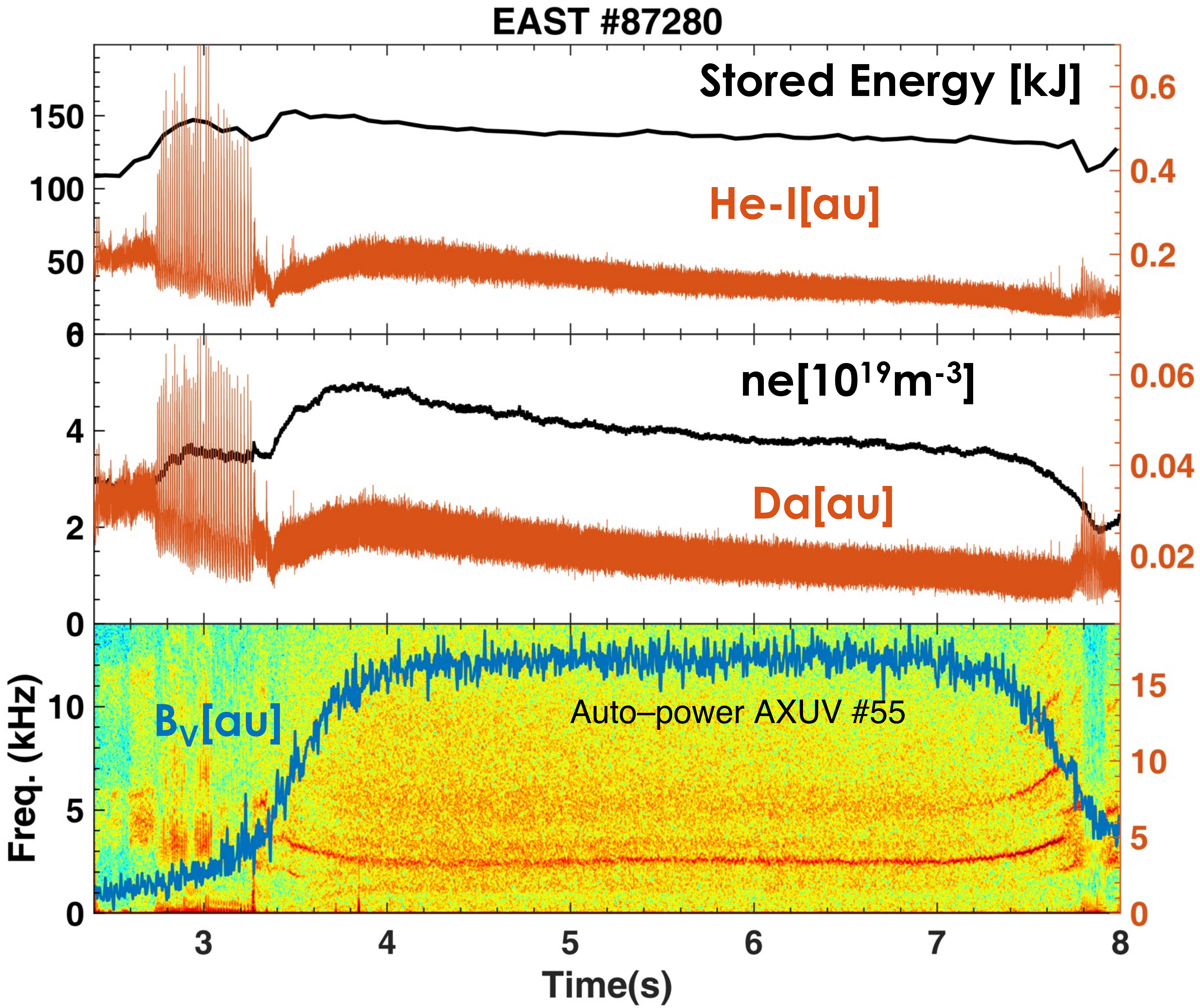


ELM suppression obtained with different I_p & q_{95}



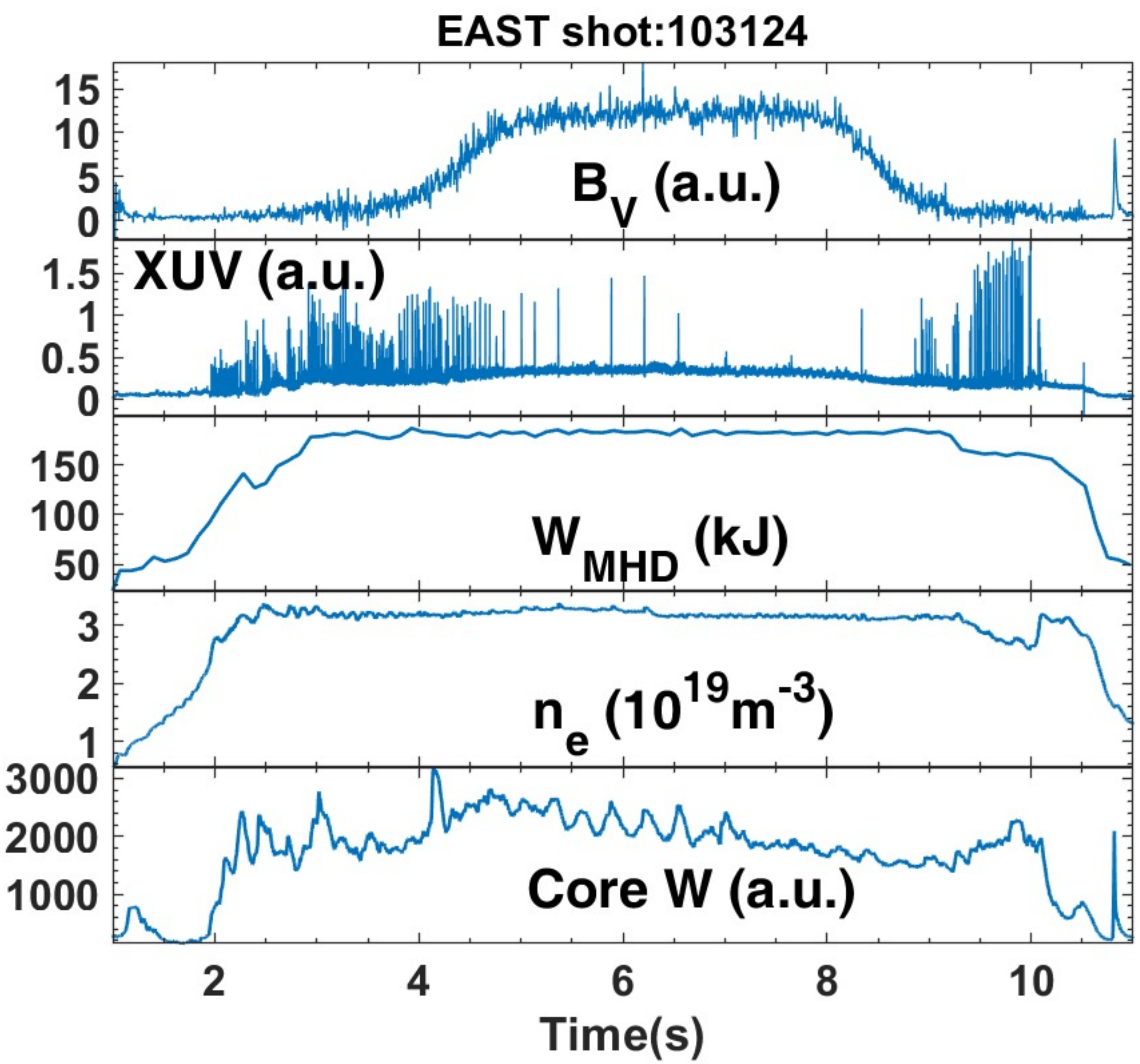
Ip =350-570kA, 4.8<q_{95}<7.2, applicable for a high magnetic field tokamak

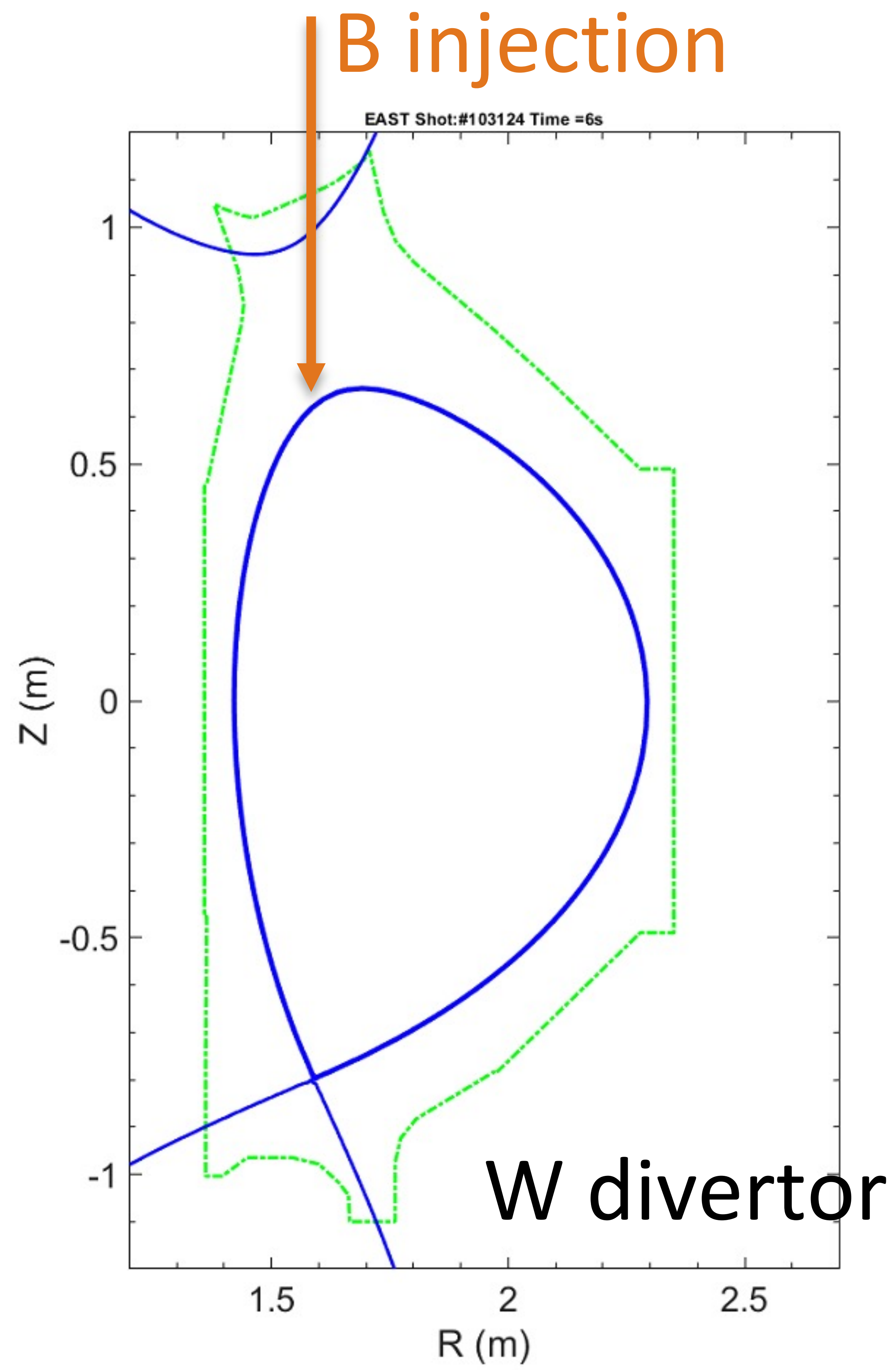
In He-plasmas: ELM suppression was also achieved



- He-plasmas with 30-40% D

ELM suppression with LSN and lower W divertor





0.5MA, LSN, fav. Bt, P_{heat}~6MW, n_e~3.2x10^{19} m^{-3}

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- ELM mitigation by Lithium granule injection
- ELM suppression by Boron powder injection
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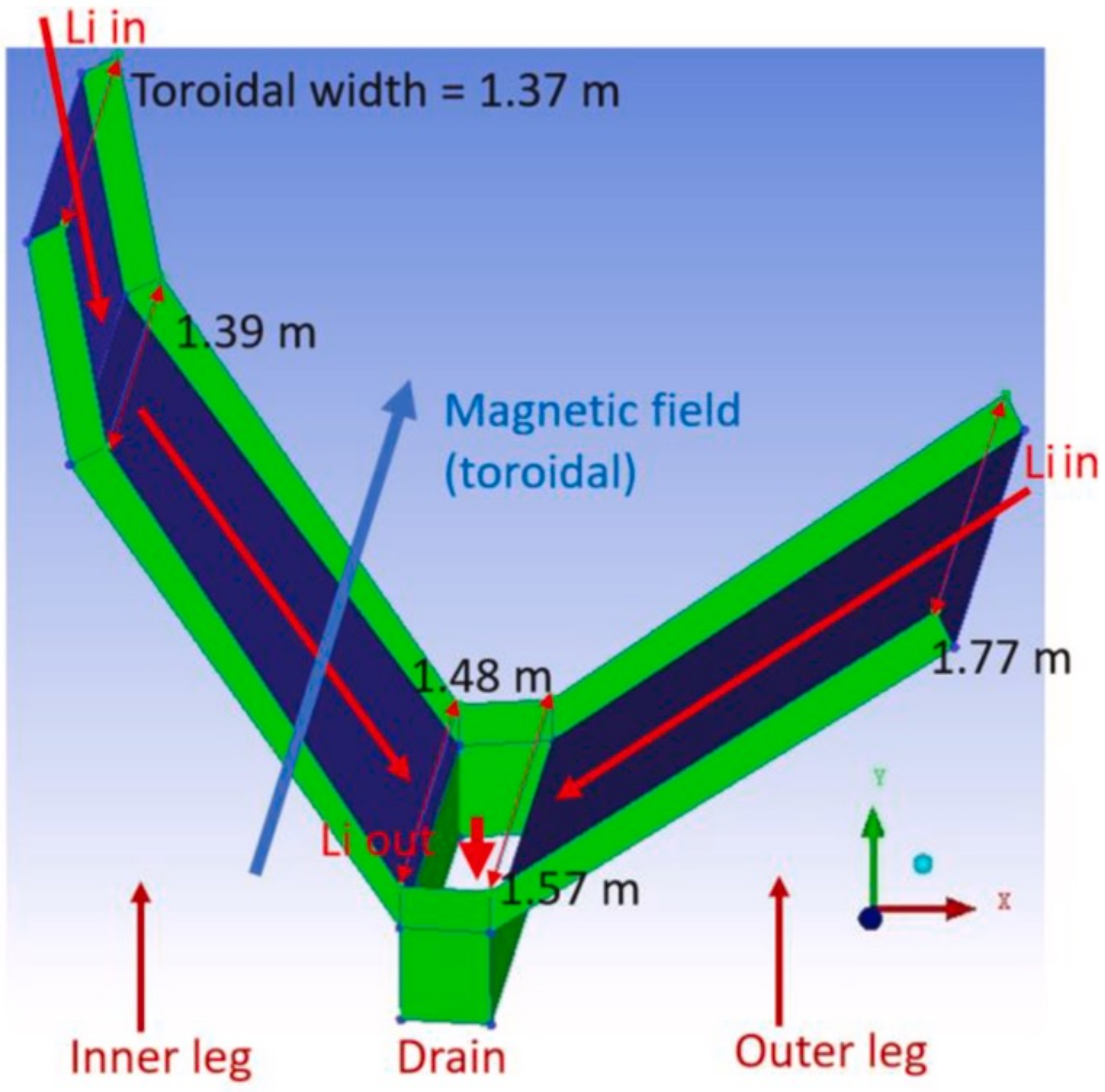
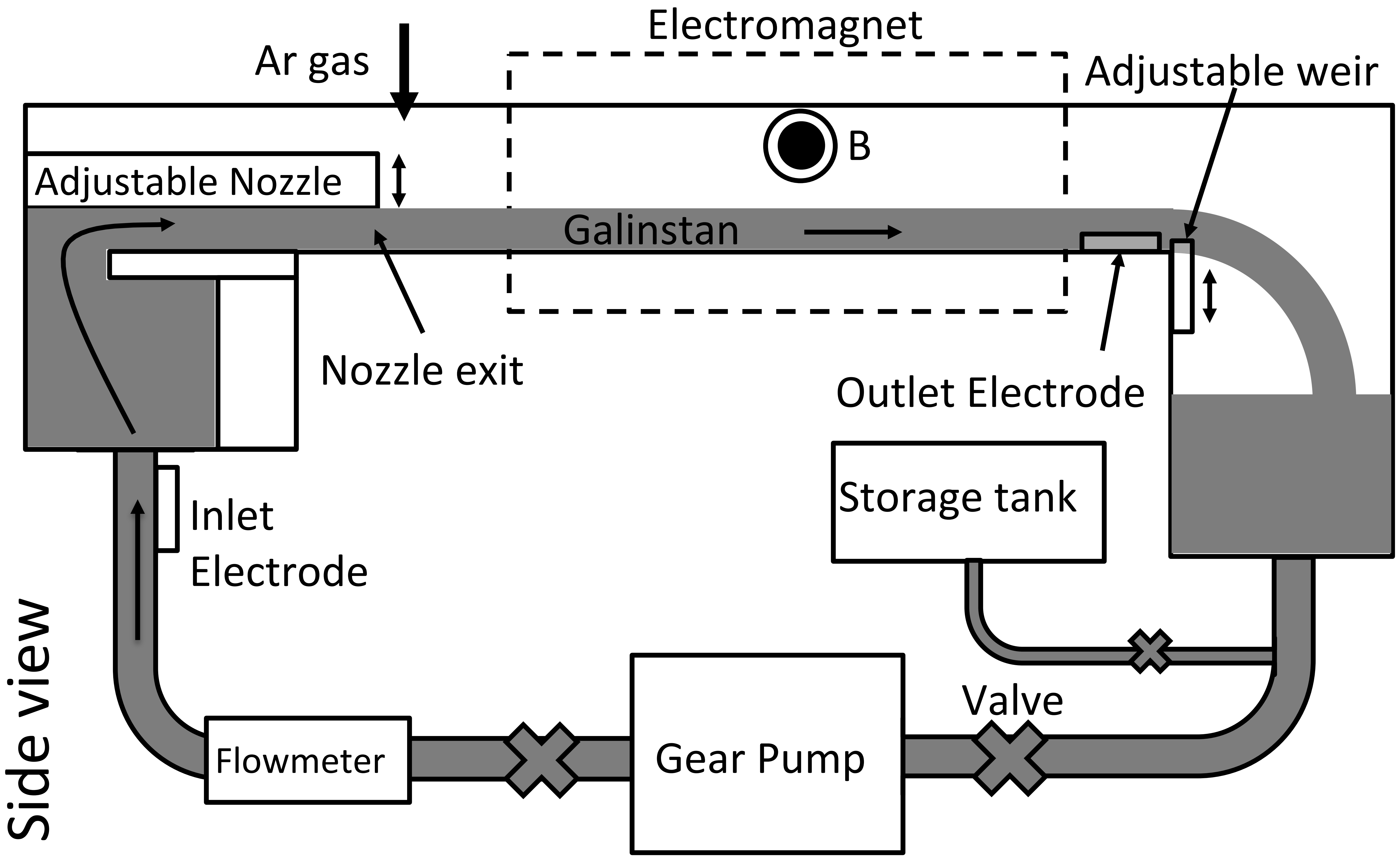
Free surface flow an optional choice for LM walls

- **Analytical and simulation study for free surface flow conducted**
- **Experimental study of MHD effect is scarce**
- **Simulation or theory validation needs experiment results**

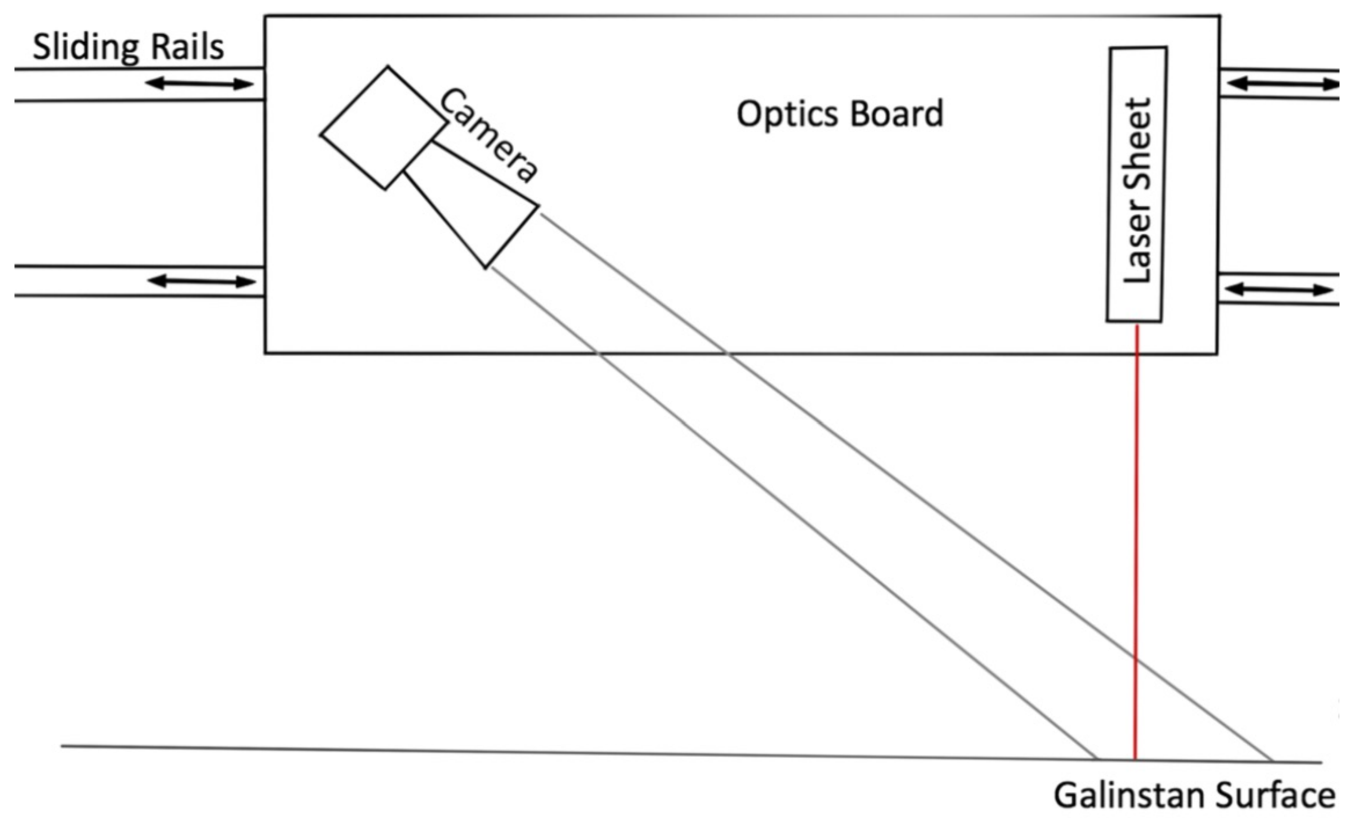
S. Smolentsev FED 2021



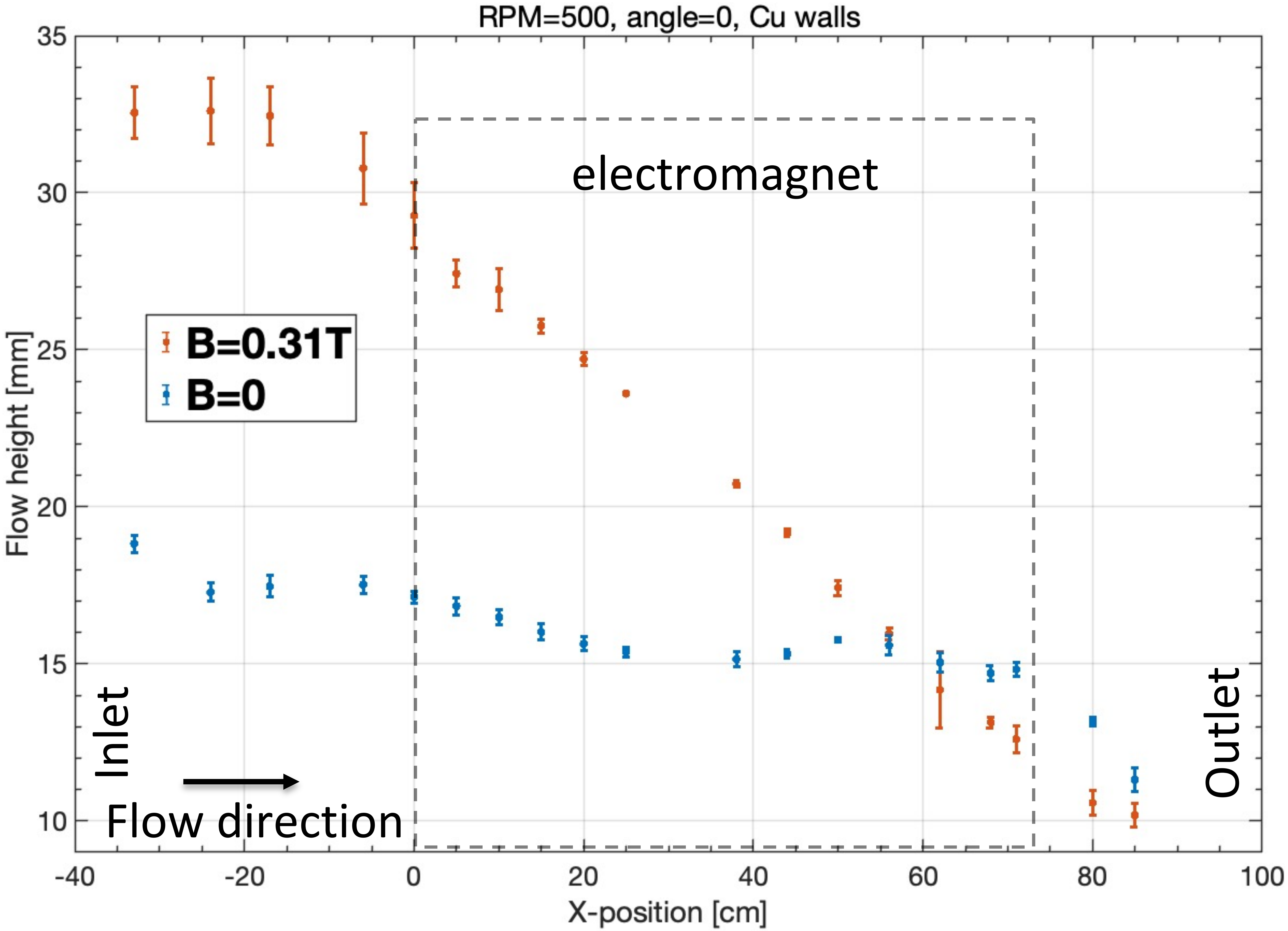
LMX overview



- Rotary gear pump to circulate Galinstan
  - 0-19GPM
- Channel liner: plastic/copper/SS
- Magnetic field: 0-0.33T
- Inclined angle: 0-7
- Laser sheet + camera→ LM height
  - Averaged velocity=Q/(height*width)
- Surface velocity: particle tracking

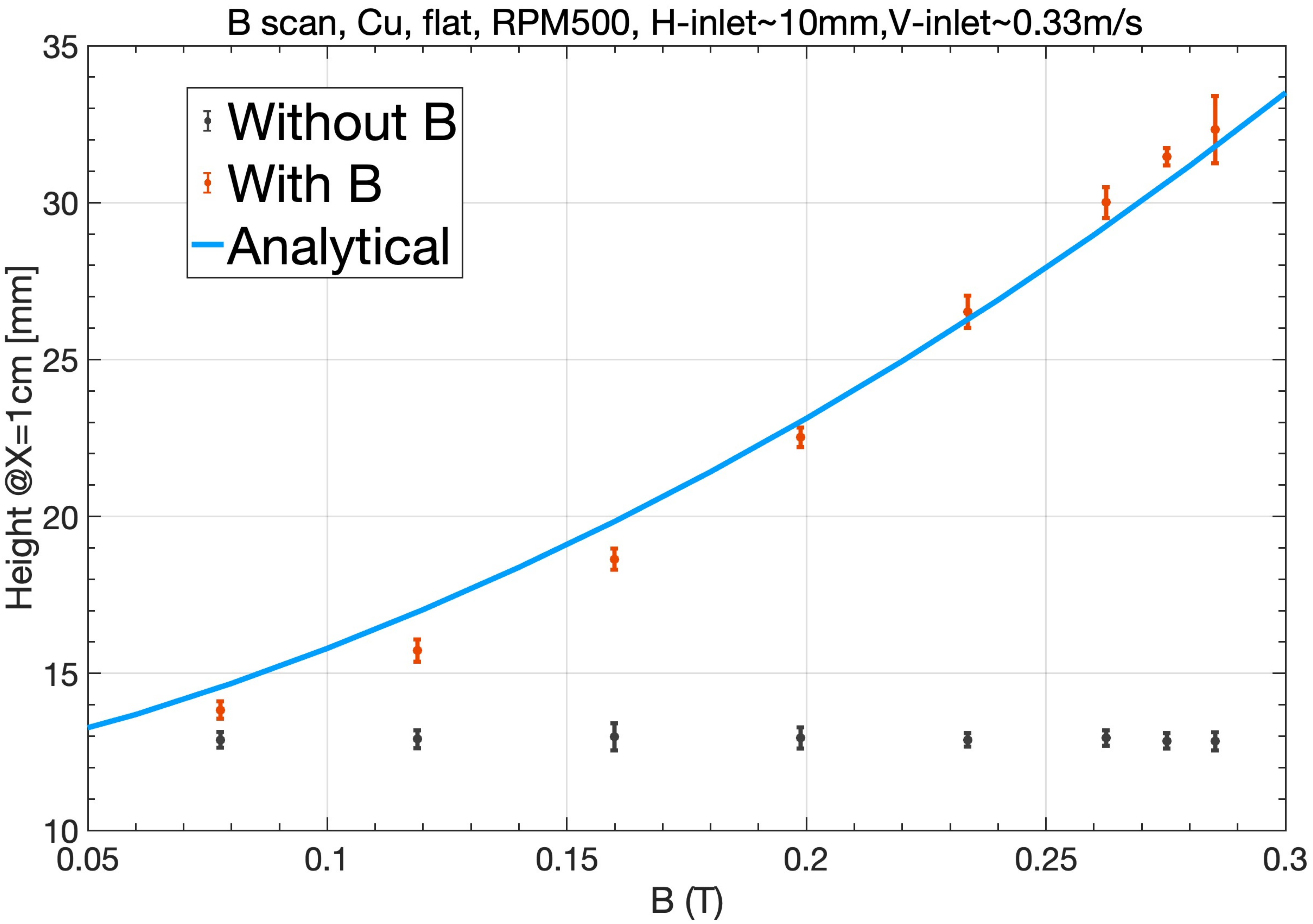


LM piled up in the channel inlet due to MHD drag



- **MHD brakes LM flow**
- **LM thickness increases gradually from the outlet to inlet**

Analytical model matches with experiment



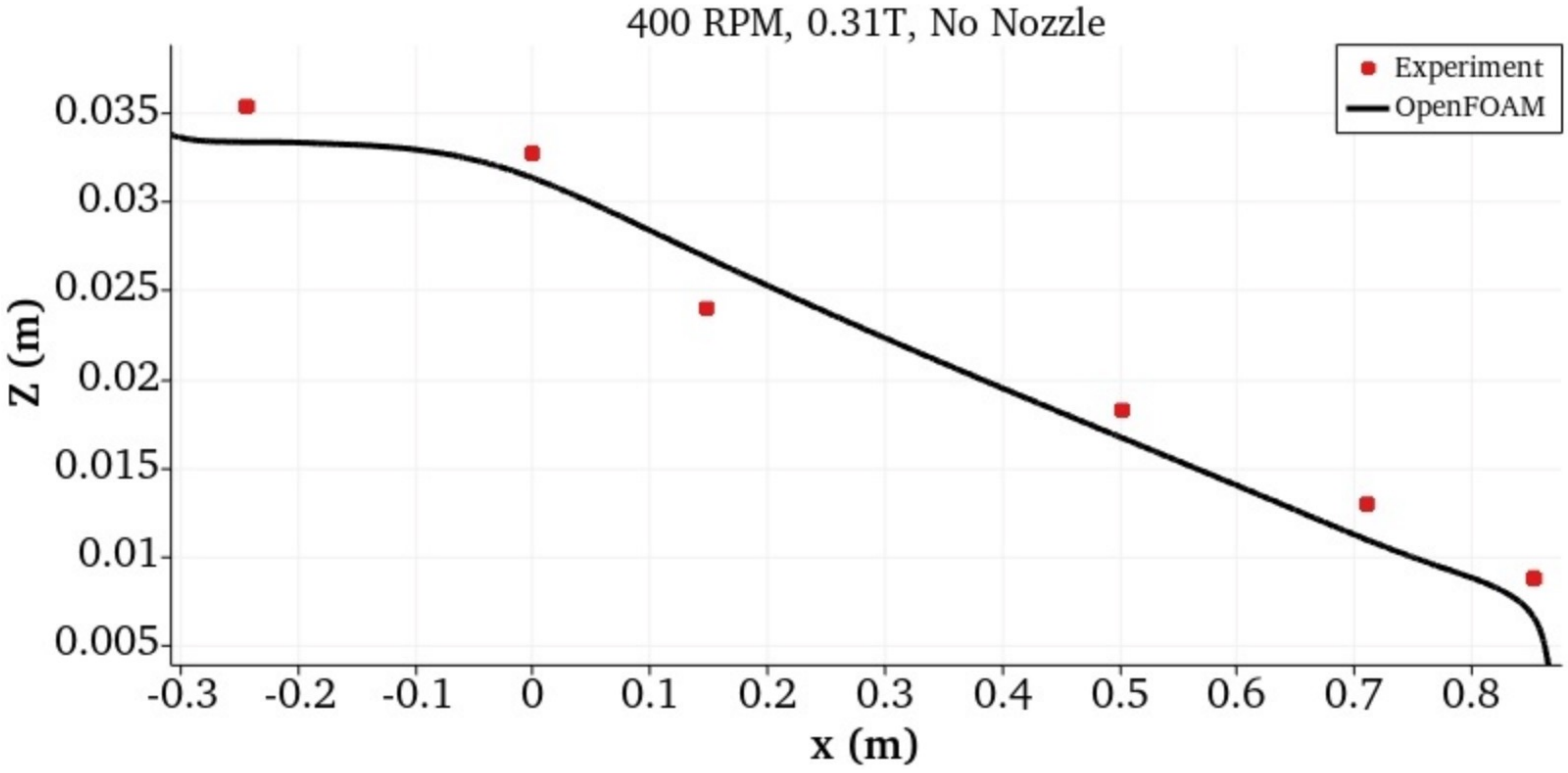
- **Experiments show LM height@inlet increases with ~B²**
- **Analytical model fits well with a proper K**

$$P_1A_1 - P_2A_2 - \int_0^L P_{MHD}(x)A(x)\,dx = \rho\,Q\,(u_2 - u_1)$$

$$\left(\frac{\rho\,g\,h_1^2\,w}{2}\right) + \frac{\rho\,Q^2}{h_1\,w} - K\sigma_{LM}QB^2L = \left(\frac{\rho\,g\,h_2^2\,w}{2}\right) + \frac{\rho\,Q^2}{h_2\,w}$$

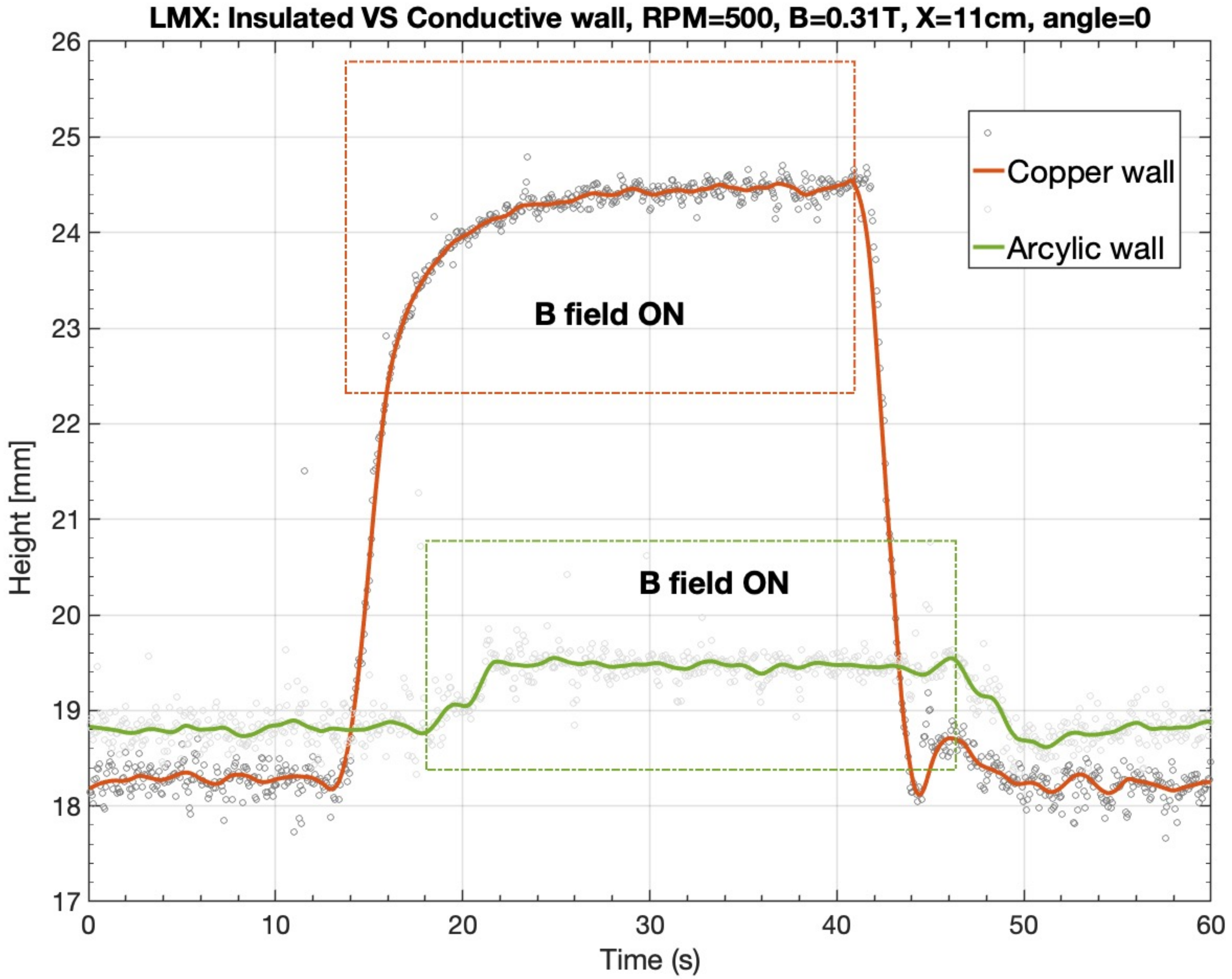
$$\frac{dP_{MHD}}{dx} \approx \boxed{K}\,\sigma_{LM}\mathrm{u}B^2$$

First stimulation by OpenFOAM matches with experiment



Courtesy of J. Salami

Insulating wall or coating could be a solution to reduce the MHD drag



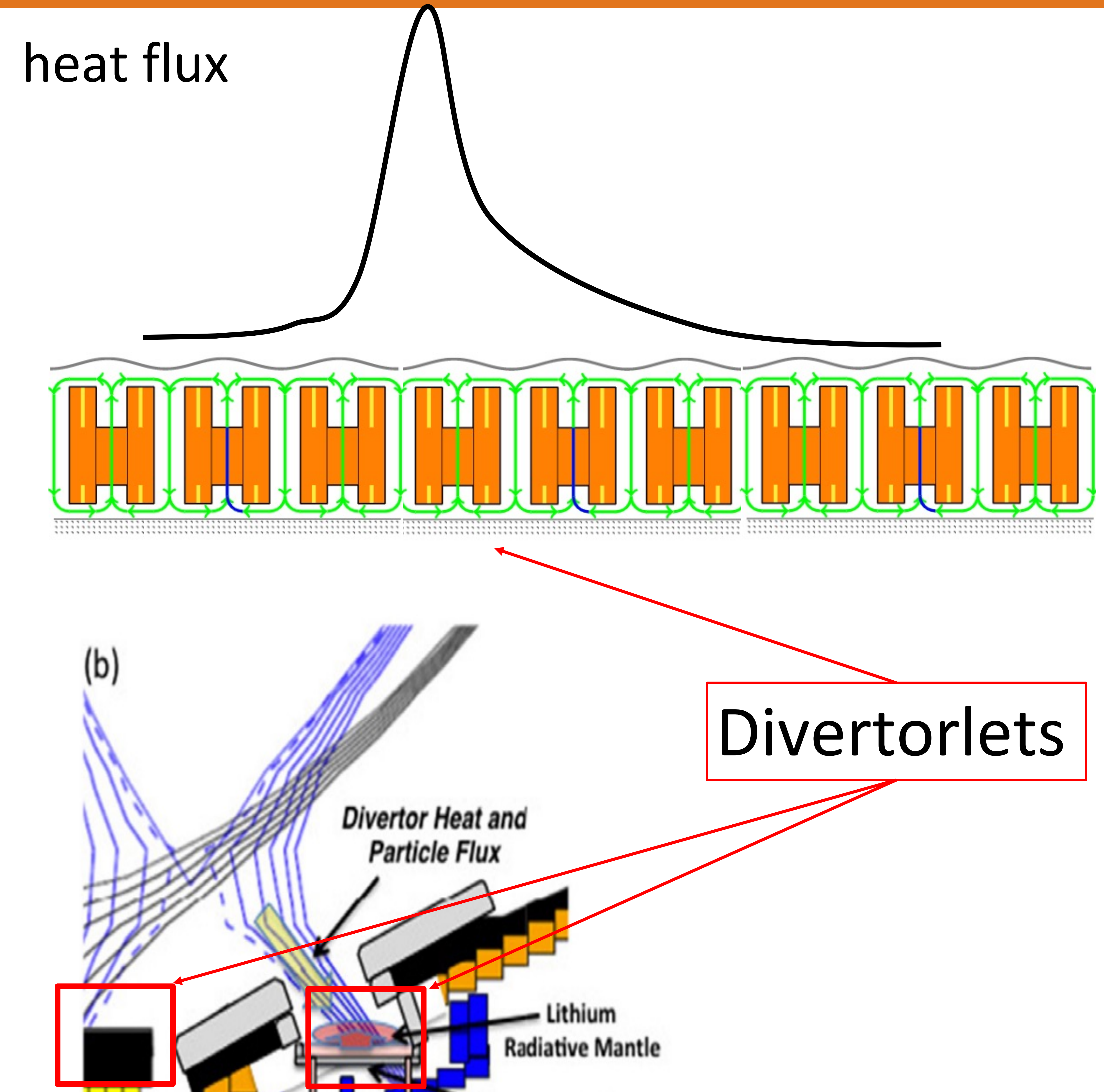
- **Plastic wall : increase by ~3%**
- **Copper wall: increase by ~30%**

- **Ha~650, Re~2520, no nozzle, flat**

Z. Sun, NF, in preparation

Divertorlets concept

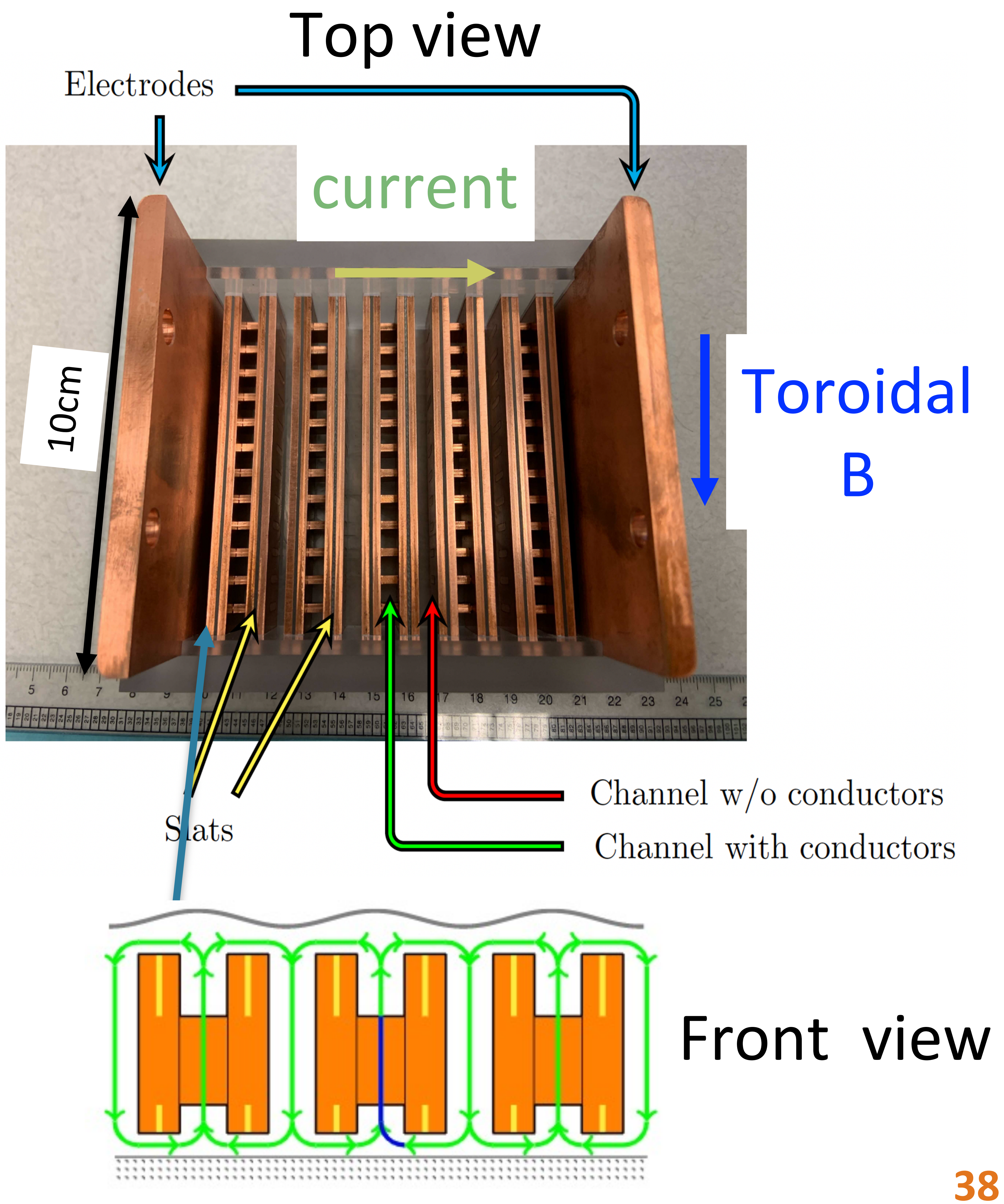
- Use many flow paths → reduce exposure time
  - $N = \frac{D_{exp}}{W}, u = \frac{D_{exp}}{t_{Cr}} = \frac{D_{exp}/N}{t_{Cr}}, N \uparrow u \downarrow$
- Reduce necessary speed for avoiding evaporation
- Reduce MHD drag



A. Fisher, Z. Sun, E. Kolemen, NME 2020

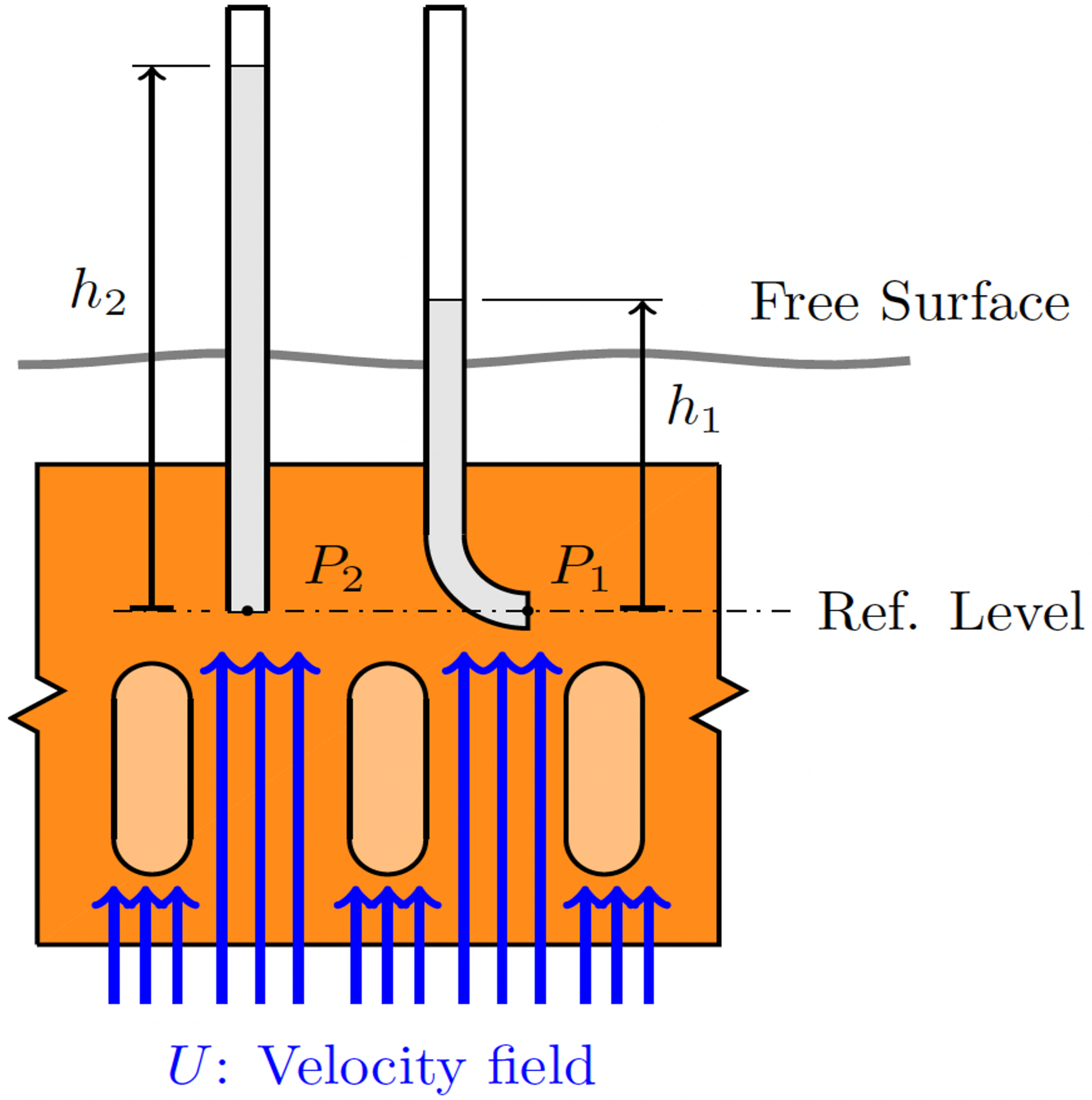
Conductive bars placed in every-other channel to produce effective pump

- **JxB force in combination with toroidal magnetic field and external current**
- **High-conductive conductors take up the current and reduce jxB force**
- **JxB difference between adjacent channels → up and down liquid flow**
- **Prototype built**
  - Copper-G10-copper sandwich
  - Copper bars for conductors
  - G10 sheet(air gap) increases current fraction through the conductor



Flow velocity measured by pitot tube

- **Galinstan**
- **Straight and L-shaped tubes placed in the channel with upward flow velocity**
  - Galinstan column difference
  - L-shaped : static
  - Straight : static +dynamic

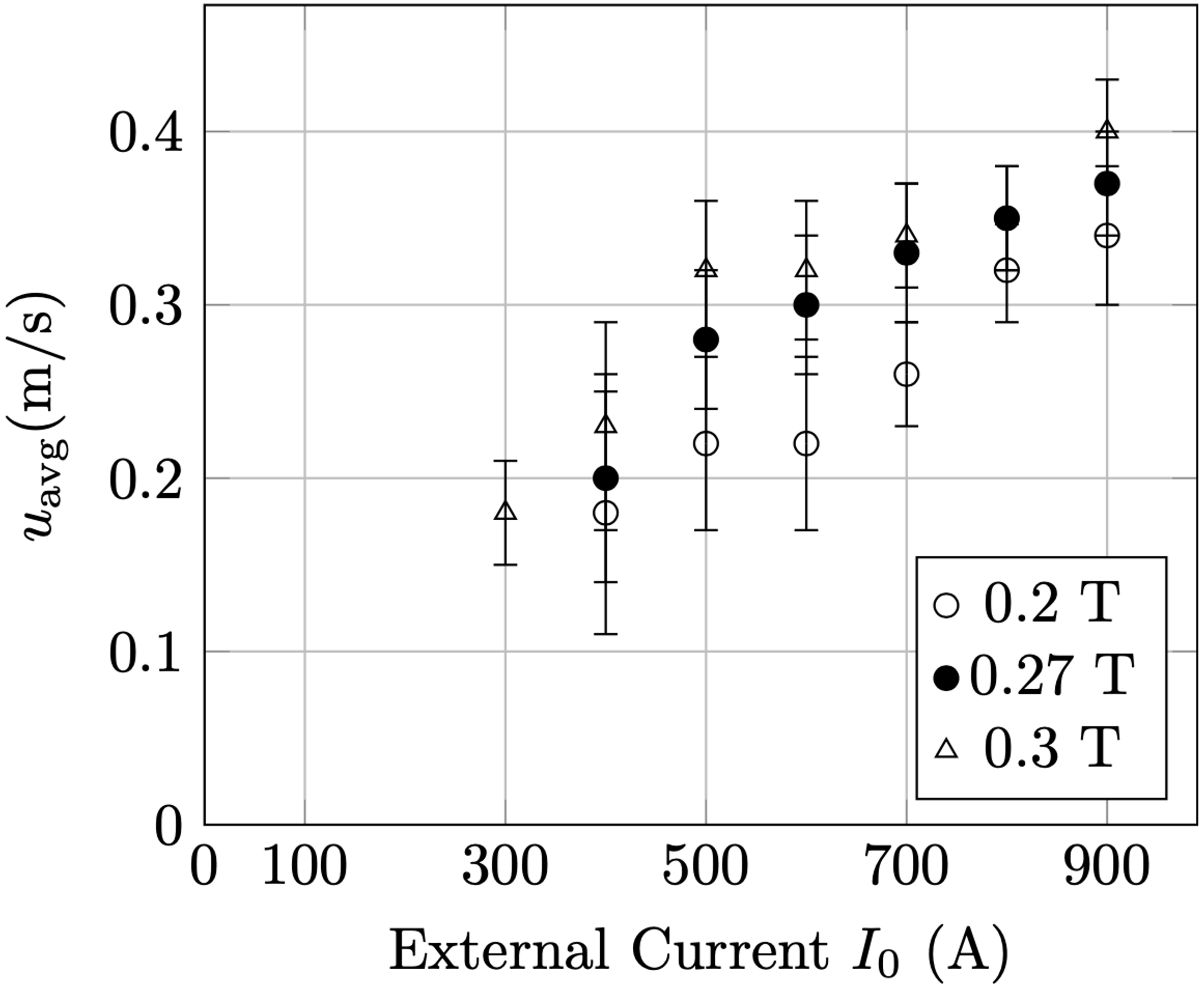


$$P_1 + \frac{1}{2}\rho U^2 \approx P_2 \Rightarrow \|\mathbf{U}\| \approx \sqrt{2g\Delta h}$$

Flow speed increases with increasing external current

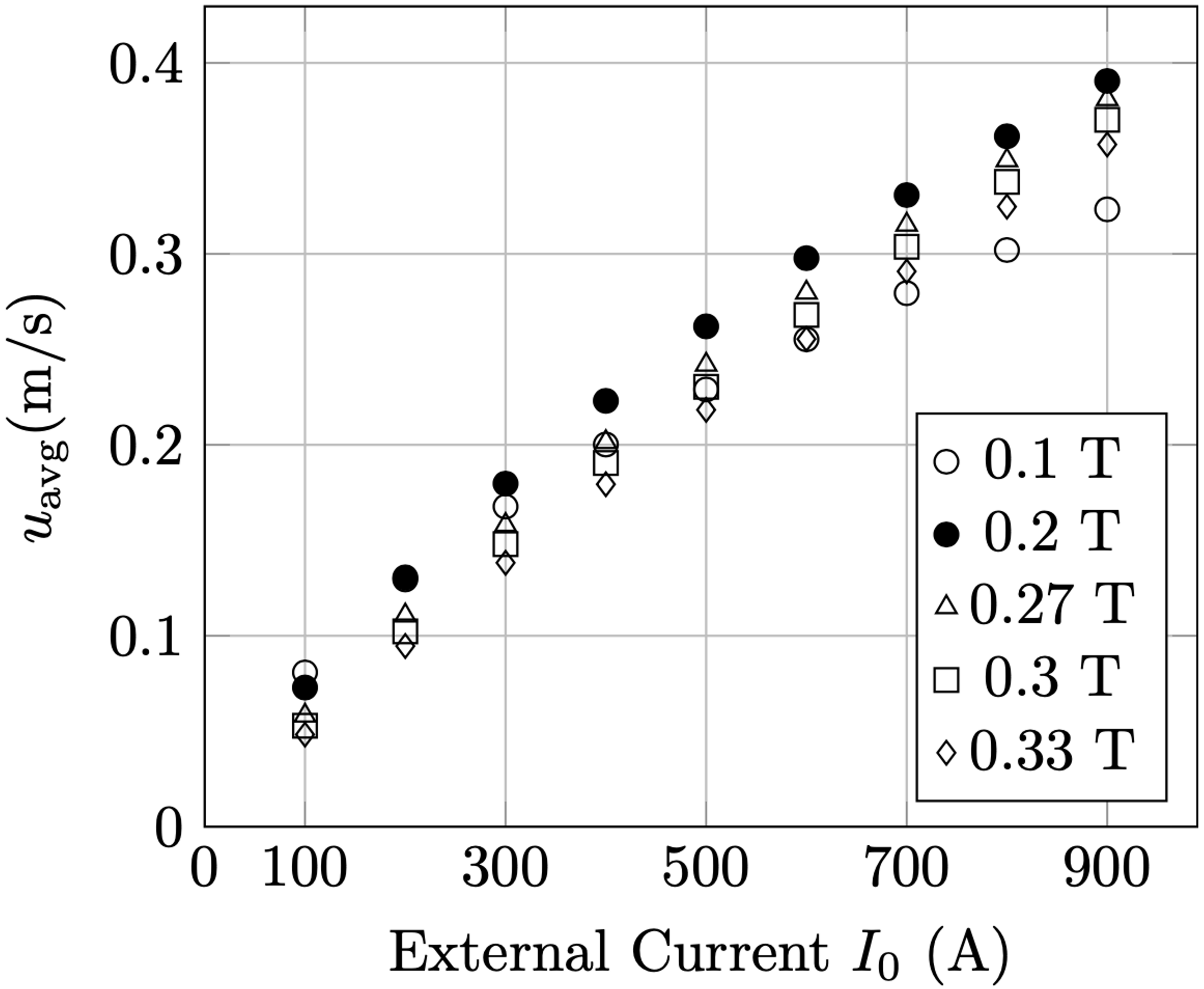
- **Pump force is proportional to the current density difference between consecutive channels and magnetic field**

- **Experiment confirmed upward velocity up to 0.4m/s**
- **Flow speed increases with increasing magnetic field**



Stimulation results match with experimental results

- **COMSOL**
- **Velocity increases from 0.05 to 0.4 m/s with current increasing from 100 to 900A**
- **Peak flow speed at 0.2 T**
  - Galinstan oxides on the walls reduce the MHD effect



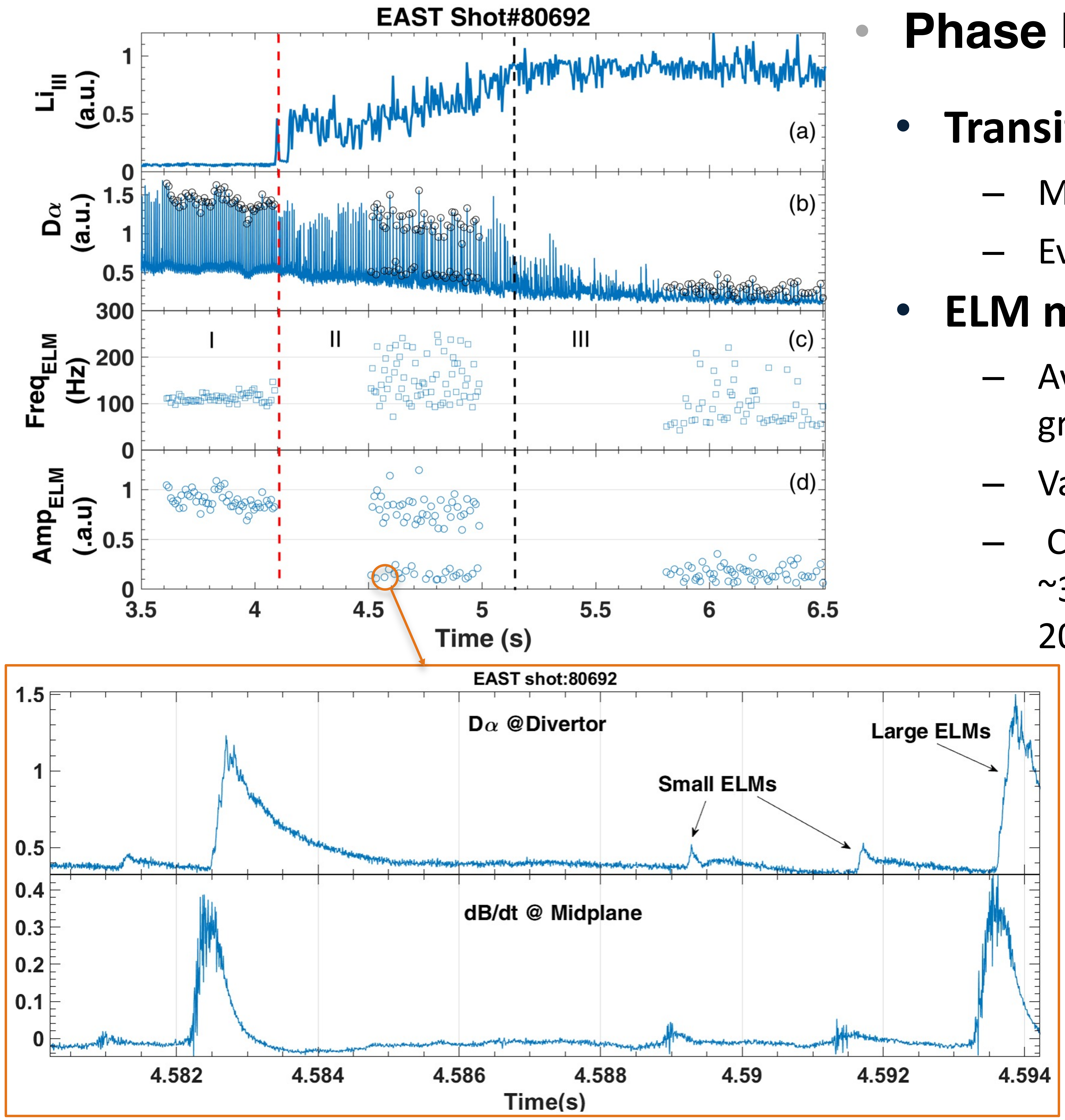
Z. Sun, SOFE 2021

Summary

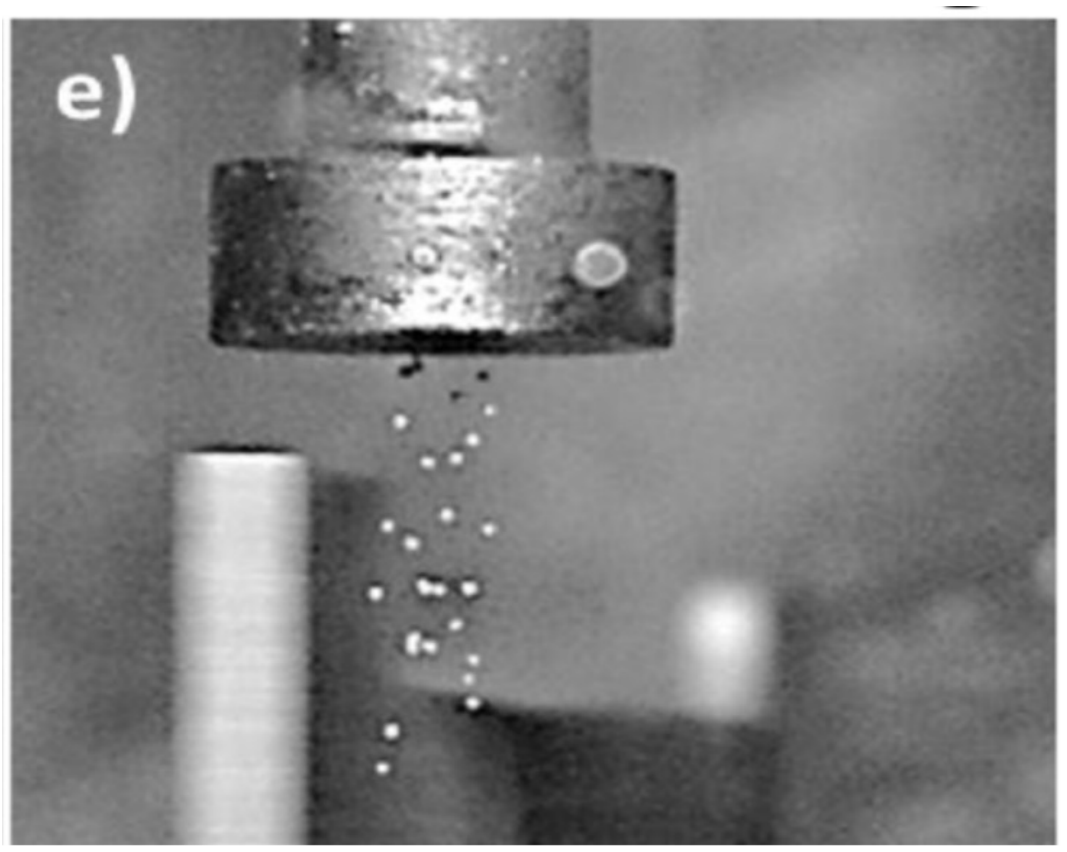
- **For ELM elimination, a simple technology of solid particle injection by gravity was successfully demonstrated in EAST**
- **High flow rate Li granule injection suppressed larger ELM associated with depressed pedestal pressure and enhanced core pressure**
- **Robust ELM suppression by B powder was demonstrated over a wide range of plasma parameters, associated with low frequency harmonic modes**
- **LM accumulation in the free-surface flow caused MHD drag was observed**
- **Experiments demonstrated successful operation of the toroidal divertorlets concept, and simulations agree with experimental measurements of vertical velocity**
- **Open questions :**
  - ➢ What is boron induced mode?
  - ➢ Role of ion dilution effect on pedestal and core plasma?
  - ➢ Surface oscillations, MHD drag, and heat transfer for 'Divertorlets'?
  - ➢ …

Thank you for your attention

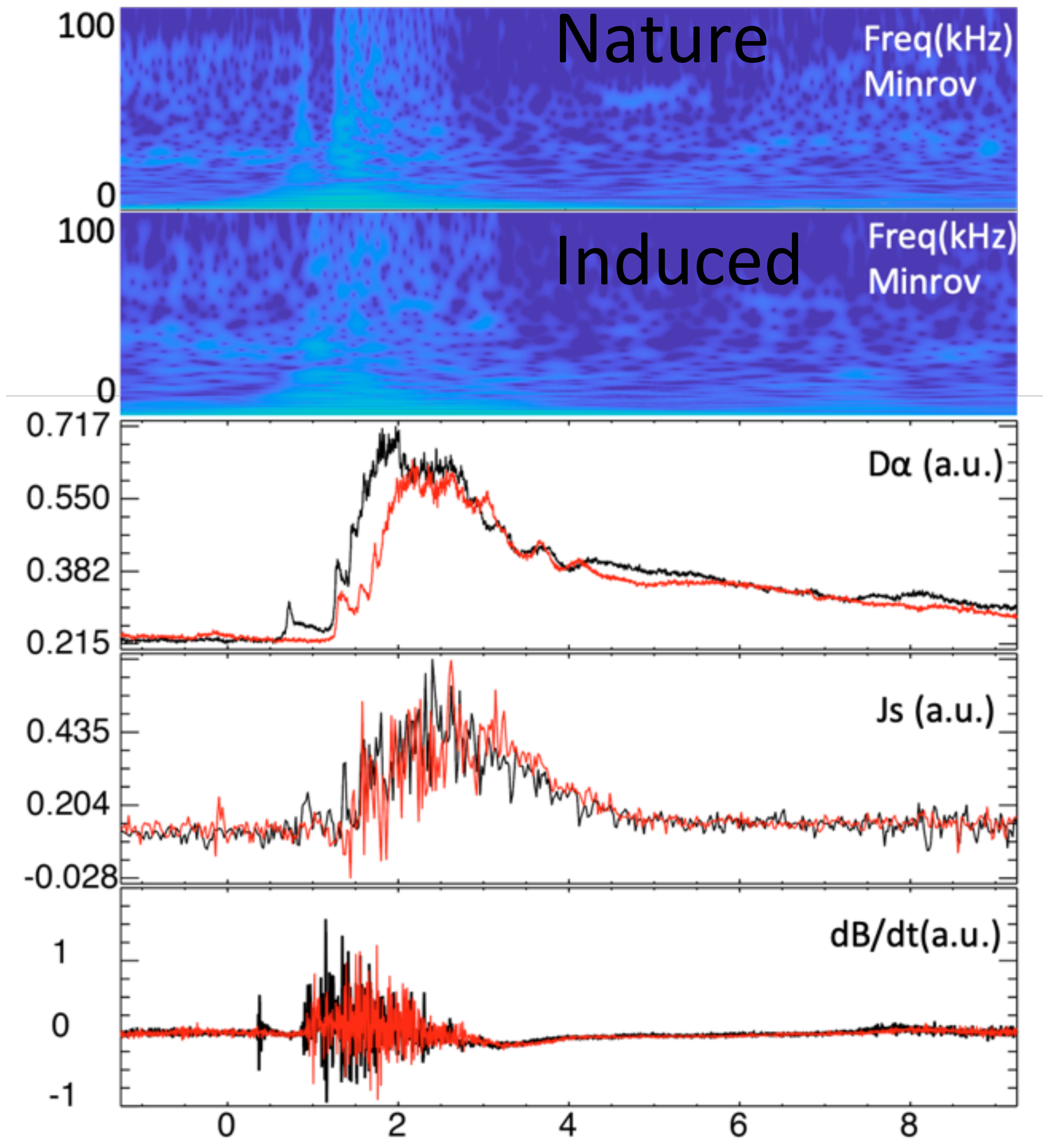
Large ELMs disappear and small ELMs triggered

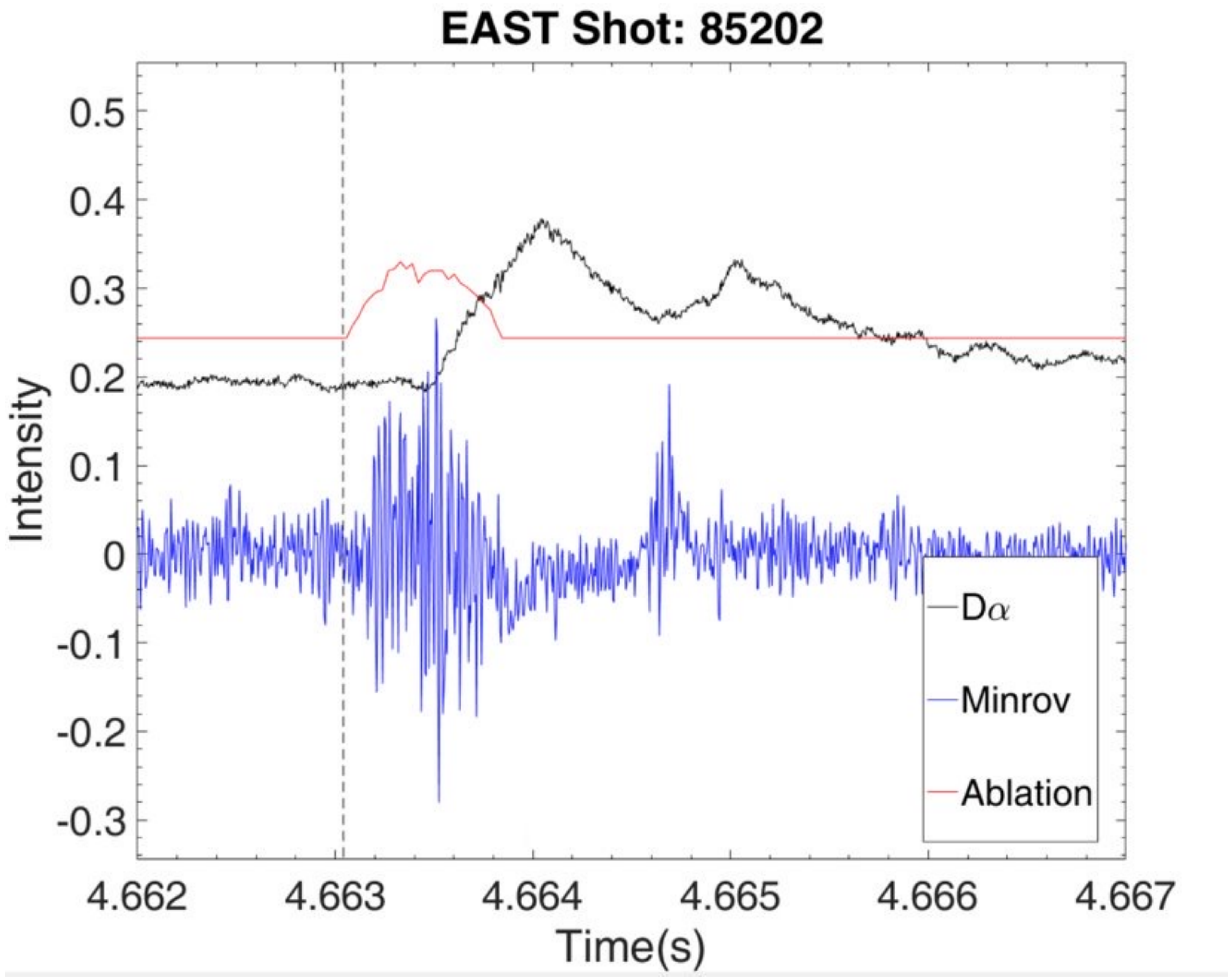


- **Phase I: regular at ~110 Hz ± 10 Hz**
- **Transition phase II:**
  - Mixed small and large-amplitude ELMs
  - Evidence for the granules triggering ELMs
- **ELM mitigation phase III:**
  - Averaged ~80Hz<<2000Hz, not all granules triggering ELMs
  - Variable frequency, spreading in 30-220Hz
  - Clustering likelihood with 3 or 4 granules ~3%-10% →expected ELM freq.~60-200Hz

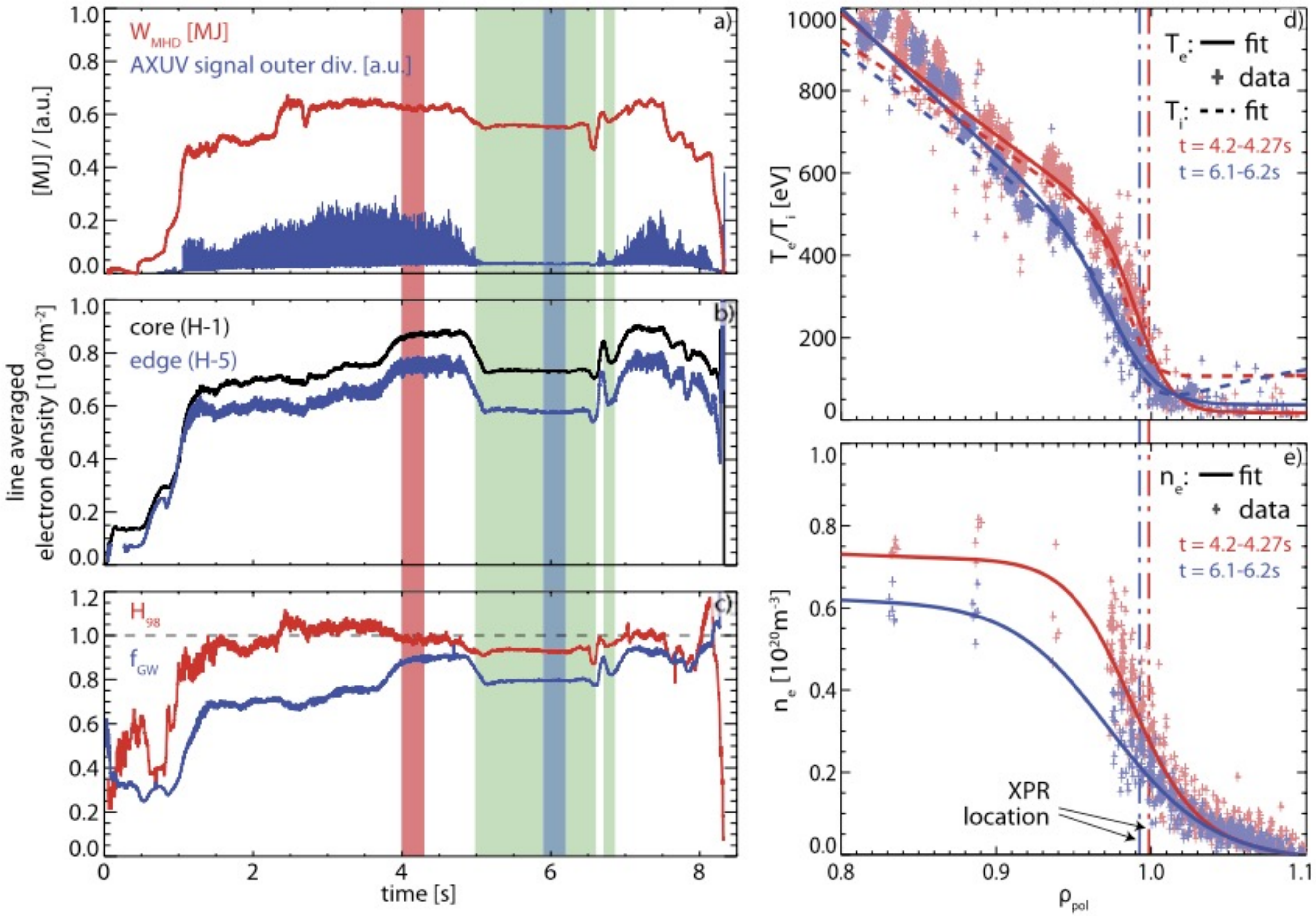


ELM triggered by granule in ELM-free H-mode





AUG N2 injection



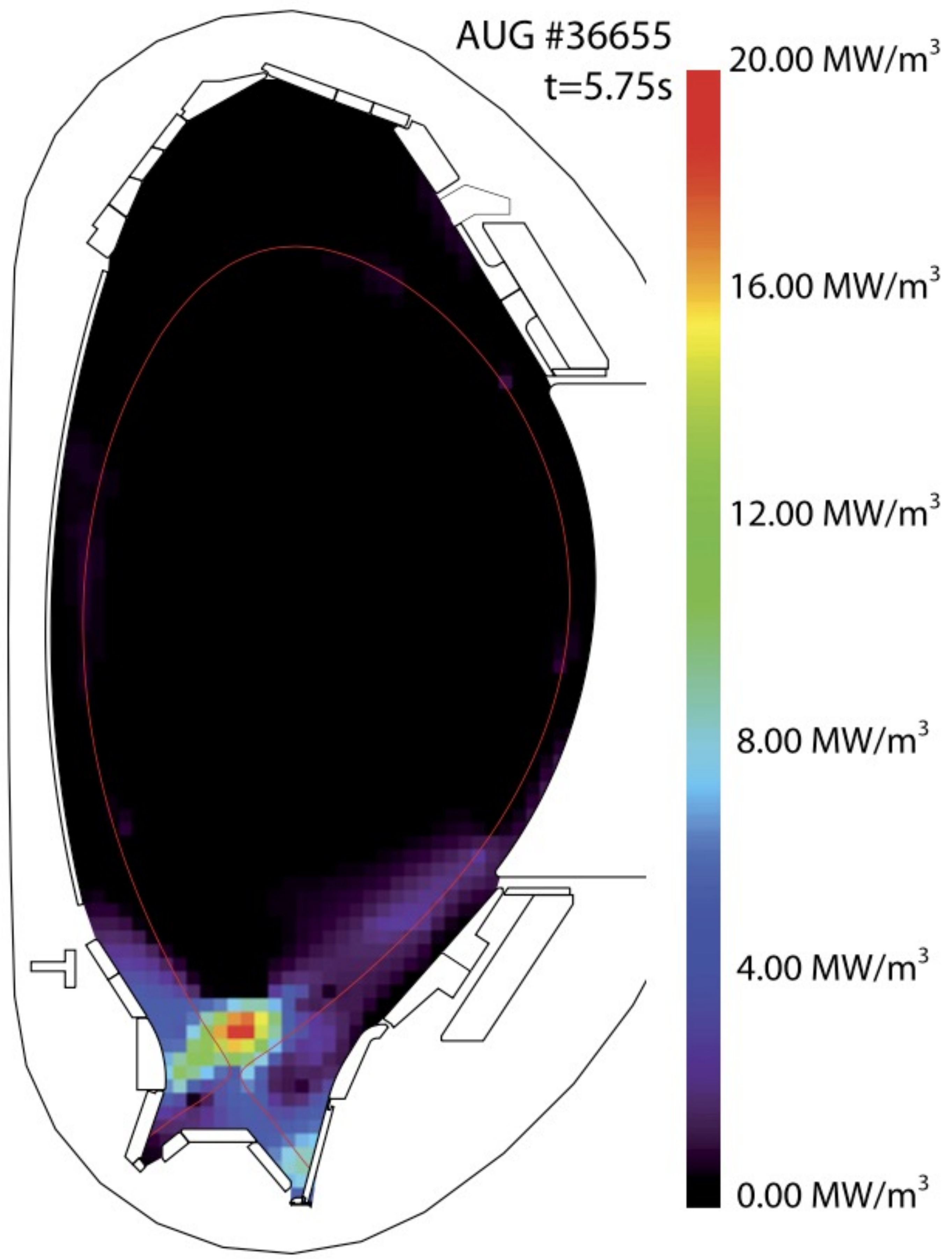
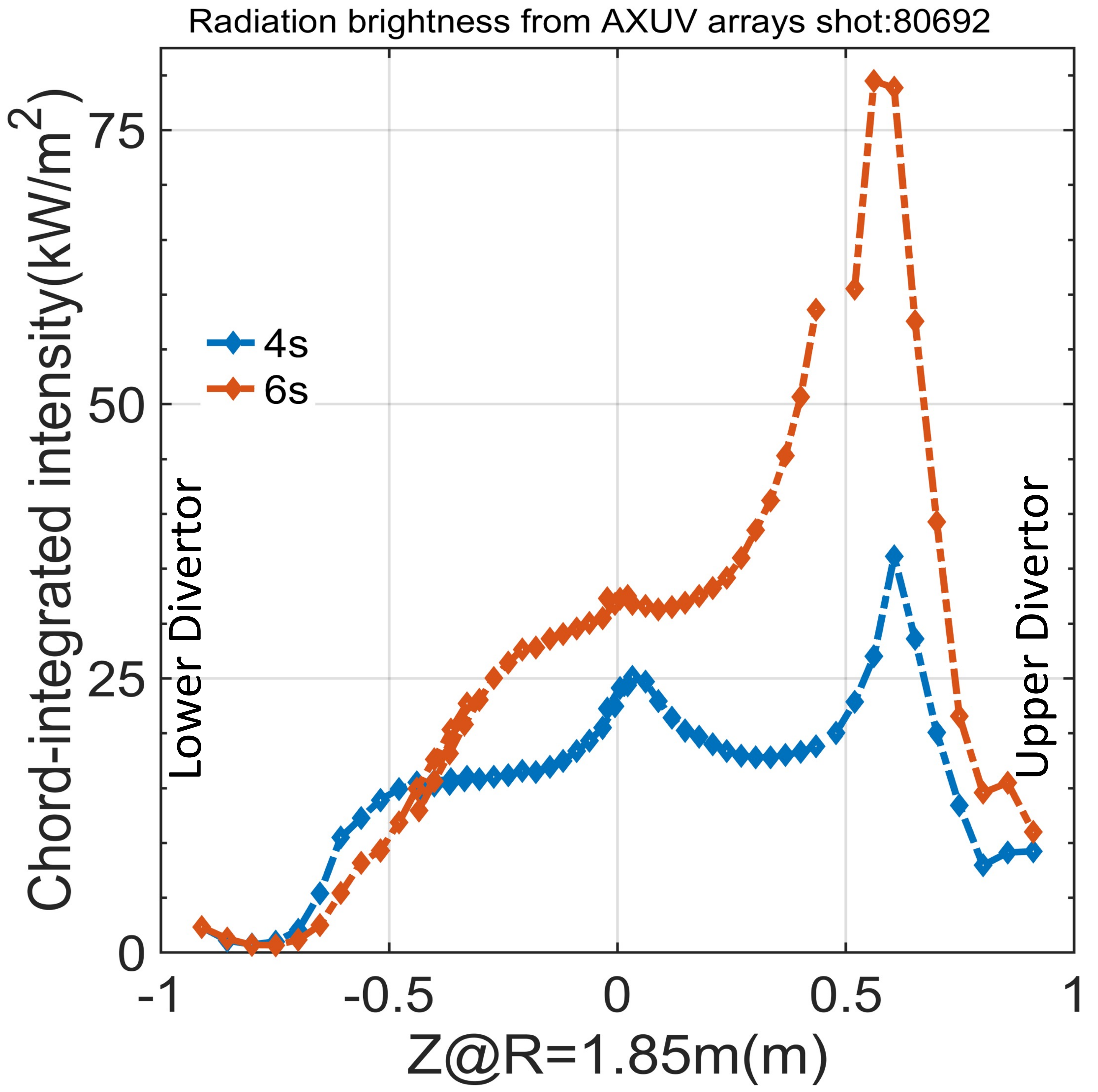
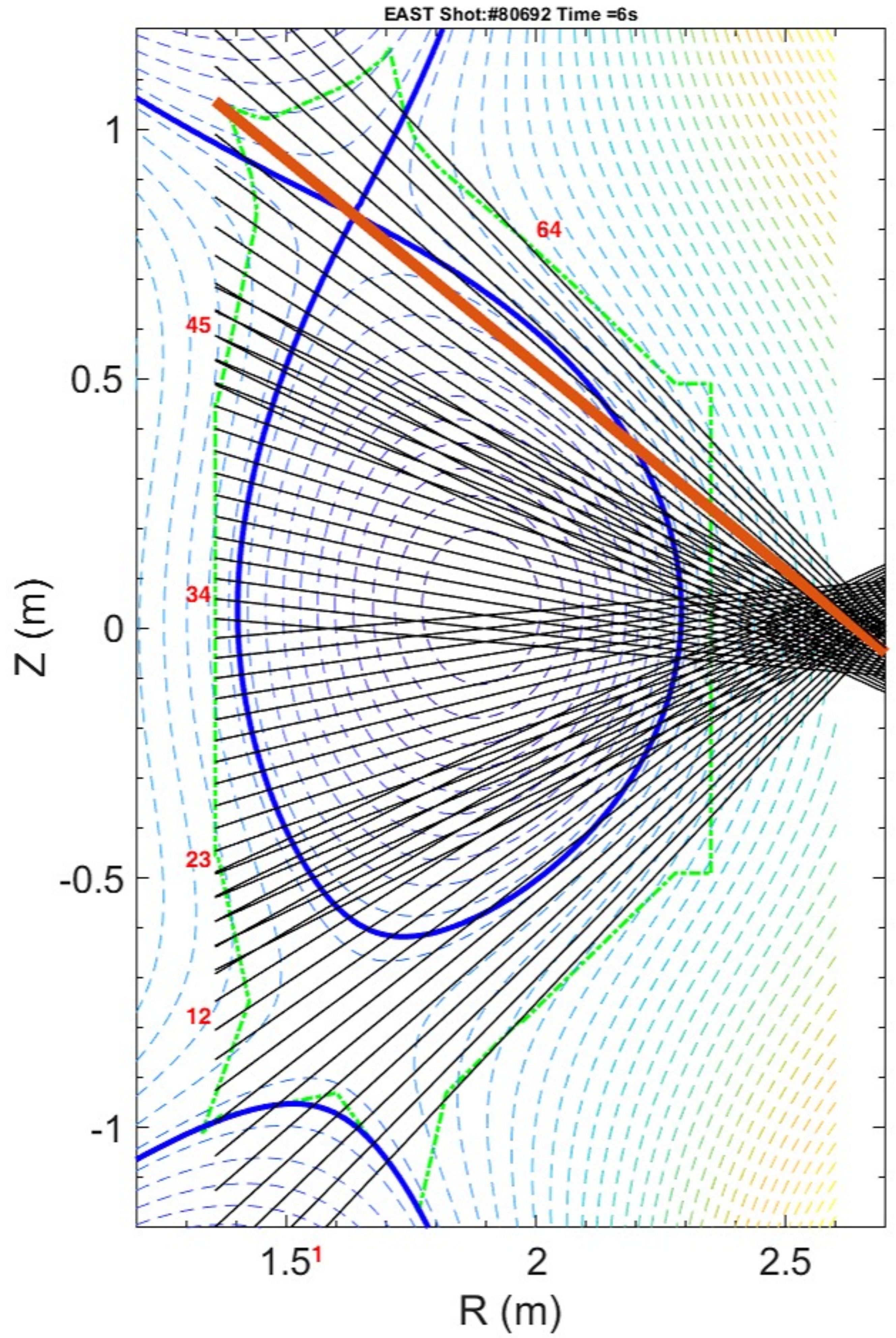


Figure 1. Tomographic reconstruction of the radiated power for AUG #36655, the XPR is present.

Edge cooling is likely responsible for the depressed pedestal Te

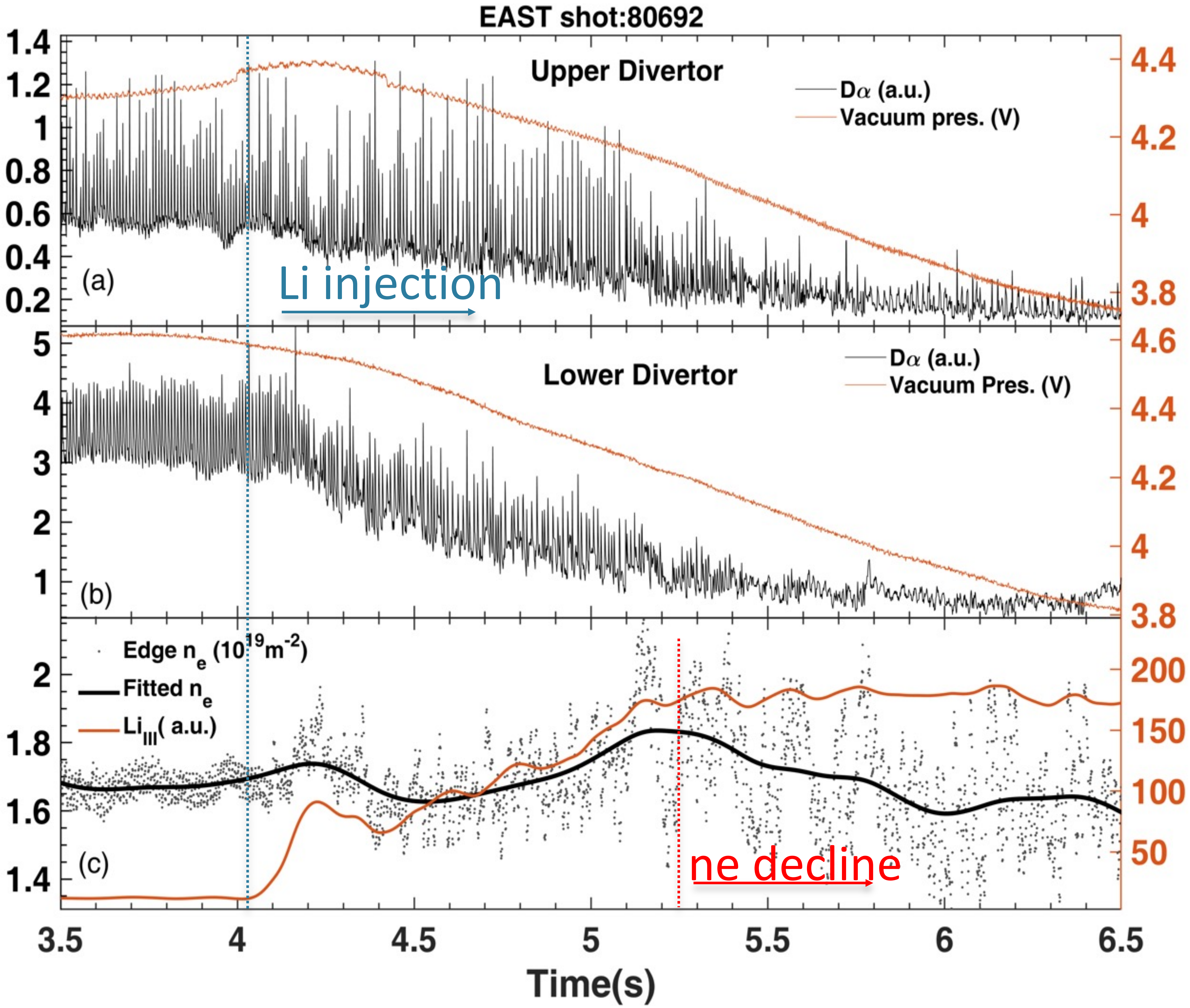
- **Radiation dominated in the upper divertor region**
- **Channel with maximum value localizes the upper X-point, ↑~3.2x**



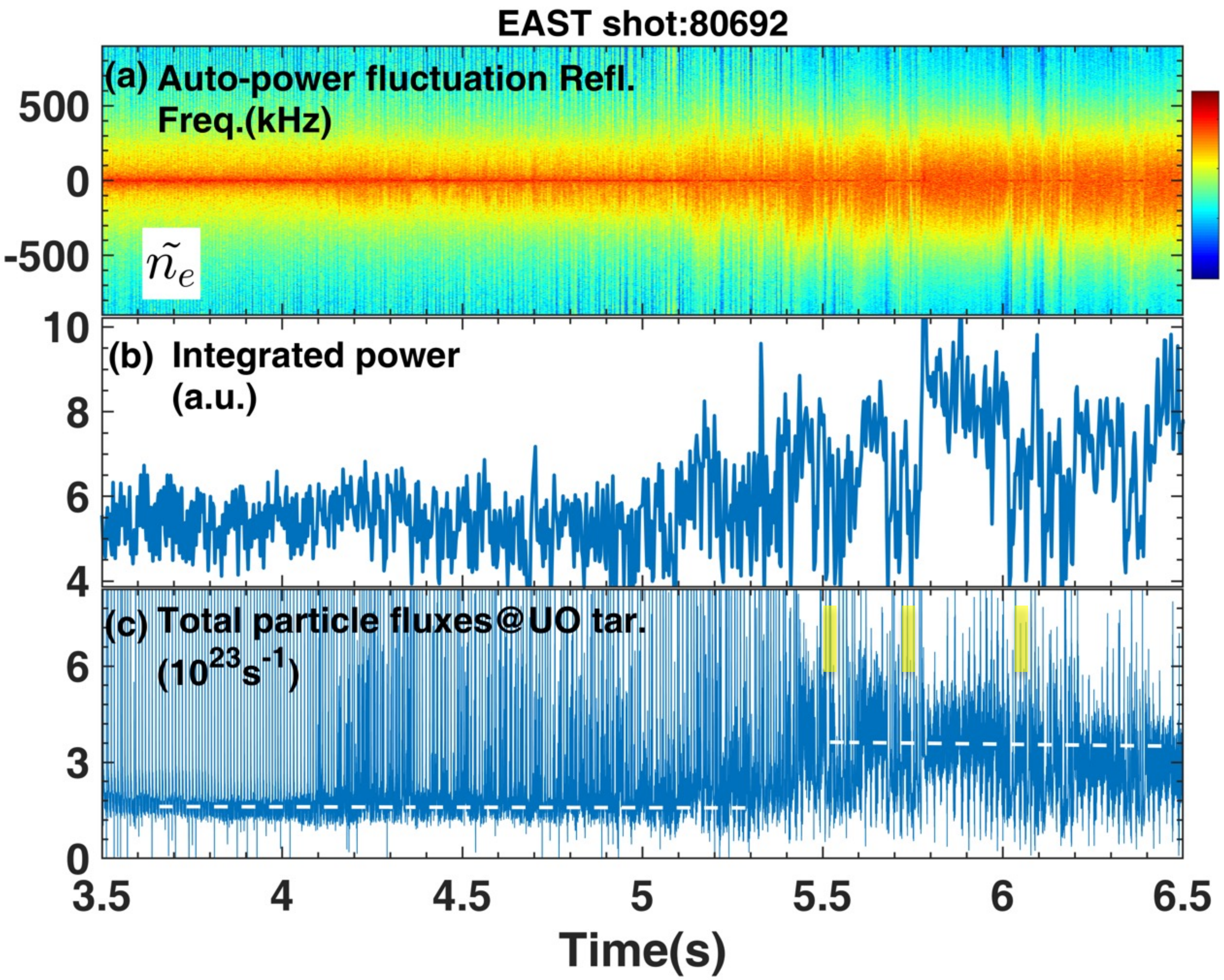


Pedestal ne reduction possibly stems from D recycling control with sufficient Li on the wall

- **Pedestal ne starts to decline as the D recycling control becomes more effective**



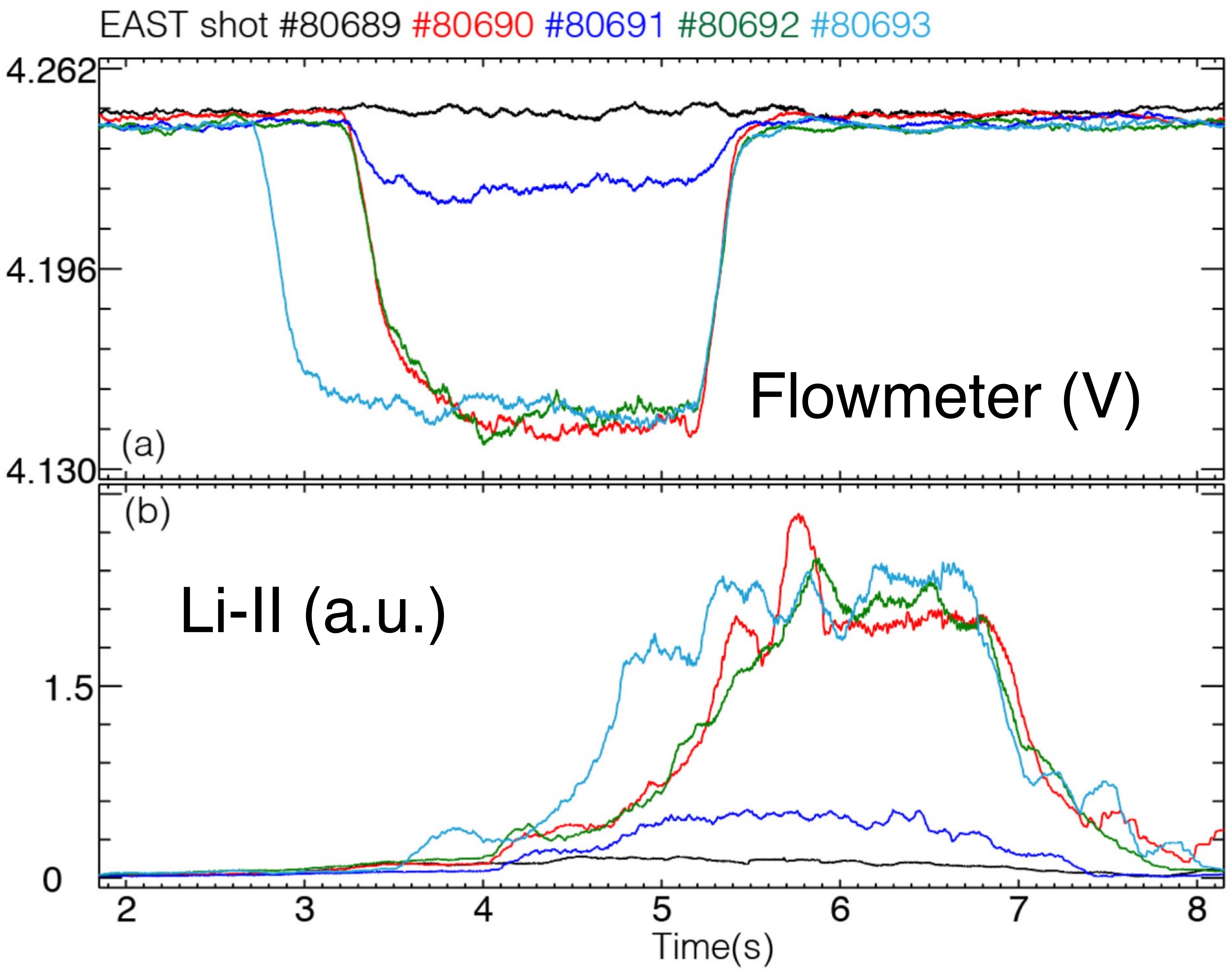
Enhanced background turbulence and transport

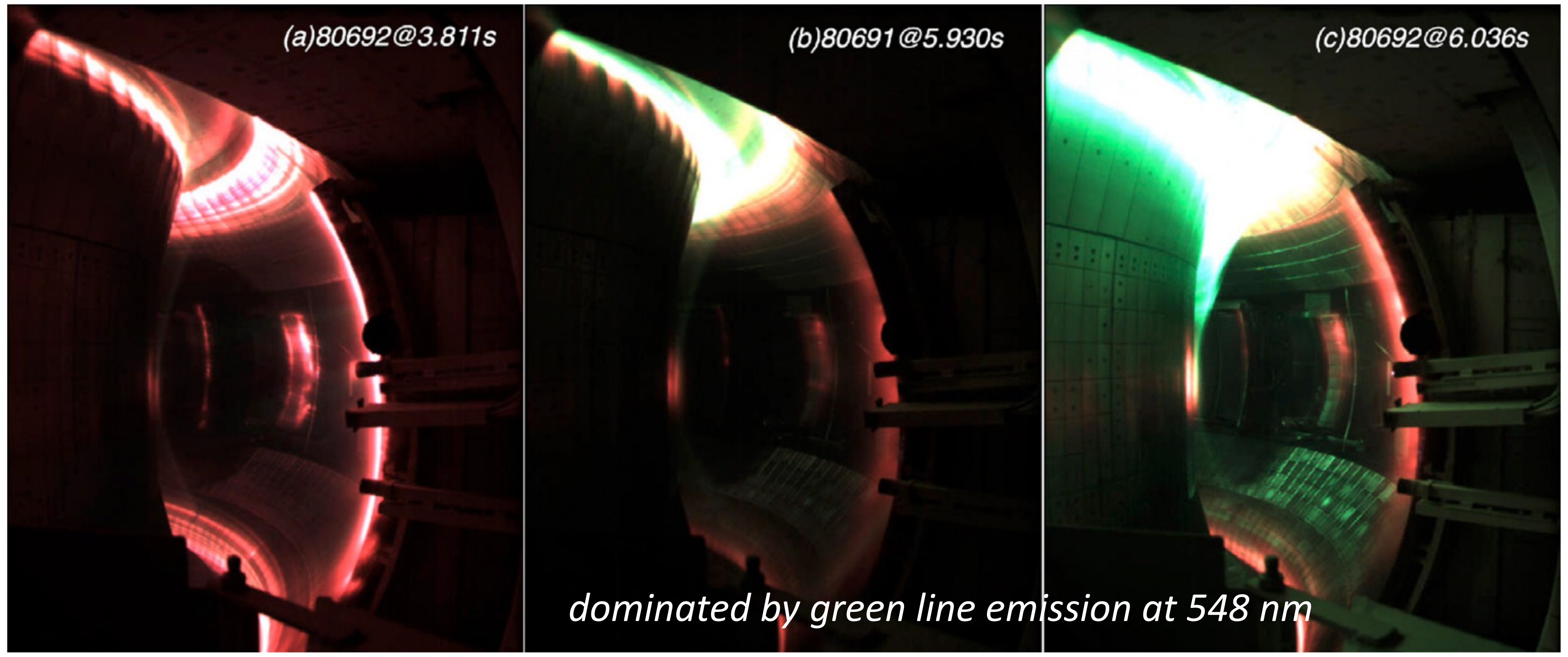


- **Pedestal density fluctuations ↑~50-100%**
  - O-mode reflectometer
  - Around the pedestal top
  - No obvious increase in pedestal foot and steep region
- **Particle flux between ELMs in ELM mitigation phase elevated ~2X , suggesting particles outward transport**

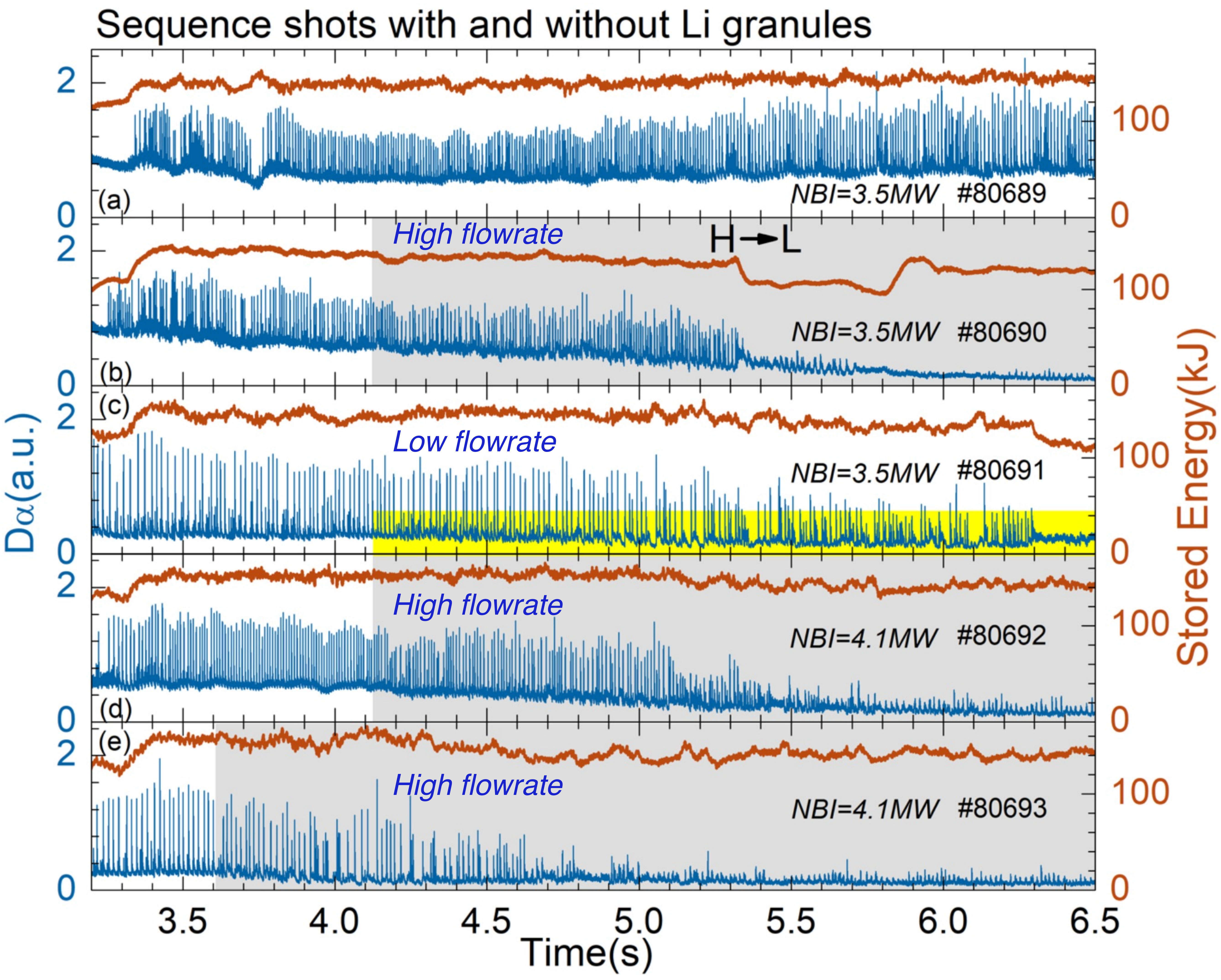
Gravity assisted Li granule injection into plasma

- 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



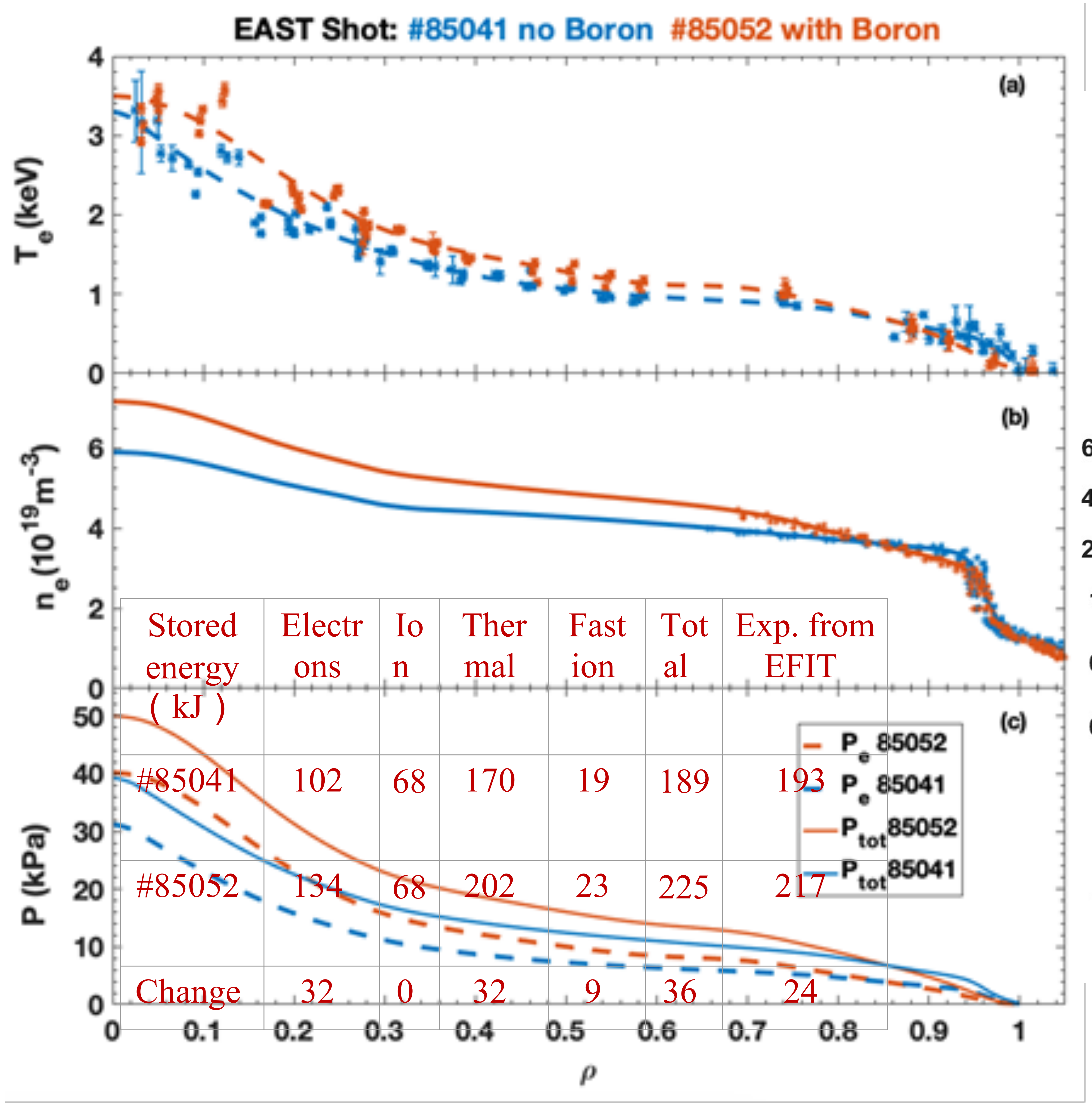


Reproducible ELM mitigation with modest stored energy reduction

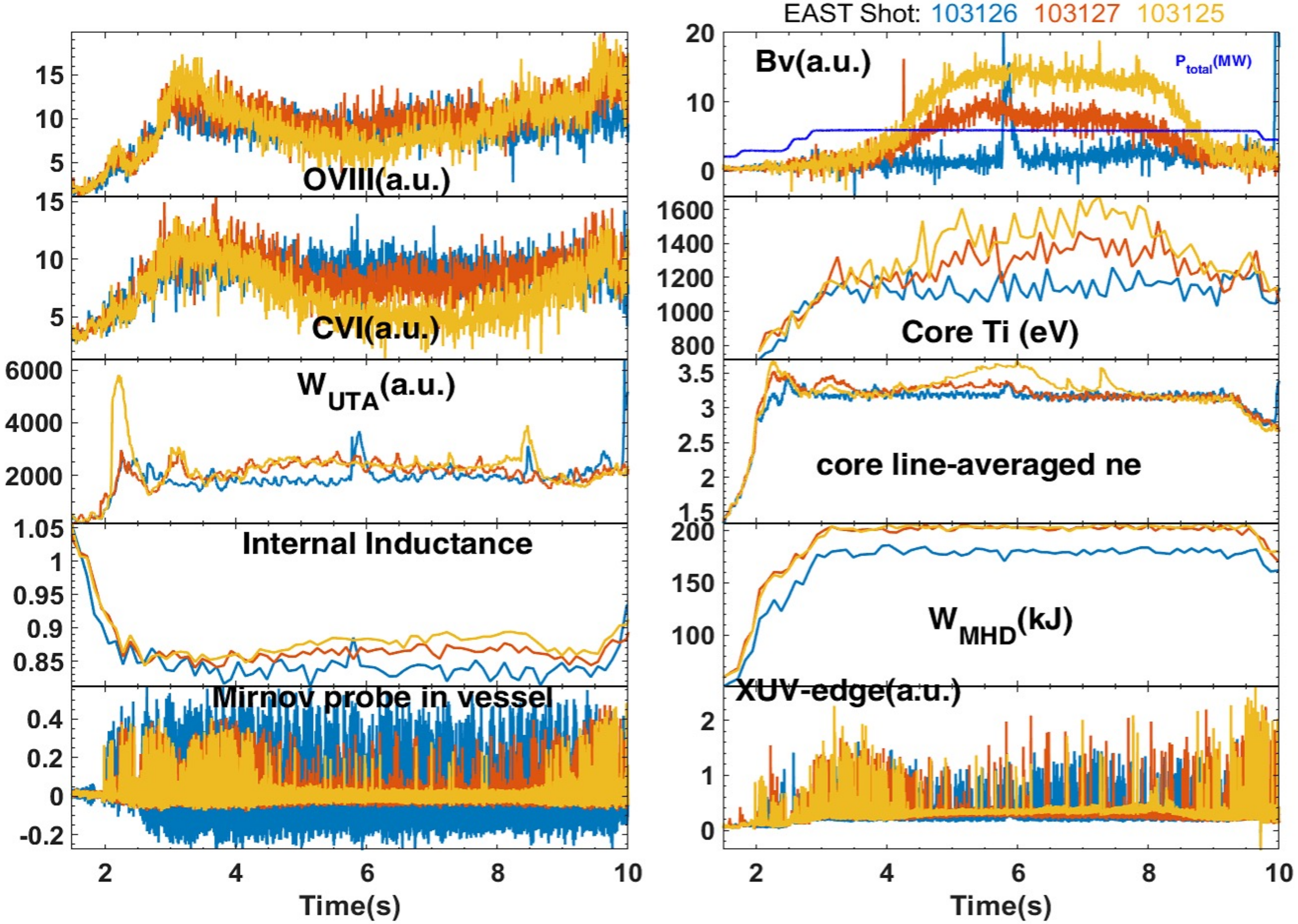


- No Li, No mitigation
- High flowrate (194mg/s) and low power(3.5MW), H→L transition
- Too little Li(32mg/s), the effect discounted
- No H→L transition with high power(4.1MW)
- Earlier contacting plasma, earlier ELM mitigation, reproducible
- ELM mitigation accompanied with small W_{Dia} reduction, <10%

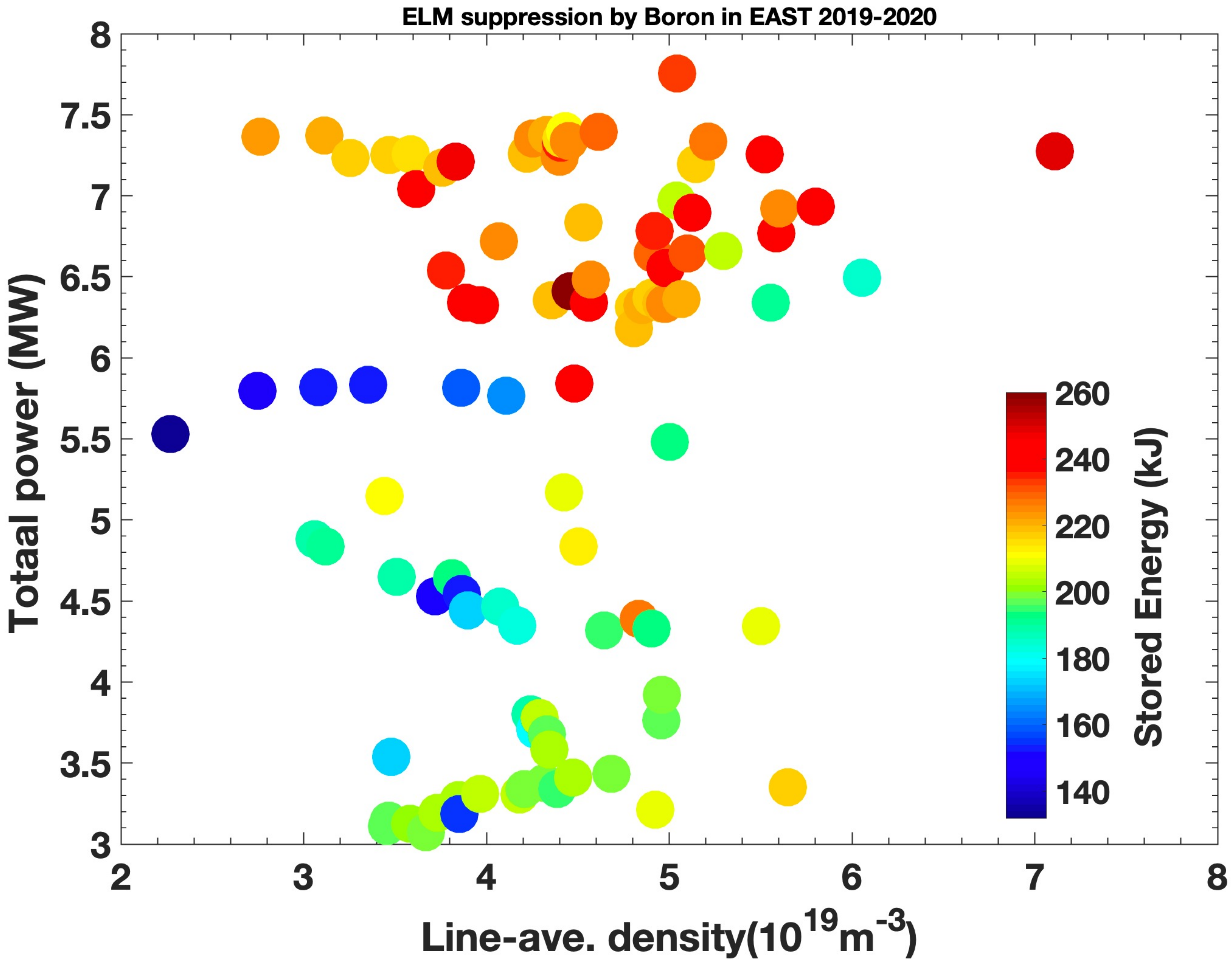
Boron on Te ne Ti



Stored energy (kJ)	Electrons	Ion	Thermal	Fast ion	Total	Exp. from EFIT
#85041	102	68	170	19	189	193
#85052	134	68	202	23	225	217
Change	32	0	32	9	36	24

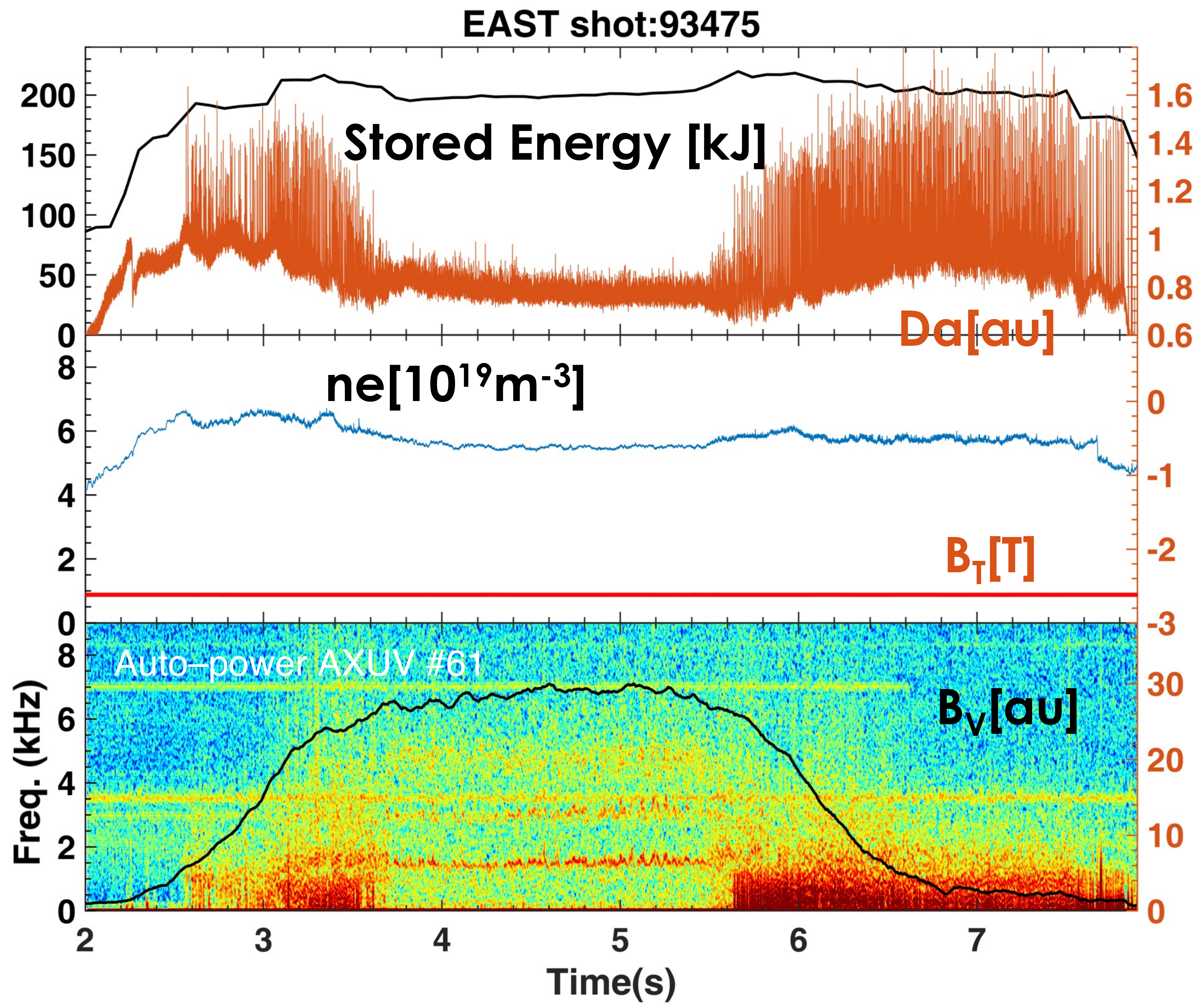


ELM suppressed over a wide range of ne and υ_e^*



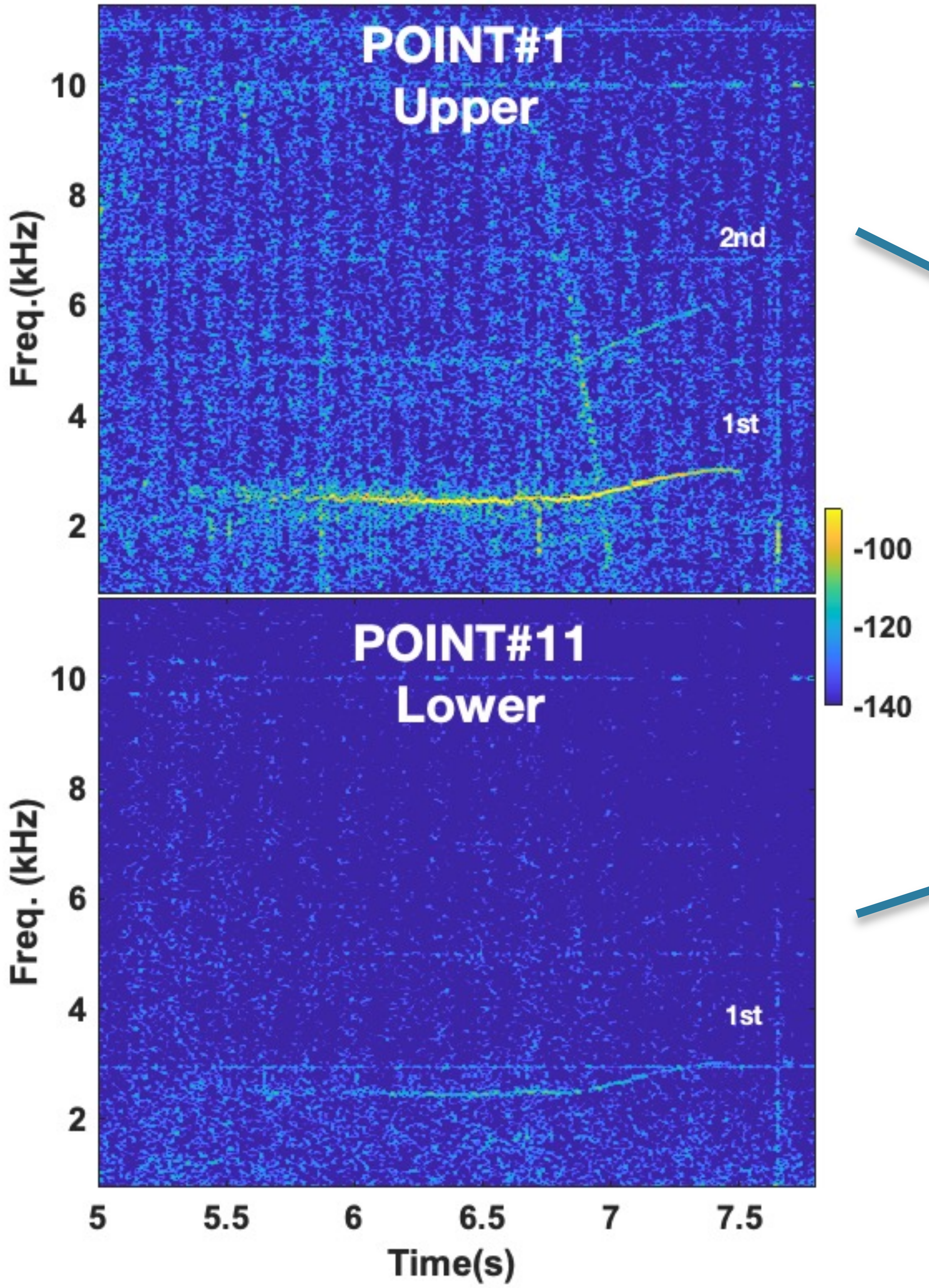
- n_{GW} ≈ 0.28-0.87
- stored energy ≈ 120-254 kJ
- $\upsilon_{e,ped}^* \propto n_e/T_e^2$ ~0.7-6

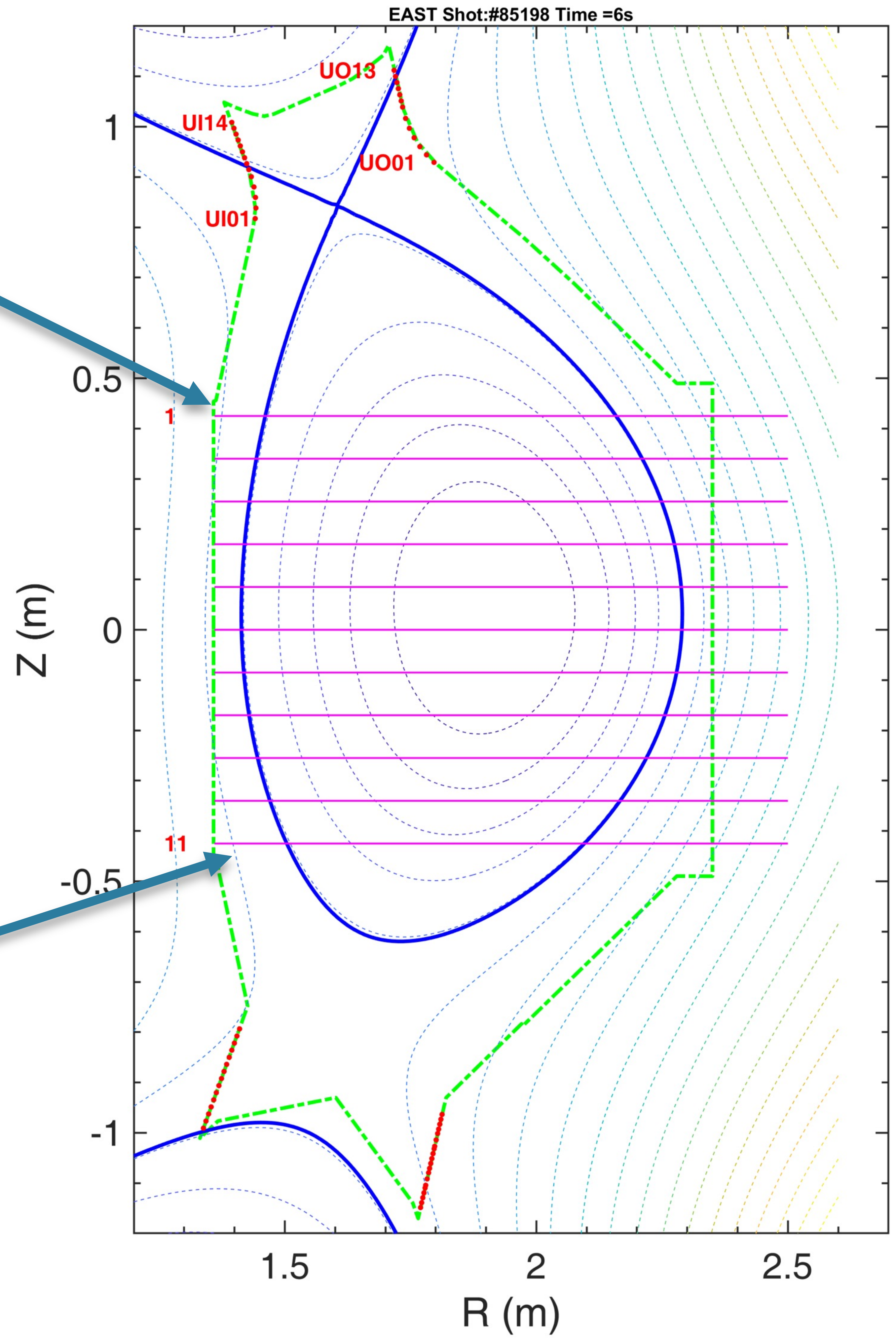
ELM suppression and the mode obtained with unfavorable B_t

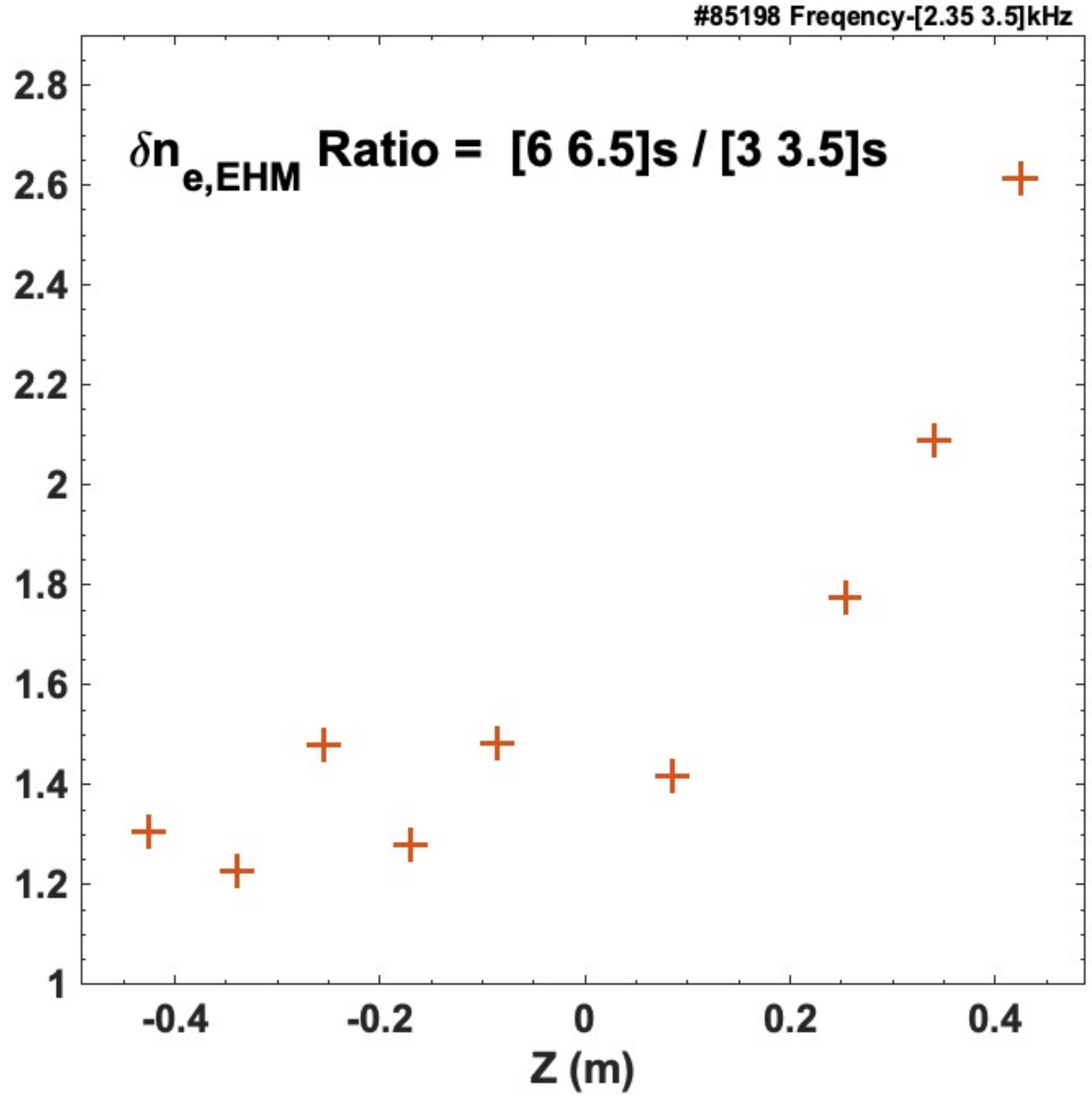


- **Total power~7.2MW**
  - NBI~3.9, RF~3.3
- **USN, Reversed B_T ~2.6T, B ×∇B↓**
- **Density and stored energy drops slightly ~5%**
  - Perhaps due to the opposite drift direction

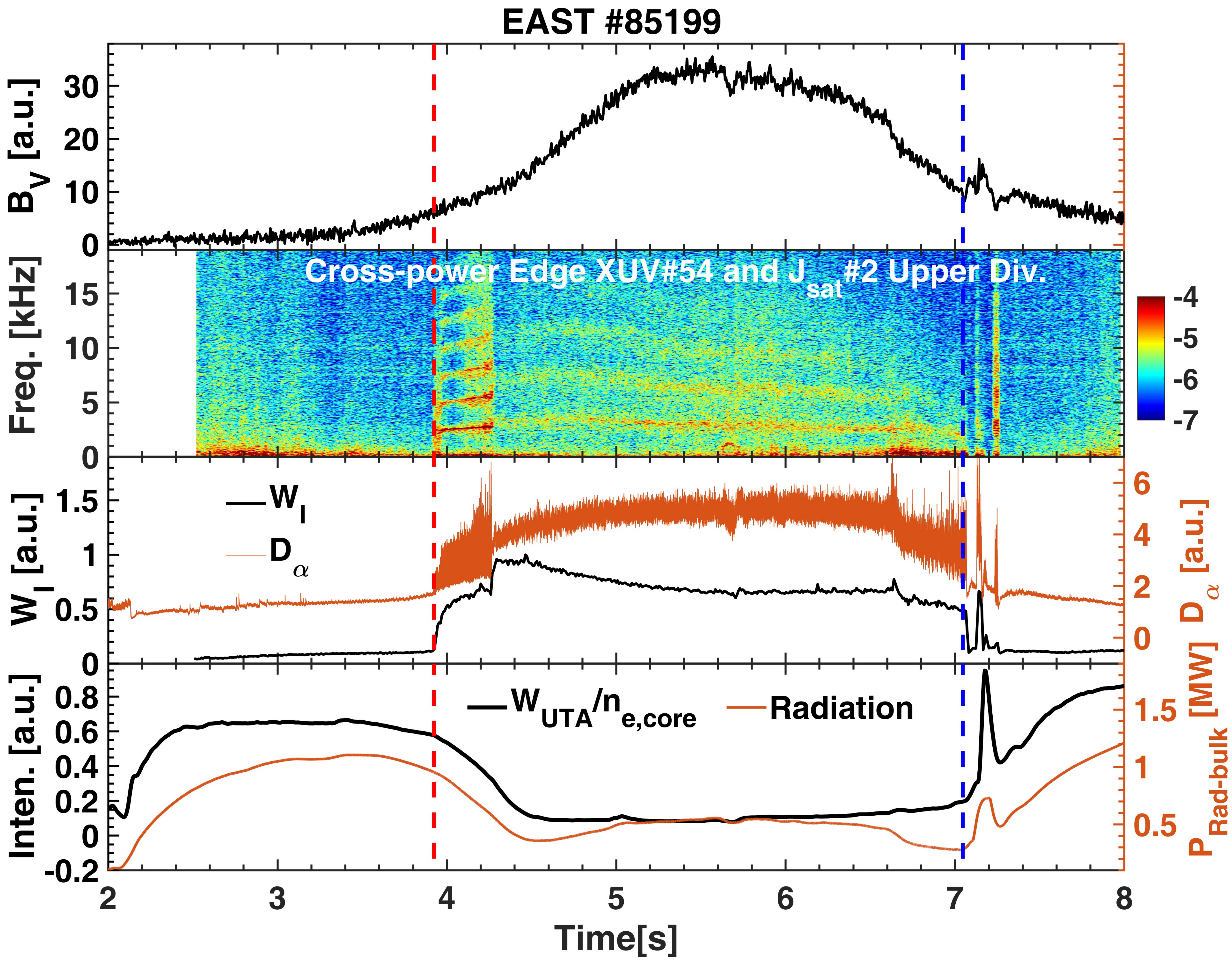
The mode not uniform along the poloidal cross section







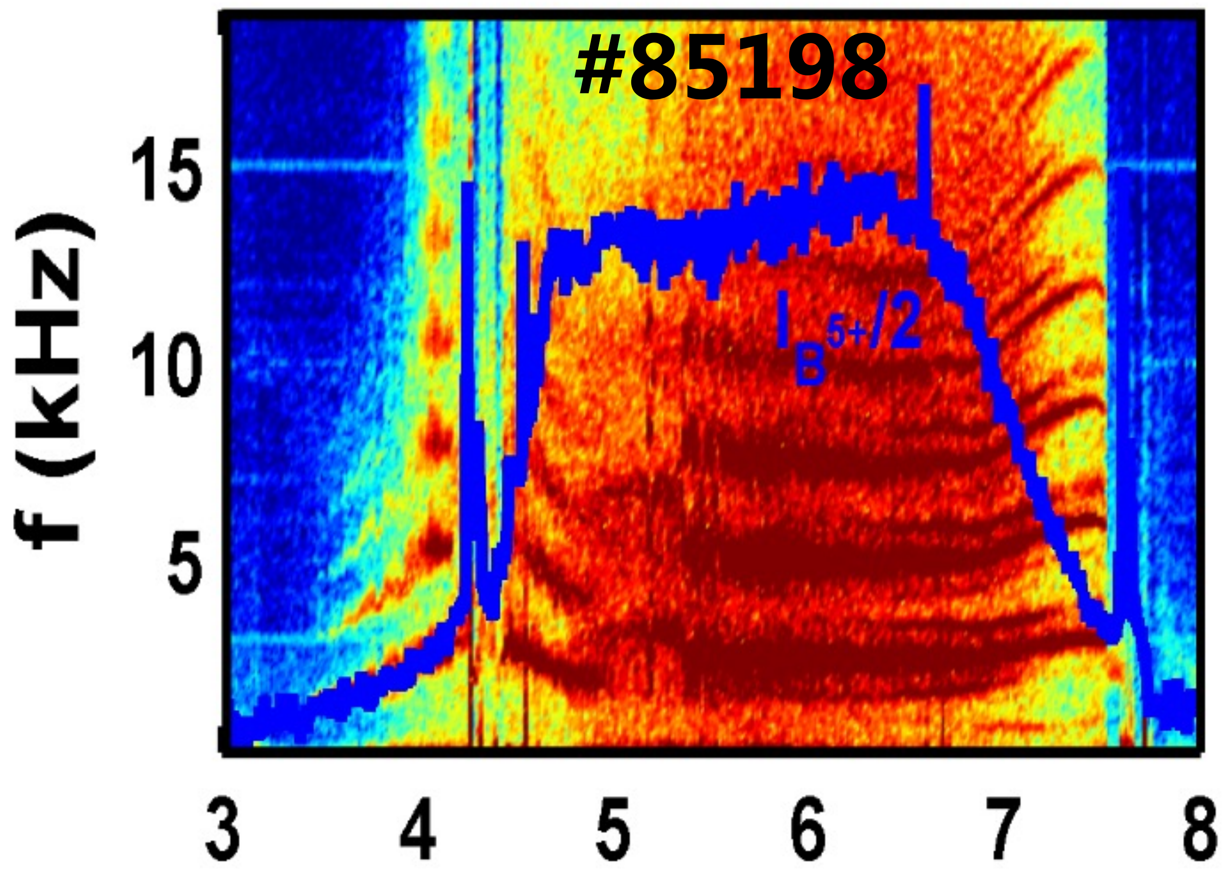
Mode produces net transport and drives particles out from the core into the wall



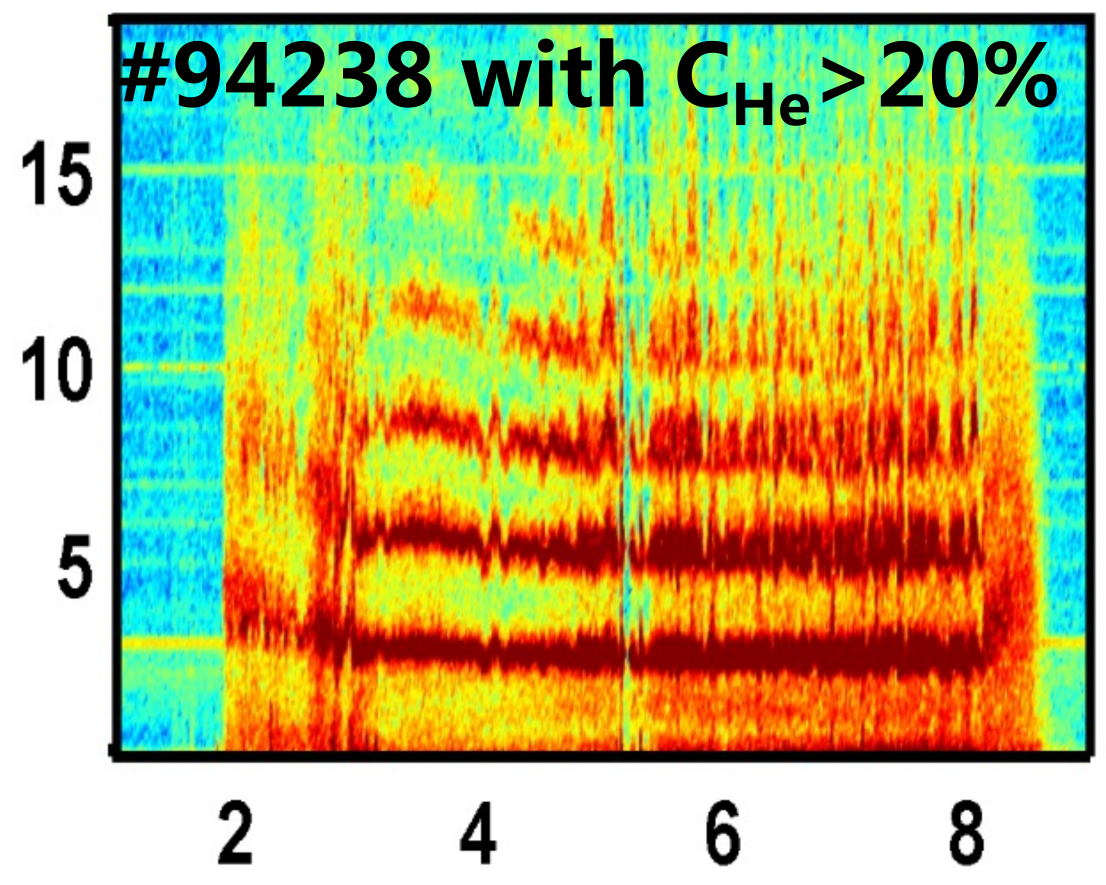
- **The mode onset, shown as the red line**
  - D_α baseline and W_I emission ↑
  - $\widetilde{D_\alpha}/\overline{D_\alpha}$: <1% → ~6%
  - Core W density & radiation↓
- **The mode disappears, shown by the blue line**
  - D_α baseline and W_I↓
  - core W and radiation power ↑

The mode can be observed with different impurity species

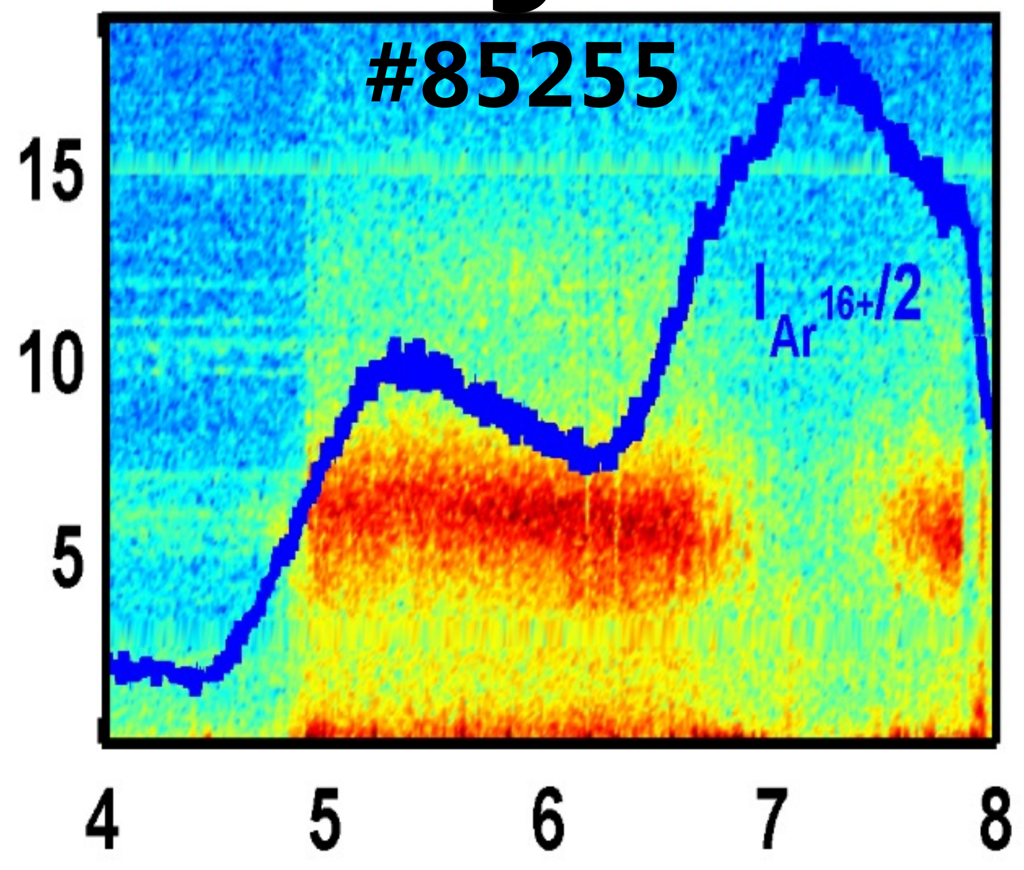
Boron



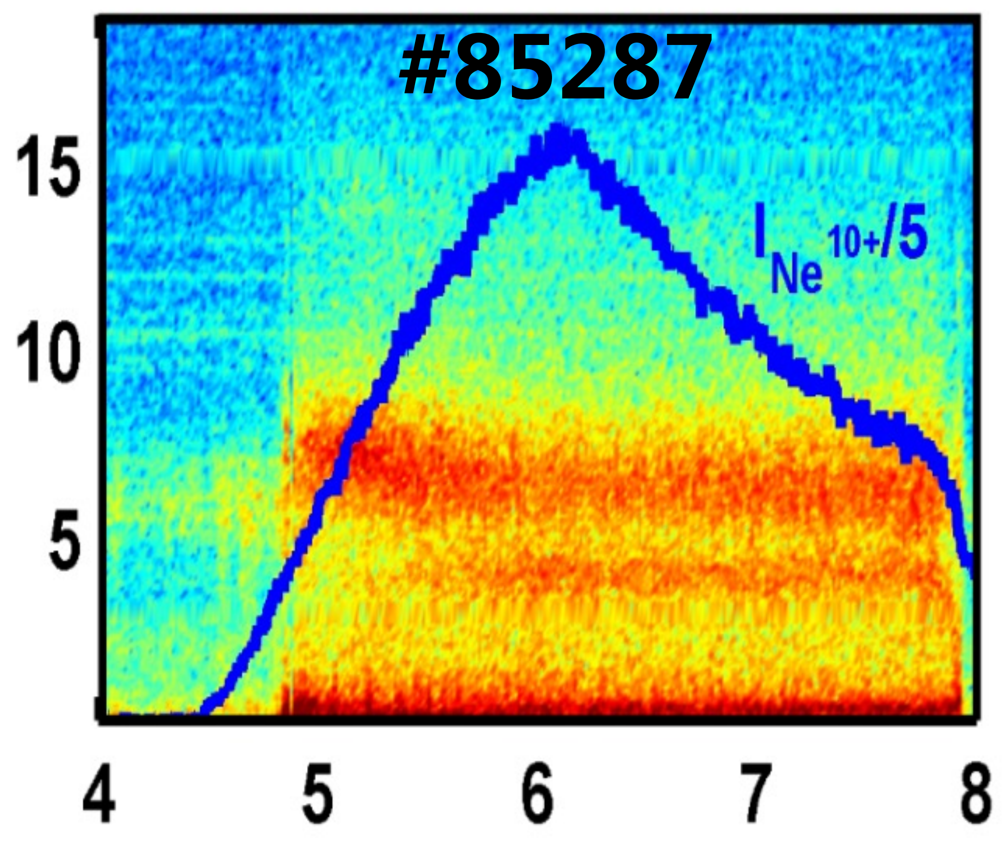
Helium plasma



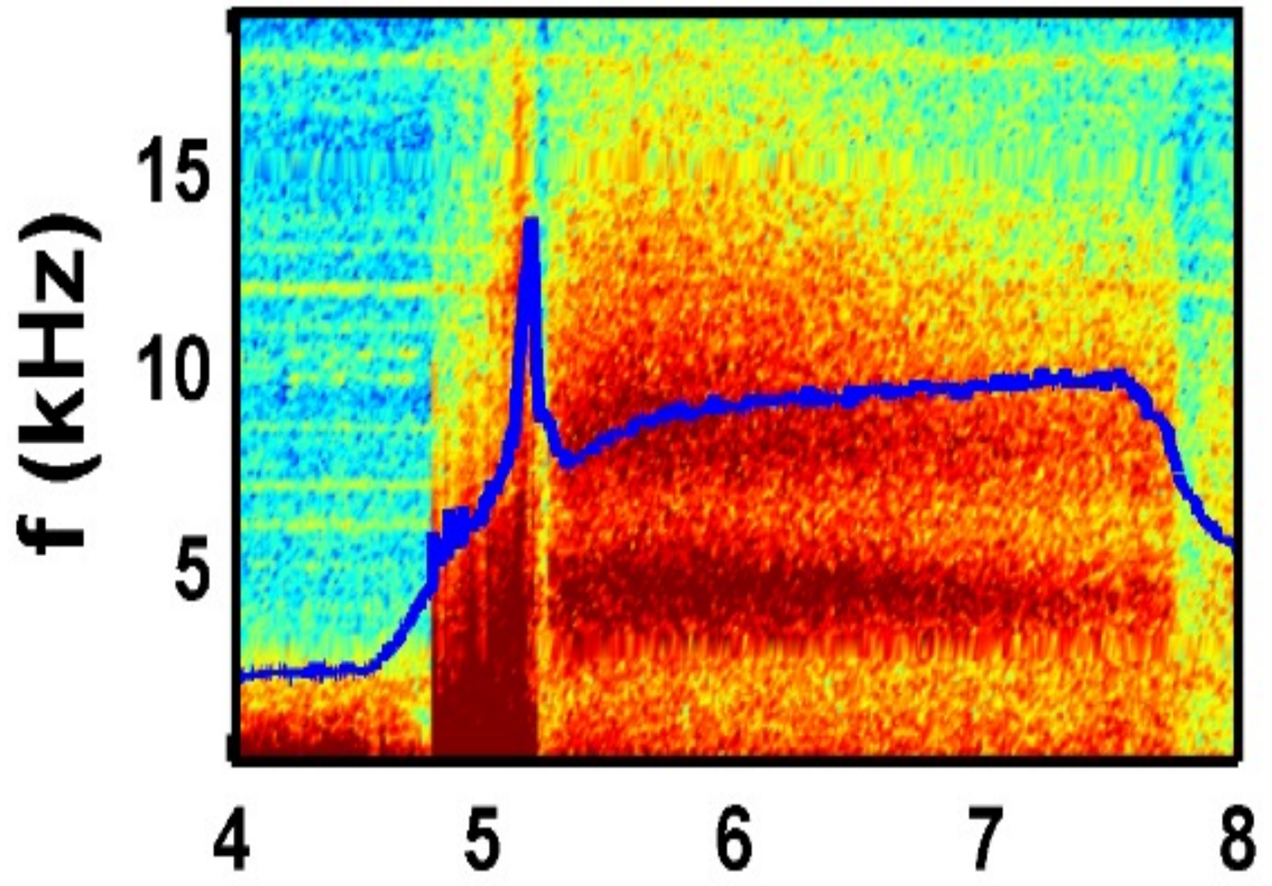
Argon



Neon



CD4

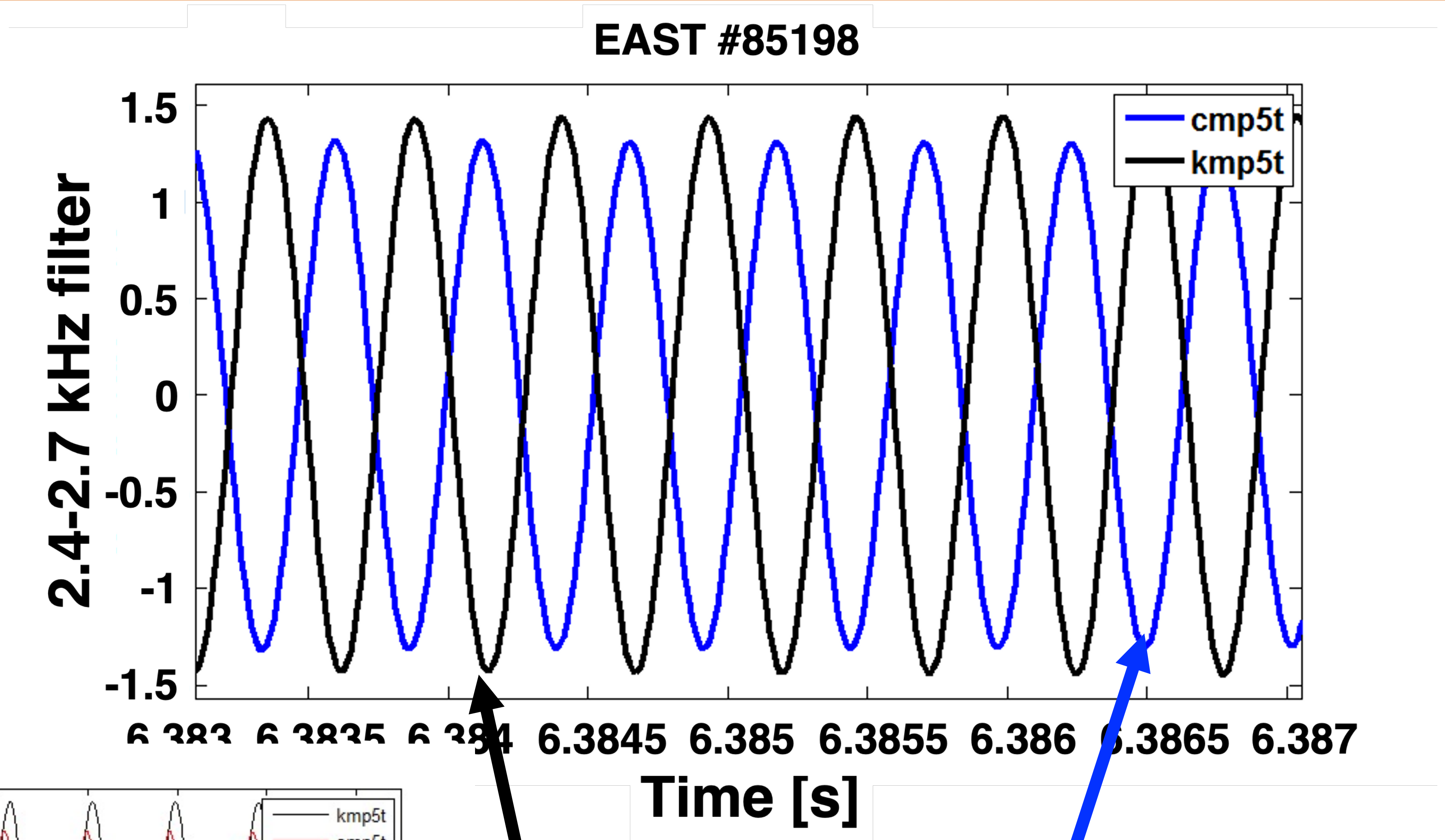


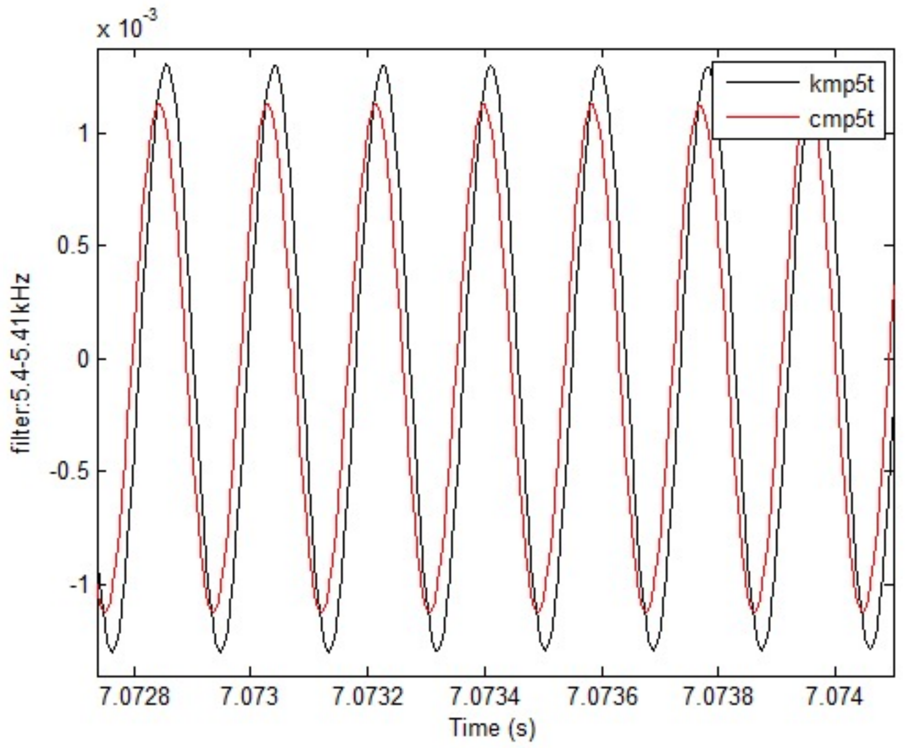
- **Boron is easiest to excite the EHM**
- **Harmonic number is different**

Mode appears on all poloidal section by Minrov probes

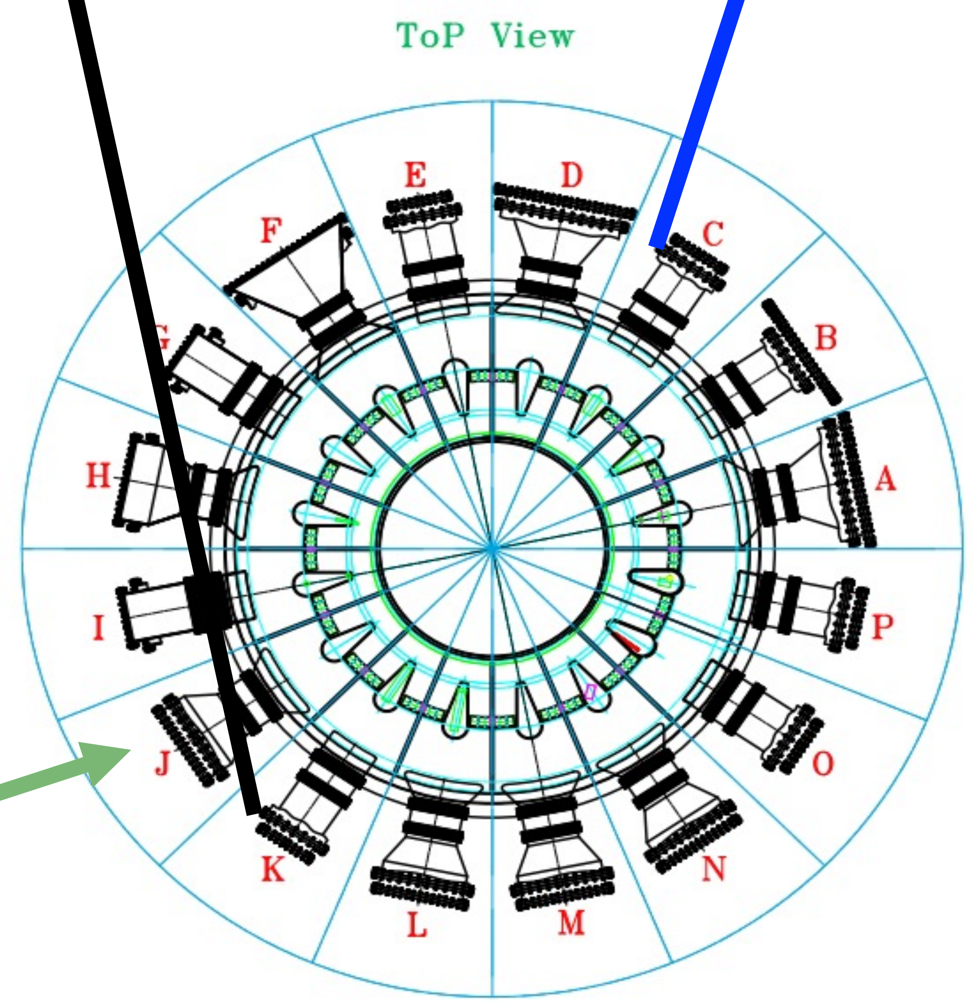
n=1 mode indicated by Mirnov coil measurements

$\Delta\phi=\pi$

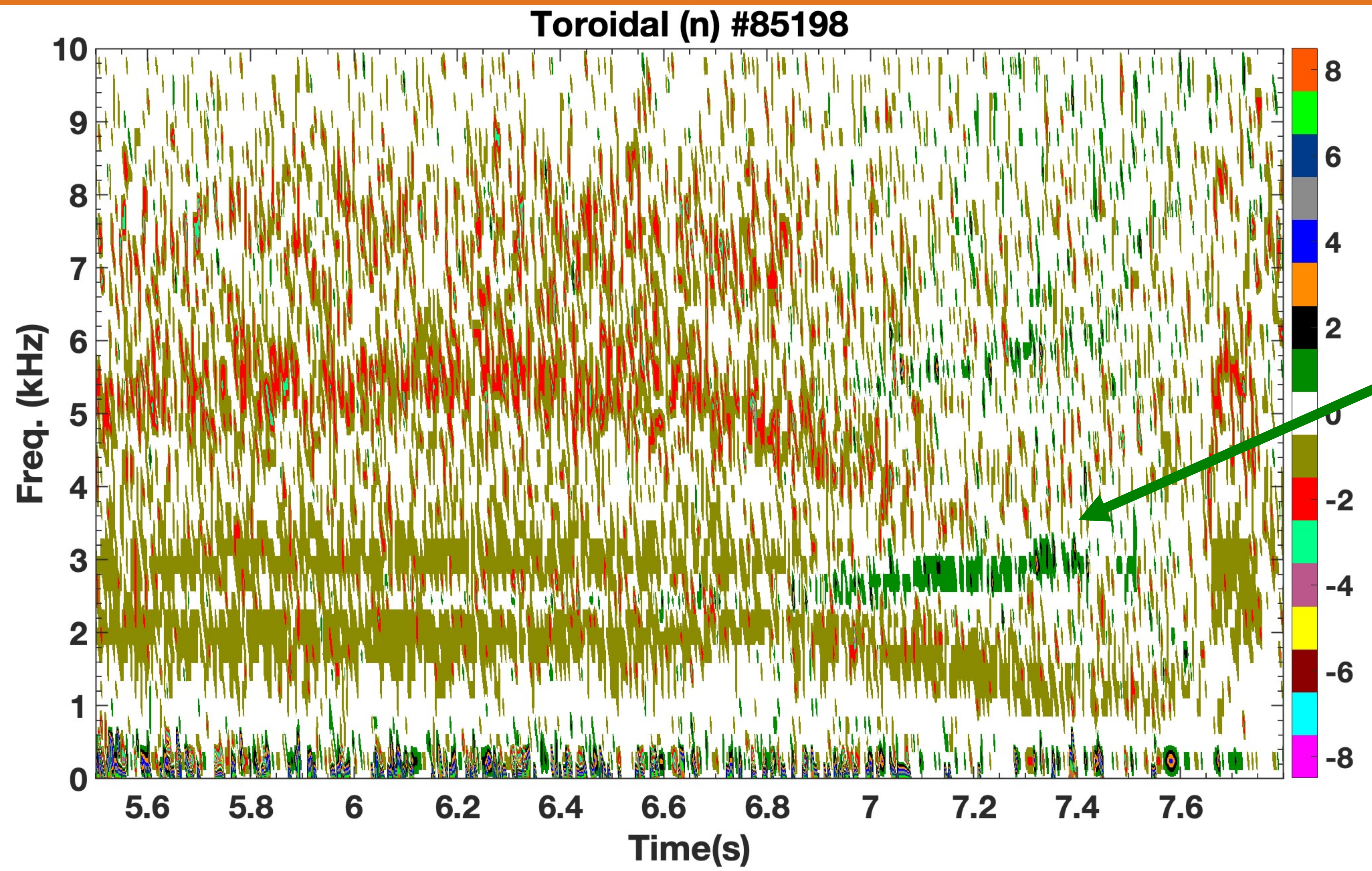




2nd harmonic $\Delta\phi\sim0$



IPD



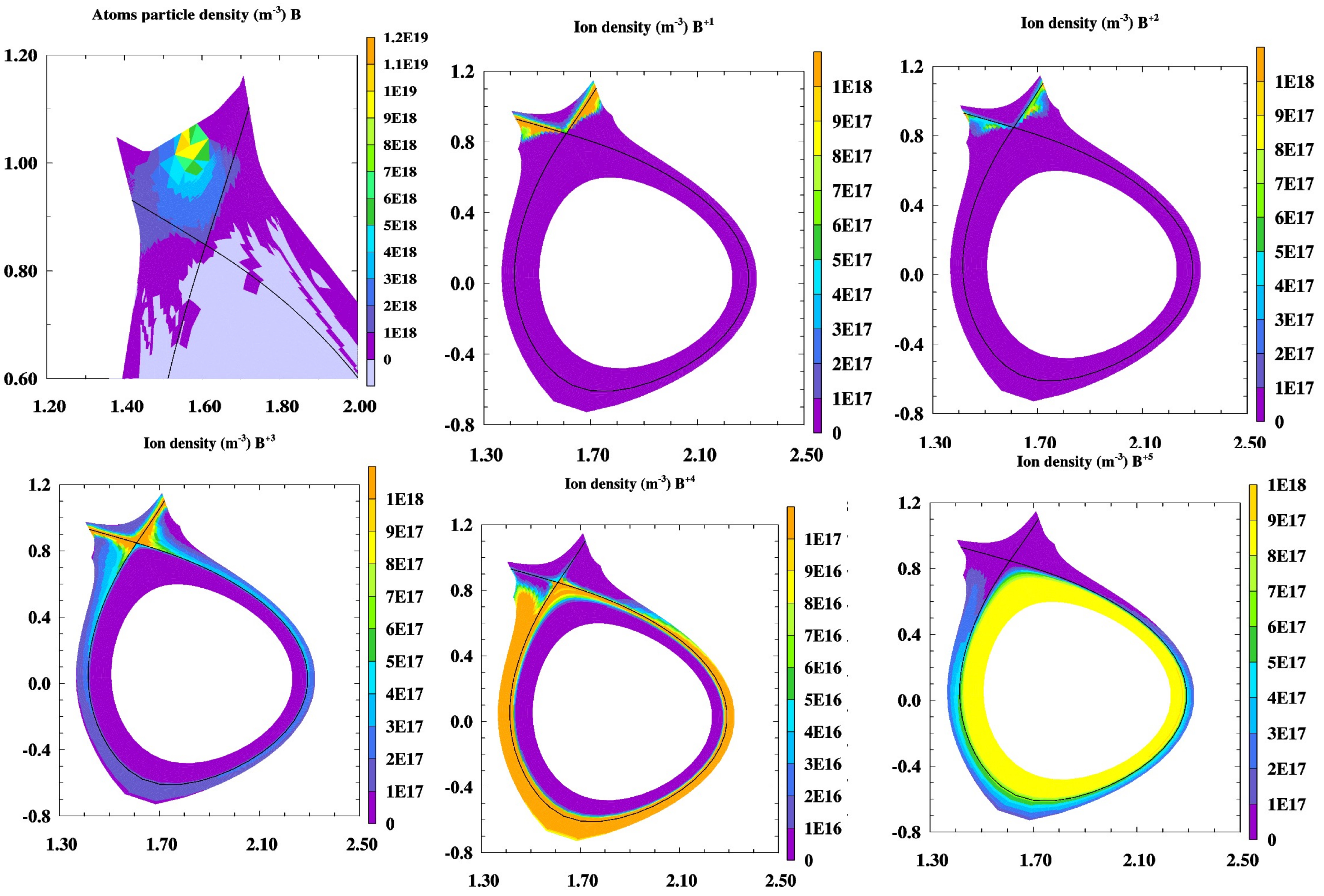
n=1

Different with the n=0 thermal current convective instability, i.e., the so-called fluctuating state mode, observed in AUG/JET/COMPASS/DIII-D and EAST

n=0 mode:

Loarte PRL 1999; Potzel JNM 2013; Potzel NF 2014; Komm NF 2019; Krasheninnikov POP 2016

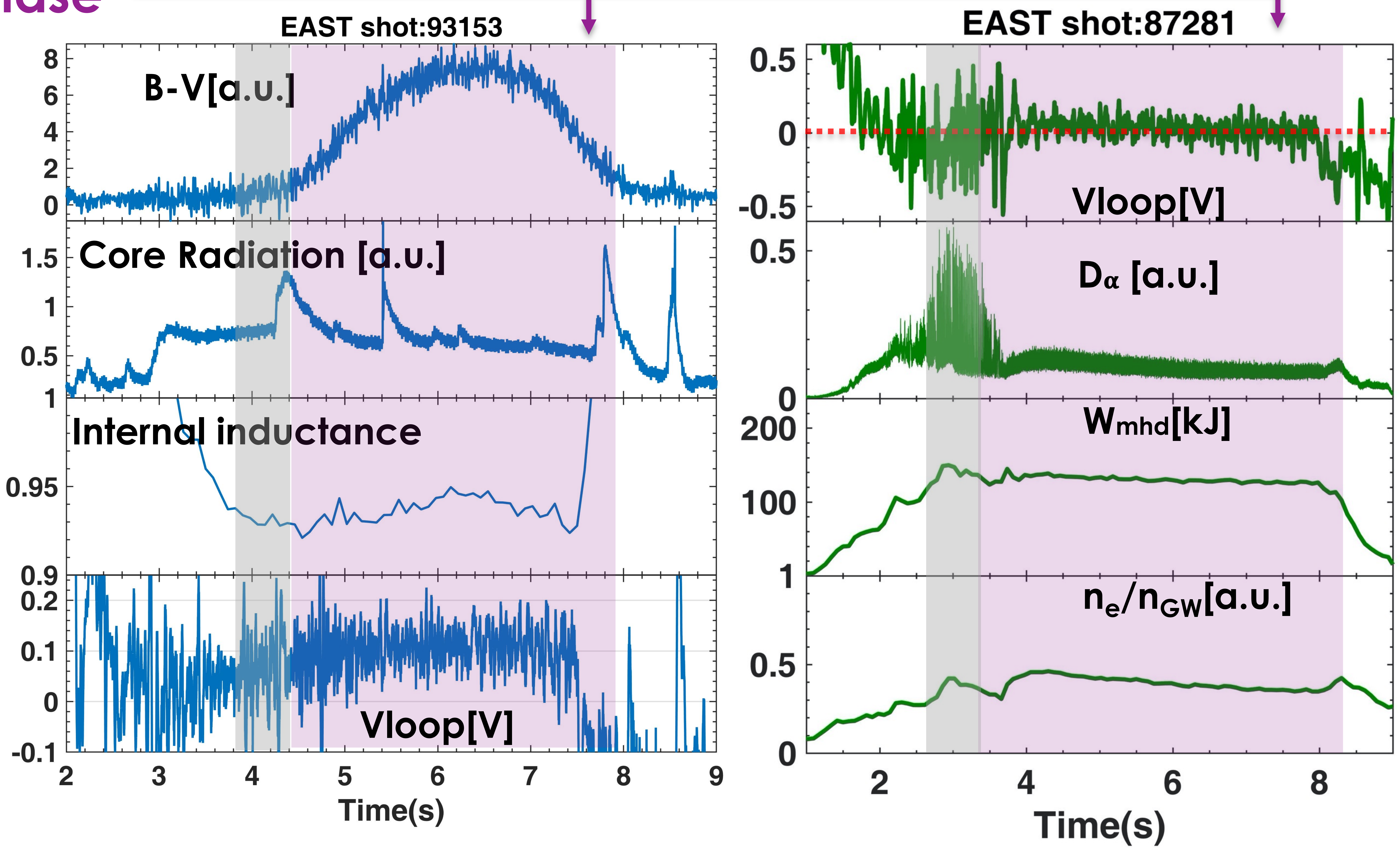
Boron species distribution by SLOPS



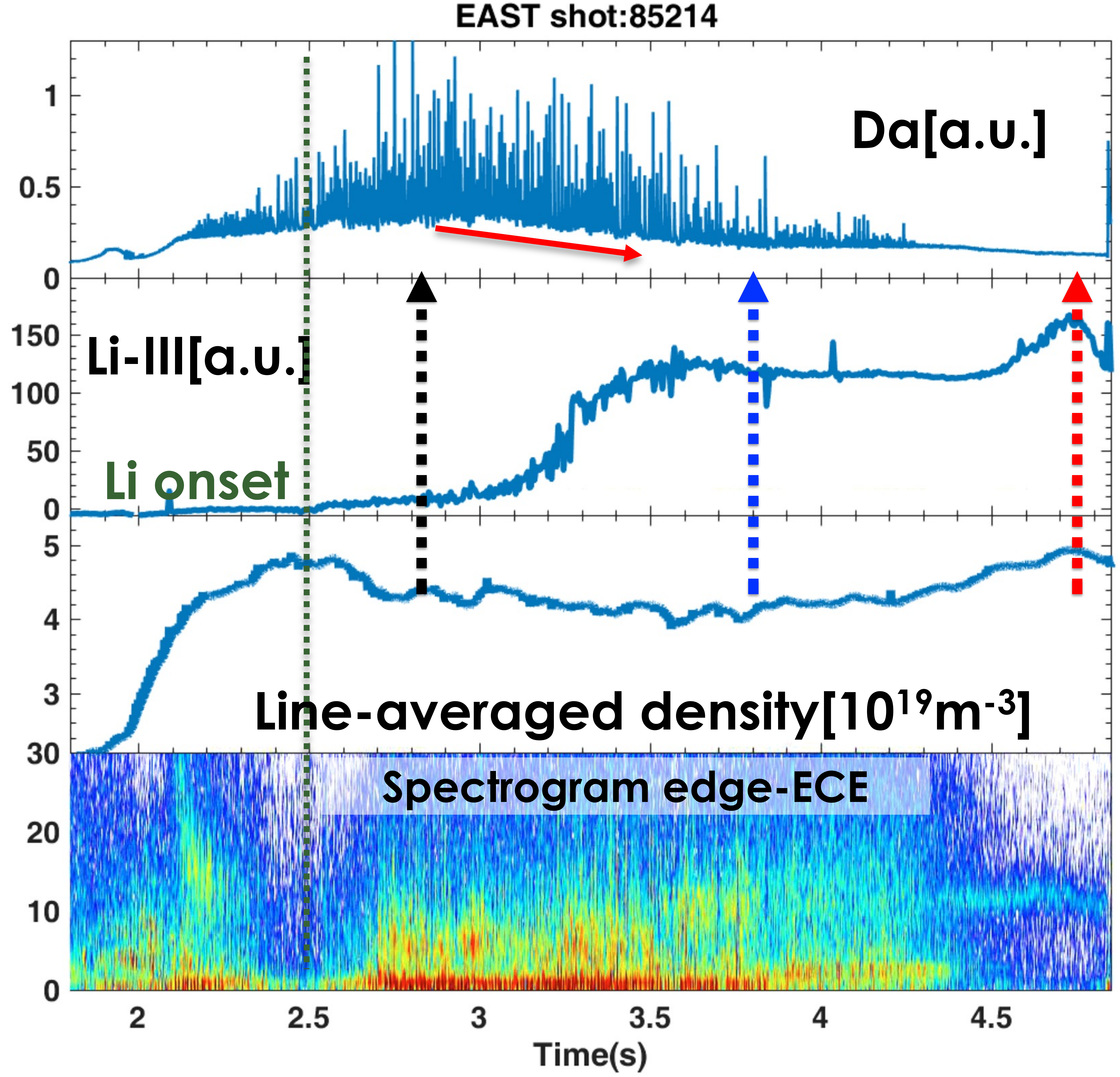
ELM suppression demonstrated in RF only discharges, paving the way for future long pulse demonstration

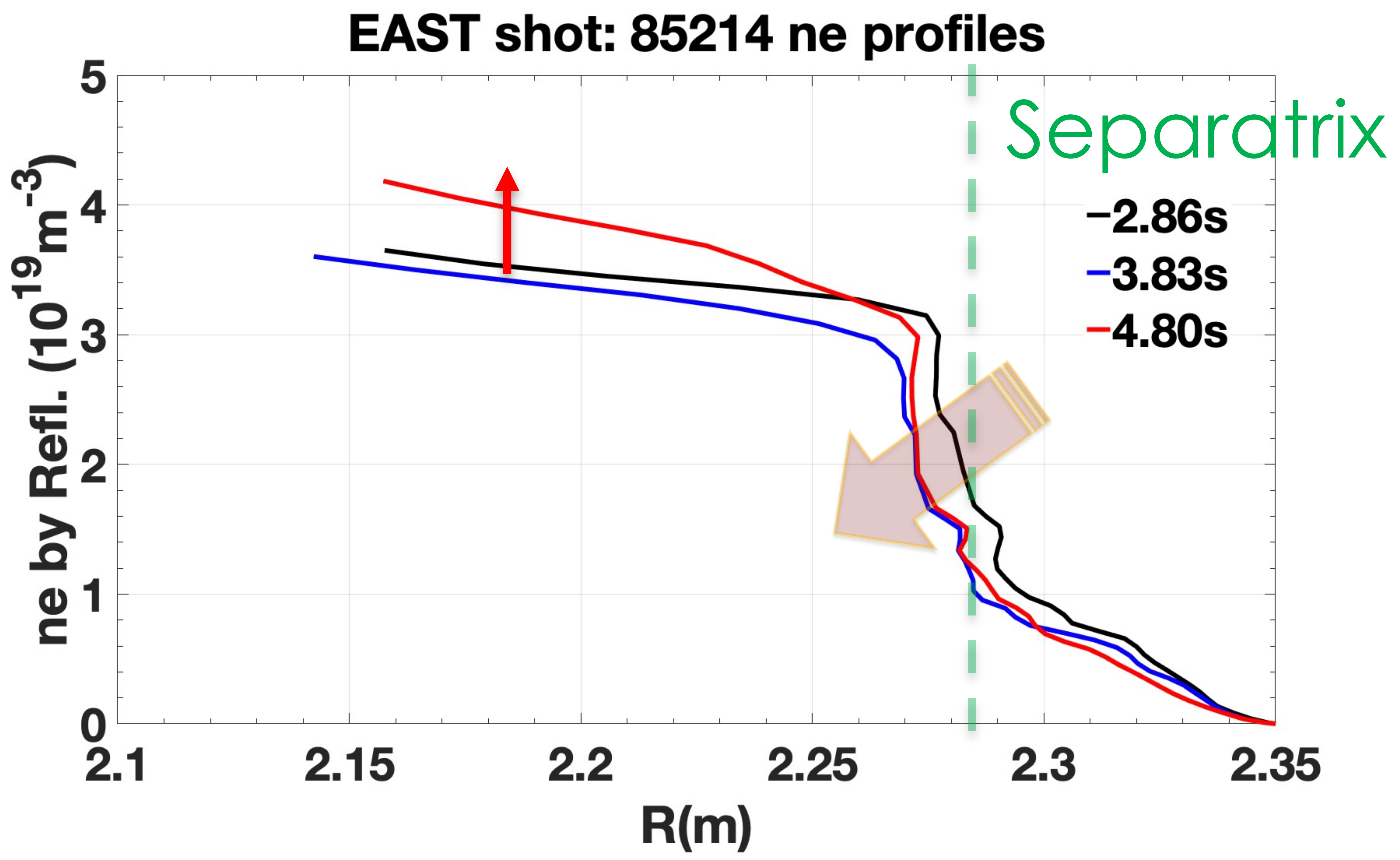
Boron injection phase

- ECH+LHW+ICRF
- No effect on core radiation
- Slight effect on li and loop voltage increase
- Constant W_{MHD} and ne
- Vloop~0.0V



Li ELM suppression related to pedestal density moving inward; ECM not enough strong to drive particles out

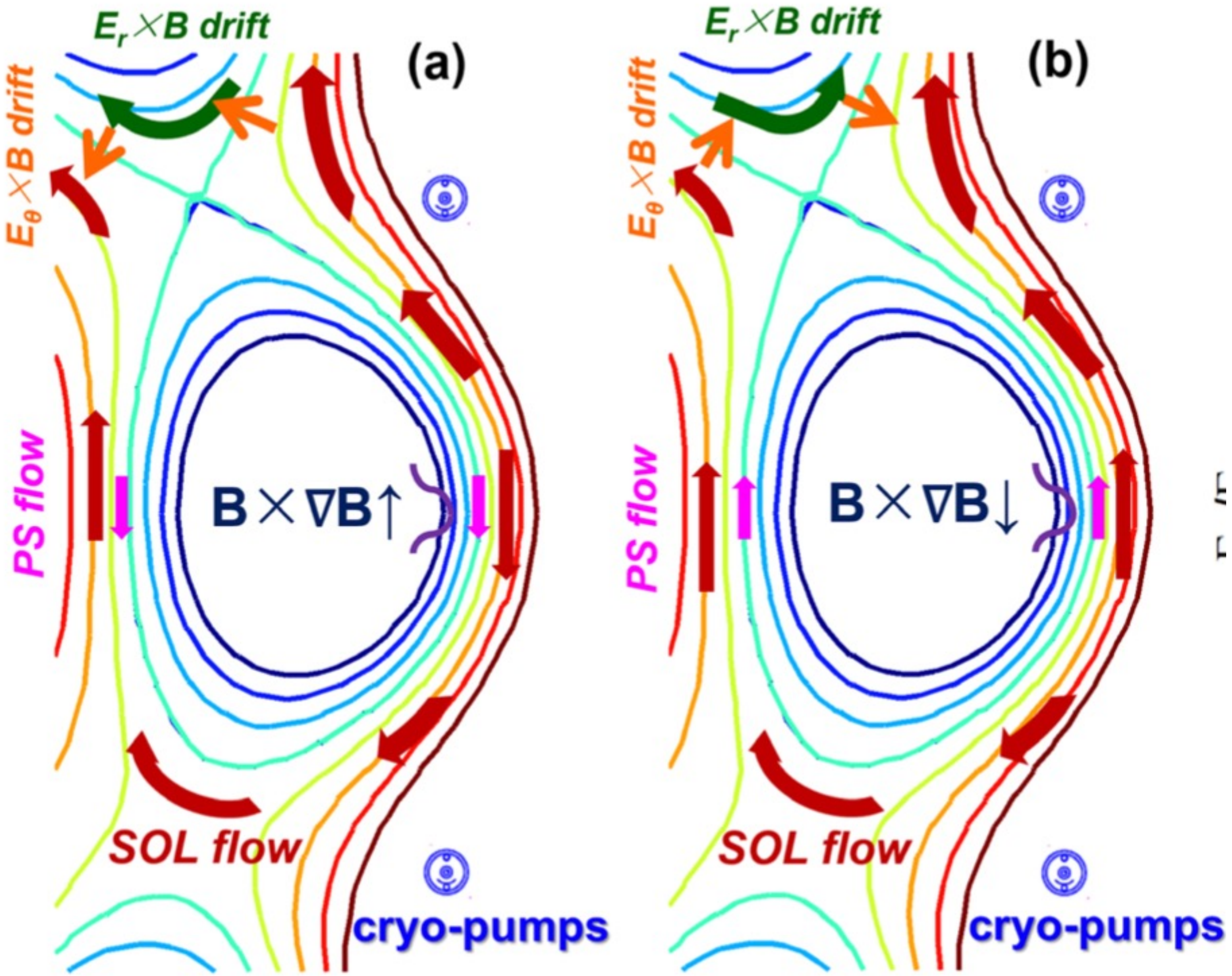




- Stronger ability Li pumping with metal wall→ pedestal density reduce →ELM mitigation/suppression→ core density gradually ramp up, similar as NSTX
- No observation of enhanced ECM amplitude

Reversed Bt

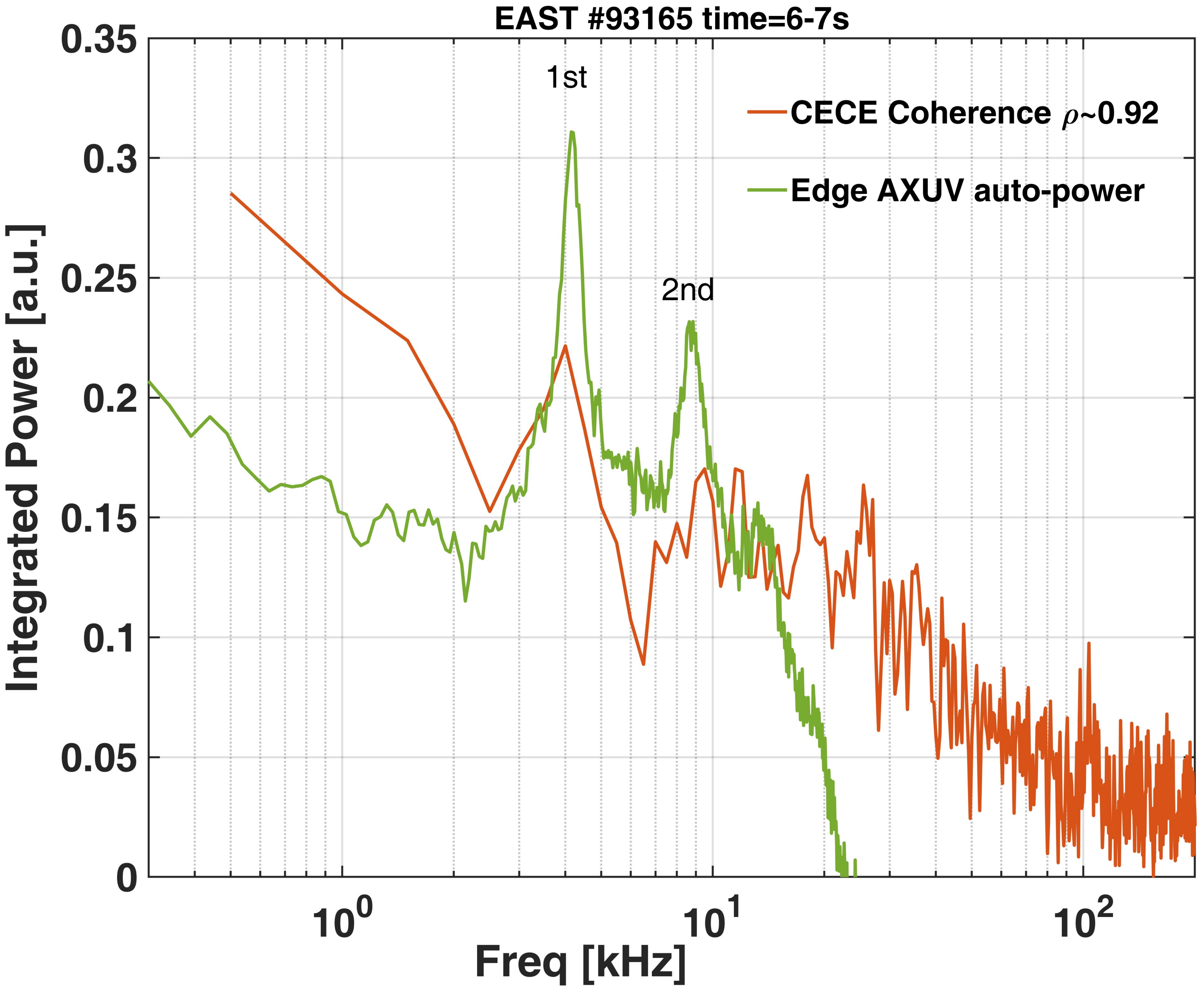
-



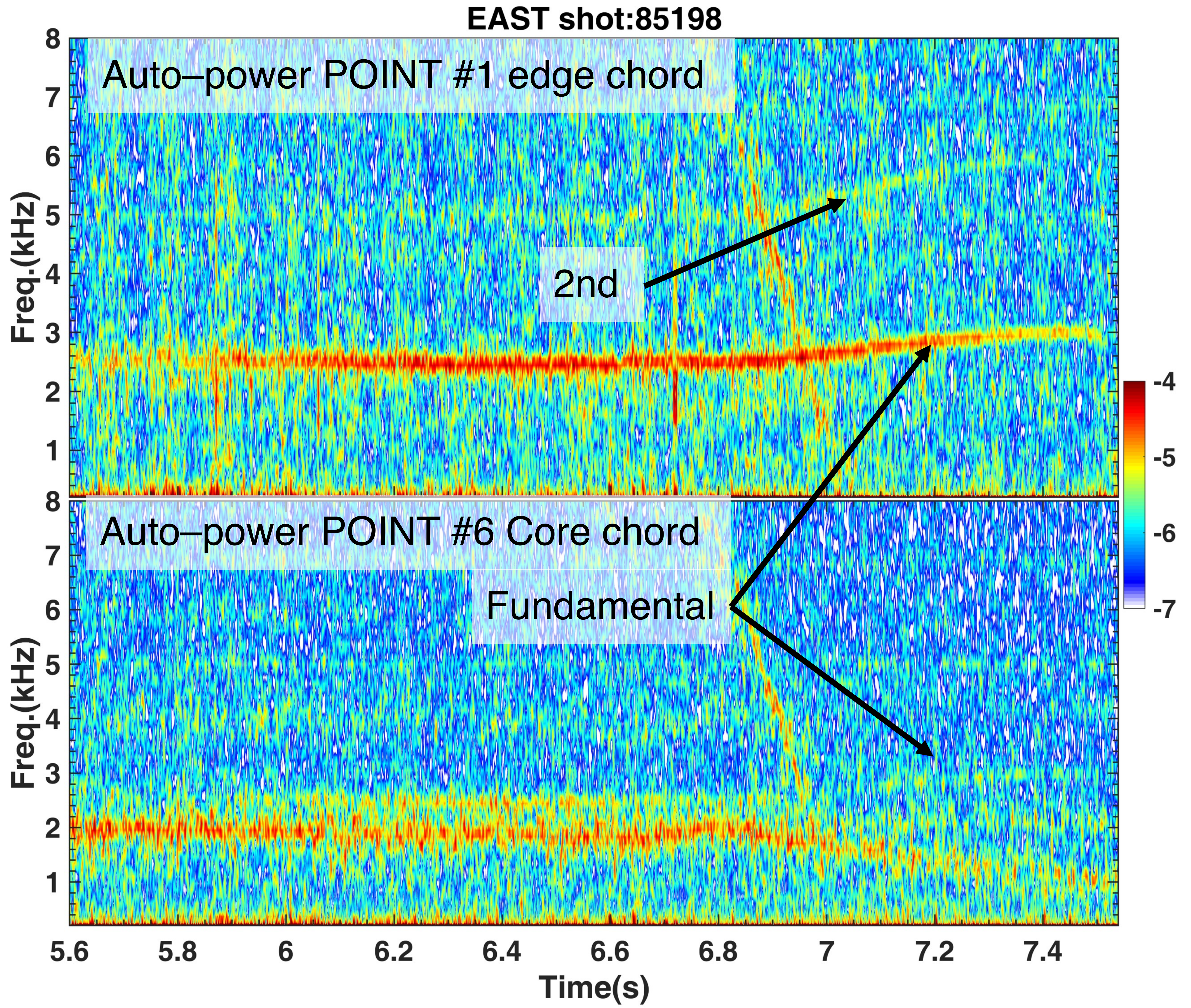
$E_r \times B$ drift
(a)
$E_\theta \times B$ drift
PS flow
$B \times \nabla B \uparrow$
SOL flow
cryo-pumps
$E_r \times B$ drift
(b)
$E_\theta \times B$ drift
PS flow
$B \times \nabla B \downarrow$
SOL flow
cryo-pumps

The harmonic mode observed in Te and ne fluctuation

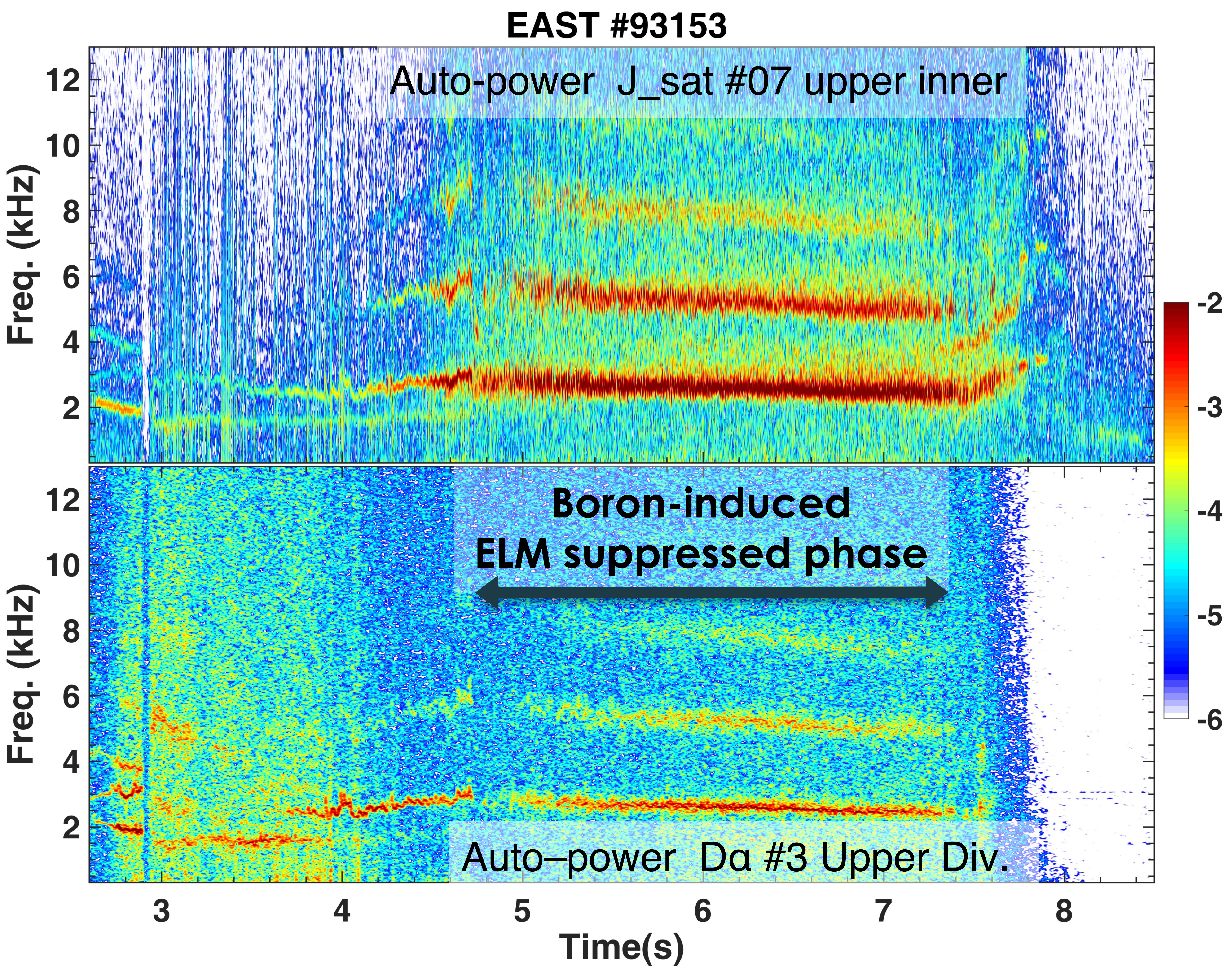
- XUV signal is proportional to $n_e^2 \times n_z \times f(T_e)$
- Observed the fundamental mode 0.89< ρ <0.95 by multi-channel correlation ECE

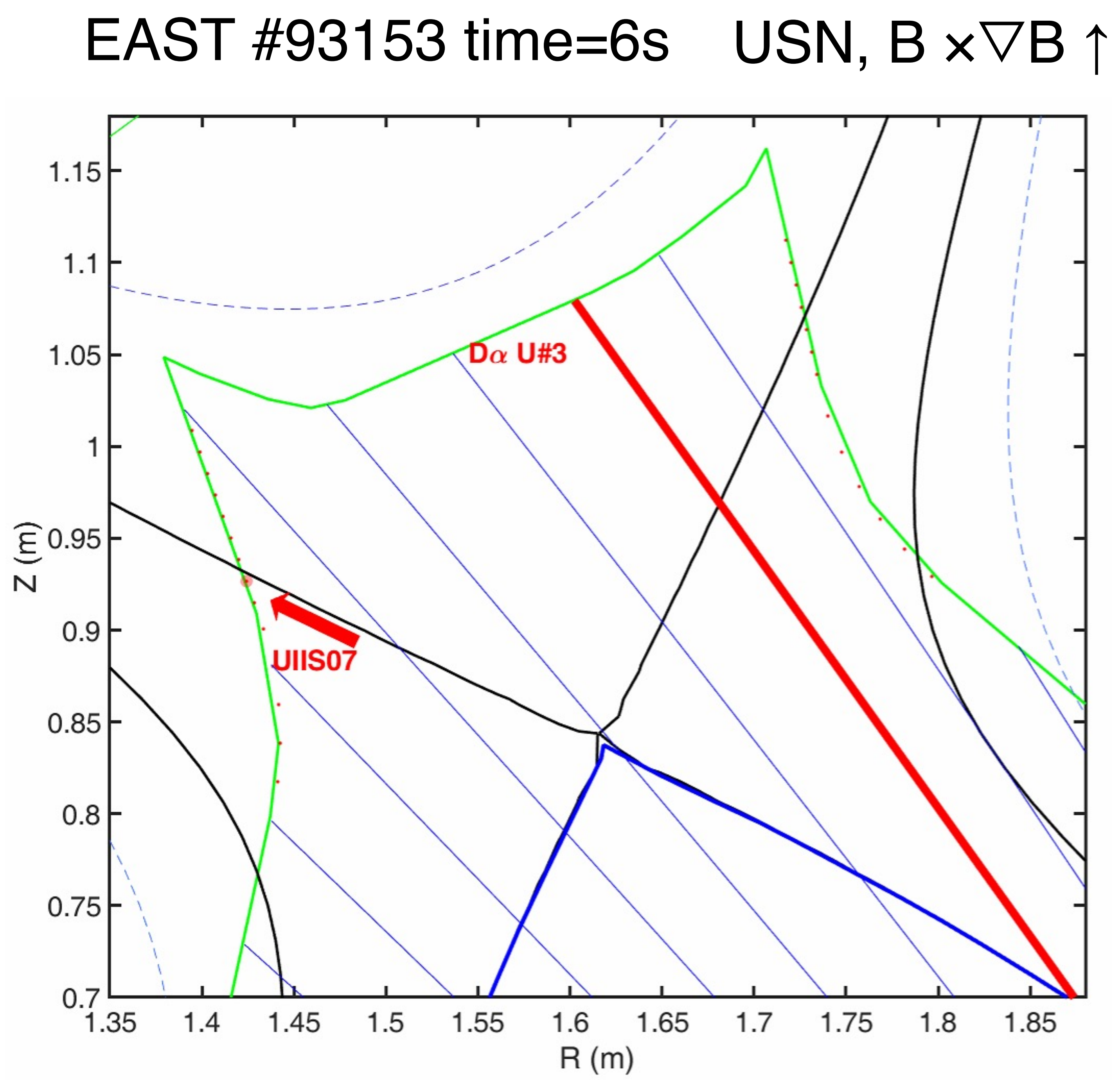


- Stronger intensity in edge density fluctuation measured by interferometer across pedestal than center



B-induced mode affects the particle transport

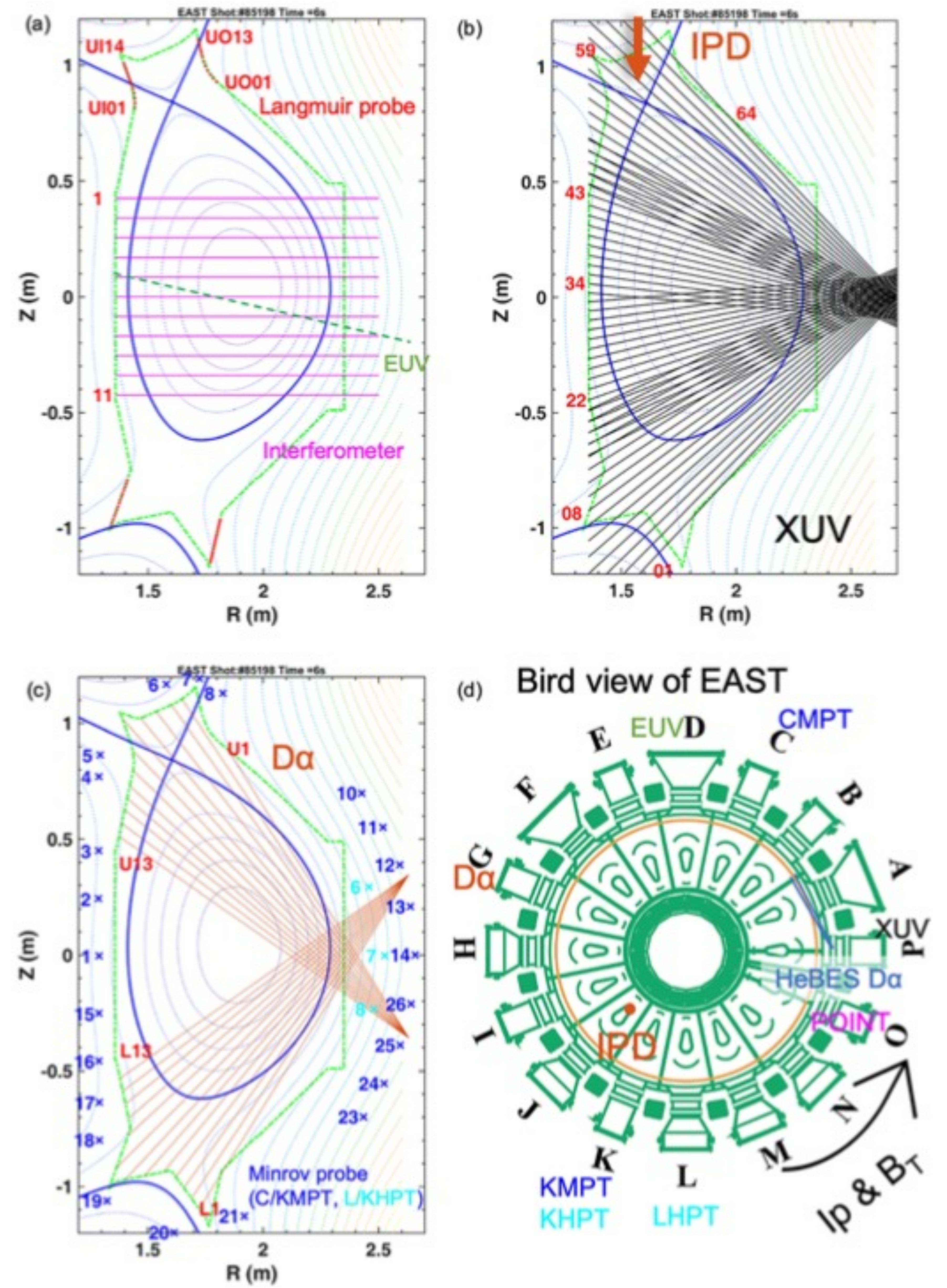




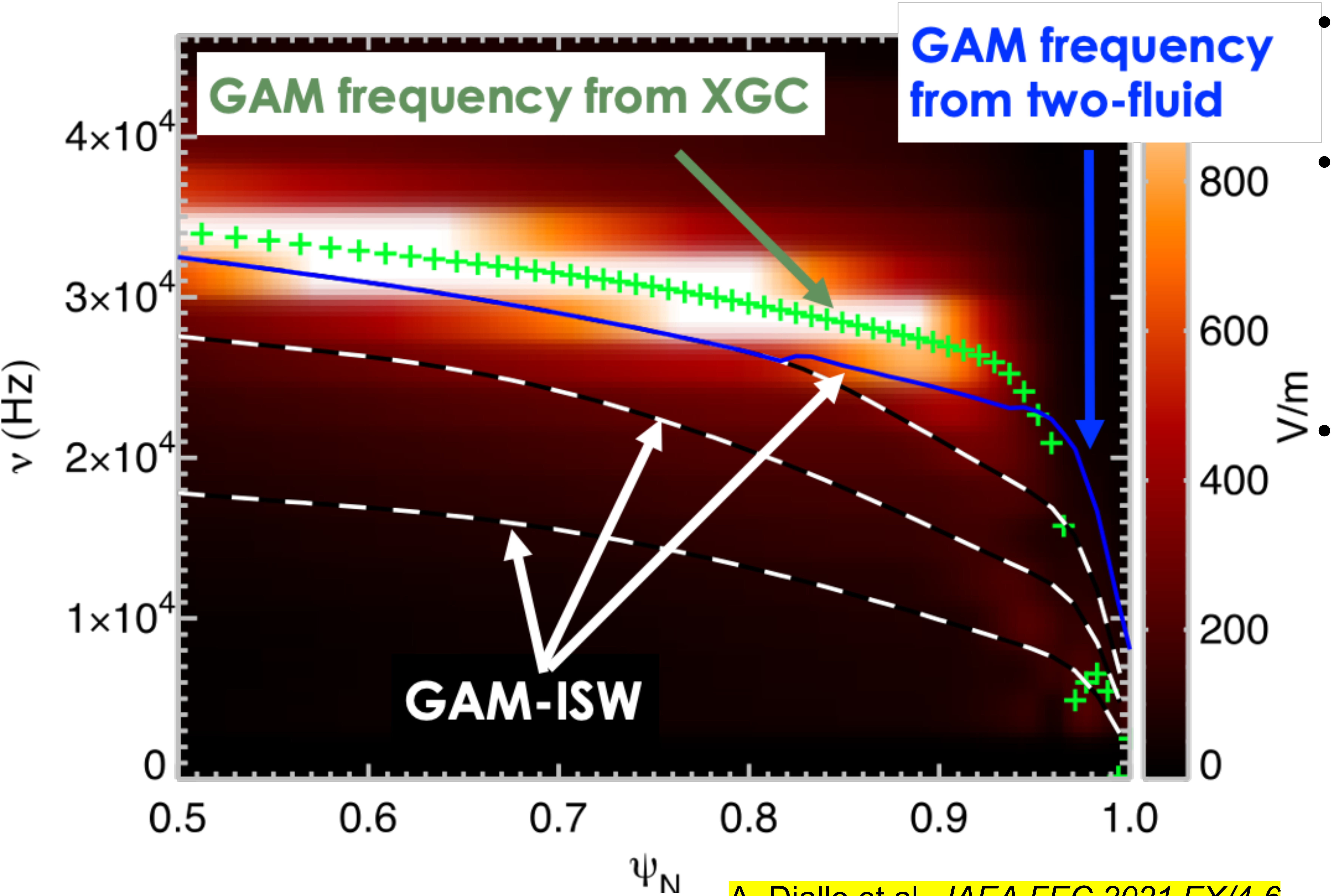
- **Observed in the divertor using D_a and Langmuir probes**

- **Suggests particle transport relating with the mode**

EAST diagnostics



Observed frequencies in the pedestal from neoclassical (XGCa) modeling consistent with Geodesic Acoustic Mode



- X-point drop location important
- While the n=1 mode can be excited, coupling to an n=0 is not yet clear
- Future work: extension of simulation coupling boron ablation and turbulence in XGC

A. Diallo et al., *IAEA FEC 2021 EX/4-6*

Origin of this mode?

- **Ablated Boron in X-point produces density perturbation akin of a density accumulation**

A density perturbation in the X-point results in perturbation that is effectively sensed poloidally (due the long connection length)

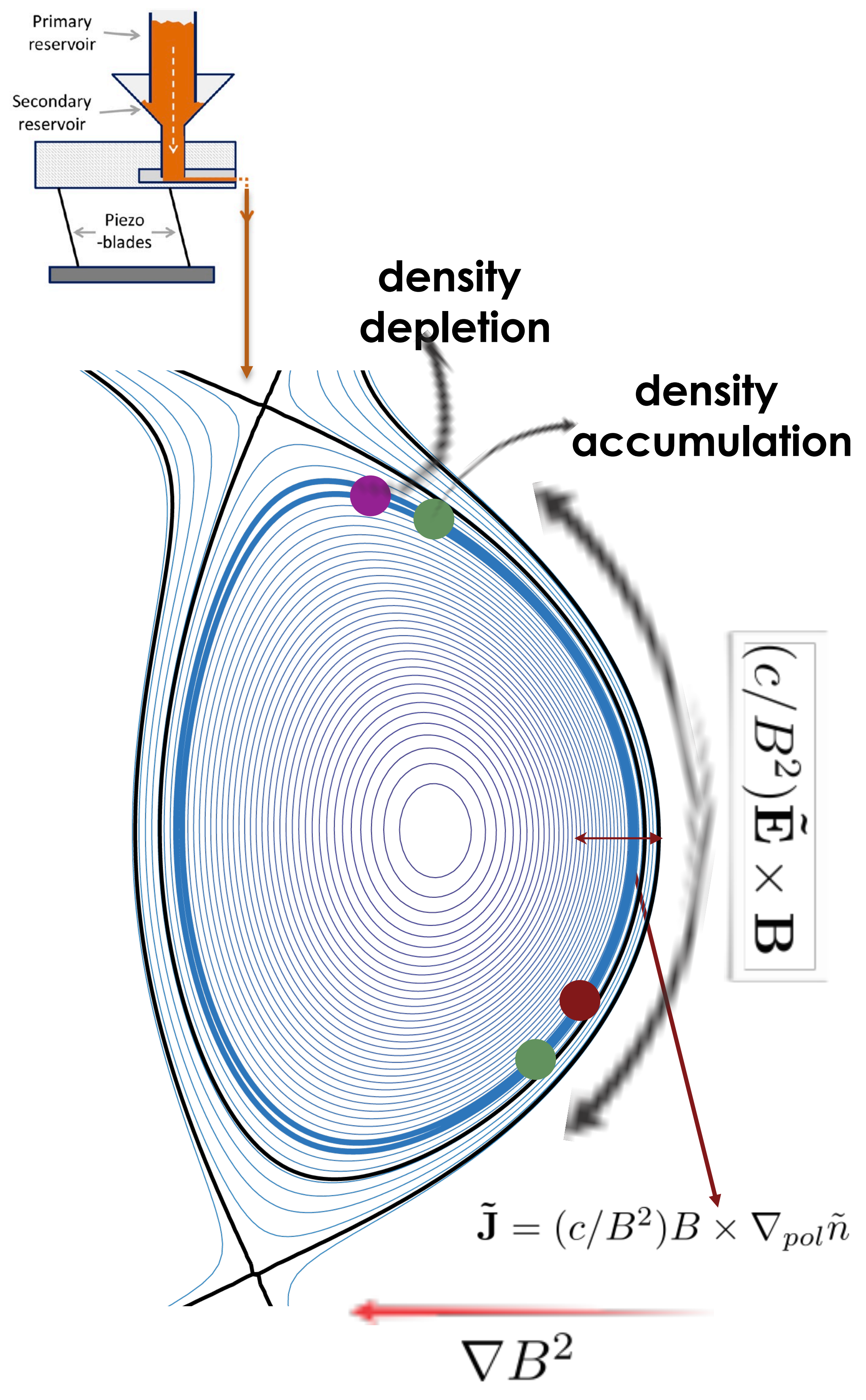
- **This density perturbation leads to poloidal asymmetries of charges**

⇛ Resulting in a perpendicular velocity (e.g., in the radial direction)

- **Asymmetries cause a radial current which transport charges across the magnetic surfaces**

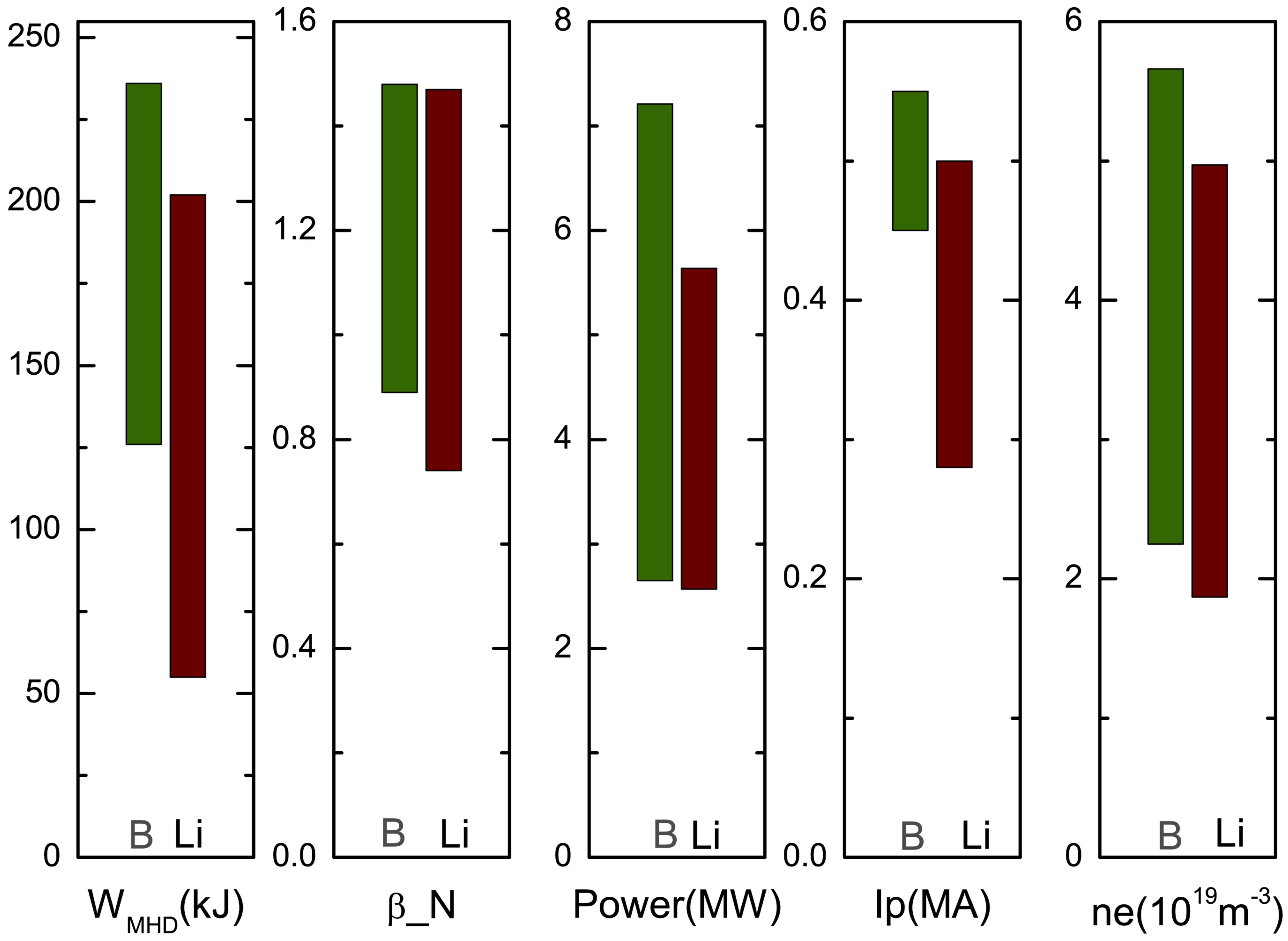
⇛ This current tends to reverse the perturbed E-field

- **➥Leading to a feedback and establishing a GAM-like mode**

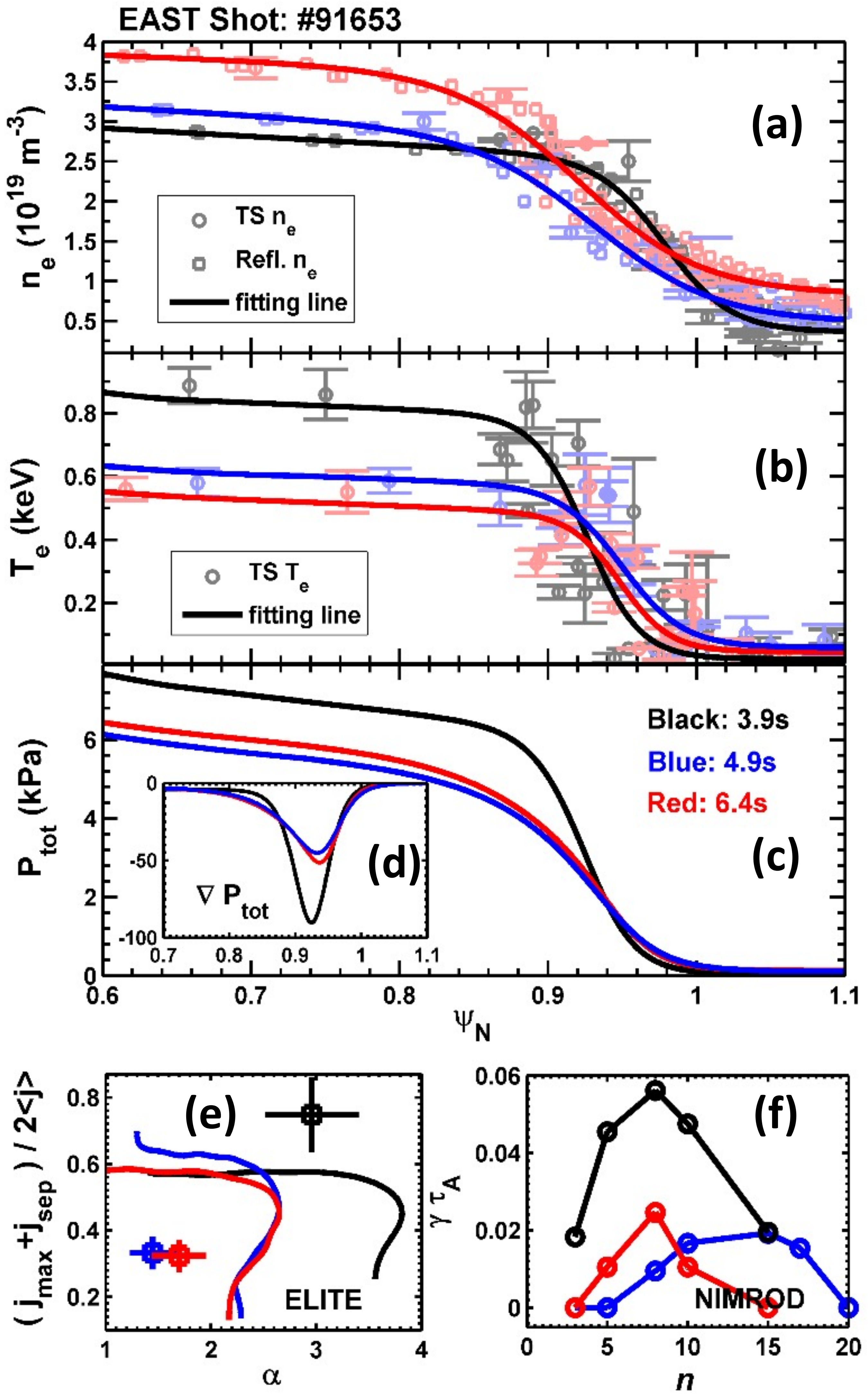


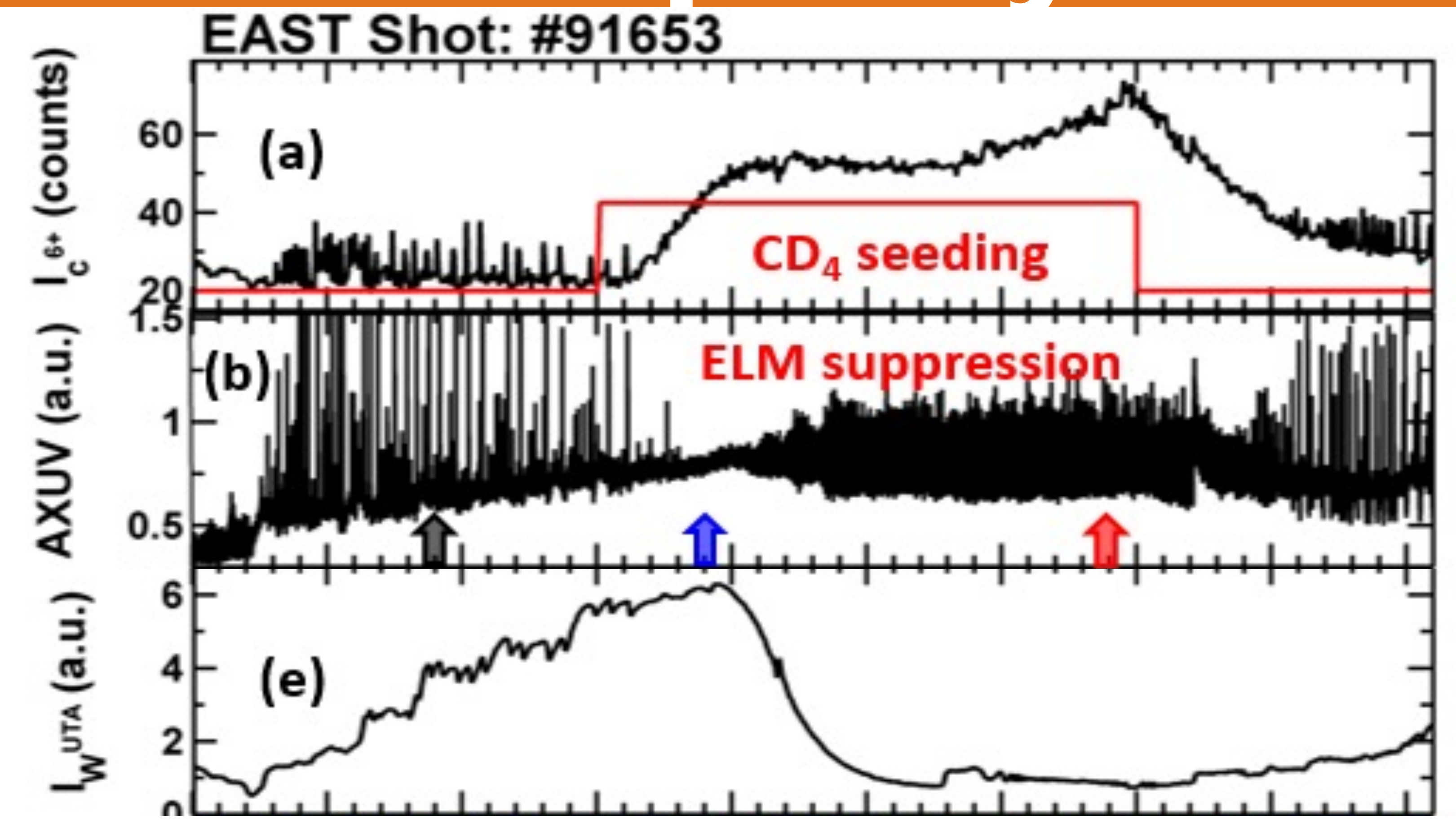
Global parameters range for impurity dropper induced ELM suppression

- **Operation window for B and Li is wide**
- **Boron ELM suppression achieved in high heating power and higher density**



The mode appears to help maintain a state with flat pedestal pressure gradient and low impurity concentration





Black (ELMy) → Blue (ELM free)

- **CD_4 seeding → detachment → edge recycling ↓ → particle fueling ↓ → pedestal electron density profile flatten;**
- **Impurity radiation cooling → electron temperature ↓;**
- **Pedestal pressure gradient and current density decrease by ~50% → ELM suppression;**
- **However, the high-Z impurity concentration continuously increases.**

Blue (w/o the mode) → Red (with the mode)

- **CD_4 seeding ↑ → pedestal top and foot density ↑, a low pedestal density and pressure gradient is maintained → the state of ELM suppression and low impurity concentration is maintained.**

A simplified theory for MHD drag in LMX

$$\sum F = \rho Q\,(u_2 - u_1)$$

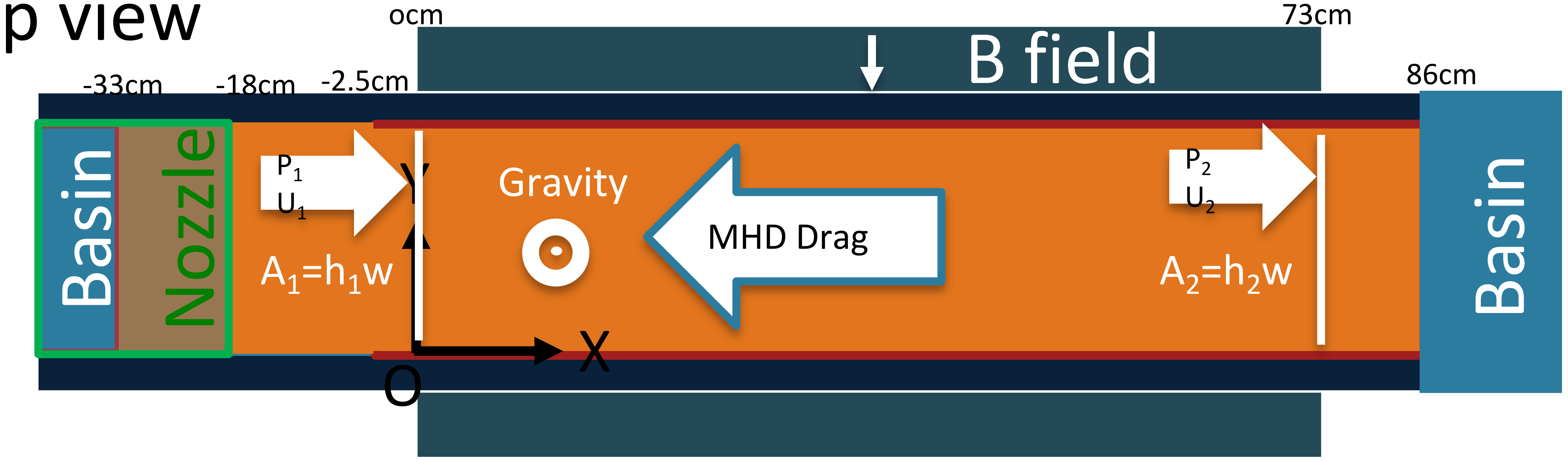
$$P_1A_1 - P_2A_2 - \int_0^L P_{MHD}(x)A(x)\,dx = \rho\, Q\,(u_2 - u_1)$$

$$\frac{dP_{MHD}}{dx} \approx K\sigma_{LM} \mathrm{u} B^2$$

$$\left(\frac{\rho\, g\, h_1^2\, w}{2}\right) + \frac{\rho\, Q^2}{h_1\, w} - K\sigma_{LM}\mathrm{Q}B^2L = \left(\frac{\rho\, g\, h_2^2\, w}{2}\right) + \frac{\rho\, Q^2}{h_2\, w}$$

$$\mathrm{K}= {}^{C}\Big/_{1+\frac{w}{3h}+C} \qquad \mathrm{C}= \frac{\sigma_w}{\sigma_{LM}}\frac{t_w}{w}$$

Top view



Assumptions:

- **Steady-state, fully developed, inviscid flow**
- **Simple derivation based on electrical approach**
- **Uniform current density, expected to be valid for higher magnetic field, highly conducting walls, low conductive wall leads to a not uniform j**

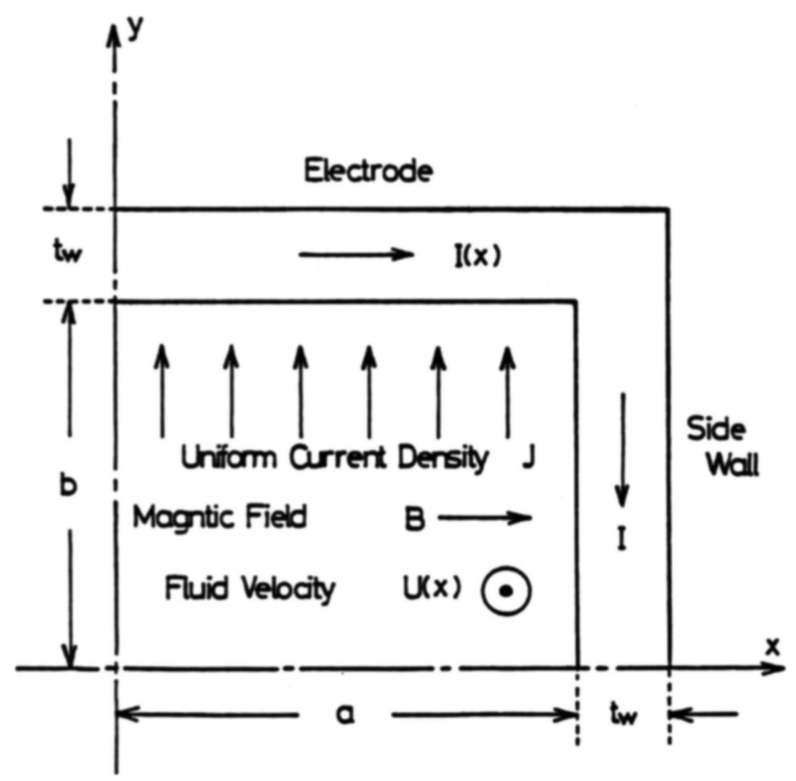


Fig. 1 Illustrative diagram for theoretical analysis

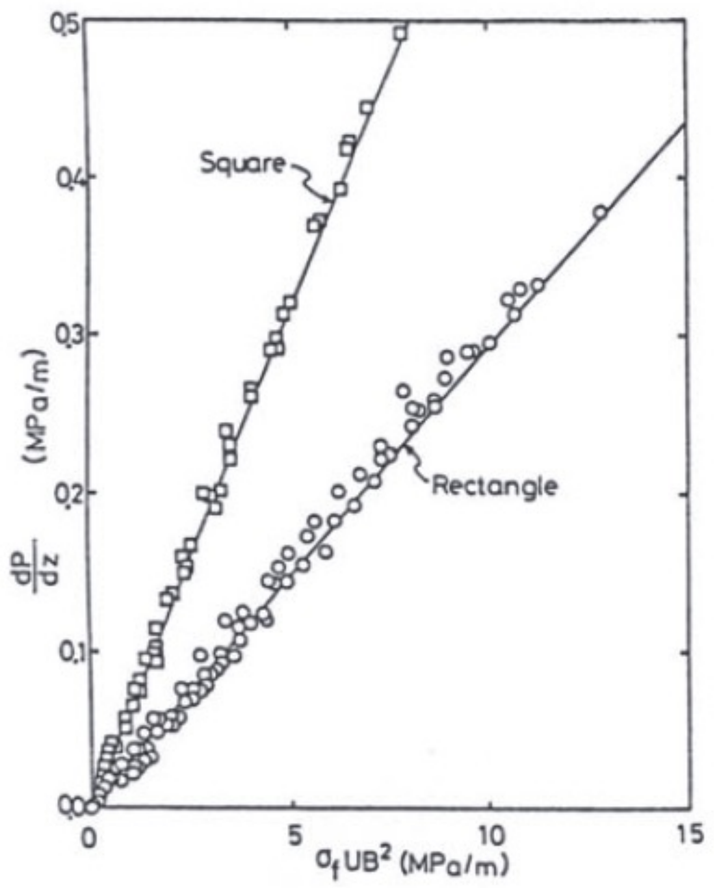
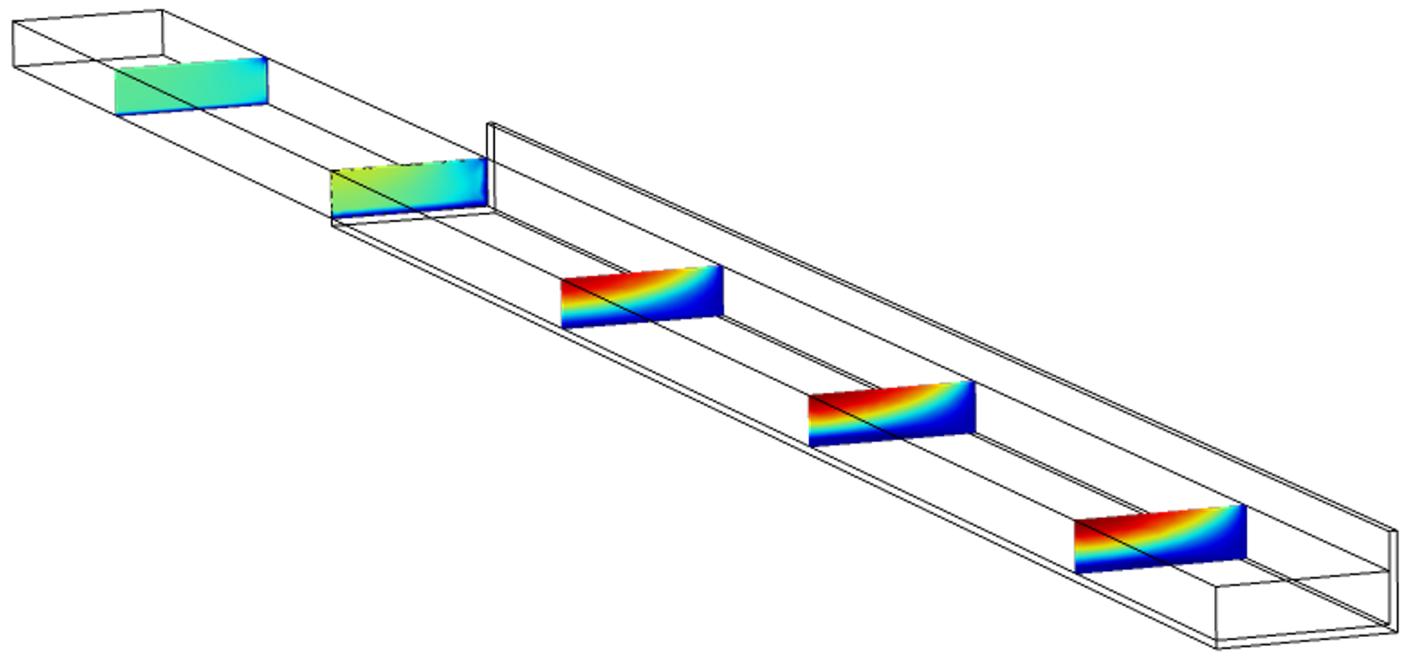


Fig. 6 Pressure gradient of Li flow in rectangular ducts under uniform B

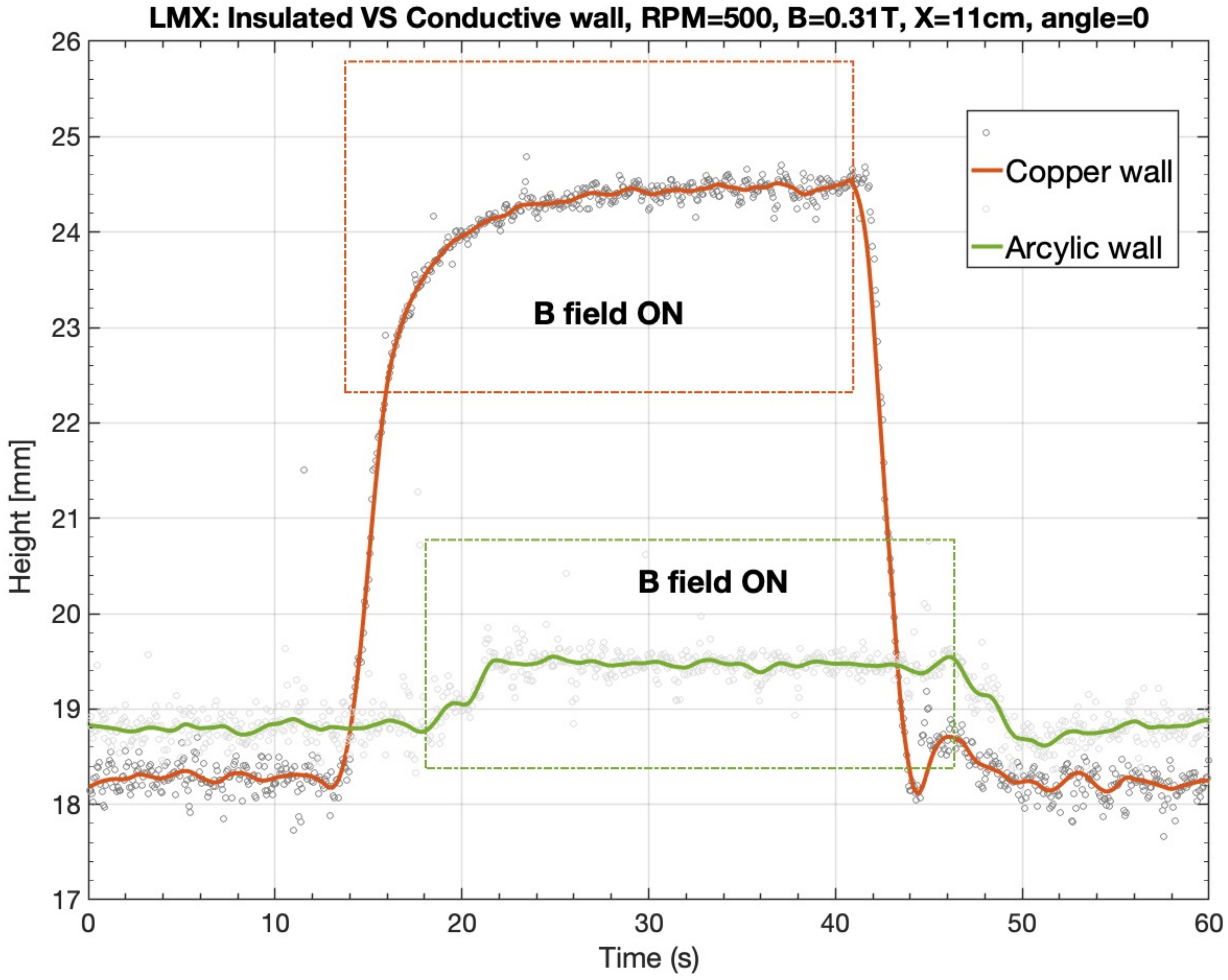
K. Miyazaki (1983). MHD Pressure Drop of Liquid Metal Flow in Circular and Rectangular Duct under Transverse Magnetic Field.

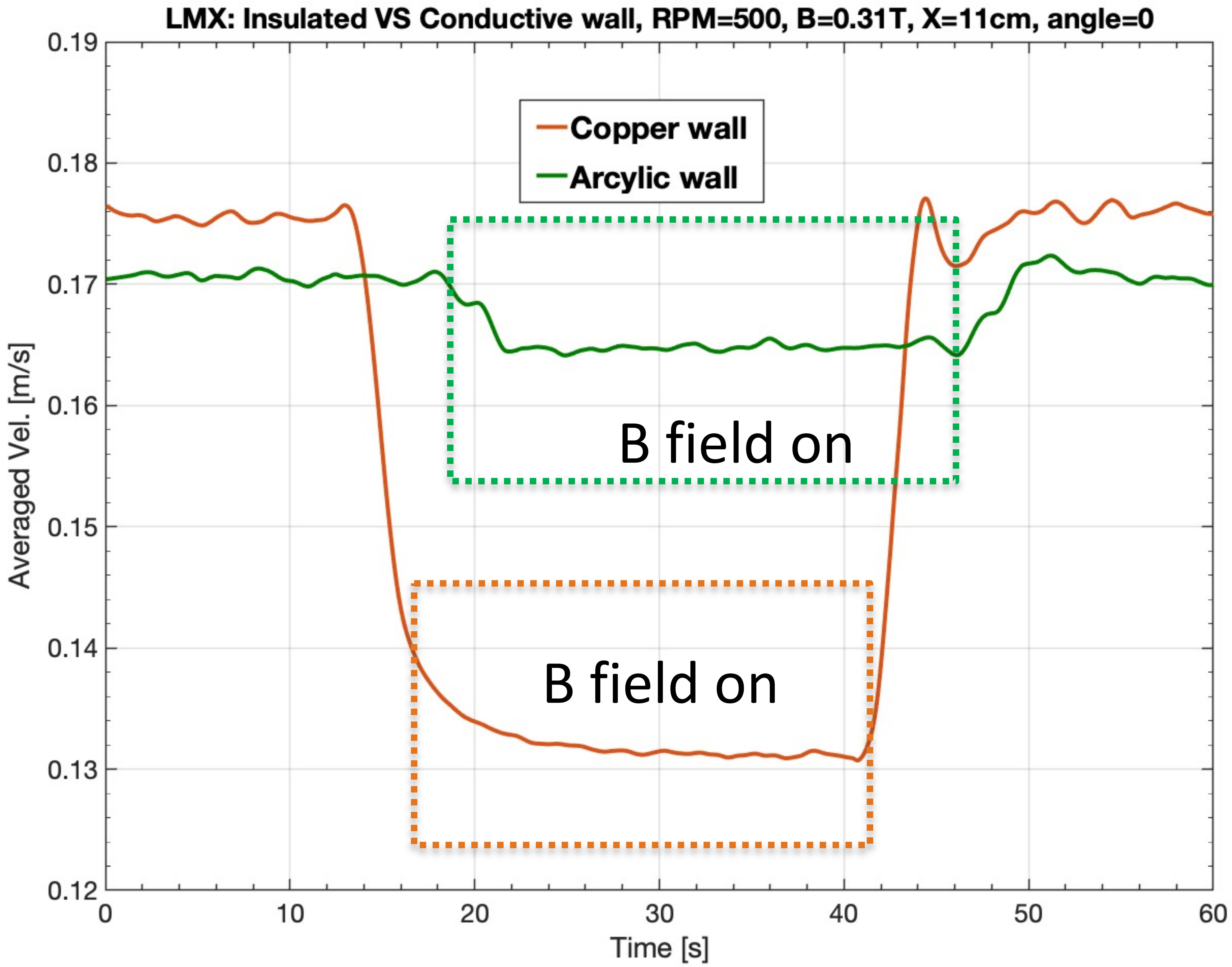
COMSOL simulation setup

- **Uniform height along channel length: 15mm.**
- **Uniform velocity profile at inlet.**
- **Slip boundary condition at the “free surface”,**
- **No-slip for side walls and bottom wall.**
- **Symmetry applied at the center of the channel.**
- **Copper liner, thickness: 0.08 in ~ 2 mm.**
- **Scan for:**
  - B = 0.1 T, 0.2 T, 0.3 T.
  - Flow rate: 7.89 L/min, 12.31 L/min, 16.64 L/min, 20.97 L/min.
- **Dimensions of LMX channel.**



Detectable MHD effect in LMX with conductive and insulated wall

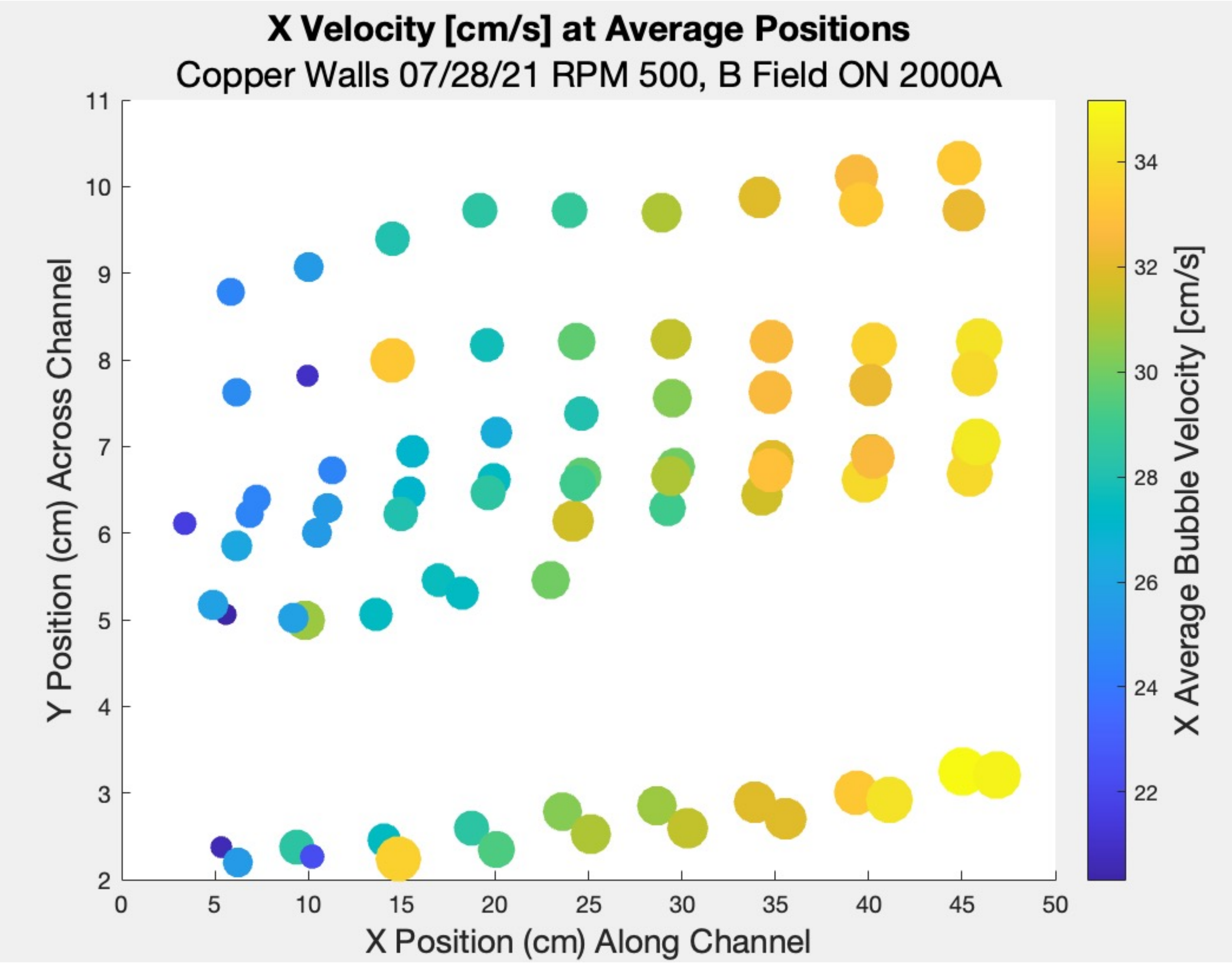




- **Ha~650, Re~2520, no nozzle, flat**

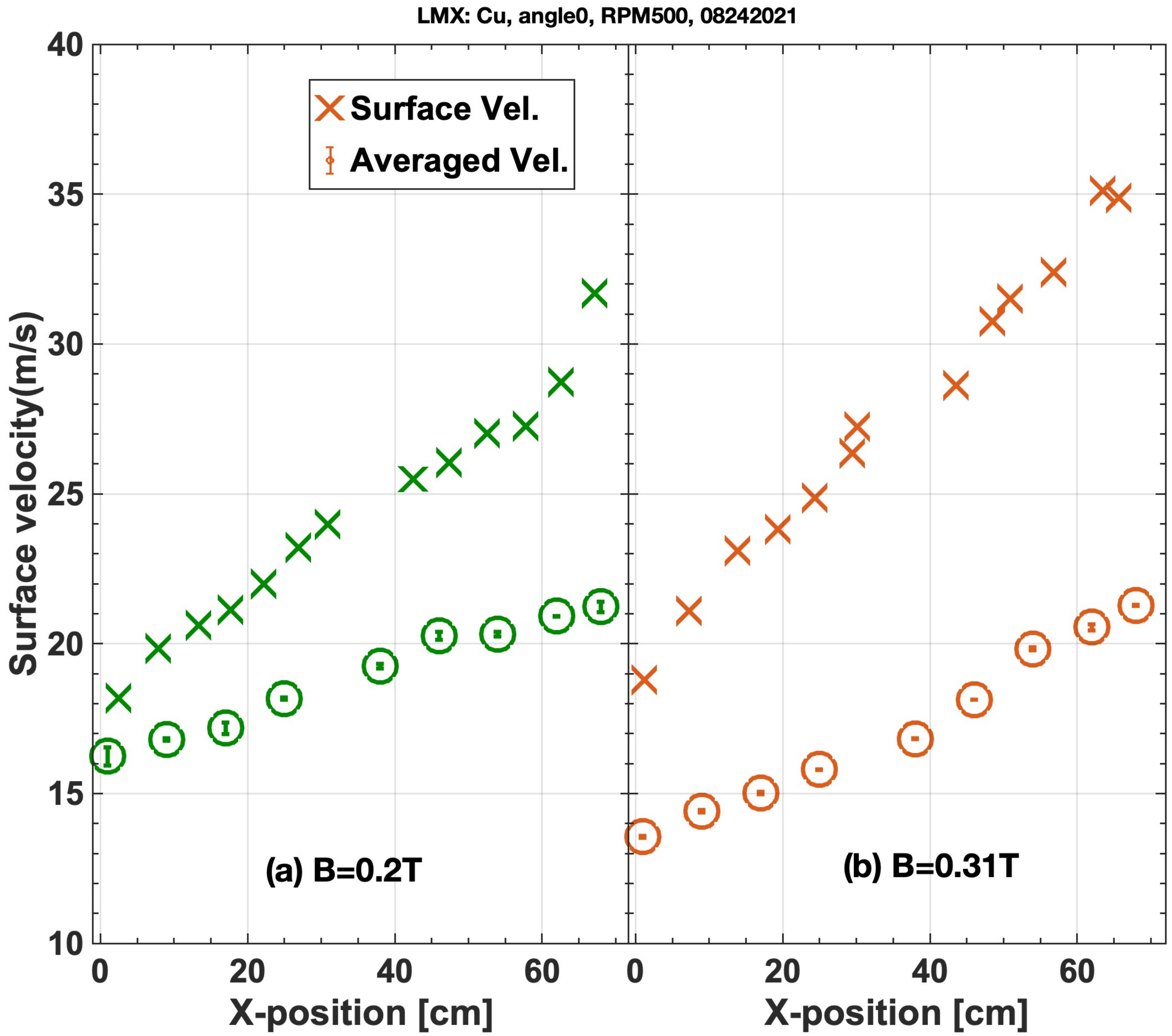
- **Reduced by ~3%**
- **Reduced by ~26%**

Profile of measured surface velocities



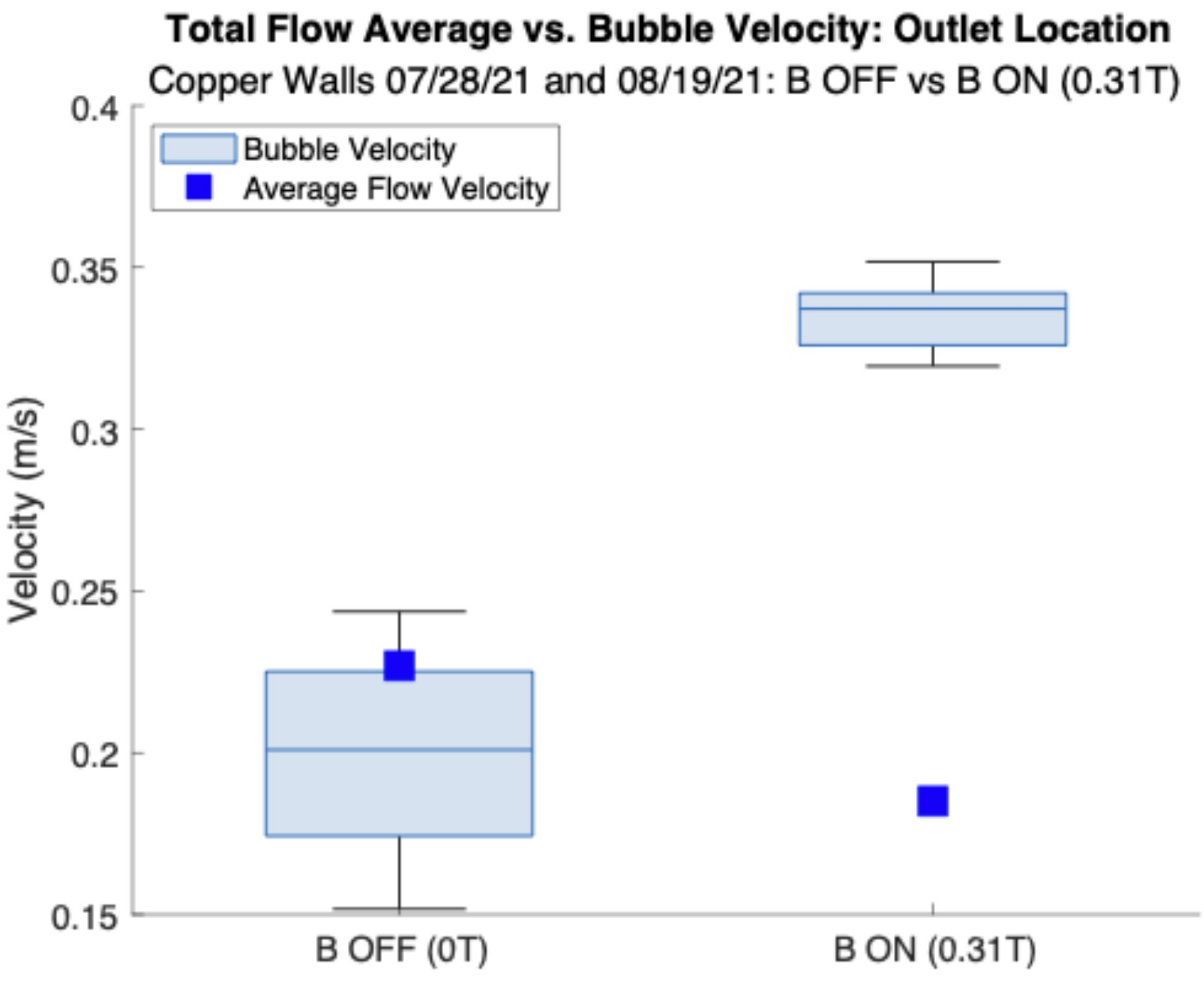
- **Bubble and introduced particles tracking**
- **Surface velocity was increased along streamwise direction**
- **Across Y direction (channel width), velocity are close**

Surface velocity increased as B field

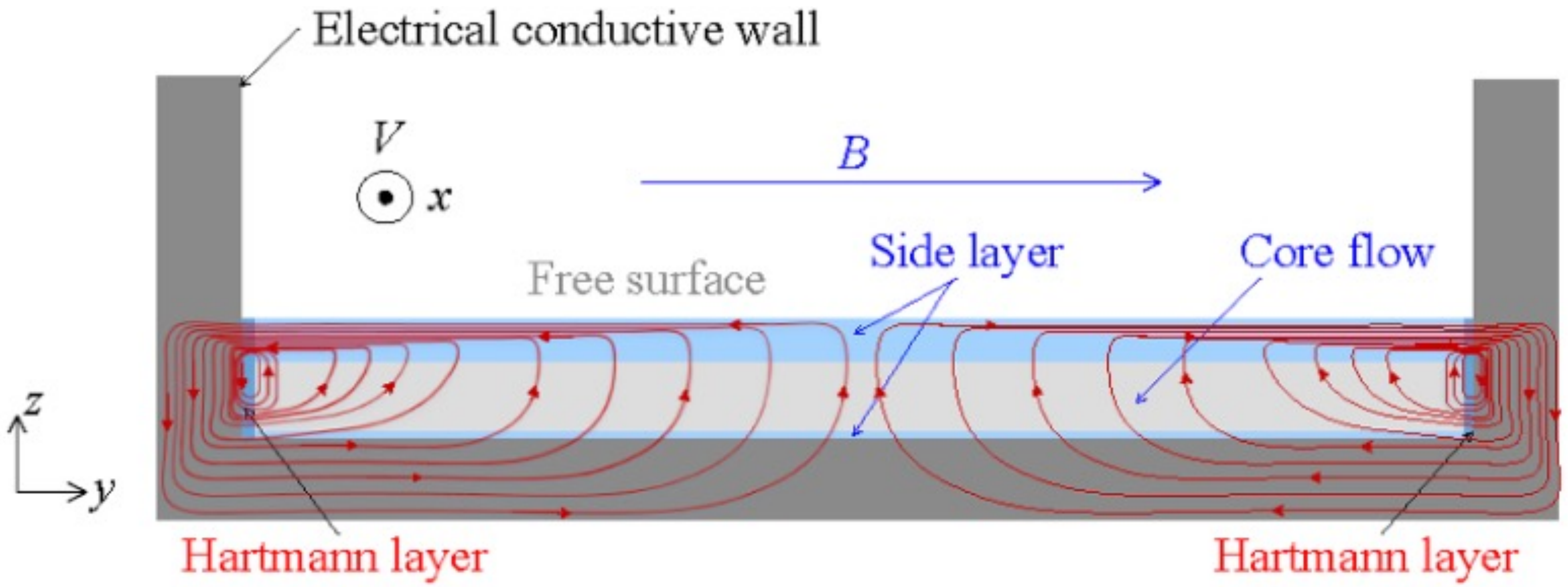


- Surface velocity increases with B
  - Higher magnetic field generates stronger MHD drag
- Thickness of high-surface-velocity layer???
- How the high-velocity-region affect heat flux transport?
- Is high-velocity-region beneficial for surface refresh, e.g. improving recycling control (Li)??

Surface velocity @ outlet increased by 75% to no MHD

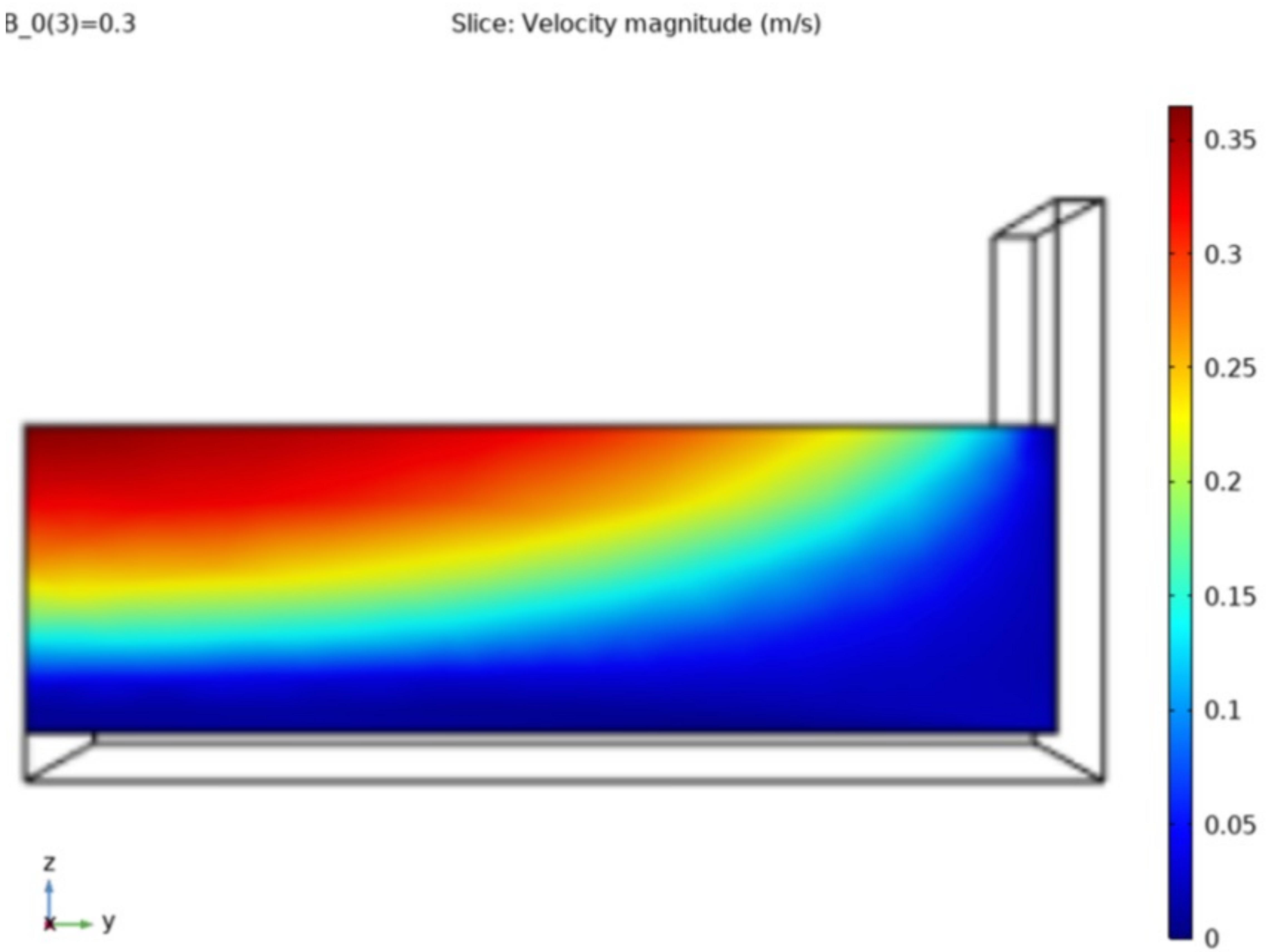


- Without B, averaged velocity close to surface velocity
- With B, averaged velocity reduced, but surface velocity increased significantly
  - Velocity at the free surface is high, due to the small Lorentz force and a less viscous friction force, while the averaged velocity is reduced due to the existence of the Lorentz force



Velocity redistribution

- Free top boundary and current perpendicular to B approaching 0, leading to overall velocity redistribution, and reducing velocity in the channel core
- In the core flow region, induced currents interact with magnetic field, causing Lorentz force as the retardant force
- Simulation results qualitatively agree with experiment

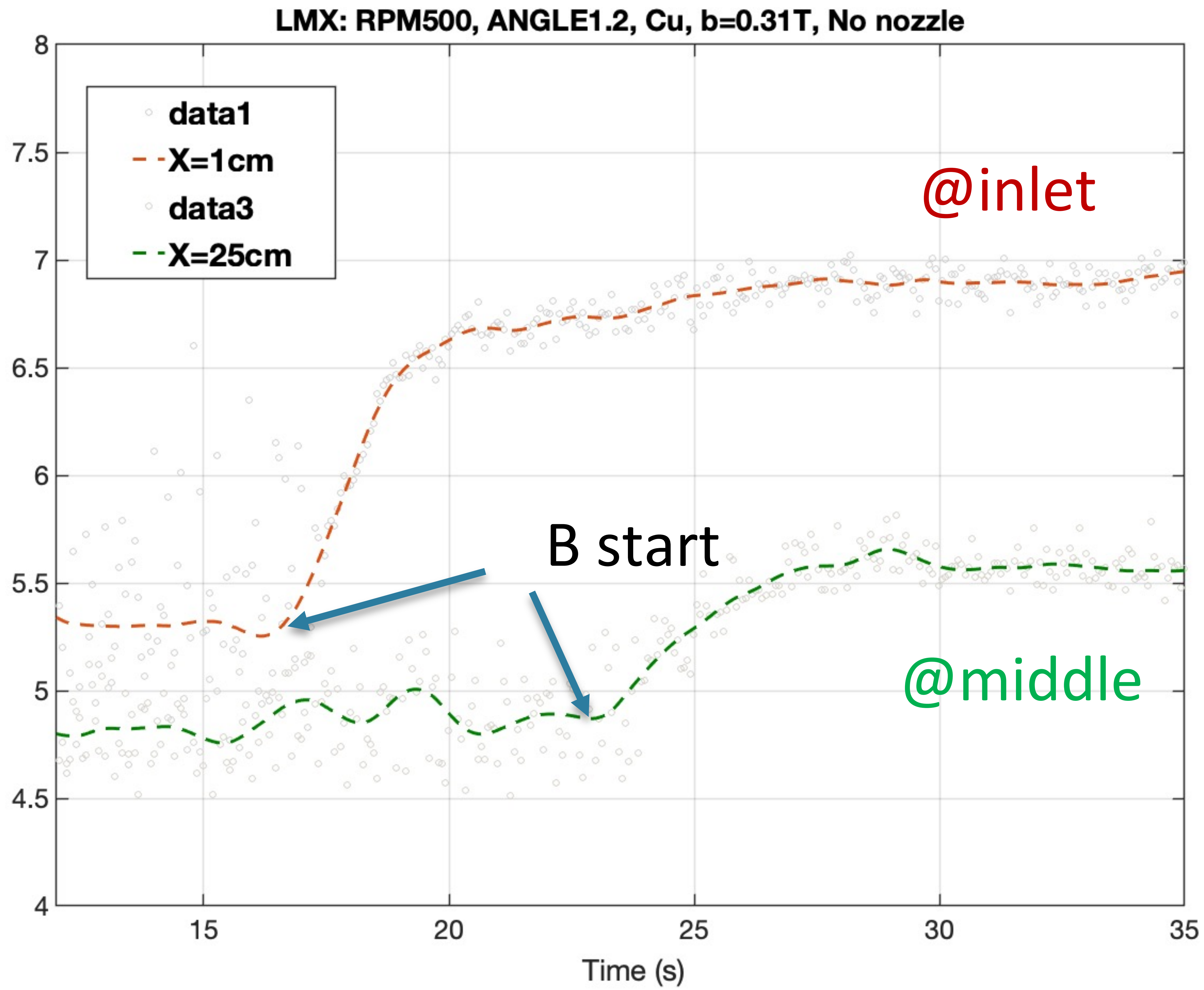


B=0.3T, RPM=500, V_0=0.225m/s

LM accumulation reduced significantly with a small inclination angle

$$P_1A_1 - P_2A_2 - \int_0^L P_{MHD}(x)A(x)\,dx + \boxed{\rho g \Delta H} = \rho\, Q\,(u_2 - u_1)$$

- **Angle~1.2**
- **LM accumulation in inclined flow is much smaller than a flat flow**
  - @ inlet: 5.4mm→7mm, Δh~1.6mm
  - Galinstan density ~13xLi



Stimulation confirmed the flow patten and velocity scale

- COMSOL 5.6 with CFD and AC/DC modules
- Free surface: slip; other surfaces: no-slip
- Up and down flow pattern matches with experiment observations
- Upward velocity up to ~0.5m/s