IMPROVED FUSION PLASMA PERFORMANCE IN FUSION DEVICES ENABLED BY A NEW IMPURITY POWDER INJECTION SYSTEM

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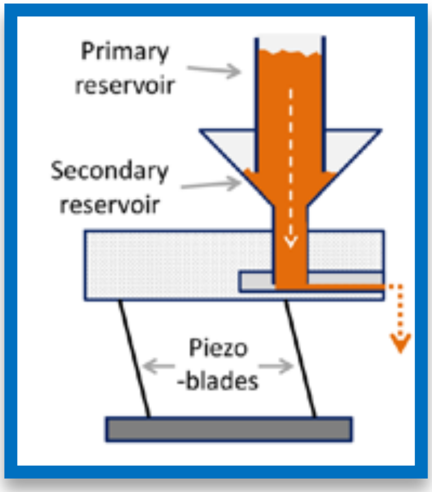
The Advent of Impurity Powder Injectors has opened up new science areas in fusion devices

- A new impurity powder droppers (IPD) has been developed at PPPL over the past 4 years
  - Uses piezoelectric crystal motion to drop particles
  - Capable of injecting a wide range of impurity materials (Li, B, B_4C, BN, C, Si, Sn, …) and sizes (10 μm – 1mm)
  - Builds on PPPL design that worked with metallic powders
  - Has an onboard set of diagnostics
- IPD deployed on six fusion devices worldwide
  - Used to improve wall conditions, enhance power exhaust, and control the pedestal and edge-localized modes (ELMs)
- EAST: B powder enables ELM-stable H-mode
- KSTAR: BN powder enables ELM quiescent phases

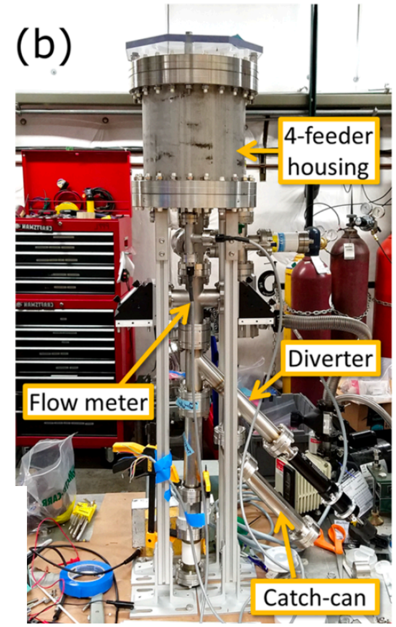
Real-time impurity powder injection used for ELM control, wall conditioning and power exhaust

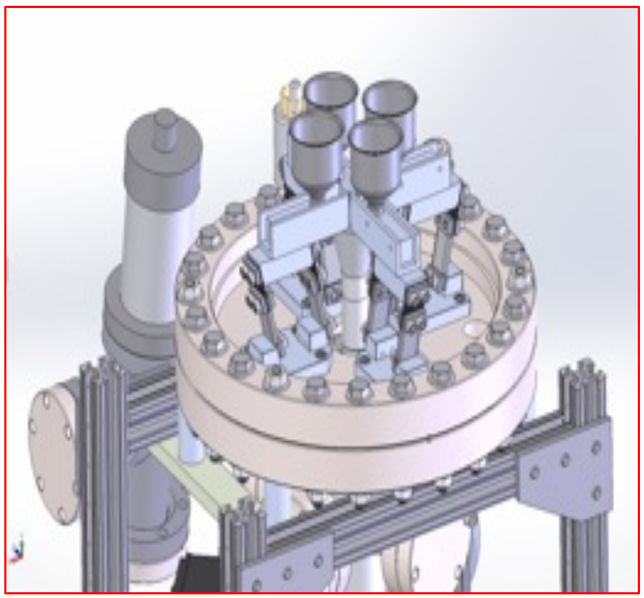
- ELM control: alter edge stability toward ELM-stable or small ELM regimes
  - EAST, KSTAR
- Wall conditioning: continuously repair wall coatings for improved PMI and core performance
  - AUG, DIII-D, EAST, KSTAR, LHD, W7-X, WEST
- Power exhaust: enhance divertor and boundary power dissipation to heat flux control
  - AUG, EAST, DIII-D

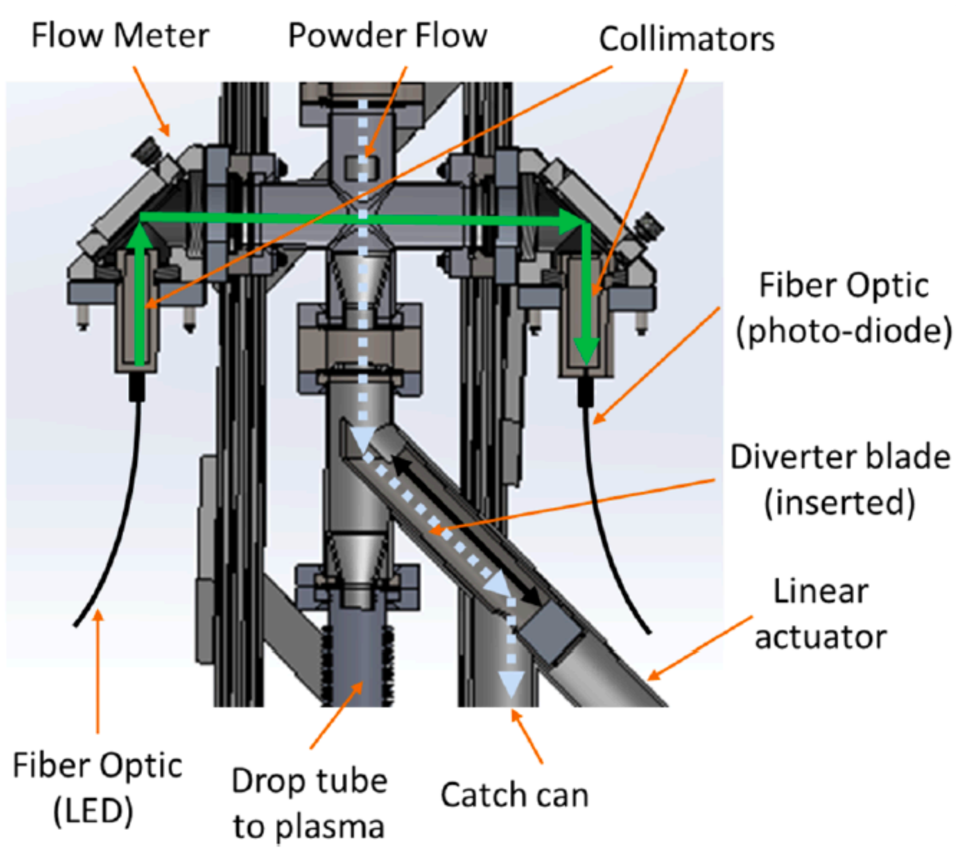
Impurity Powder Dropper layout

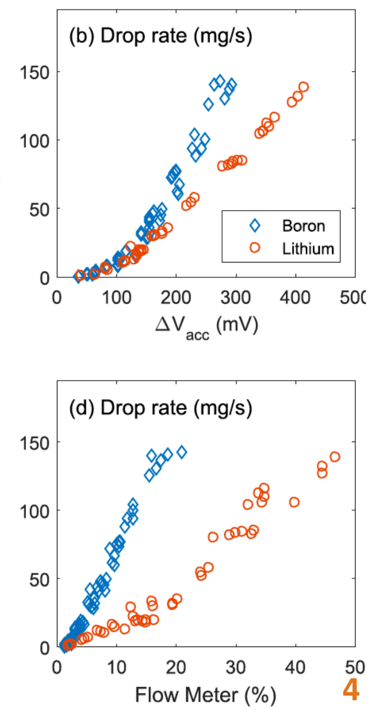


- Linear feed using piezoelectric crystals
  - 1 mm side to side motion drives particles over trough
  - Calibratable





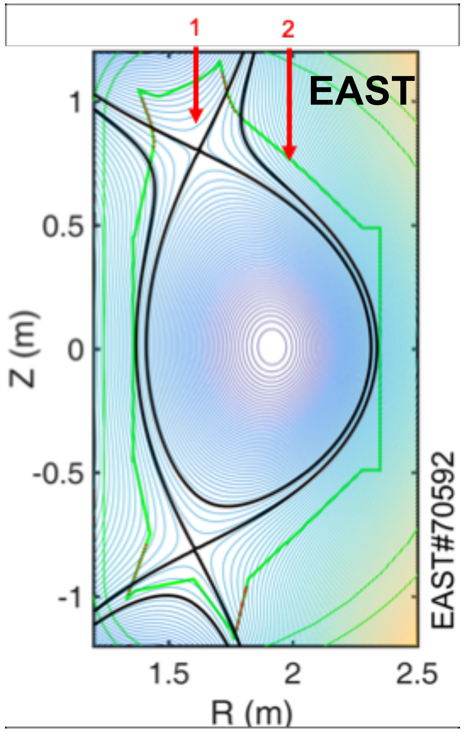


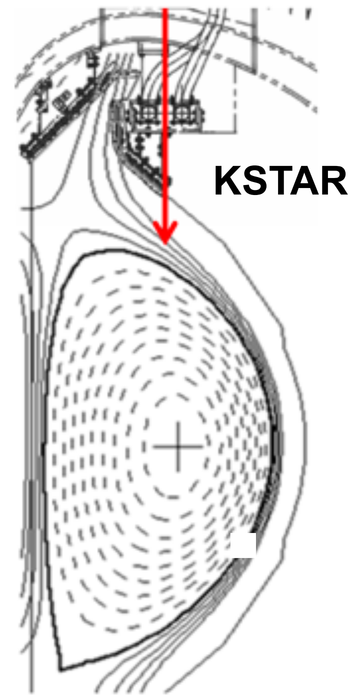


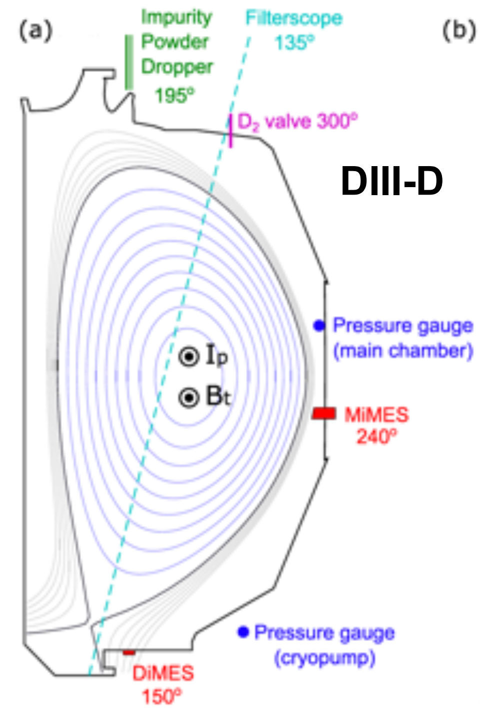
IPD: A. Nagy et al., *RSI* **89** (2018) 10K121

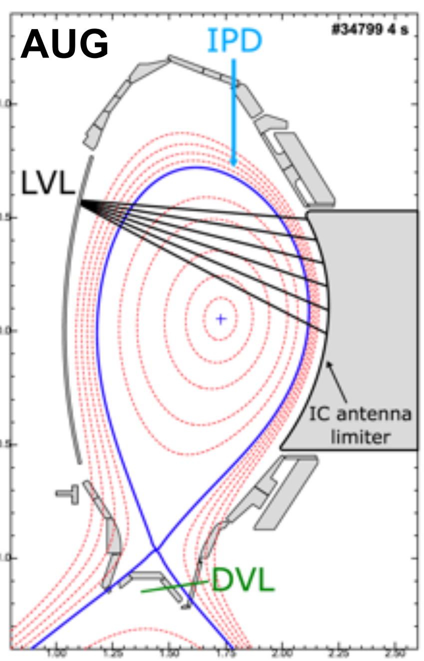
LiPD: D.K. Mansfield et al., *FED* **85** (2010) 890

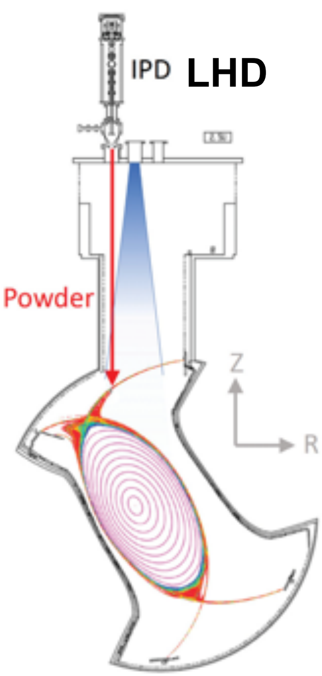
IPD Installed on Multiple Devices

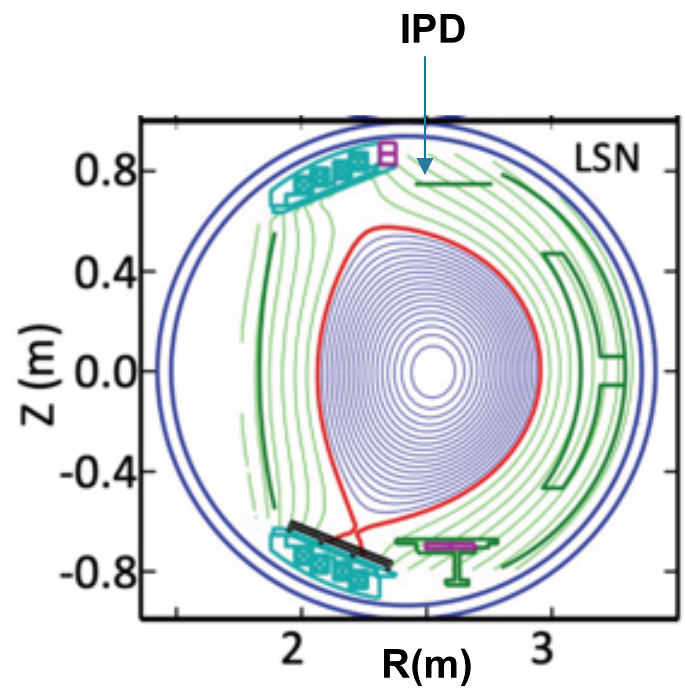












EAST summary: ELM suppression with B powder injection achieved with concomitant edge mode with harmonics

- **Wide range of operation conditions**
  - RF-only & RF + NBI heating: 2.8 MW – 7.5 MW
  - q95 between 4.4 and 7.2 (typical 0.5 MA, 2.5 T)
  - Density range: 2.5e19 – 7.5e19 (0.25 – 0.85 n_{GW})
  - With D or He majority
  - Both directions of grad-B drift
  - ELM suppression achieved in every condition we tried! (> few shots)

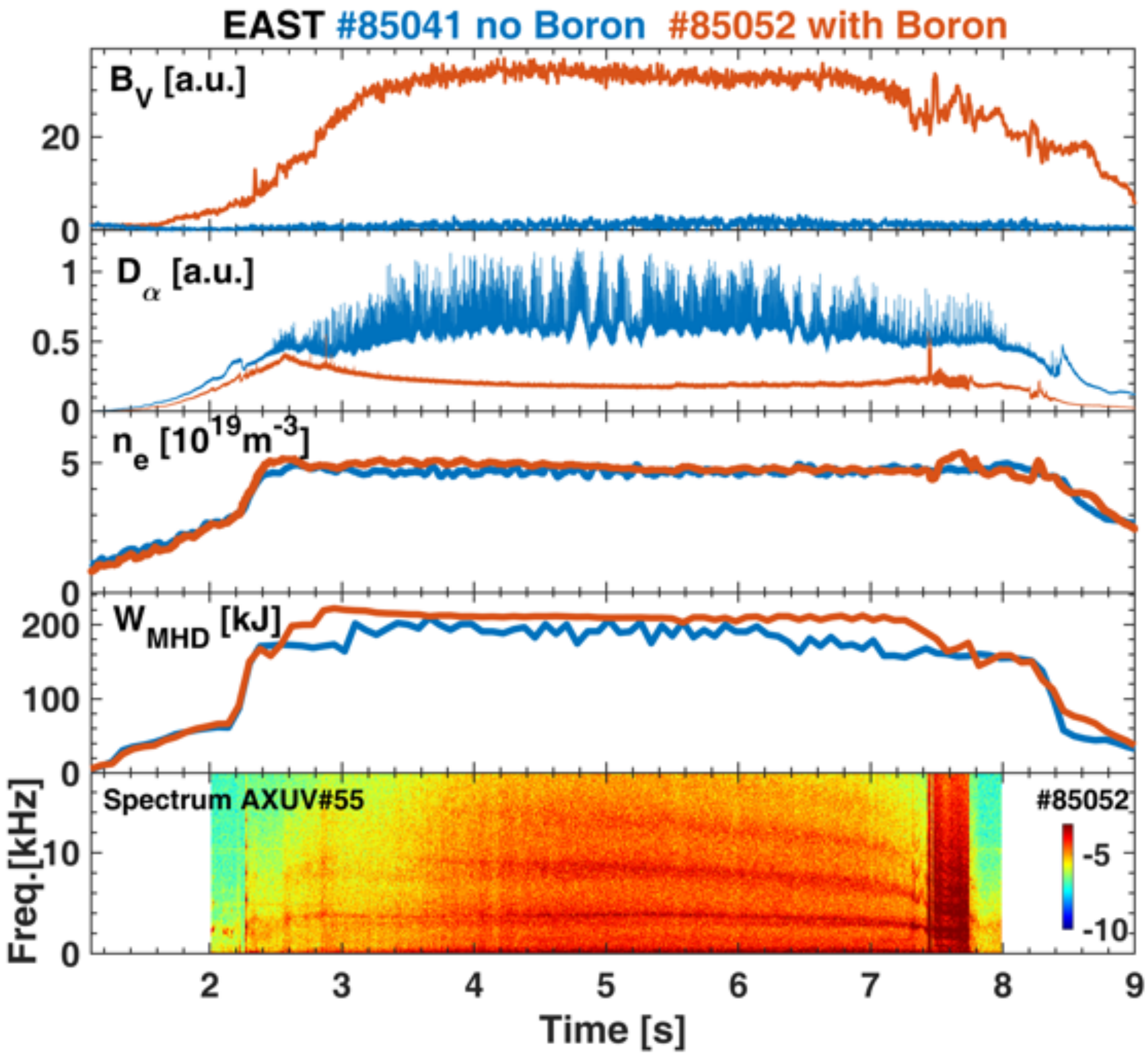
- **Threshold B injection rate observed for suppression**
  - Increased with heating power

- **Mode triggered and observed on multiple diagnostics**
  - Multiple harmonics ~ 2-5 kHZ fundamental; only with Boron
  - Localized near separatrix and drives particle transport
  - Seen in AXUV, magnetics, divertor D_α (in, out, top, bottom), tile-embedded Langmuir probes, POINT, tangential D_α (BES chords)

Powder injection via IPD and related devices are being used in many tokamaks and stellarators

Device	Impurities used in IPD	Wall Conditioning e.g. D$_\alpha$ reduction	Power exhaust enhanced	ELMs mitigated or pedestal improved or τ_E increased
EAST	B powder Li powder Li granules (0.7mm)	√ √ √	√	√ √ √
KSTAR	B powder BN powder	 √		√ √
DIII-D	B powder BN powder Li powder	√ √	 √	 √
ASDEX-Upgrade	B powder BN powder	√ √	 √	 √
LHD	B powder	√		√
WEST	B powder	In progress		
NSTX* (LiPD)	Li powder	√		√
W7-X** (probe mounted injector)	B_4C powder			√

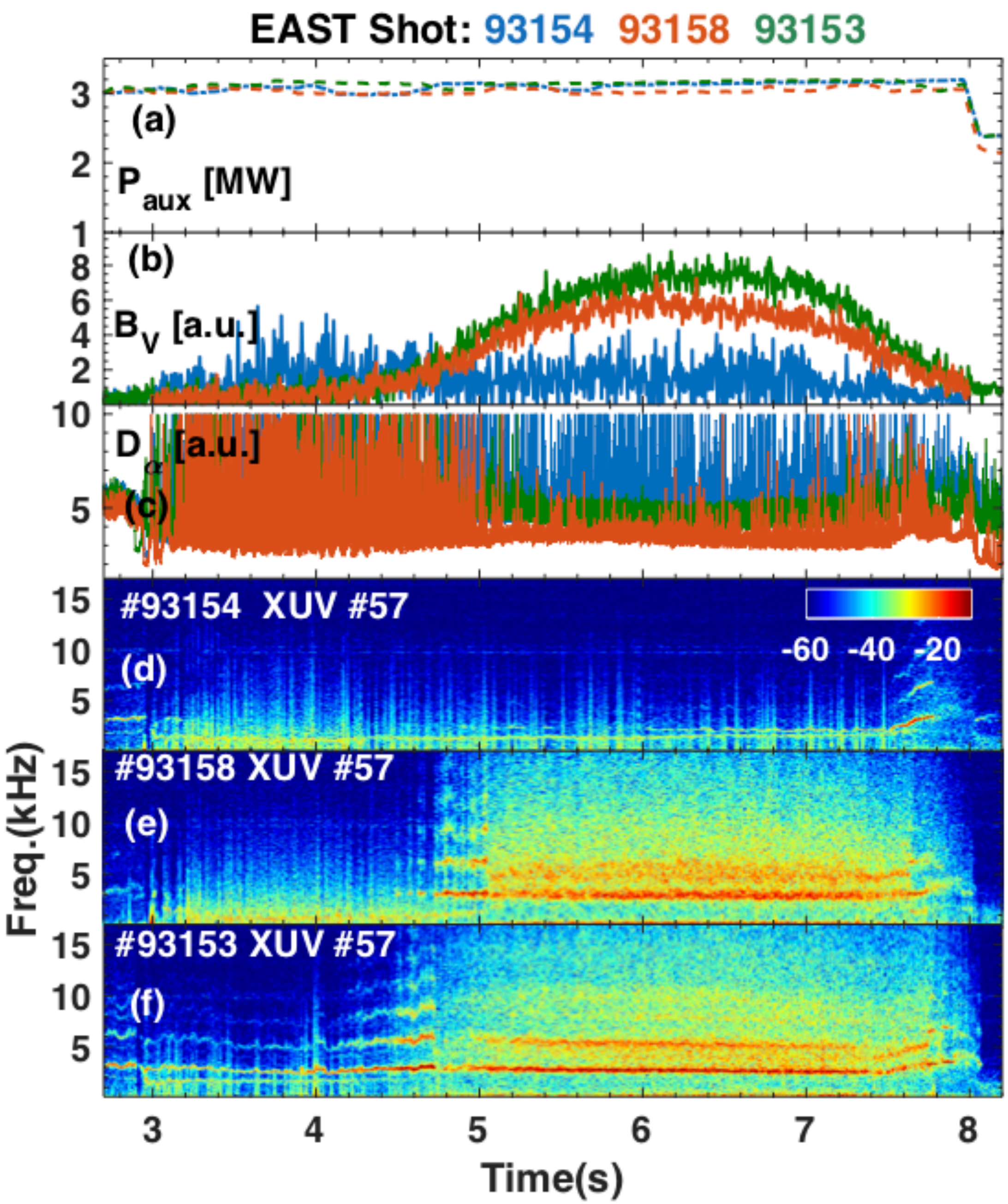
EAST: Boron powder injection suppressed ELMs with constant density and stored energy



Z. Sun et al., *Nucl. Fusion* **61** (2021) 014002

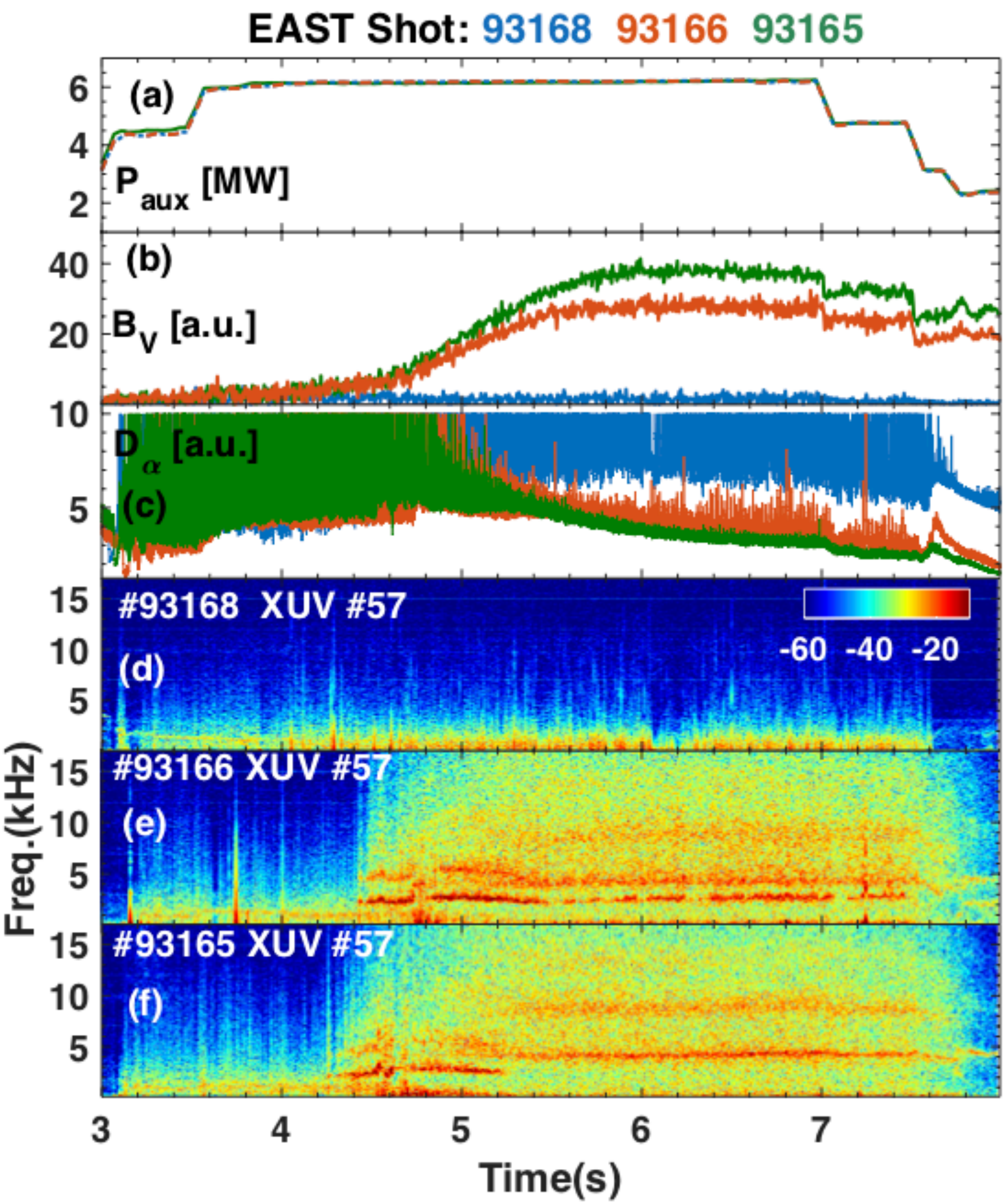
- Edge B-V emission when B injected (from T_e ~ 150 eV)
- D_α reduced w/B inj.; no ELMs
- Density stable and matched
- Stored energy increased slightly
- Harmonic mode destabilized
  - Fundamental n=1
- I_p = 0.5 MA, B_t = 2.5 T, P_{heat}~ 6 MW, USN, grad-B drift ↑, toward X-point
  - Type-I ELMs, $H_{98(y,2)} \sim 1$

Threshold B injection rate for ELM suppression measured with 3 MW of heating power (EAST)



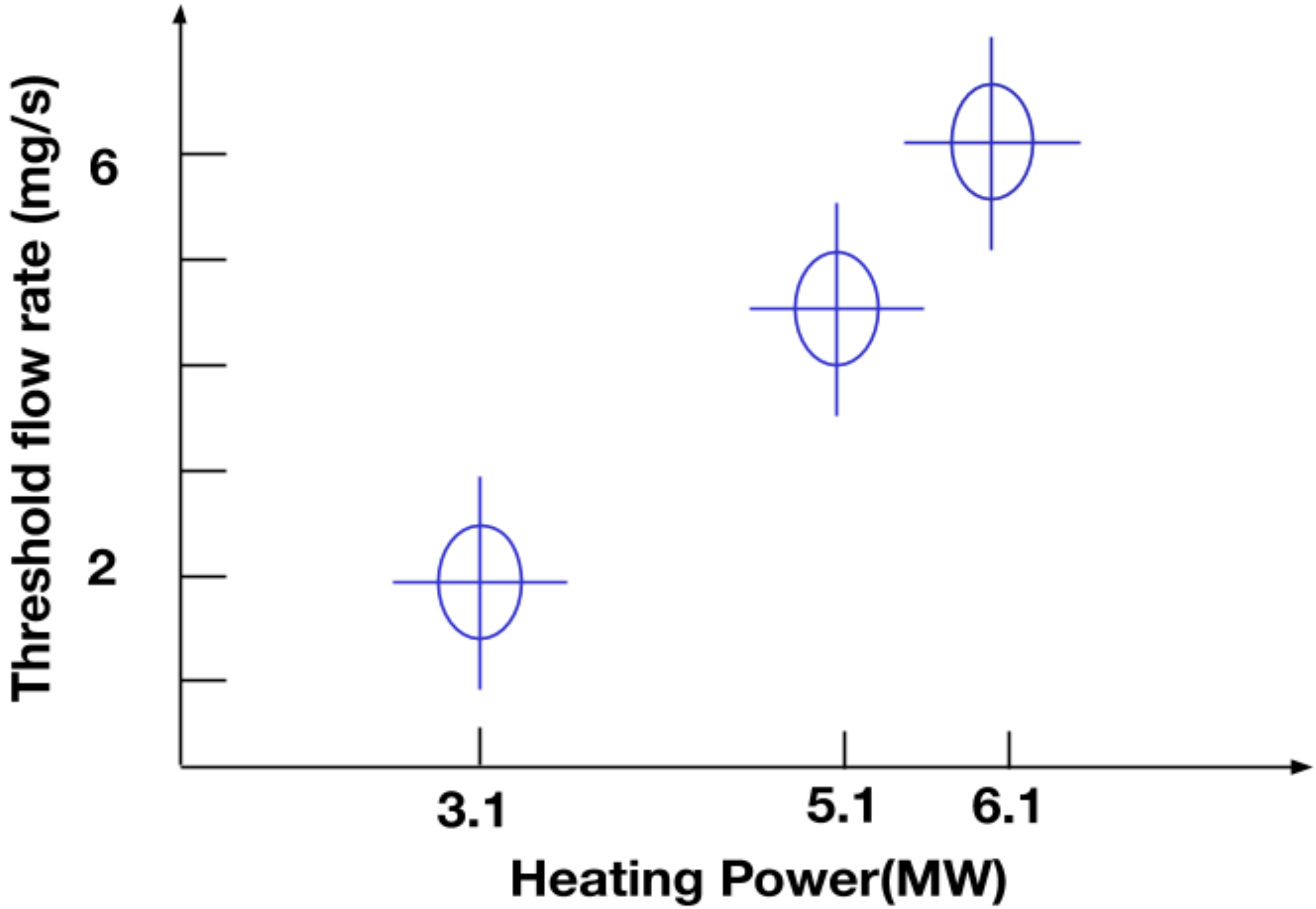
- Matched NB power
- B_V emission just below and above B threshold rate
- D_α shows ELM modification
- No Mode in no B reference
- Harmonic mode intermittent during ELM mitigation
  - Fundamental n=1
- Harmonic mode steady during ELM suppression

Threshold B injection rate for ELM suppression measured with 6 MW of heating power (EAST)



- Matched NB power
- B_V emission just below and above B threshold rate
- D_α shows ELM modification
- No Mode in no B reference
- Harmonic mode intermittent during ELM mitigation
- Harmonic mode steady during ELM suppression

Required B threshold flow rate increases non-linearly with heating power (EAST)



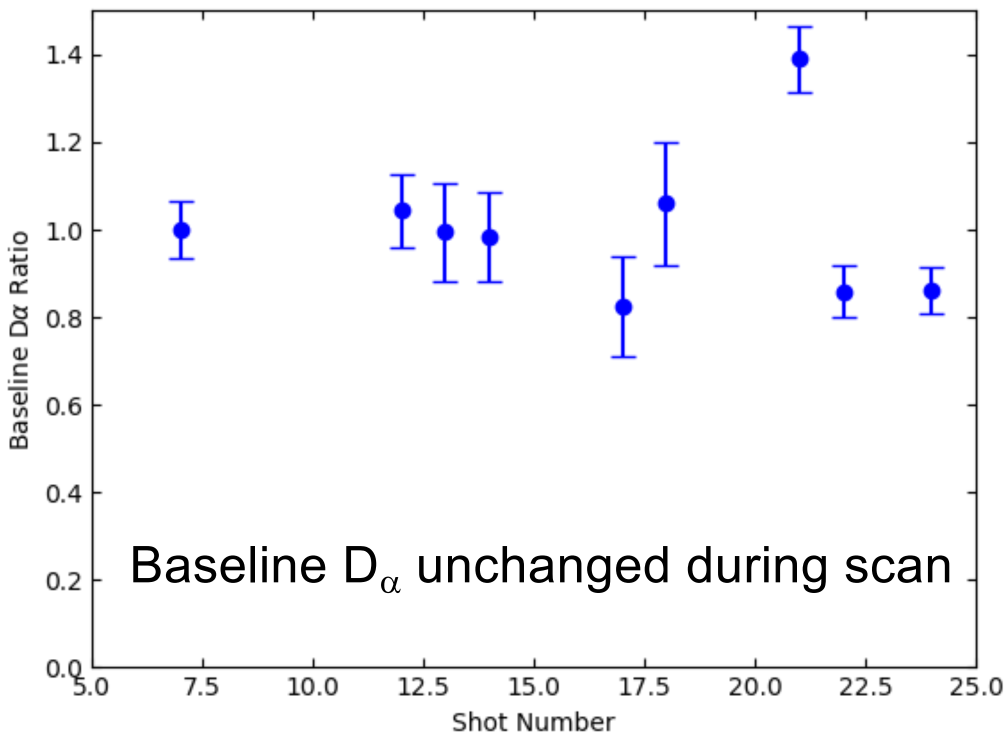
KSTAR Summary: ELM quiescent phases triggered with B or BN injection

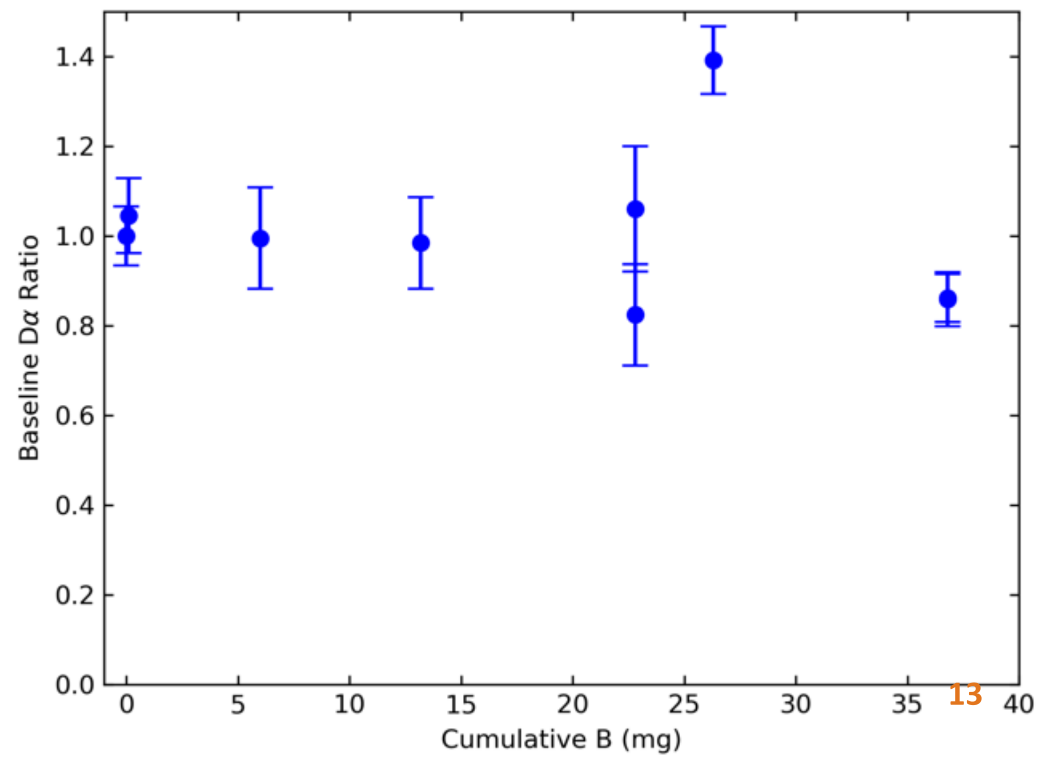
- B powder injection reduced ELM frequency and created a few short lived ELM quiescent phases
  - Baseline D_{α} emission unchanged by B injection
- BN powder injection reduced ELM frequency and created ~ 5sec long ELM quiescent phases
  - Baseline D_{α} emission reduced by BN injection when used in discrete, high amplitude bursts
  - Continuous burst resulted in an ELM frequency and size reduction, as measured by D_{α} spikes
  - ELM quiescent phases could not be reproduced in 2019, despite a reduction in baseline D_{α} emission
- Lack of reproducibility not understood

KSTAR: B powder dropped in six discharges, with two intermixed reference no B discharges

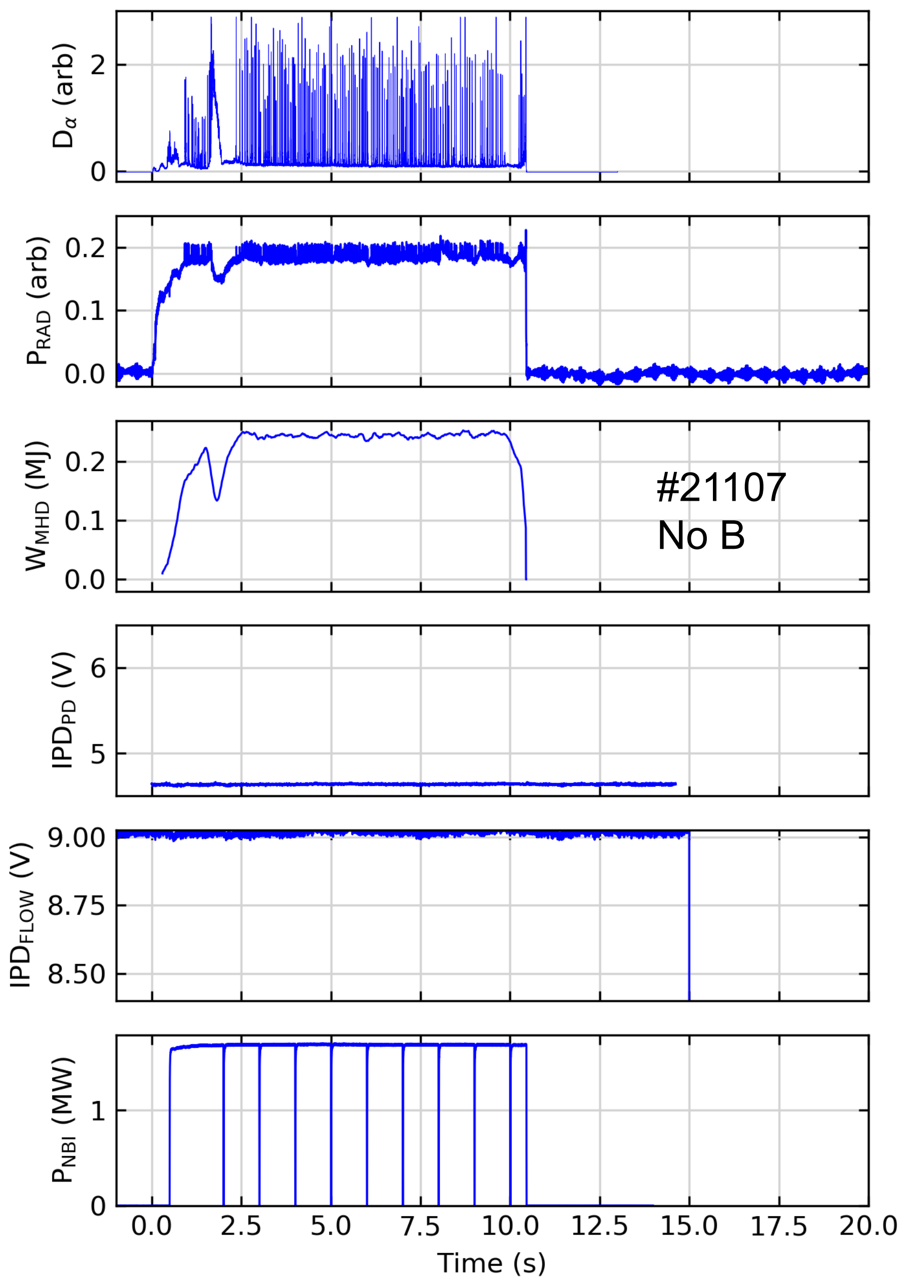
21107	Reference shot #20999	1.5 MW, 500 kA standard ELMy H-mode, Bt = 1.82 T
21112	To ramp-down t = 10 s	3.5 mg/s powder 4 – 5 s, 7 – 8 s
21113	Disrupted t = 6 s	3.5 mg/s powder 4 – 5 s
21114	Disrupted t = 6 s	10 mg/s powder 4 – 5 s
21117	Reference 10 s, ELM-free phases	No IPD
21118	Reference 10 s, ELM-free phases	No IPD
21121	20 s pulse, ELM-free phases	5 mg/s 3.5 – 4 s, 8.5 – 9 s, 13.5 – 14 s
21122	Disrupted t = 5 s, 50% lower Dα	5 mg/s 3.5 – 4 s,
21124	Disrupted t = 18 s	5 mg/s, 8.5 – 9 s, 13.5 – 14 s, 17.5 – 18 s

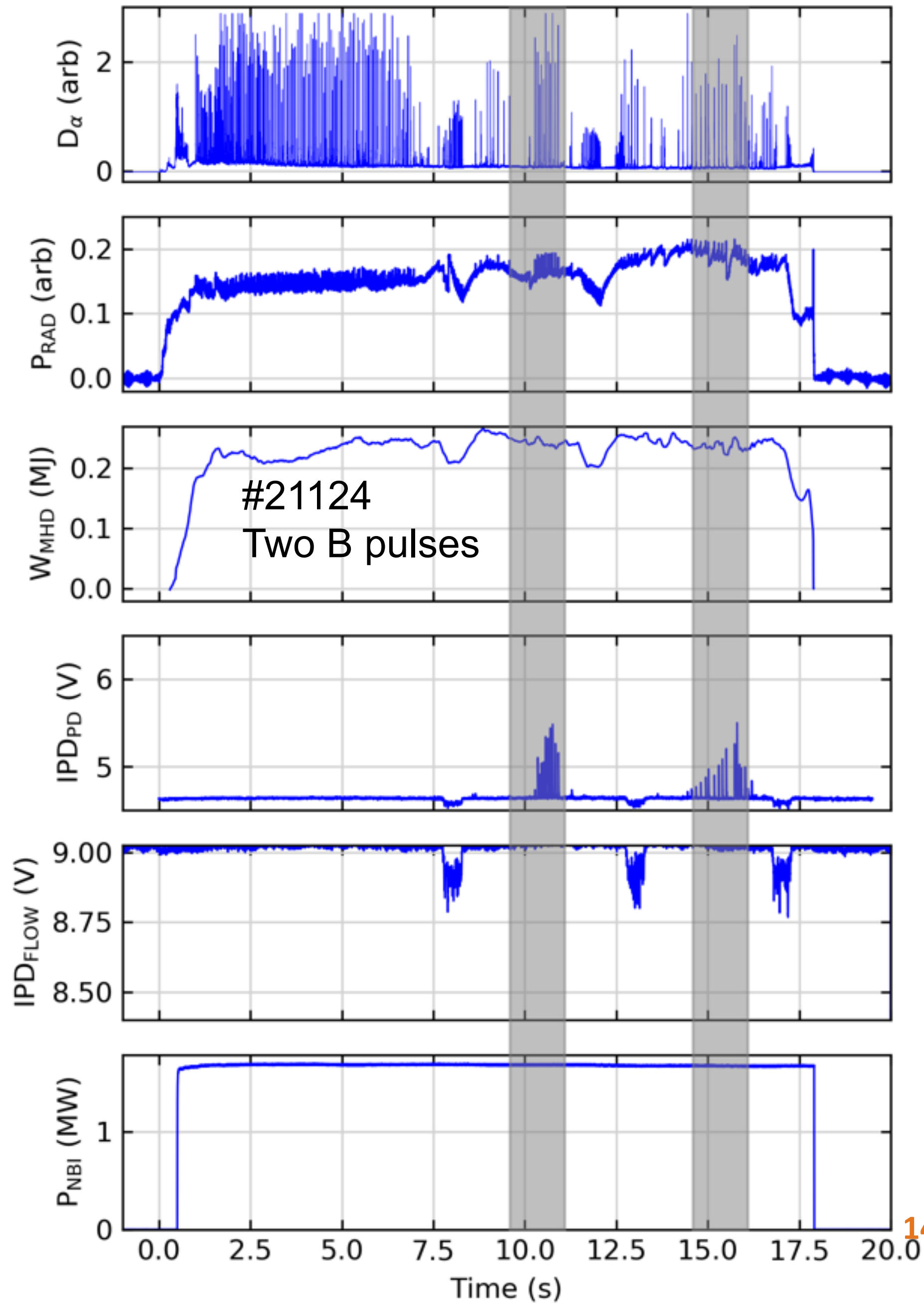
21108 – 21111, 21115 – 21116, 21119 – 21120, 21123 --- various startup and L-H timing problems





ELM quiescent phase triggered by B powder injection in KSTAR

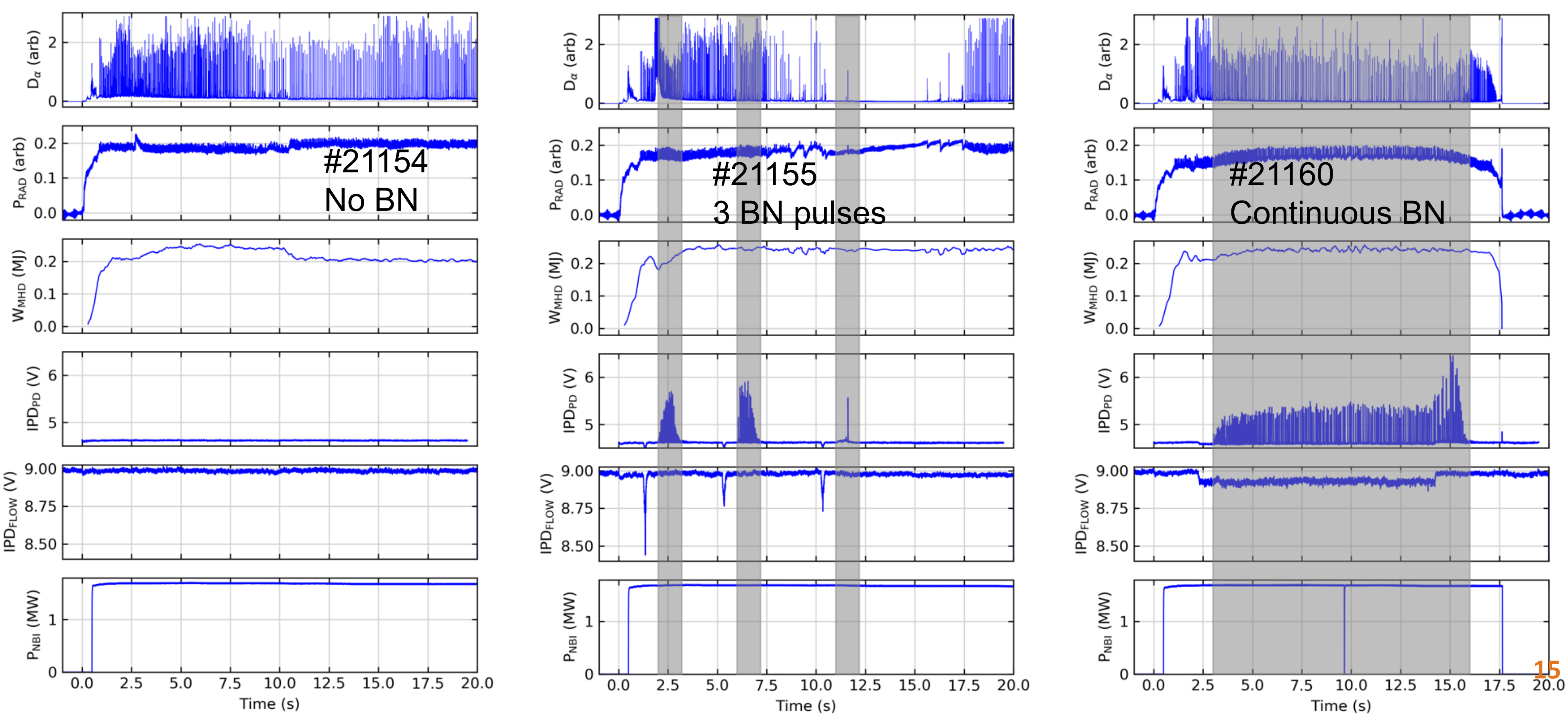




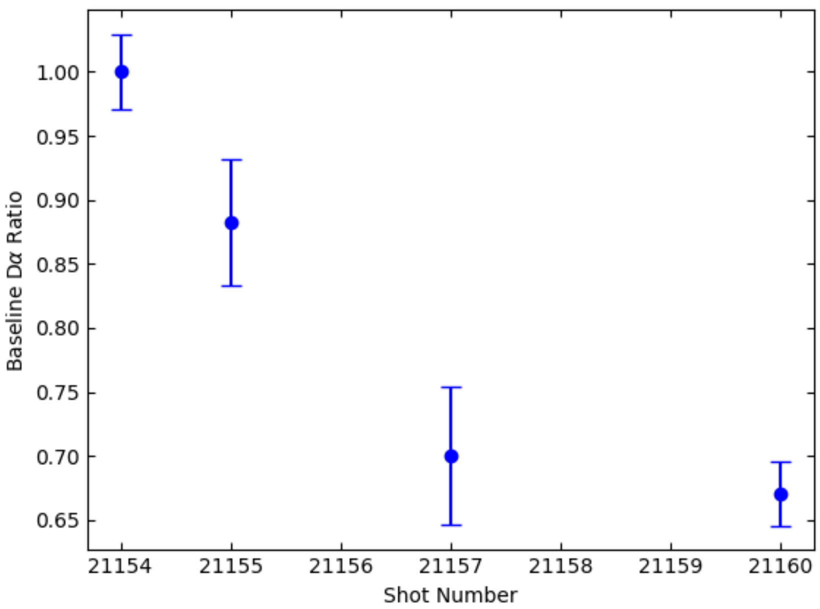
ELM quiescent phase triggered by BN powder injection in KSTAR

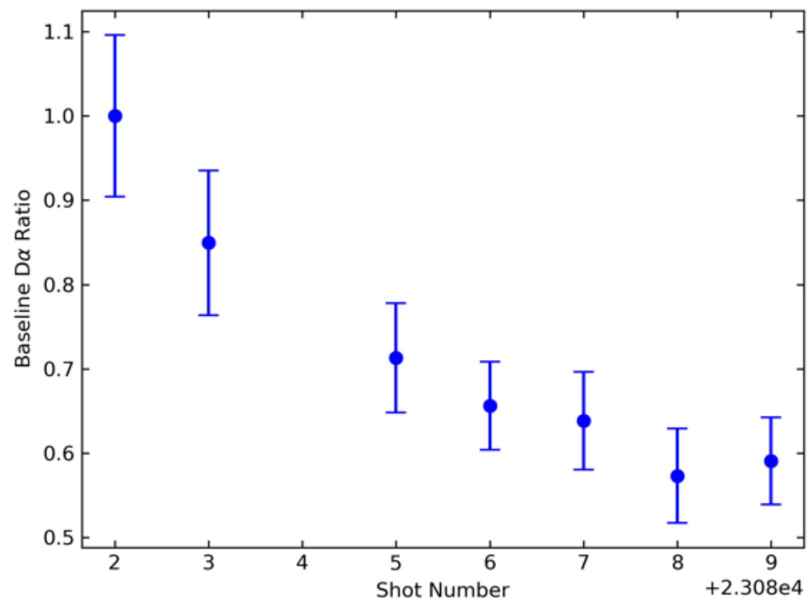
21154	Ref. #21124 (#20999)	1.5 MW, 500 kA standard ELMy 20 s H-mode, Bt = 1.82 T
21155	20 s, BN, ELM-free region	0.1 s bursts @ 25 mg/s powder at t = 2, 6, 11 s
21156	Failed startup	
21157	20 s, BN	0.1 s bursts @ 12 mg/s powder at t = 3, 7, 11, 15 s
21158	Failed startup	
21159	Disrupted at t = 6 s	
21160	18 s, BN	CW @ 2.5 mg/s from t = 5 – 15 s

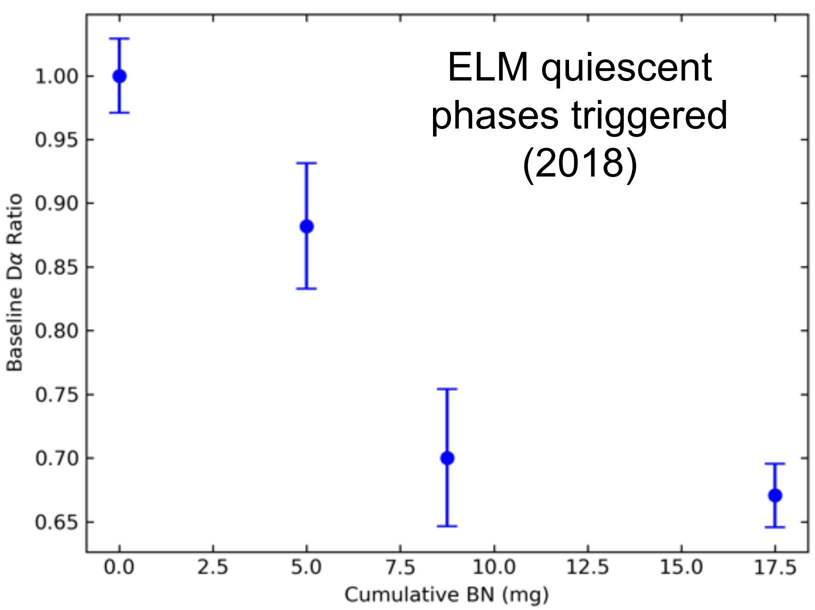
E.P. Gilson et al., *Nucl. Mater. Energy* (2021) subm.

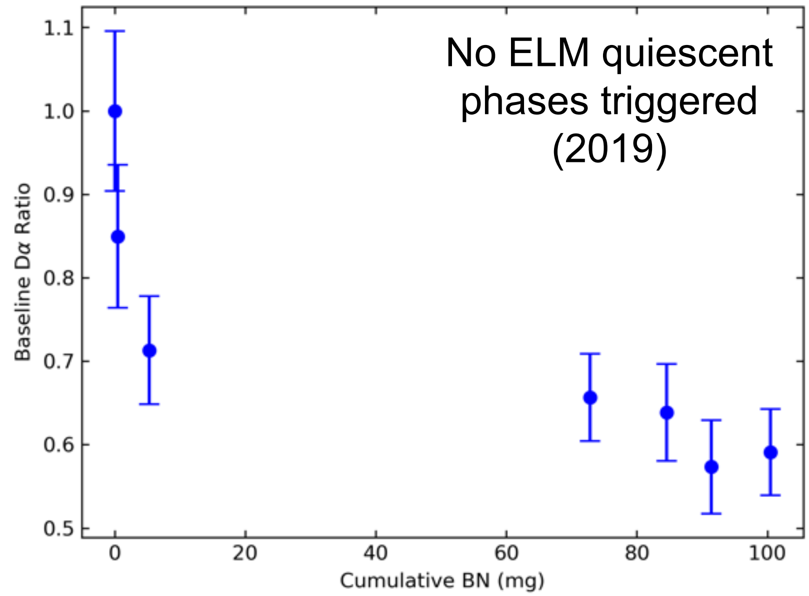


Divertor D_α emission dropped markedly in experiments with BN powder in KSTAR









Summary and Future Work

- ✓ B suppresses ELMs quite easily in EAST
  - ➢ Constant or increased W_{MHD}, works with SMBI density feedback, no wall hysteresis, over a range of conditions (P_{heat}, density, and ν*)
  - ➢ Works with pure RF heating: paves the way for long-pulse usage at low B injection rates
  - ➢ Easier to suppress ELMs with B than Li
  - ➢ Need to investigate where B mass ends up
  - ➢ New experiment: inject C, B_4C from IPD to see if Z_i matters
  - ➢ New experiment: compare X-point injection with LFS injection

- ✓ BN and B trigger ELM quiescent phases in KSTAR
  - ➢ More prominent with BN than B in 2018
  - ➢ Recycling reduced with BN but not B
  - ➢ Could not be reproduced in 2019 with BN, despite reduced recycling observation: need to examine a range of explanations