EAST: opportunities for collaboration

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On behalf of the US-China PMI collaboration:

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Co-PI: Z. Wang, LANL
Co-PI: D.G. Whyte, MIT
Co-PI: J.M. Canik, ORNL
Co-PI: D. Andruczyk, UI-UC
Co-PI: B.D. Wirth, UT-K

**Happily acknowledge participation by T.H. Osborne, GA*

NSTX-U Monday Physics Meeting
13 Feb 2017

Goal of collaboration is to help EAST manage PMI for long pulse operation

- Evaluate performance of W, Mo, and C PFCs, and optimize Li delivery
  - Powder droppers for recycling and ELM control (PPPL, JHU, ORNL, GA*, LANL)
  - Granule injectors for ELM triggering and pacing (PPPL, LANL)
  - Flowing liquid lithium limiter to optimize PMI (PPPL, UI-UC)
  - Improved core SXR system for impurity diagnosis (JHU)
- Analyze role of Li and cryopump for recycling control
  - Physics based lower divertor cryopump design (ORNL, PPPL)
  - Divertor heat flux footprints (PPPL, ORNL, UT-K)
- PFC tile diagnosis
  - Net erosion and deposition with depth markers on tiles (MIT)
  - Analysis of removed tiles (UT-K)

Outline

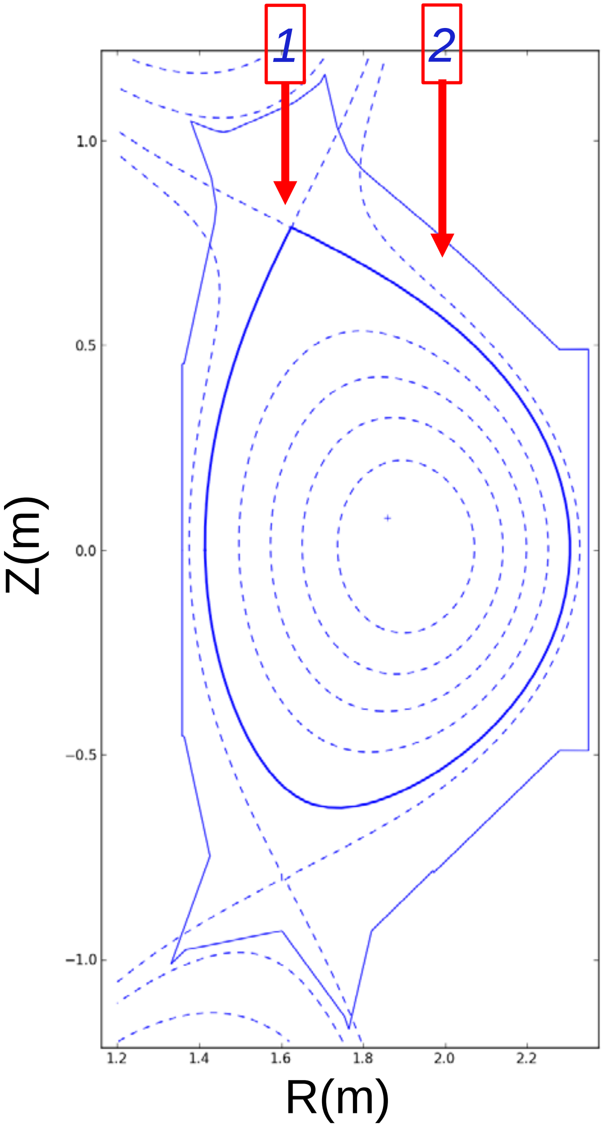
- **First set of experiments in Dec. 2016**
  - **All shots in Upper-Single Null**
  - **Ion grad-B drift toward bottom; “unfavorable” direction**
  - **Mix of heating methods, and powers**

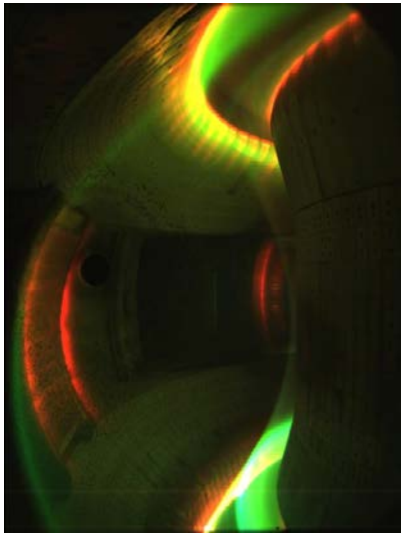
- Plans for remainder of 2017

Very good progress made on Li collaborative experiments in Dec. 2016

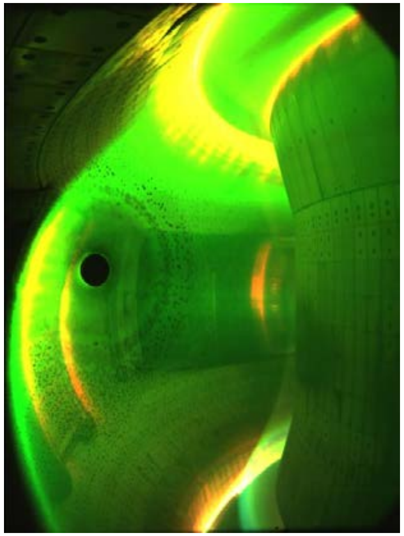
- **Part 1a: mitigate/suppress ELMs with dropper**
  - Previous: ELM suppression in 2013 in C divertors
  - Issue: No effect on ELMs in all metal ASDEX-U, with Li seeding via pellets [P. Lang, R. Maingi, D. Mansfield, NF 2013]
  - New: ELM suppression in EAST achieved for 4 sec
  - Conditioning effect of dropper seen in following discharges
    - **SMBI feedback off – important element of result**
- Part 1b: expand the ELM suppression with dropper to higher heating power
- Part 2: determine the dependence of ELM pacing on lithium granule size and speed
- Part 3: Flowing liquid lithium limiter experiment

New Capability in 2016: EAST outfitted with two droppers, and a W upper divertor





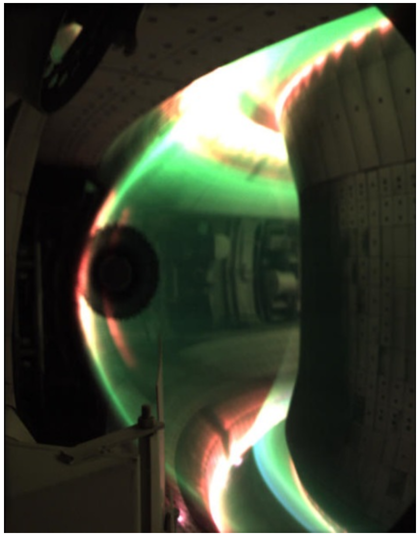
Before



After

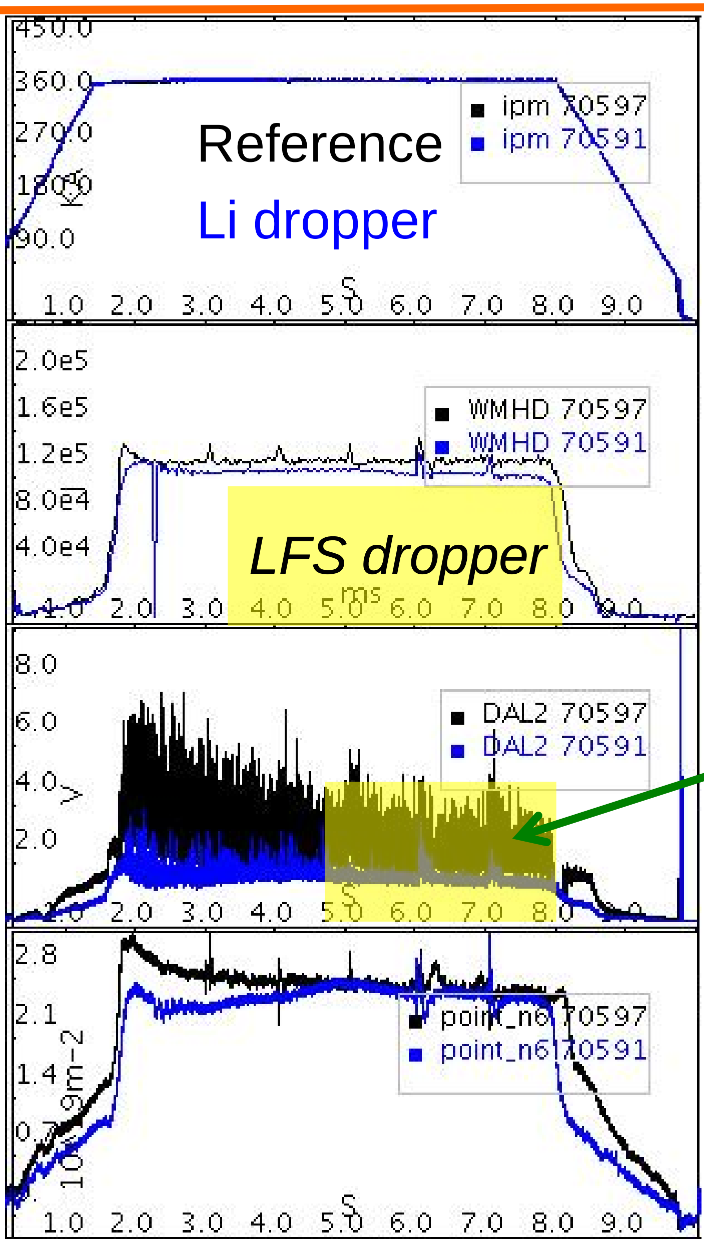
CCD_G

True color



CCD_D

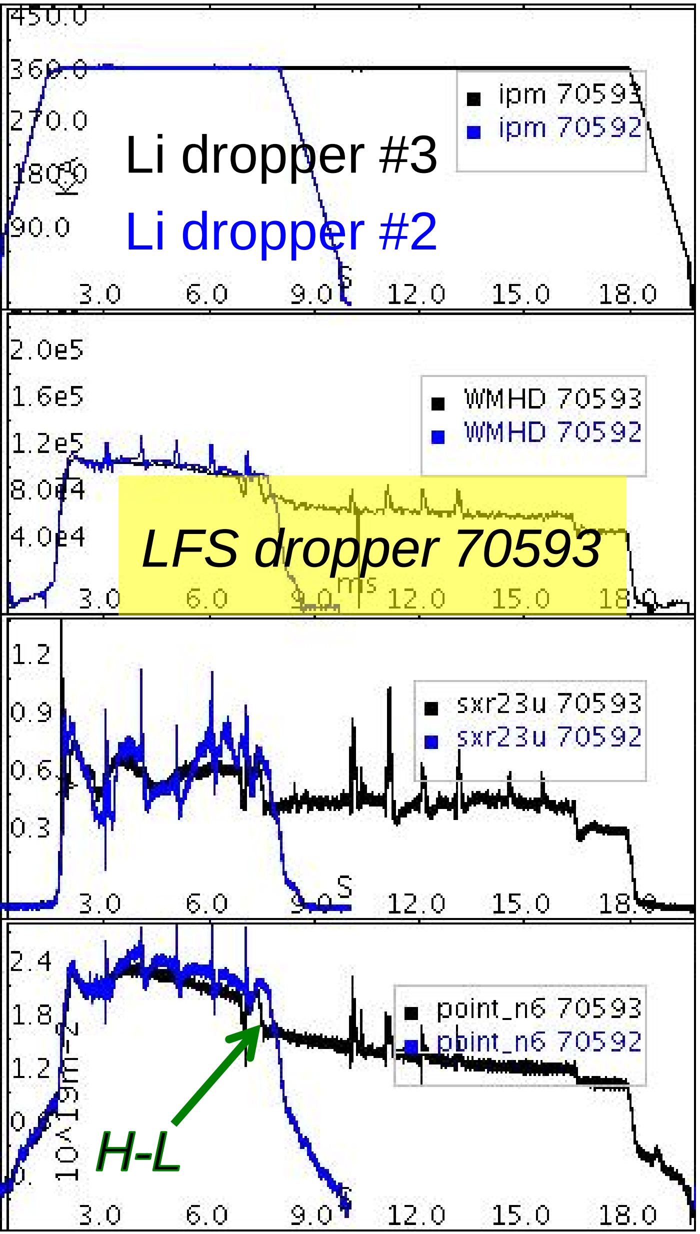
New Result: ELM Suppression Achieved with Lithium Dropper into an USN discharge using W divertor in EAST

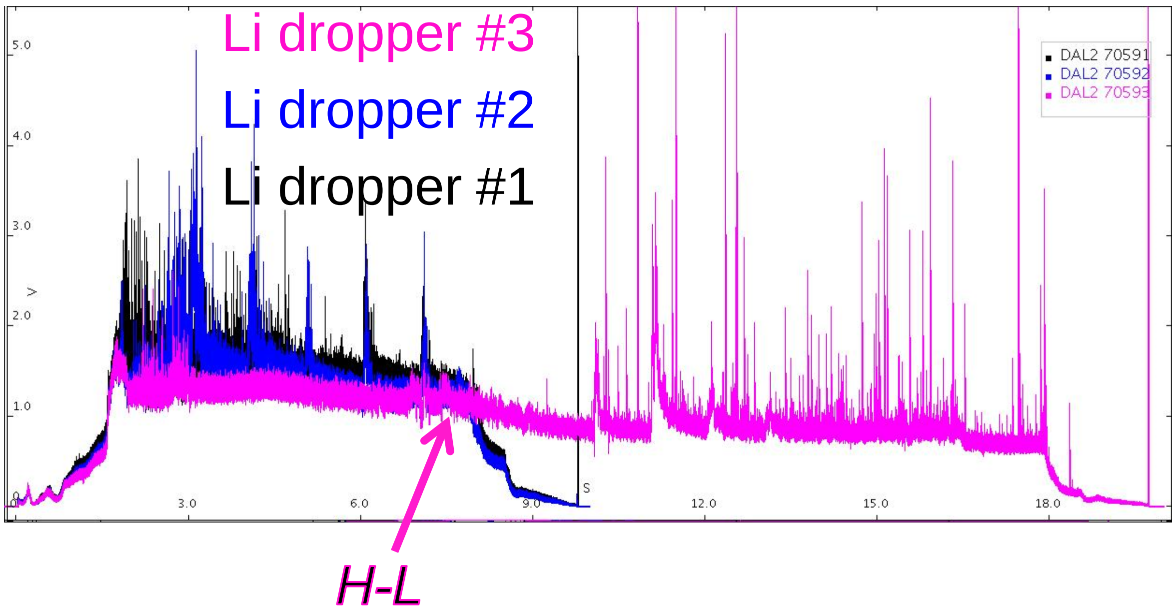


- 0.45 MA, 2.5 T, P_{aux} ~ 3 MW
  - 2 MW PLH2, 0.5 MW PLH1, 0.4 MW PECH
- Stored energy drops by <10% with Lithium dropper
- ELMs suppressed 4.7-8s
- *Next shot: ELMs suppressed 3.9-8s*
- Comparable density
  - SMBI feedback disabled
  - NBI diagnostic blips in both

ASIPP

New Result: Third shot (#70593) with dropper had no big ELMs at all in EAST, not even in the beginning





- D_α baseline reduced shot-by-shot
- Third shot ELM mitigated, even before active Li injection

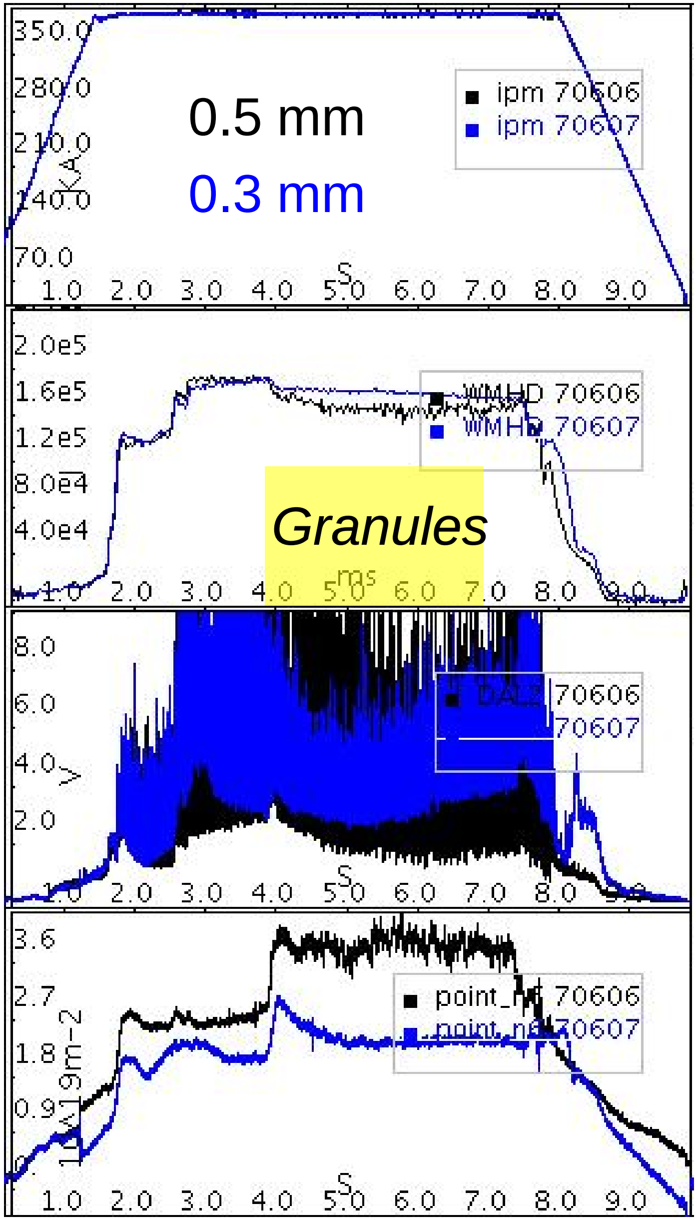
- Li @ 3.5 s -> full ELM suppression
- Third shot H-L ~ 7.5 sec
- ***Data from 12/15/16: detailed analysis in progress!***

ASIPP

Very good progress made on Li collaborative experiments in Dec. 2016

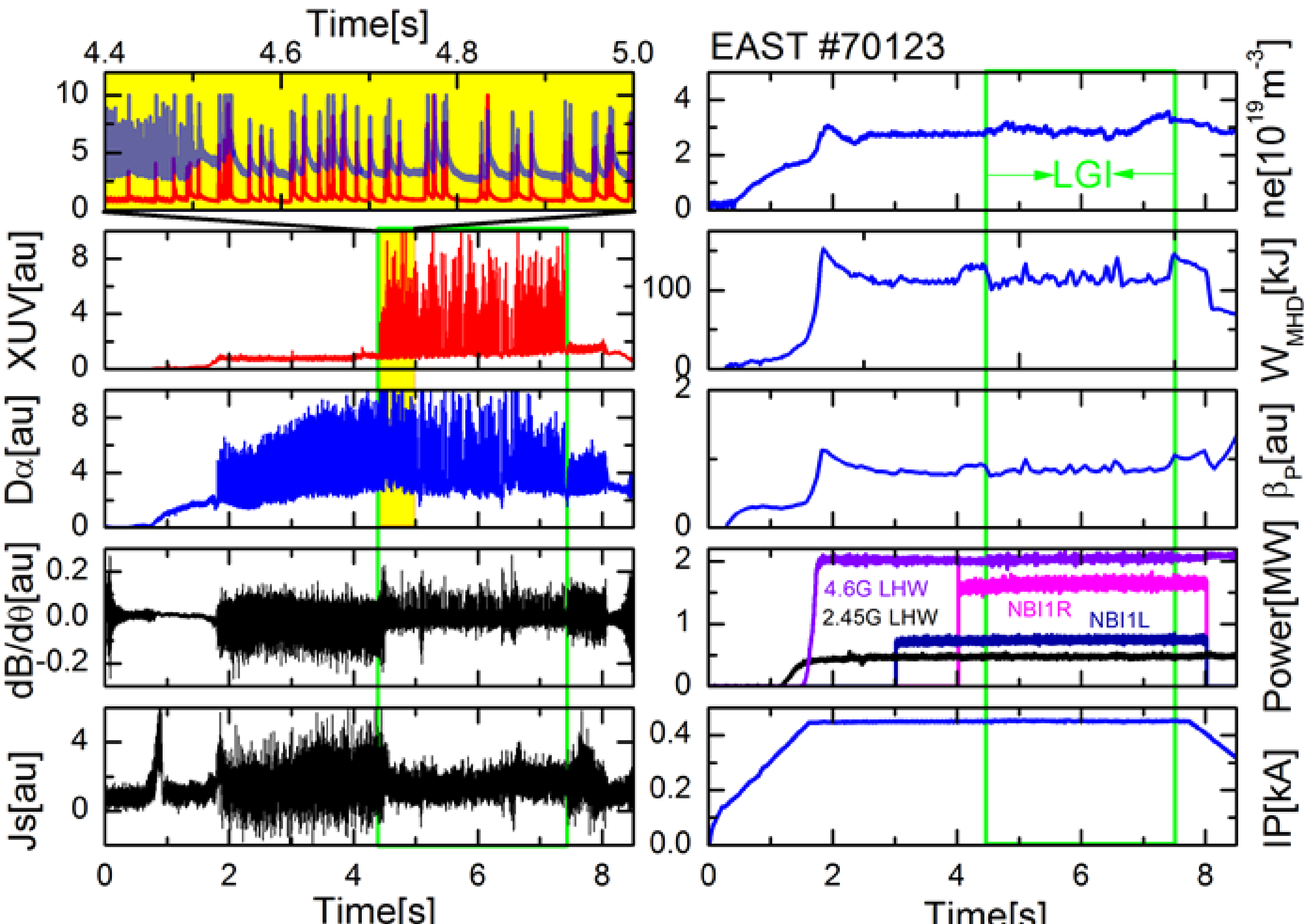
- Part 1a: mitigate/suppress ELMs with dropper
- Part 1b: expand the ELM suppression with dropper to higher heating power
- **Part 2: determine the dependence of ELM pacing on lithium granule size and speed**
  - EAST: ELM pacing previously demonstrated; 1 size granule
  - D3D: ELM heat flux mitigation observed
  - New: four different granule sizes injected; granule size threshold found (between 0.3mm and 0.5 mm)
  - Goal: do modeling to see if threshold size agrees with predictions
- Part 3: Flowing liquid lithium limiter experiment

Lithium granule injector – 0.5 mm granules usually trigger ELMs, but not 0.3 mm – near mass threshold?



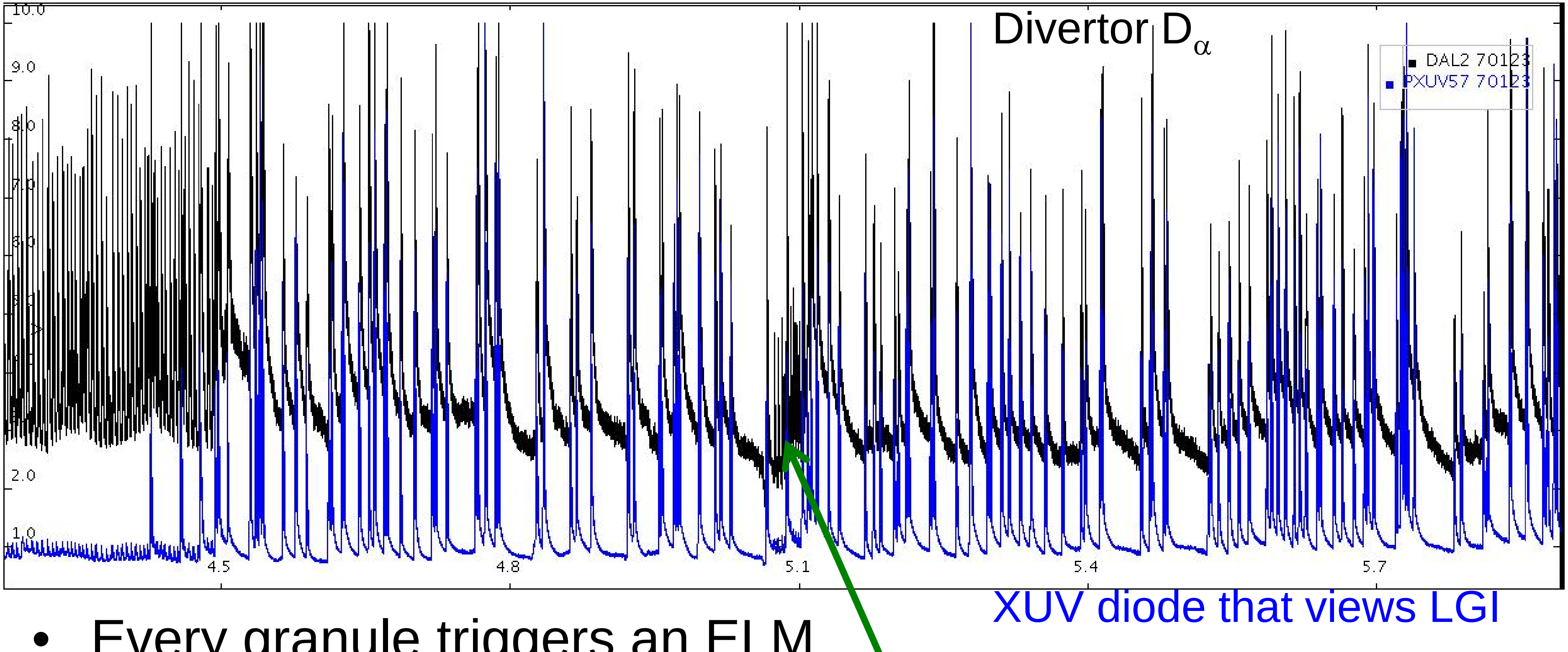
- 0.4 MA, 2.5 T, 2 MW PLH2, 3.3 MW PNBI, 0.4 MW PECH, 0.5 MW ICRF
- Stored energy relatively constant
- Black – 0.5 mm granules
- Blue – 0.3 mm granules
- More density from 0.5 mm granules

<u>ELM pacing</u> with lithium granules achieved transiently in EAST with W divertor (small granules)



ELM pacing with lithium granules achieved transiently in EAST with W divertor *(no ELM size mitigation)*

- Rapid ELMy plasma converted to 50-60 Hz ELMy plasma



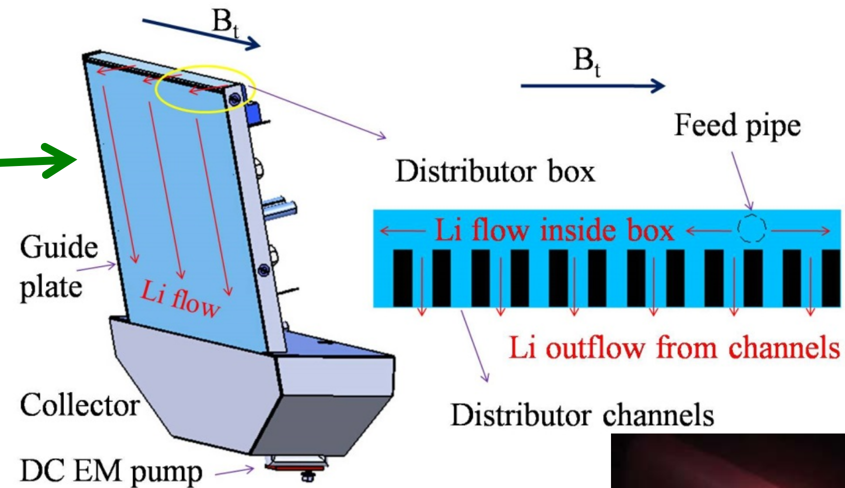
- Every granule triggers an ELM
- In one phase, plasma resumes rapid ELMs for short time
- 4-5 granules required for transition
- Maintained for duration of injection ~ 3 sec

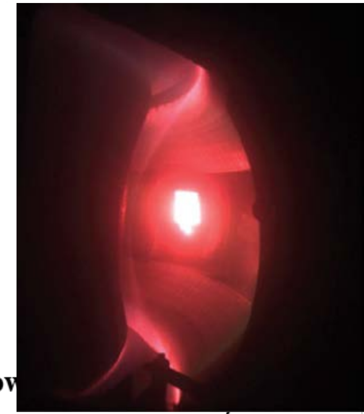
Very good progress made on Li collaborative experiments in Dec. 2016

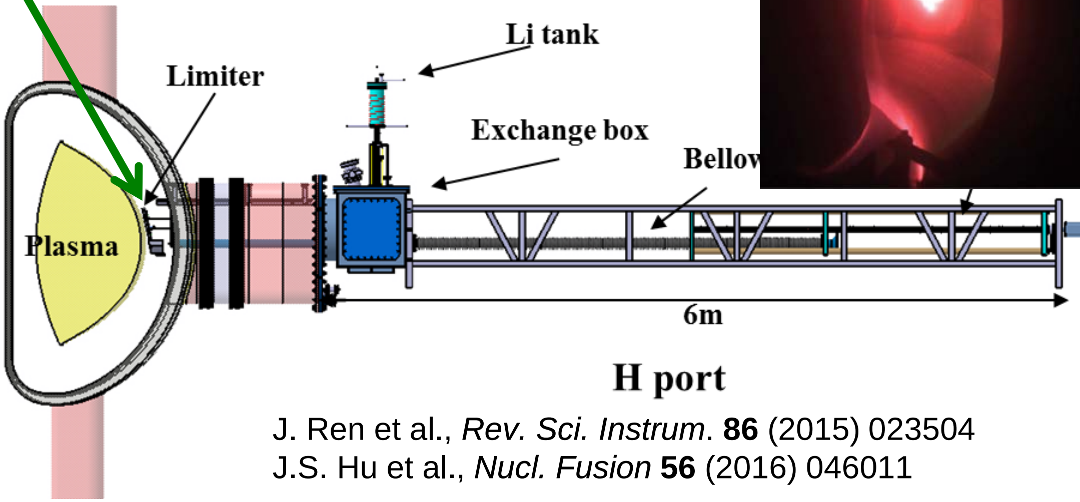
- Part 1a: mitigate/suppress ELMs with dropper
- Part 1b: expand the ELM suppression with dropper to higher heating power
- Part 2: determine the dependence of ELM pacing on lithium granule size and speed
- **Part 3: Flowing liquid lithium limiter experiment**
  - Previous: limiter compatible with H-mode, but damage to front face
  - New: limiter put into higher power discharges; no damage
  - Avoided bringing limiter close to separatrix with NB heating (large fast ion orbits could have caused previous damage)

Flowing liquid lithium limiter shown to be compatible with H-mode discharges in EAST in Oct. 2014

- Goal: evaluate flowing liquid lithium as a PFC
- Designed/made at PPPL
  - \- Cu heat sink
  - \- SS protective coating
- Inserted at midplane on MAPES system
- *H-modes and ohmic discharges compatible with flowing Li limiter*
  - \- $q_{peak}^{limiter} \sim 2$ MW/m^2
- Next design will improve SS coating and heaters, followed by a re-design using a Mo heat sink



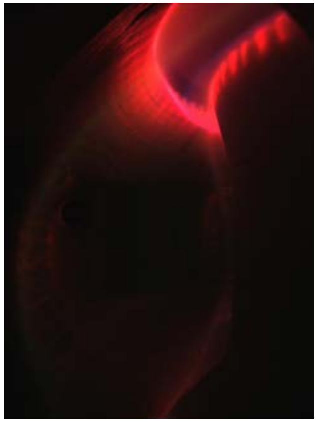


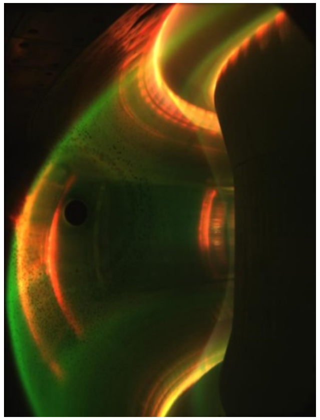


J. Ren et al., *Rev. Sci. Instrum*. **86** (2015) 023504
J.S. Hu et al., *Nucl. Fusion* **56** (2016) 046011

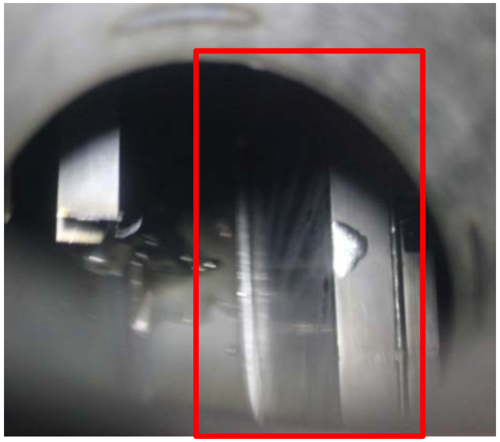
New: FLiLi compatible with H-modes in EAST; extended to higher heating power than in 2014

- Achieve flowing liquid Li (FLiLi) driven by inner EM pump
- FLiLi compatible with auxiliary heated plasmas: 0-4.5 MW
  - No obvious limiter surface damage; improvement from Oct. 2014!
  - Improved plasma performance including full-field ohmic H mode
- Possible ELM mitigation in several cases
  - Transient ELM-free H-modes observed, with strong increase of W_{MHD} and H98

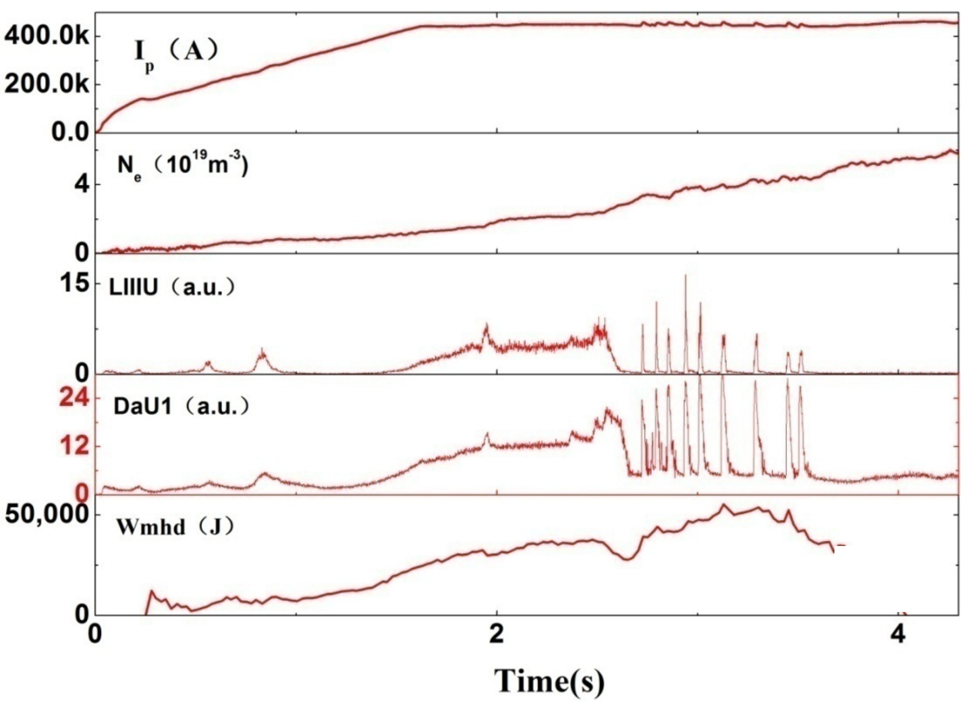

Without FLiLi

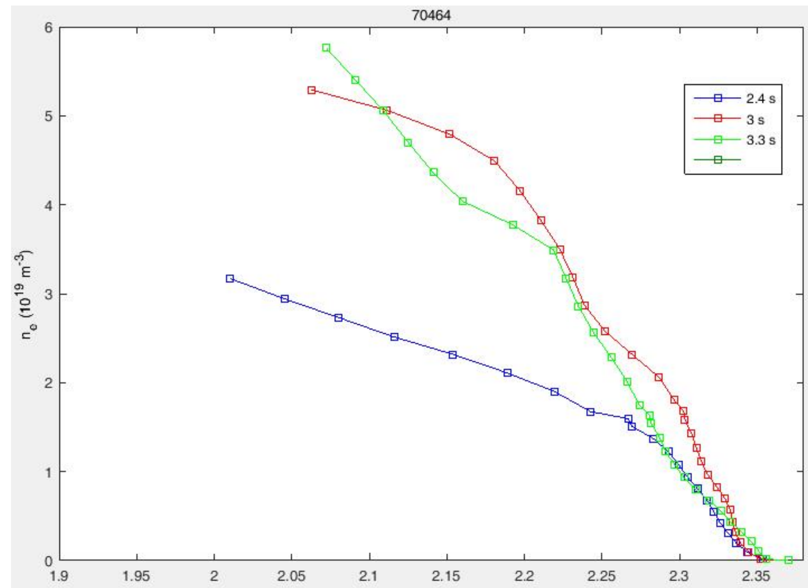

With FLiLi


Before FLiLi experiment


After FLiLi experiment

First time observation: Ohmic H-mode observed with FLiLi, with unfavorable drift direction

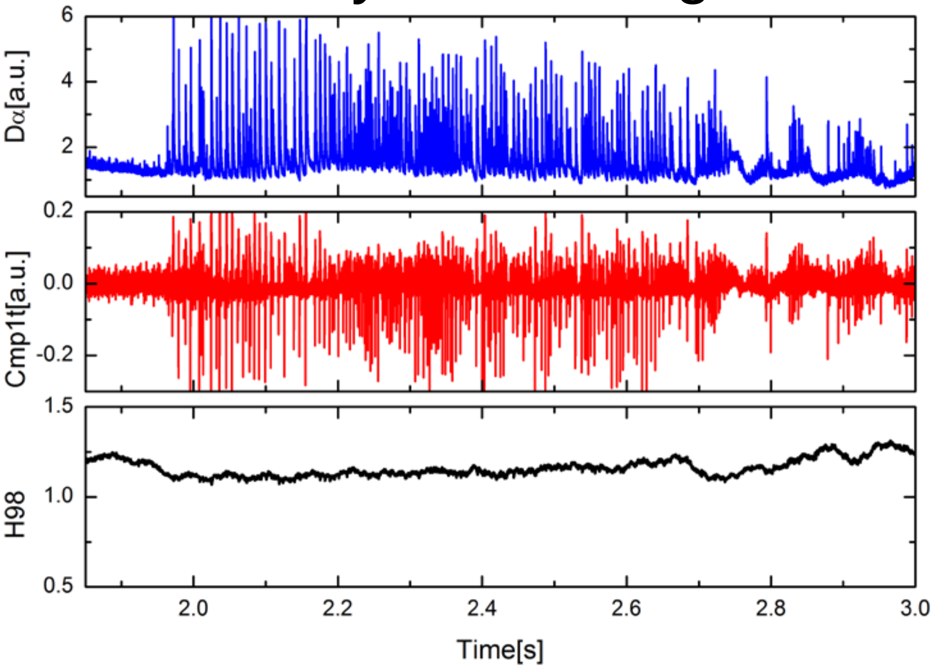




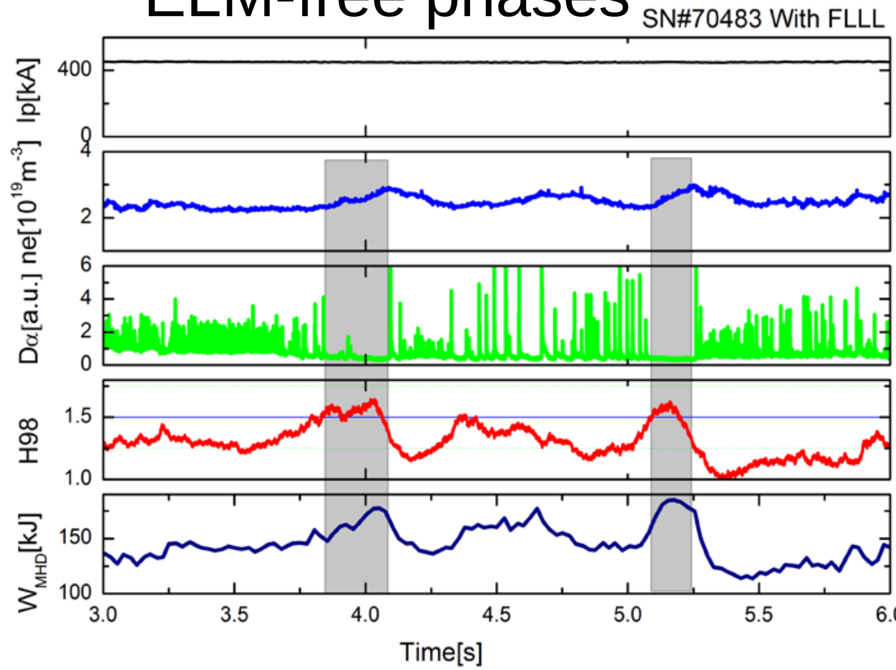
- Can this be also achieved with Li dropper?

First time observation: ELM-free H-mode observed with FLiLi, with transient increases in H98

Early in discharge



ELM-free phases



- Atypical behavior for EAST – are the continuous edge modes suppressed? True ELM-free H-mode?

Outline

- Goals of collaboration
- First set of experiments in Dec. 2016
- **Plans for remainder of 2017**

EAST schedule for next year has been disclosed

- EAST experiments stopped end of Dec. 2016
  - Shut down for Chinese New Year for 2 weeks on 1/20/17
  - An experiment planning meeting is scheduled for March 13-14, 2017, similar to the first one in Jan. 2016

- Restart operations in Spring, 2017 with no changes
  - 2 month run in May and June
  - Opportunities for follow-on lithium experiments
  - Lower divertor has damage – cannot put much power on it

- Shut down summer 2017 to install W lower divertor
  - Start-up ~ early 2018 with all metal walls
  - Plan for a controlled lithium introduction after assessing uncoated tungsten performance

Potential follow-on experiments

- Lithium dropper: mitigate ELMs in higher power and higher current discharges
  - Requires slow and systematic increase in P_{aux} and dropper variations to understand how much is required
  - Ohmic H-mode with dropper in USN, like FLiLi

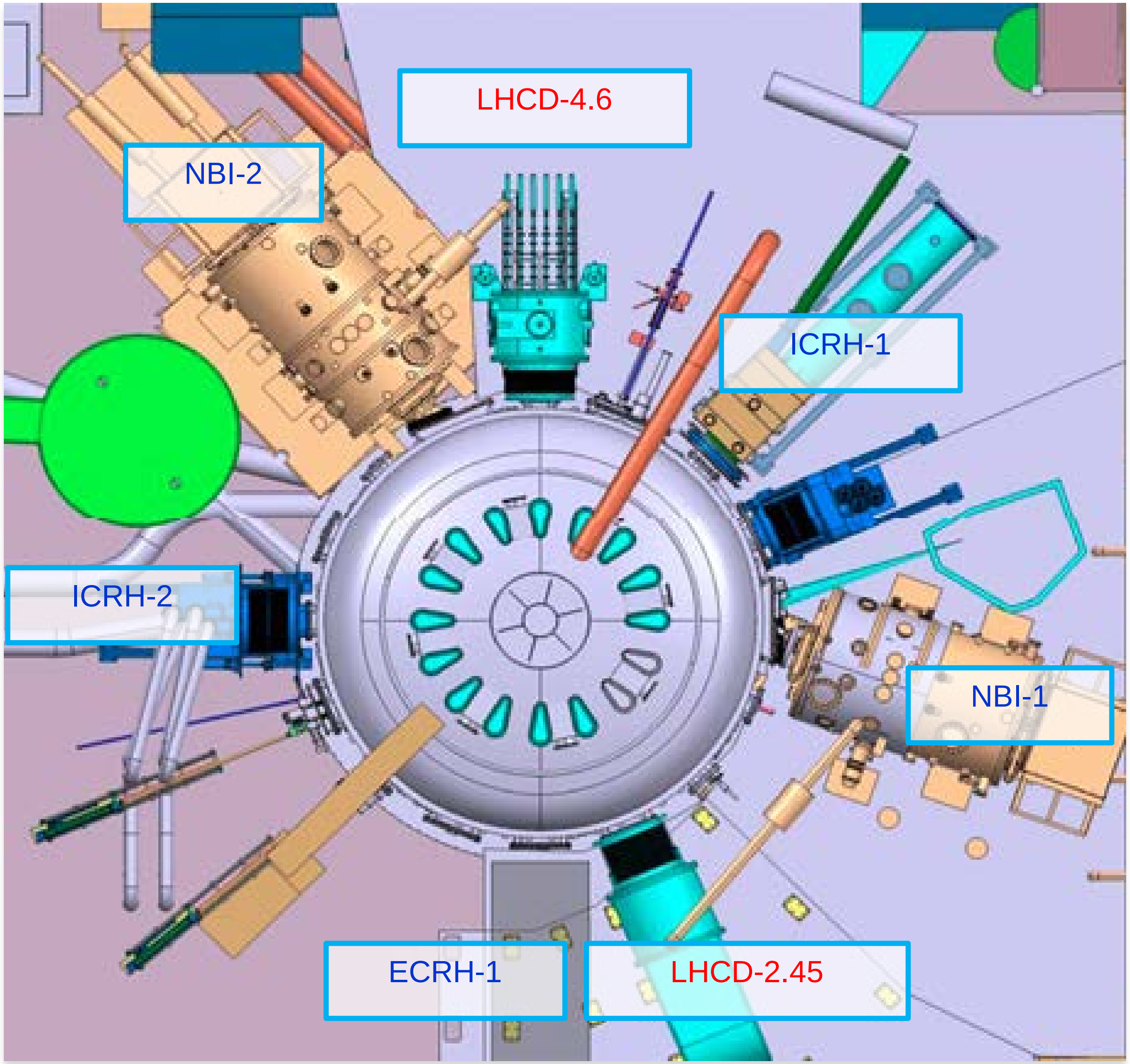
- Lithium granule injector: mitigate ELMs in ELM-free conditions, with or without dropper, or in low frequency ELMy H-mode
  - Highest power discharges probably require larger granules

- Flowing liquid lithium limiter: need to test with NBI H-mode, compatibility with fast ions (likely 2018)
  - New version of FLiLi made of Mo being designed @ PPPL

The importance of this US-China collaboration is reflected in a 2017 PPPL Notable Outcome

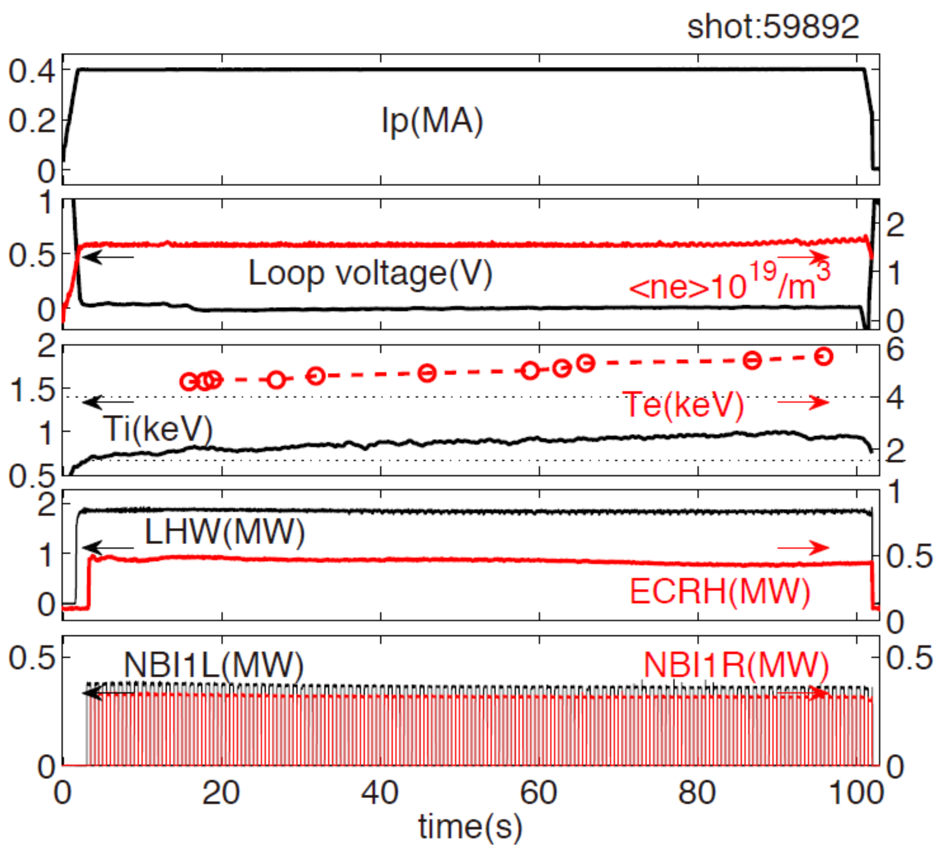
- “Deliver impactful science and provide leadership for the PPPL-led multi-institutional international collaboration on EAST, as measured by the 2017 progress report, research publications and highlights, and participation in periodic progress review videoconferences.”

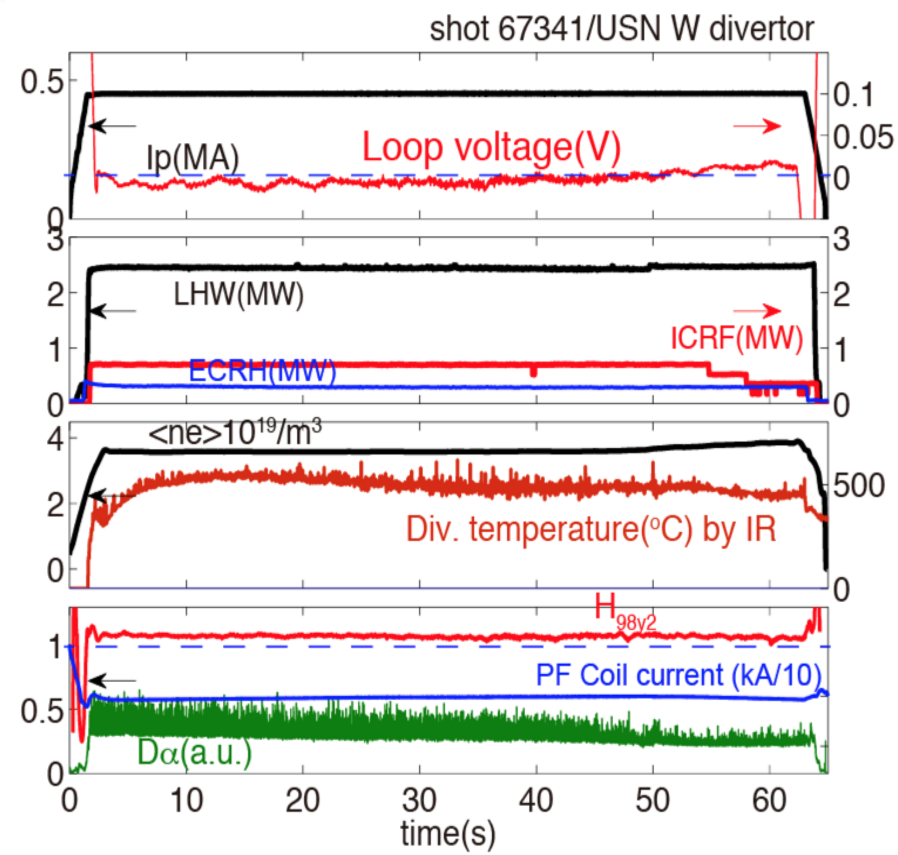
Current EAST heating capabilities



- LHCD-4.6 GHz < 3 MW (typical 2 MW)
- LHCD-2.5 GHz < 2 MW (typical 0,8 MW)
- NBI-1 (co) < 3 MW
- NBI-2 (ctr) < 3 MW
- ECRH < 0.5 MW (typical 0.4 MW)
- ICRH < 2 MW (coupling efficiency ~ 25%)

Long pulse steady-state operation on EAST





100s high electron temperature (Te > 4.5keV) operation

Minute-scale steady-state H-mode (H_{98}>1.1) operation

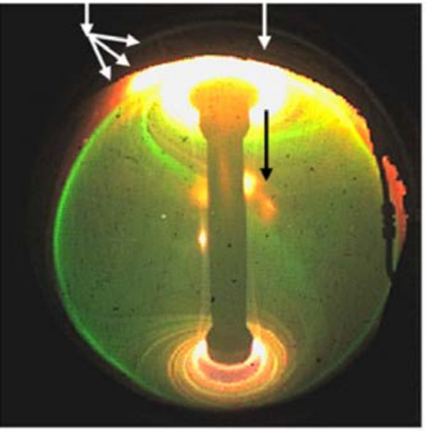
US-ASIPP worked extremely well – we used the term "ONE TEAM" as a moniker

- **Shown by EAST management in several forums**

Backup

Innovative gravitational dropper used to drop impurities and improve performance in the edge of fusion devices

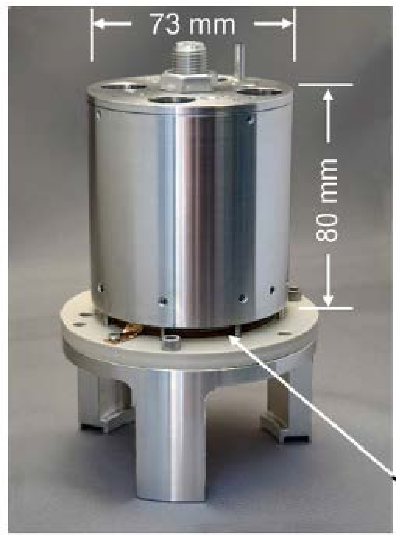
NSTX: ELM suppression



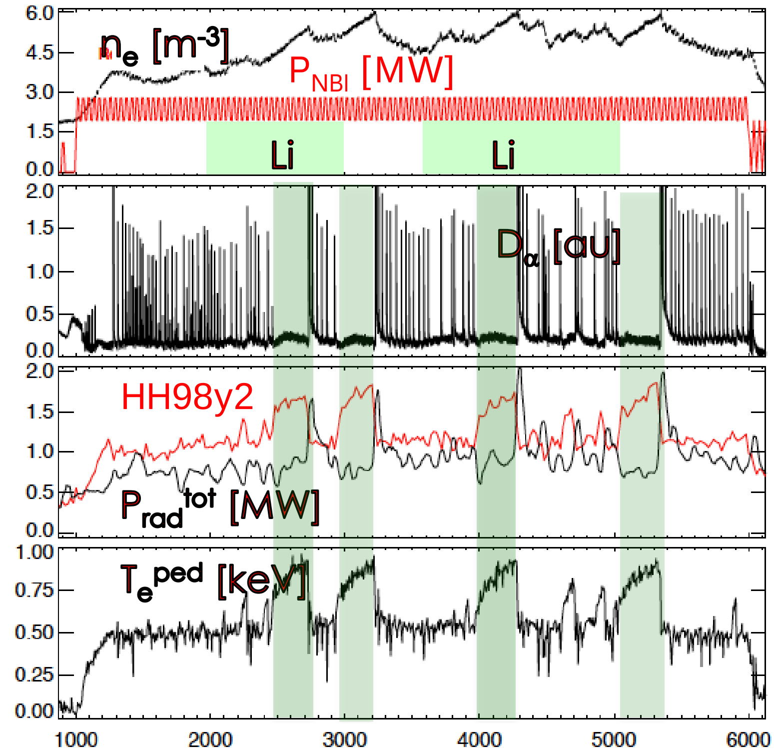
t = 655 ms

ELMs and MARFES vanish at t ~ 500 ms. Stored energy peaks and a sharp plasma edge with Li^{+1} radiative mantle develops.

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



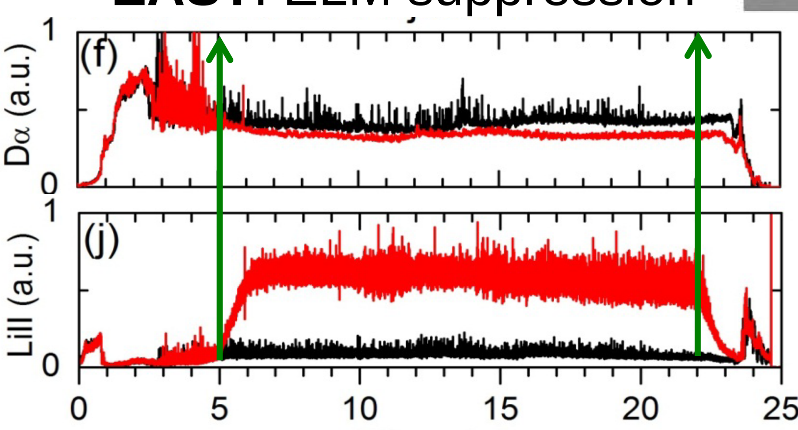
D3D: high confinement bifurcations



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

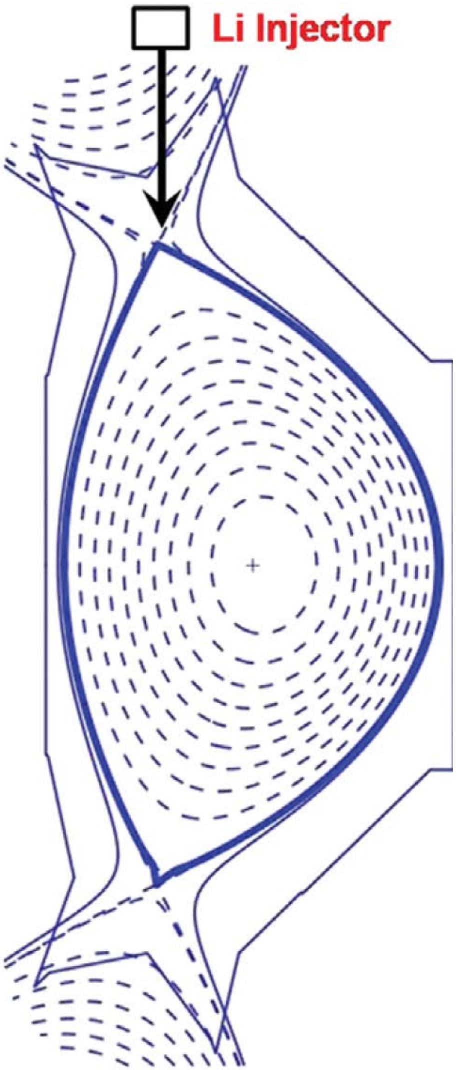
R. Maingi, H-mode Workshop, Oct. 2015

EAST: ELM suppression

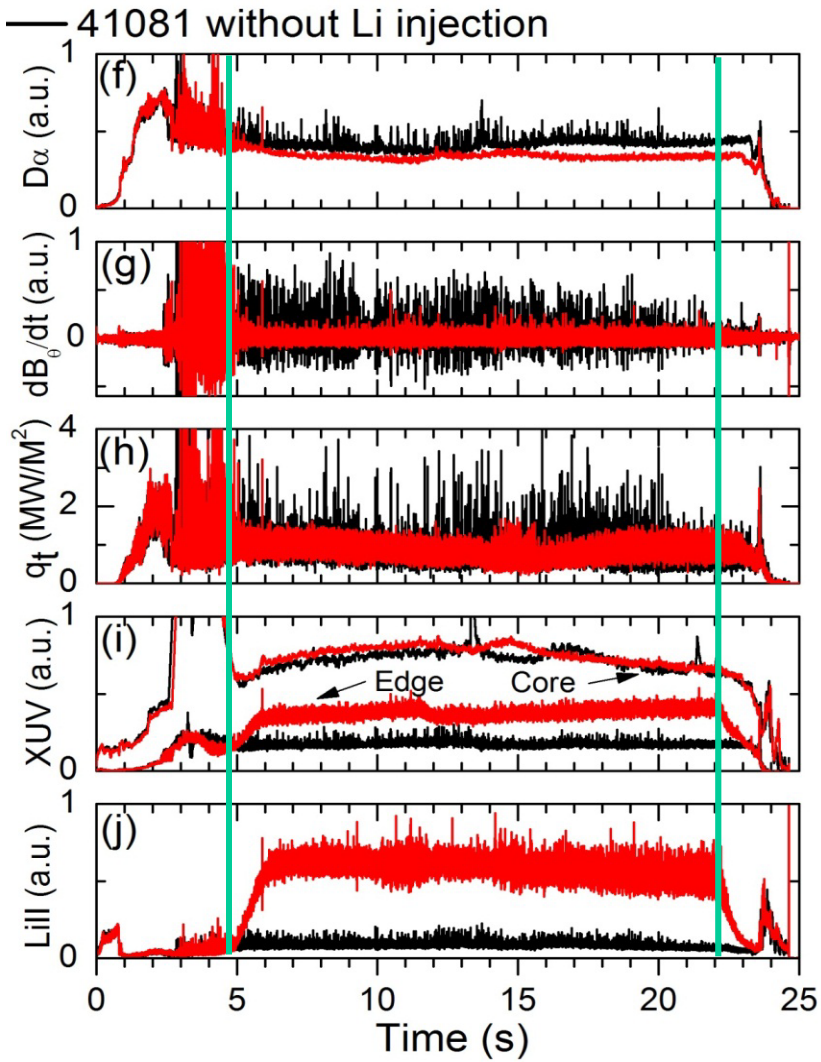


J.S. Hu, PRL **114** (2015) 055001

ELM frequency drop correlated with Li injection in EAST (2013); elimination required several sec



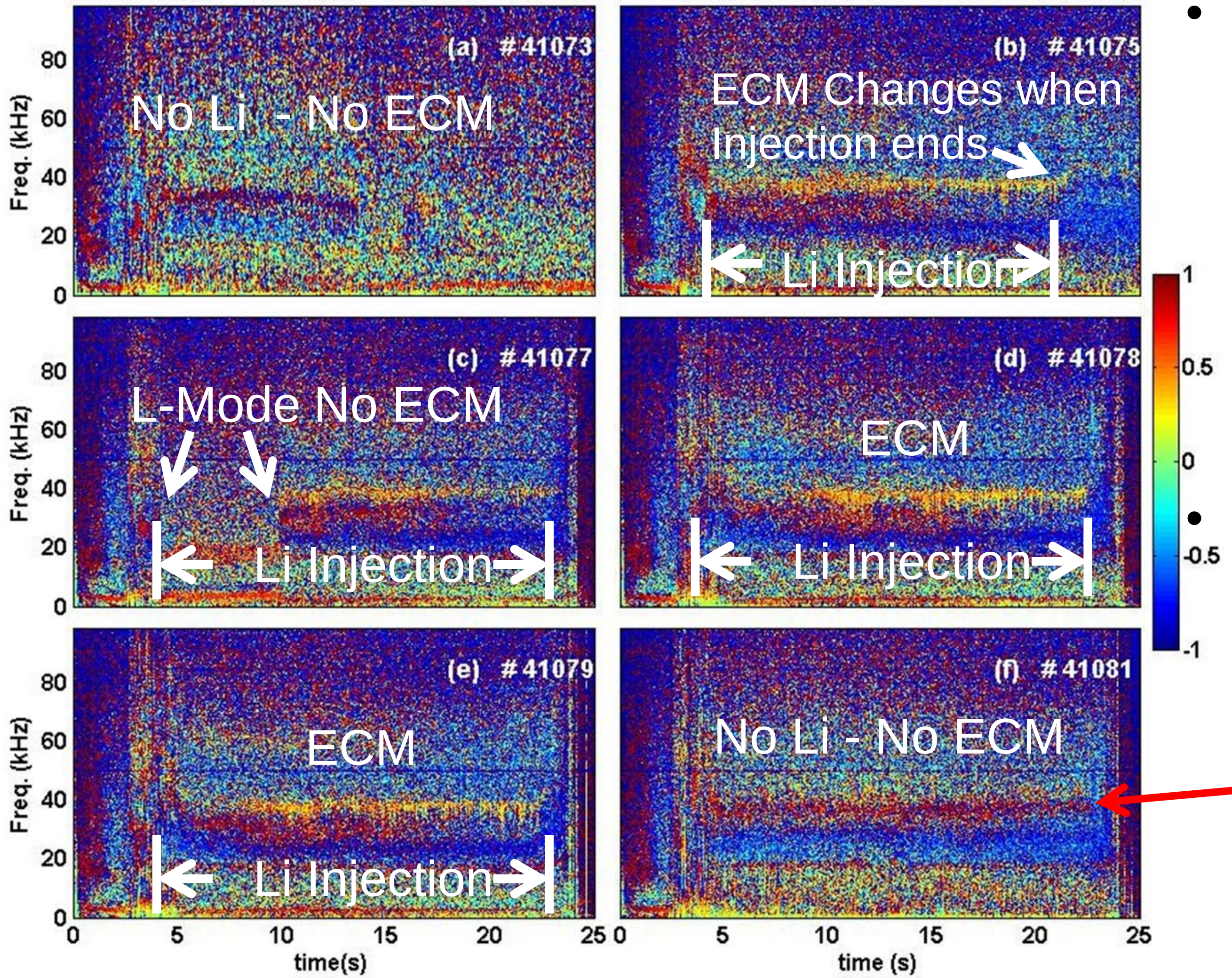
- DN
- C upper
- C lower



- H_{H98} was only ~ 0.75; type III ELMs here?

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

Edge coherent mode (ECM) turned on with Lithium injection (and correlated ELM elimination) in EAST in 2013

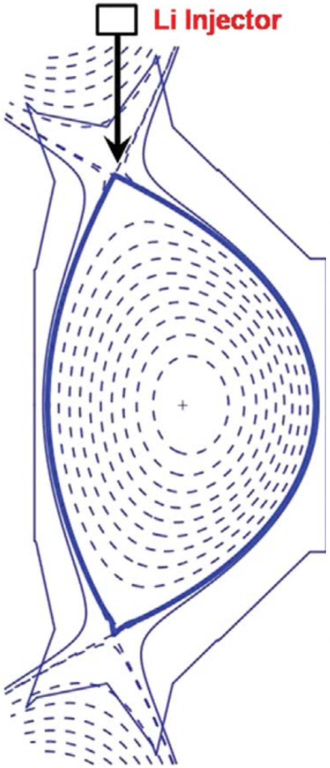


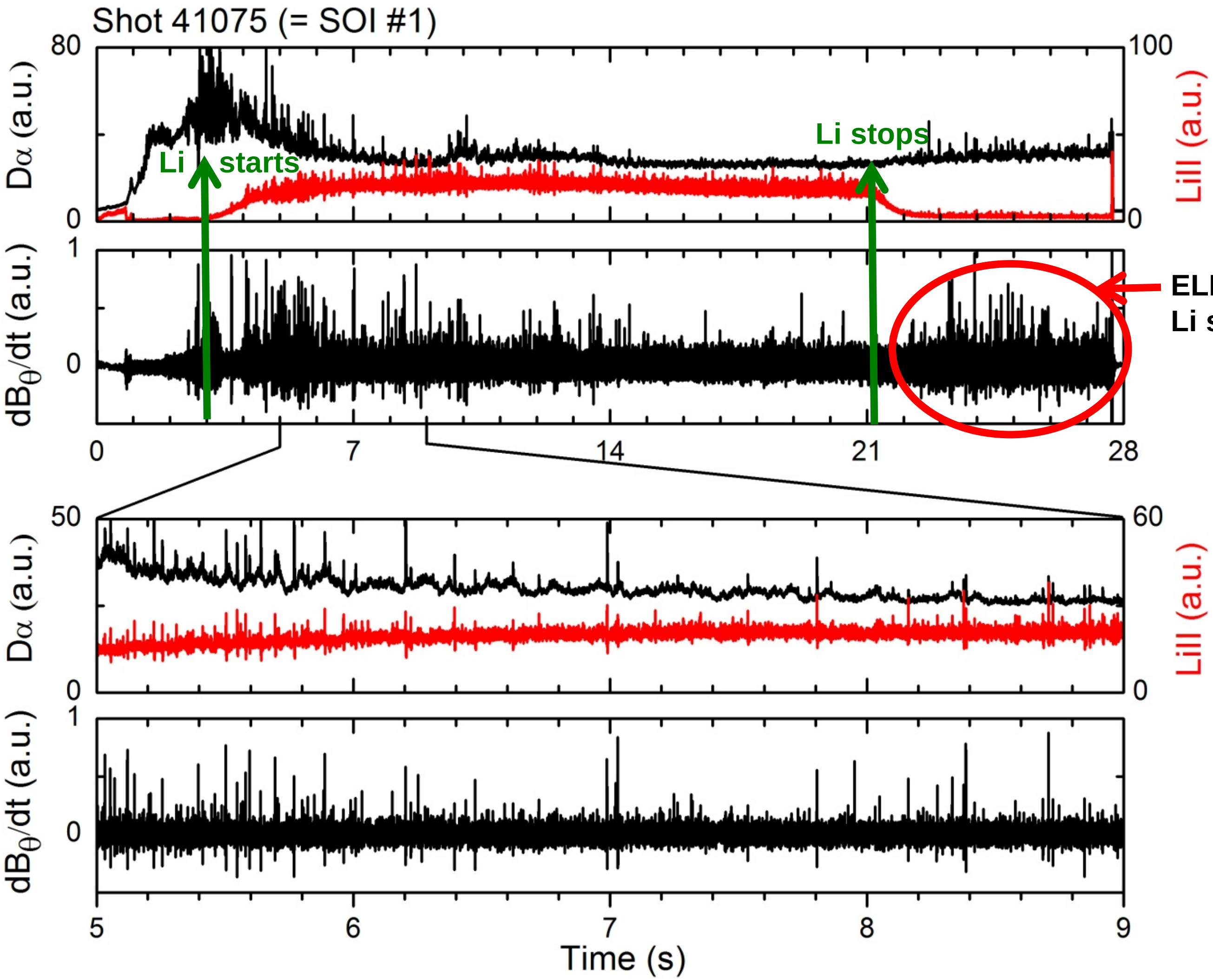
- **ECM thought to augment particle transport, which prevents impurity accumulation (Data from Mirnov coils)**
- **Analysis suggests intermediate ν* mode**

Mode in red color at same frequency as ECM but different poloidal structure

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

ELM frequency drop correlated with Li injection in EAST (2013); elimination required several sec

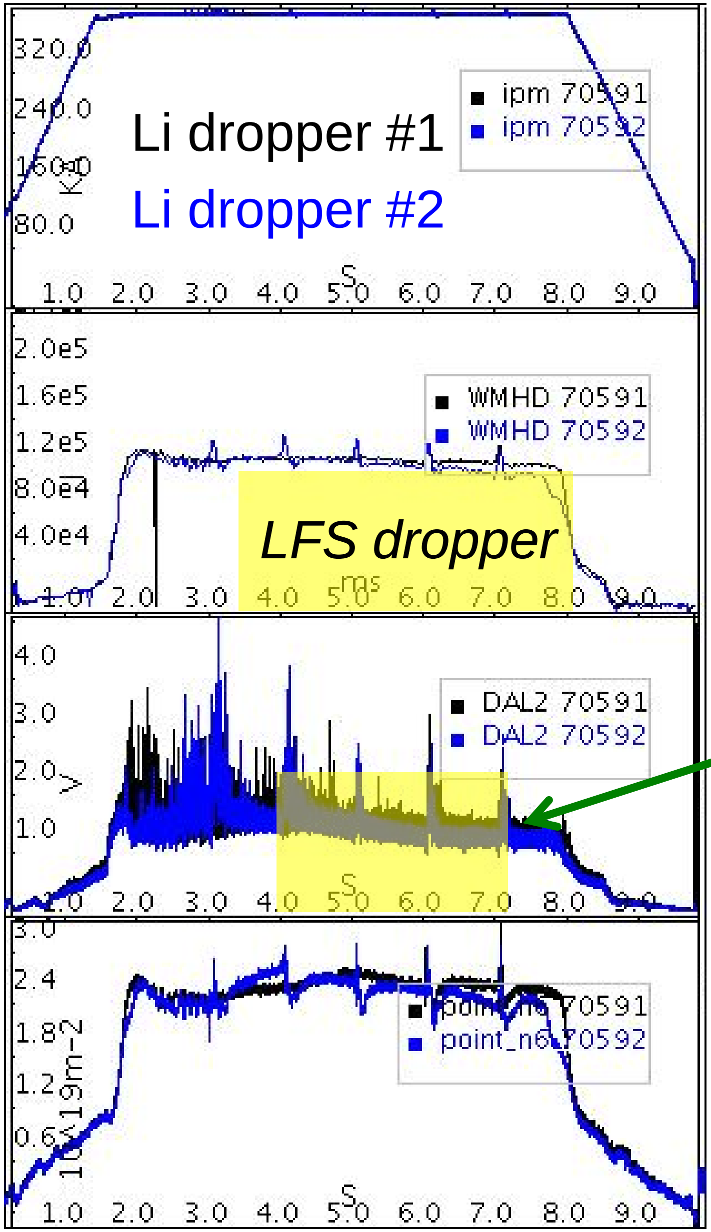




- DN
- C upper
- C lower

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

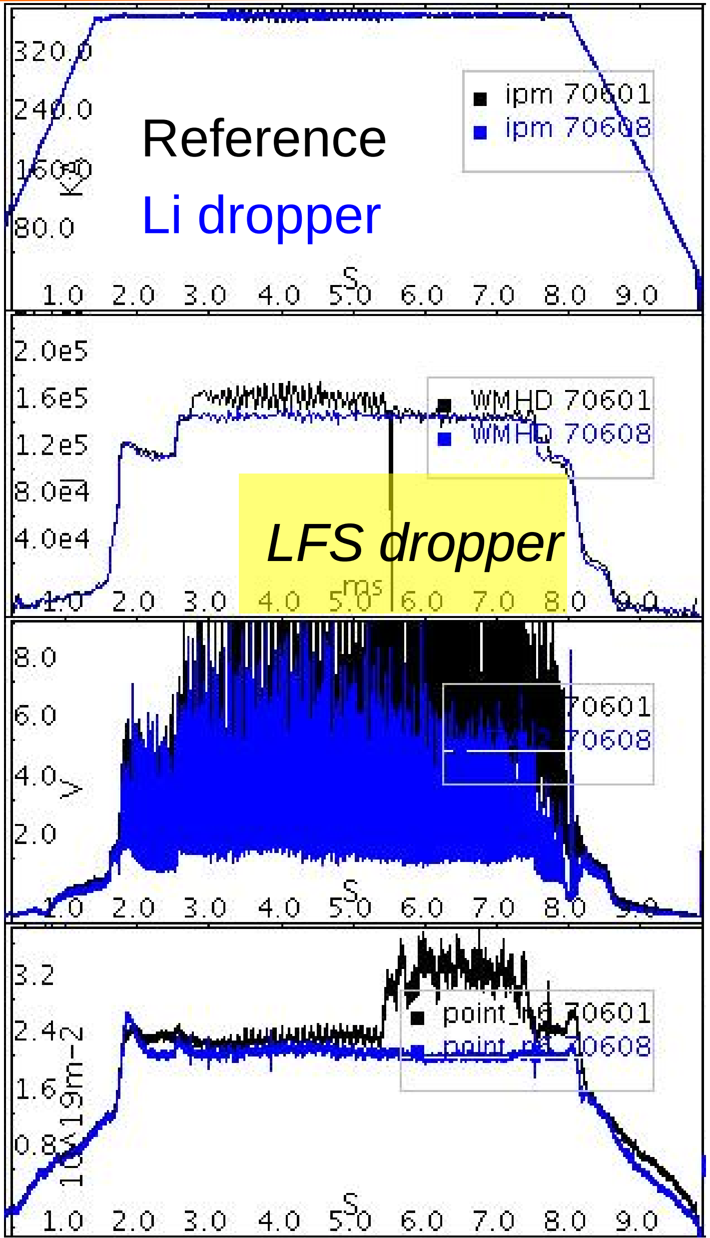
New Result: Second shot with Lithium Dropper Achieved ELM Suppression Earlier than First in EAST



- 0.45 MA, 2.5 T, P_{aux} ~ 3 MW
  - 2 MW PLH2, 0.5 MW PLH1, 0.4 MW PECH
- Stored energy drops by <10% with Lithium dropper
- ELMs suppressed 3.9-8s
  - D_α baseline lower – dropper provided real time conditioning!
- Comparable density
  - NBI diagnostic blips can trigger short burst of ELMs

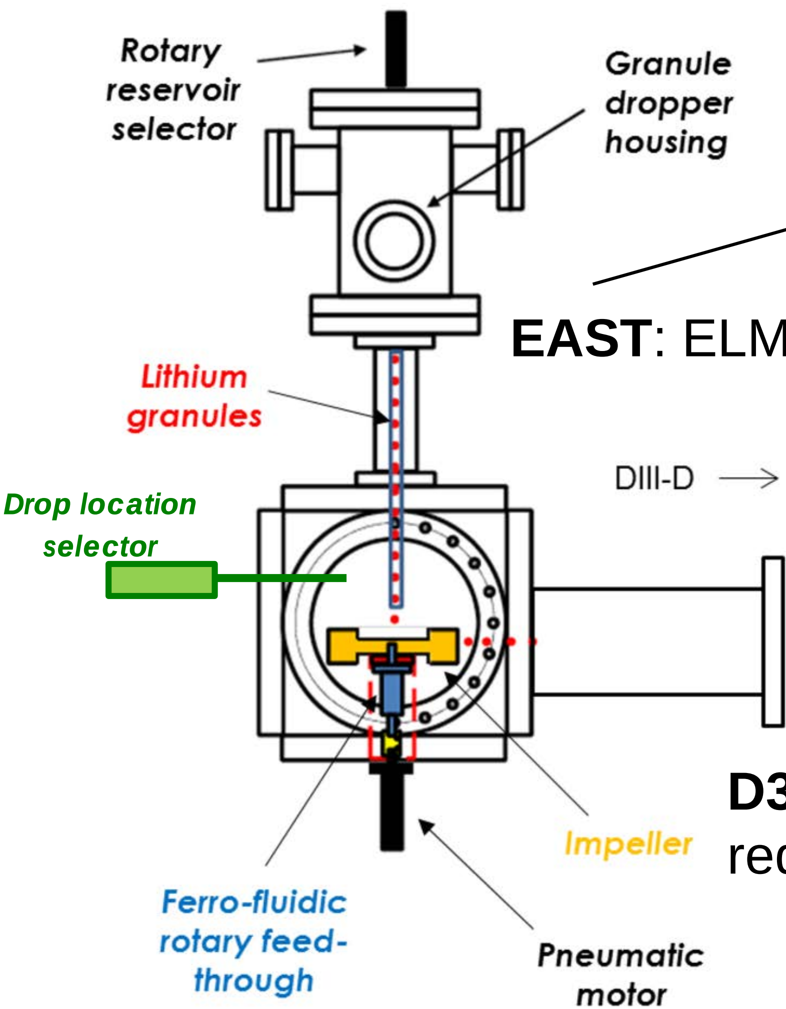
ASIPP

ELM Mitigation may have been achieved in high power discharges with lithium dropper

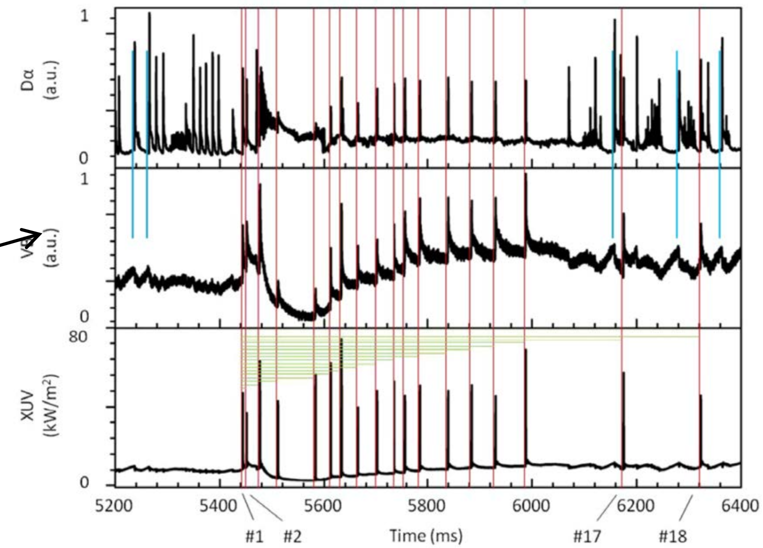


- 0.4 MA, 2.5 T, P_{aux} ~ 5 MW
  - 1.7 MW PLH2, 1.7 MW PNBI, 0.4 MW PECH, 1 MW ICRF
- Stored energy relatively constant
- D_{α} amplitude reduced – needs optimization of Li?
- Comparable density until 5.5 sec, when granules used in reference (black) discharge

Impurity granule injector used to pace ELMs and test heat flux mitigation in tokamaks

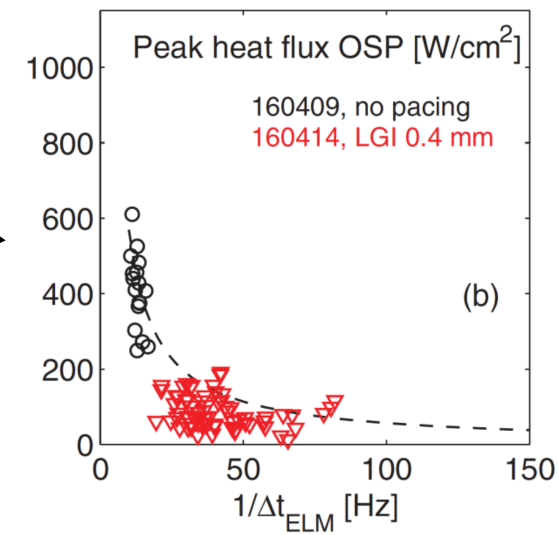


EAST: ELM pacing



D. Mansfield, NF **53** (2013) 113023

D3D: peak heat flux reduction

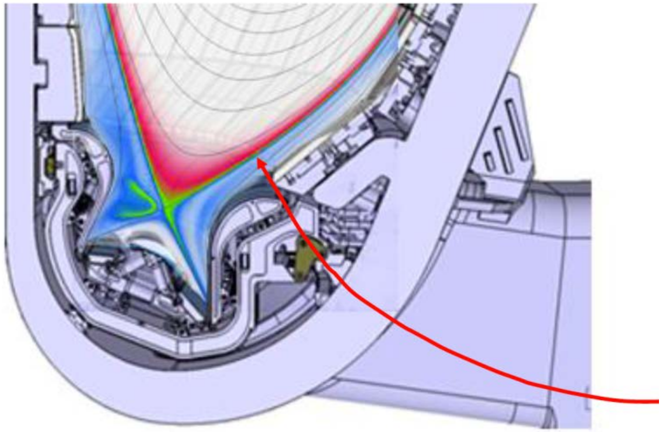


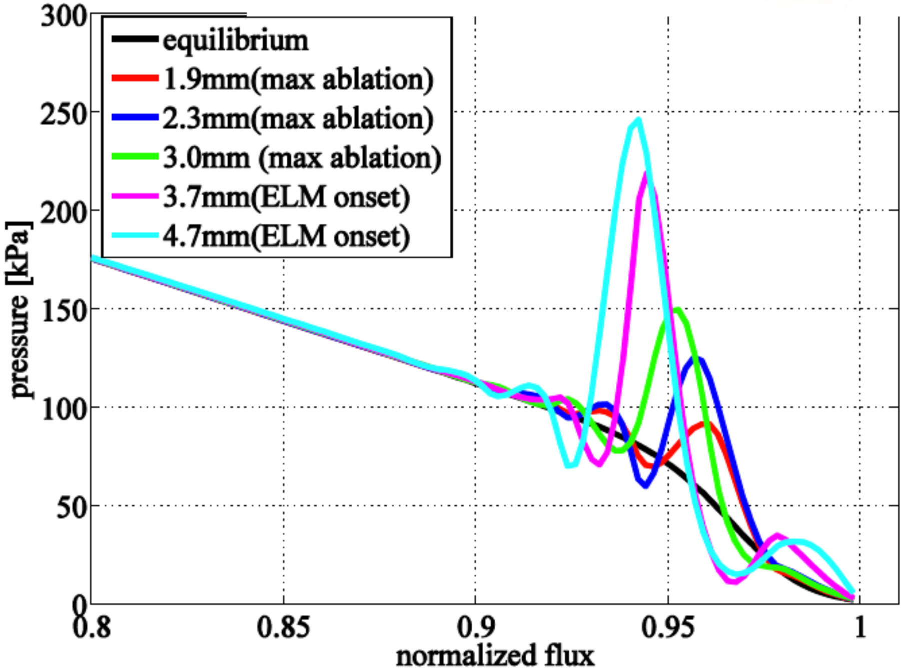
A. Bortolon, NF **56** (2016) 056008

JOREK modeling used to project size threshold for of when pellets can trigger ELMs, e.g. for ITER 15 MA Q=10 scenario

- Ballooning mode triggered roughly when local pressure reaches ~ 250% of pre-pellet pressure
  - Required $r_{pel} \geq 3.7$ mm
  - Required $v_{pel} > 350$ m/s
  - Likely an upper bound for needed pellet size, as DIII-D minimum pellet size was over-estimated by factor of 2-4

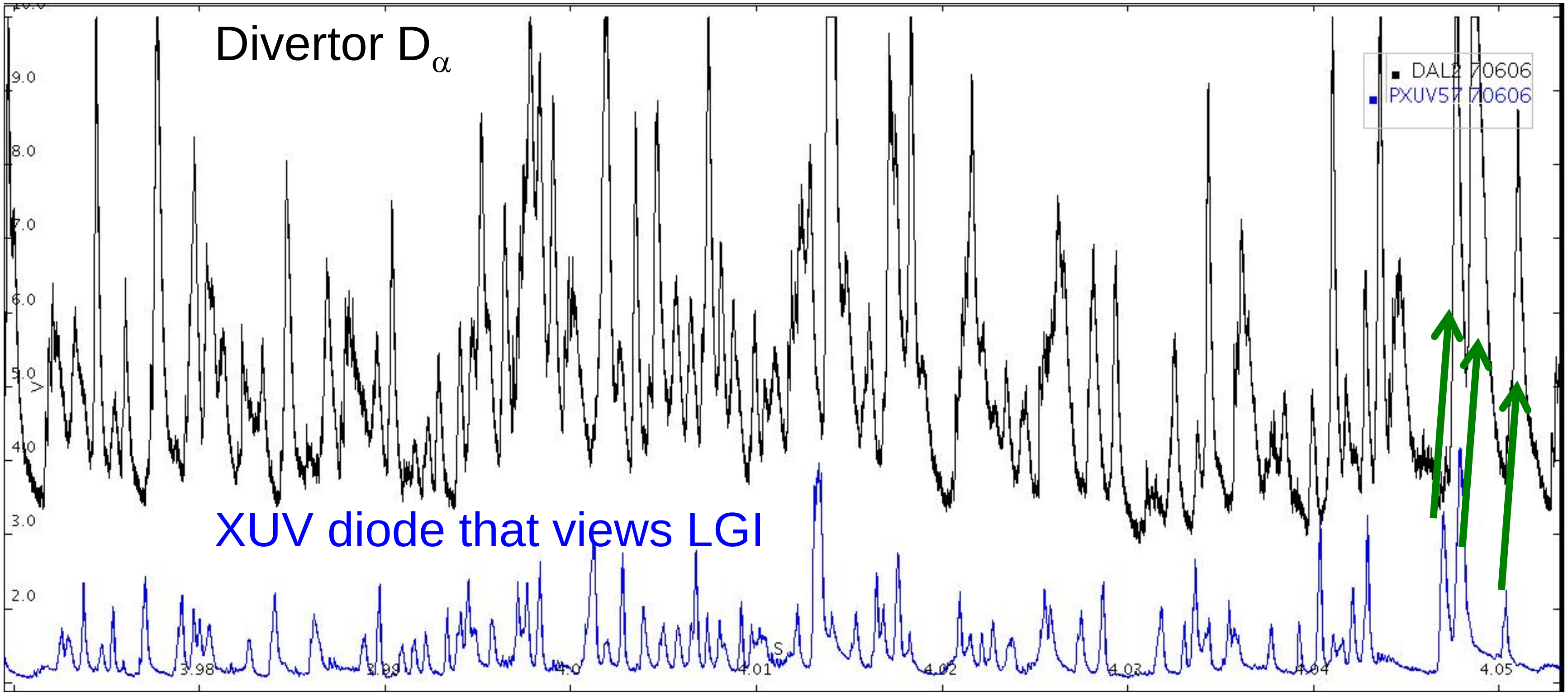
Pacing pellet trajectory schematic





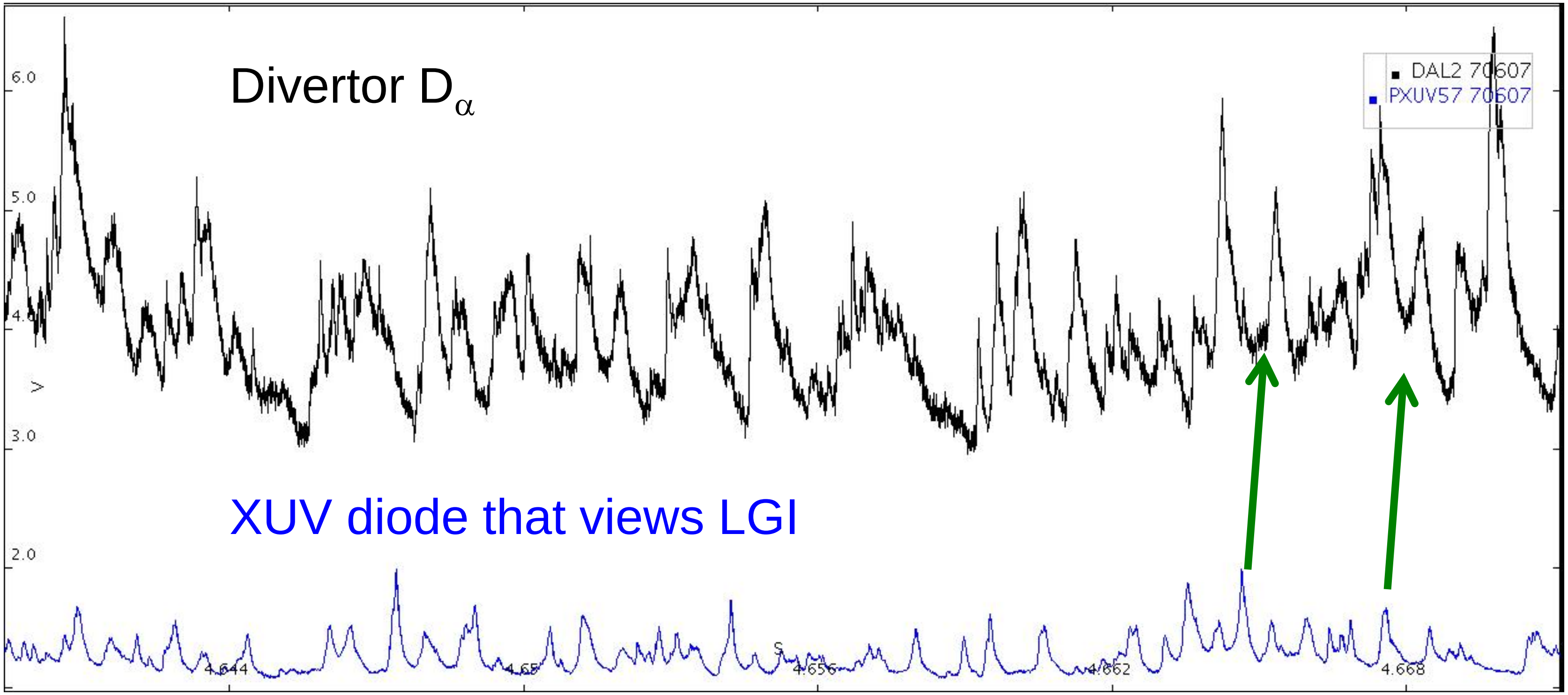
Futatani, IAEA 2012

Most (maybe all?) of the 0.5 mm granules trigger ELMs



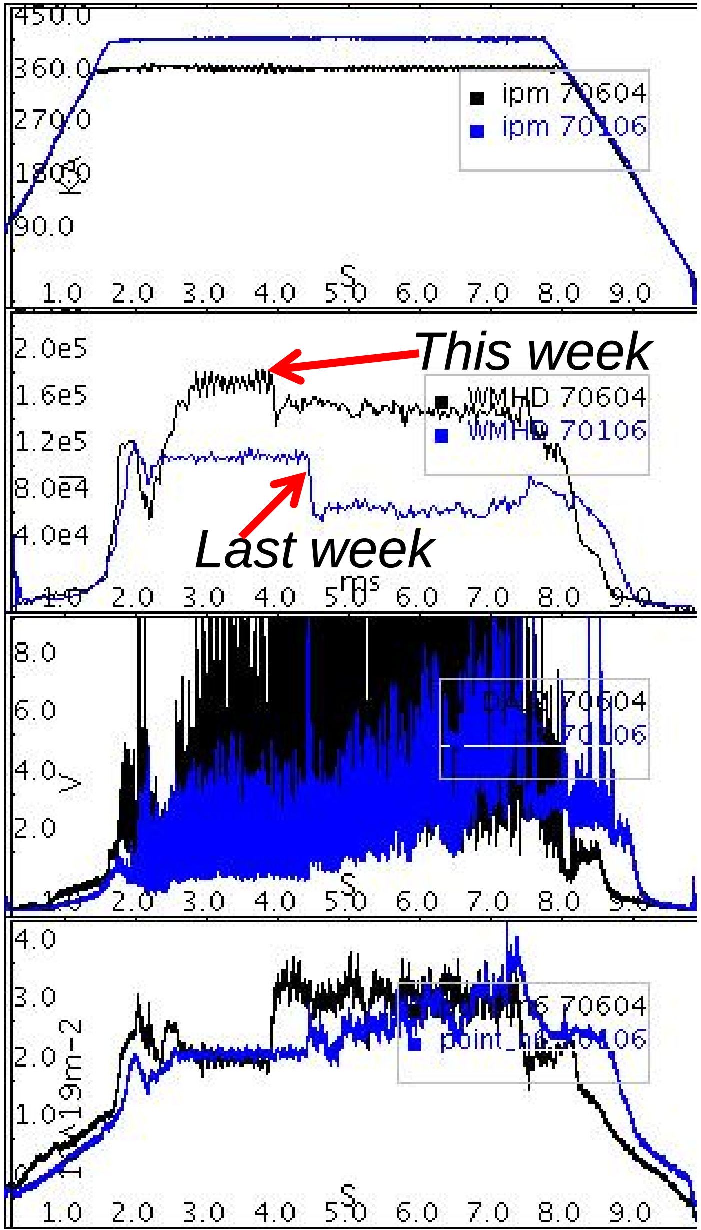
- ELMs not paced – natural ELM frequency about the same as the granule rate used

Few of the 0.3 mm granules trigger ELMs



- Some of the 0.3 mm granules that fell in clumps may have triggered ELMs
- 0.3 mm may be just below size threshold

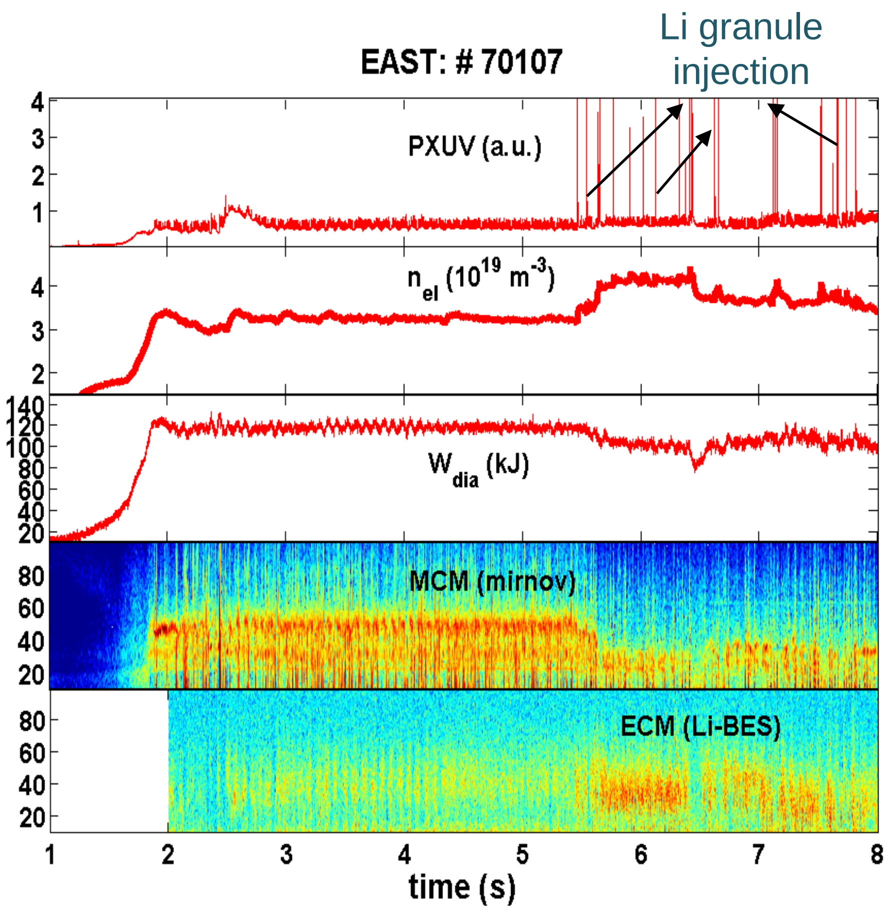
Compared to last week, substantial progress made on ELM triggering with large granules (0.7 mm shown)

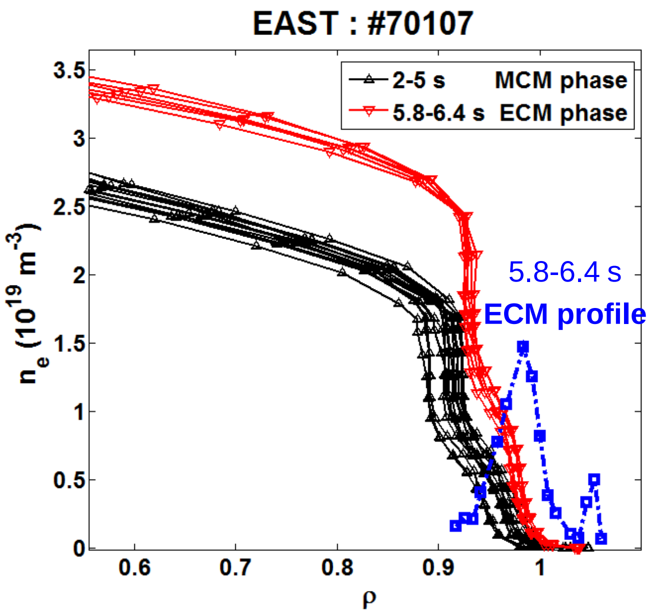


- Higher I_p, higher P_{aux} discharge chosen (based on #70195)

- Stored energy much higher in new targets
  - Previously first few (large) granules drove us to L-mode Hfactor

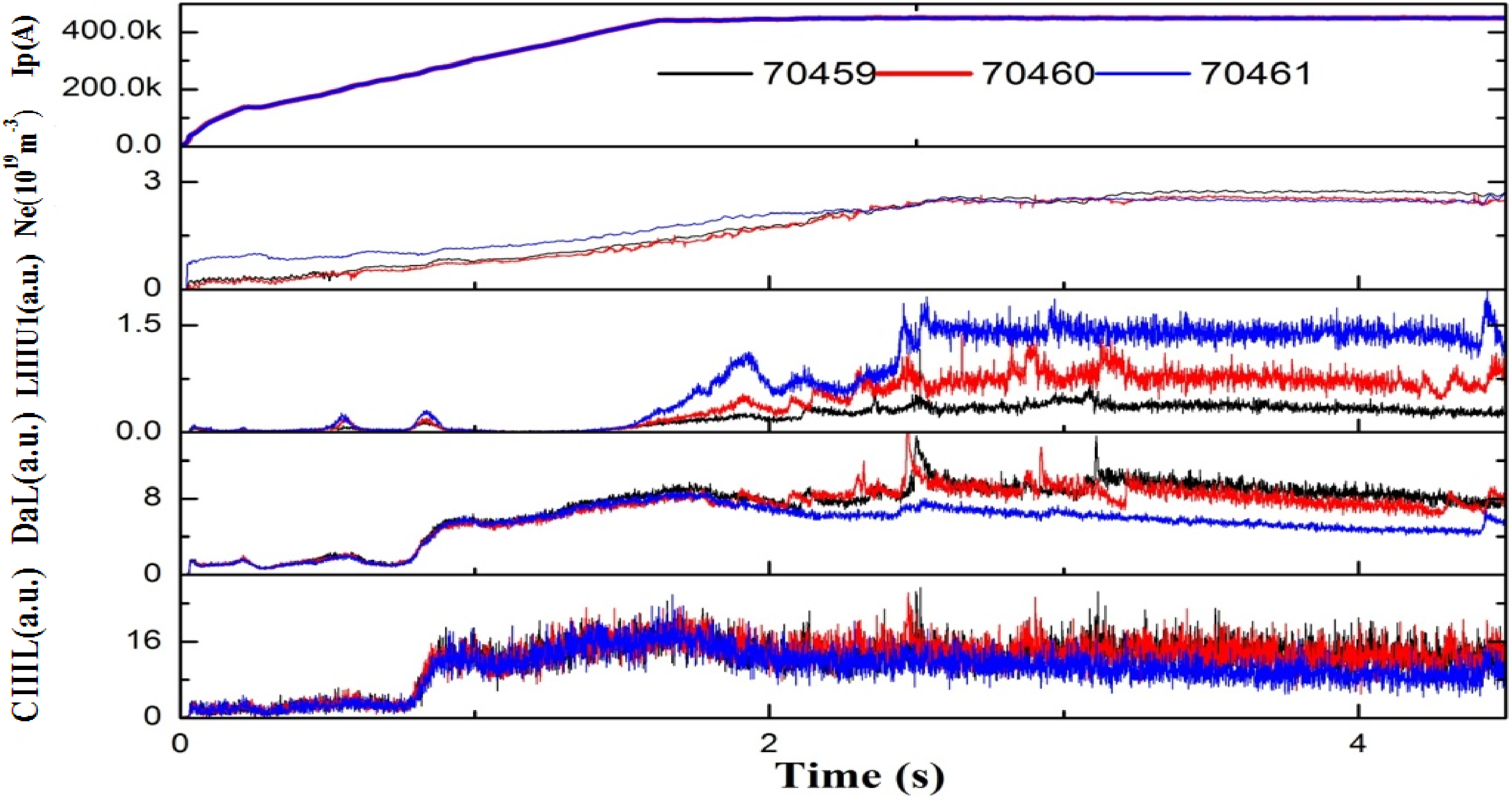
Lithium granule injection shifts the density profile outward, strengthening the ECM eliminating the MCM





FLiLi responds to bias on EM pump and proximity to separatrix

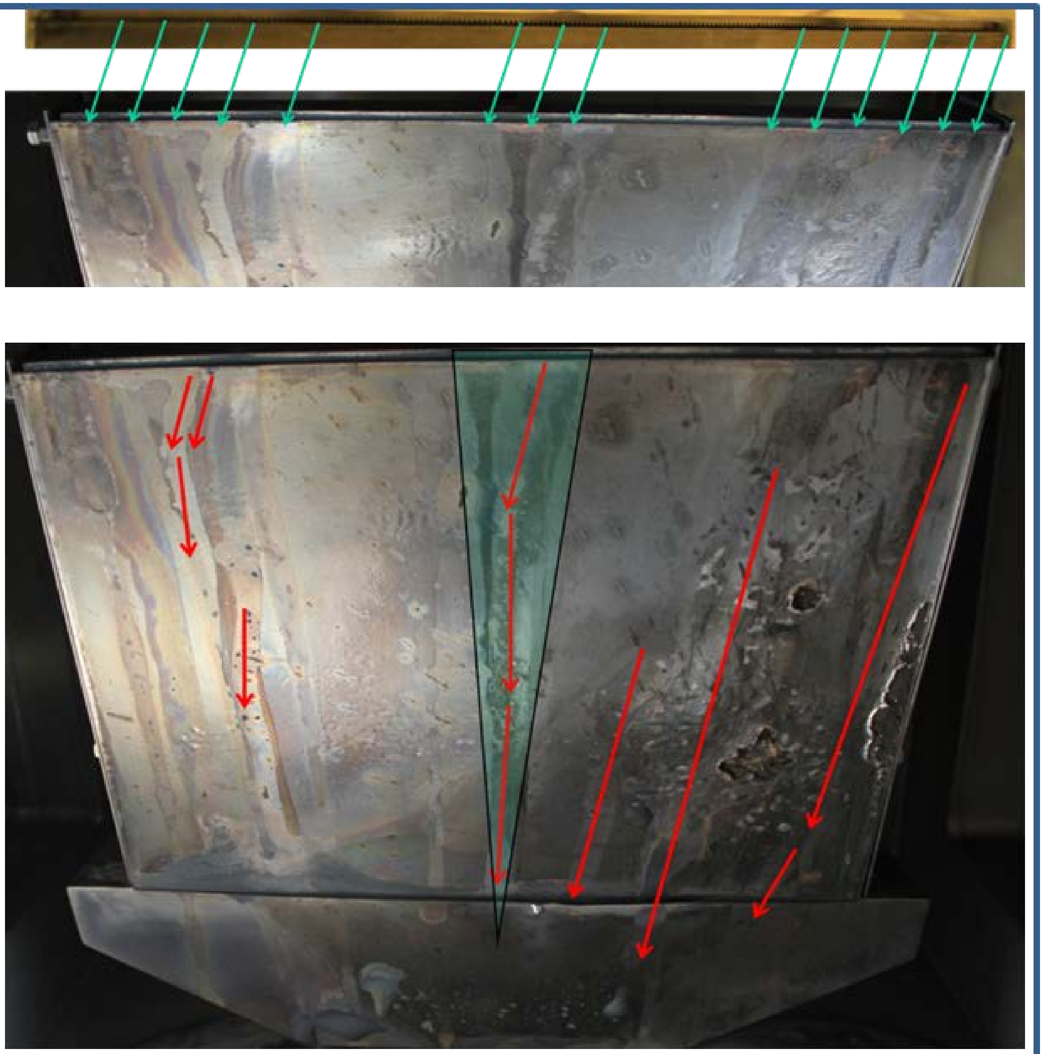
- +100 A, 1 cm in SOL
- -100 A, 1 cm in SOL
- -100 A, at the separatrix



More uniform coating of FLiLi in 2016 expt than in 2014 (next slide)

- ✓ The zones without Li cover are highlighted in red line on the LHS plot
- ✓ The Li surface coverage is above 80%; the Li wetting zone is much larger than that (~30%) in the 2014 campaign

Li flow and wetting surface in 2014



In 2014

Publication and Presentation Plan

- Planned papers, mostly in progress (US led)
  - NF letter on ELM suppression with W divertor – Maingi
  - *APS invited on ELM suppression with W divertor – S. Zhen*
  - Granule size triggering threshold – Lunsford
  - Overview granule ELM triggering – S. Zhen
  - FLiLi results – G. Zuo
  - Li dropper to suppress high-Z impurities – X. Wei

- Conferences
  - ITPA Pedestal Edge Physics, York, UK 4/17: US, China
  - ITPA Divertor & SOL, York, UK 5/17: China
  - SOFE, Shanghai, China, 6/17: China, US
  - EPS, Belfast, Ireland, 6/17: US, China
  - H-mode workshop, St. Petersburg, Russia, 9/17: China, US
  - ISLA, Moscow, Russia, 9/17: China, US?

Plans for 2017 by institution (1)

- PPPL
  - Deliver a multi-chamber granule dropper, targeting experiments in the May-June 2017 time frame
  - Initiate analysis on SOL heat flux footprints
  - Continue analysis on granule ablation ELM triggering
- UI-UC
  - Commission HIDRA for liquid lithium tests
  - Contribute to FLiLi design, including adding LiMIT features
- UT-K
  - Continue tile analysis from tiles removed from EAST
  - Initiate design of dual band IR adapter for EAST IR camera
  - Initiate modeling of surface response to PMI

Plans for 2017 by institution (2)

- ORNL
  - Initiate analysis on recycling changes induced by Li dropper
  - Initiate micro-stability analysis, if profiles sufficient for high quality kinetic equilibria
- MIT
  - Build on tile analysis initiated by UT-K
  - Continue to develop F depth marker technique, and apply to EAST tiles when fully developed
- JHU
  - Continue SXR system upgrade, to improve SNR
  - Examine impurity behavior during Li experiments
- LANL
  - Lead development of core-shell micro-pellets
  - Contribute to granule ablation analysis, with emphasis on gas shielding effects from micro to macro pellets

Final Comments on the Collaboration

- Run time & paper sharing: excellent
  - EAST management was very generous with run time, valuing the development of their younger staff as they learned from US team (30 discharges allocated, ~ 150 conducted)
  - Equitable sharing of papers & presentations

- Progress on analysis: modest pace so far
  - * *Note: 4 weeks of holiday since expt (2 in US, 2 in China)*
  - Difficulty in analyzing data remotely; we will consider EAST visits focusing on data analysis
  - Profile diagnostics not always reliable – why?

- Remote participation prospects: under investigation
  - Looking into viability of GA remote control room for our collaboration, as well as PPPL remote collaboration facilities

- *Thank you for your support of this (nascent) collaboration!*