Amelioration of plasma-material interactions and improvement of plasma performance with a flowing liquid Li limiter and Li conditioning on EAST

R. Maingi, J.S. Hu, G.Z. Zuo, Z. Sun, and the PRC-US PMI team

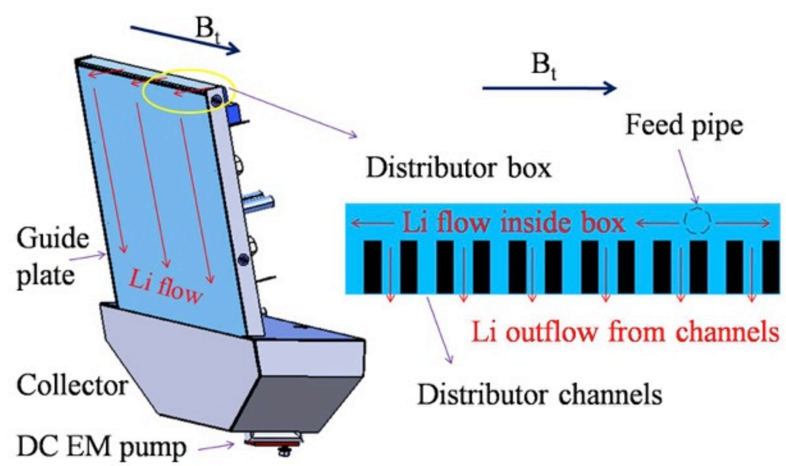
IAEA FEC 2018
Gandhinagar, Gujarat, India
Oct. 22-27, 2018

Motivation and Outline

- A main challenge for reactor designs is ability to exhaust large divertor heat loads, steady & transient
  - Handling neutron damage and PMI difficult for solid PFCs
- EAST and FTU are exploring flowing liquid PFCs
  - Liquid metal PFCs are part of European roadmap, and US and Chinese PFC strategies
- EAST: 3 generations of flowing liquid lithium limiters
  - Reduced recycling, ELM mitigation, improved power exhaust and compatibility with increasing P_{aux}, I_p
- Lithium powder and granules successful at mitigating ELMs, and reducing tungsten influx

The science and technology of flowing liquid lithium limiters has been advanced via US-PRC PMI collaboration on EAST

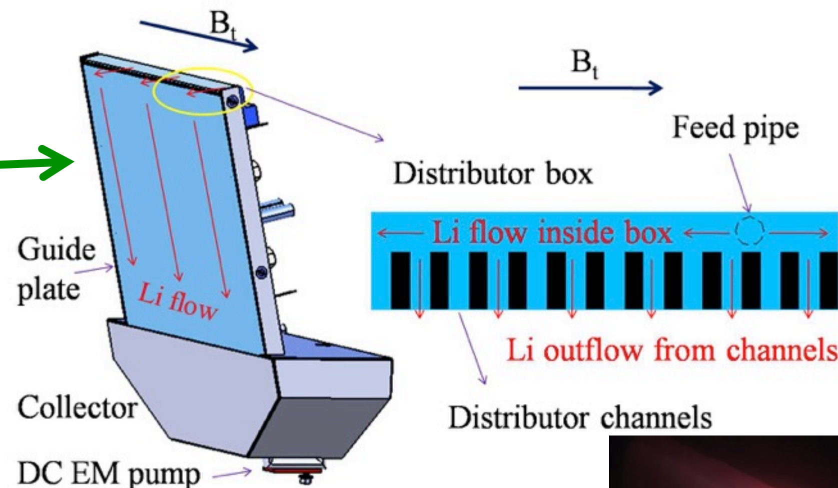
- Three generations of liquid lithium limiters tested in EAST
  - Prototype SS plate tested in HT-7
  - Gen. 1 (12/2014) tested in EAST
  - Gen. 2 (12/2016) tested in EAST
  - Gen. 3 (8/2018) tested at UI-UC and PPPL and then EAST
    - Increasing P_{aux}, W_{MHD}

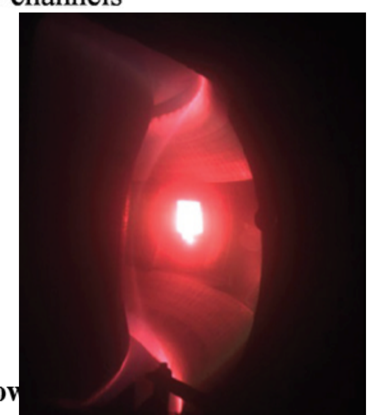


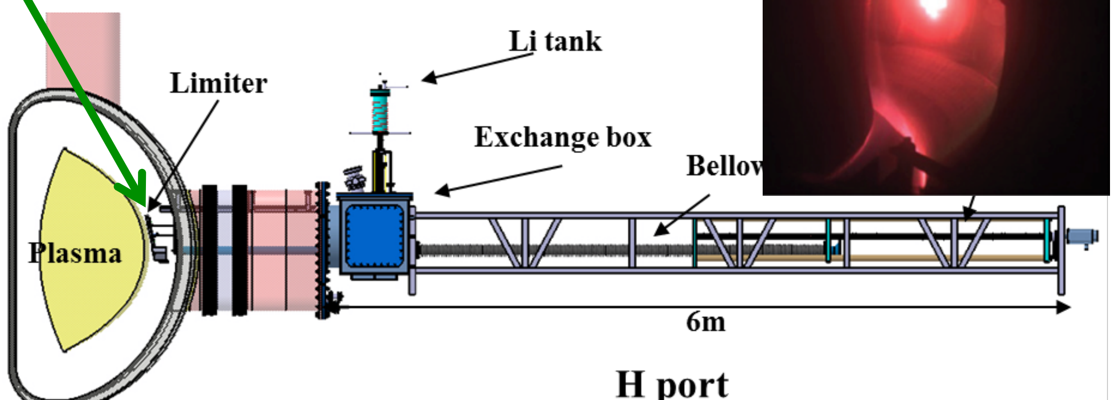
Generation	Heat Sink	SS thickness (mm)	JxB pumps	Max. P_{aux} (MW)	Max. q_{exh} (MW/m^2)	Max. W_{MHD} (kJ)
1	Cu + SS	0.1	1	1.9	3.5	120
2	Cu + SS	0.5	2	4.5	4	170
3	Mo (TZM)	NA	2	8.3	TBD	280

1^{st} Generation flowing liquid lithium limiter compatible with H-mode discharges in EAST (10/2014)

- Cu heat sink, SS coating
  - Top distributor, many holes
  - Free surface gravity driven flow on front face
  - j x B pump recirculates Li
- Inserted at midplane on MAPES system
- *H-modes and ohmic discharges compatible with flowing Li limiter*
  - $q_{peak}^{limiter}$ ~ 3.5 MW/m^2
- Limiter and distributor damaged during operations, so new design implemented for Gen. 2



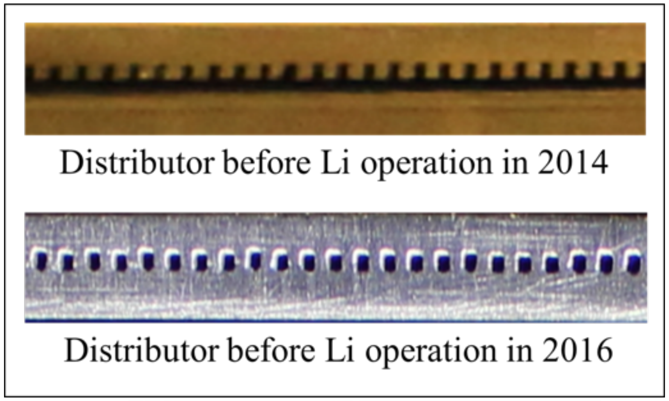


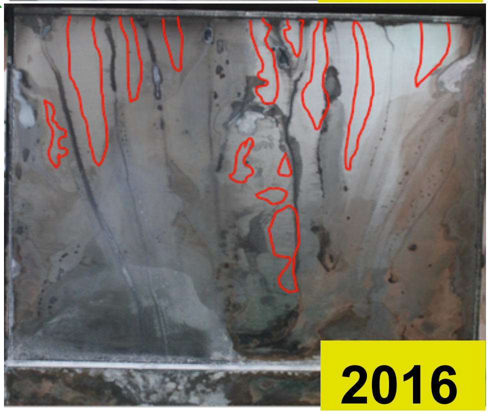


J. Ren, *Rev. Sci. Instrum.* **86** (2015) 023504
J.S. Hu, *Nucl. Fusion* **56** (2016) 046011
G.Z. Zuo, *Nucl. Fusion* **57** (2017) 046017

2^{nd} Generation flowing liquid lithium limiter (2016) had design upgrades compared to 1^{st} generation limiter (2014)

- Improved distributor manufacturing resilient to cracking
- Improved surface texturing led to improved wetting and surface coverage
  - < 30% in 2014
  - > 80% in 2016



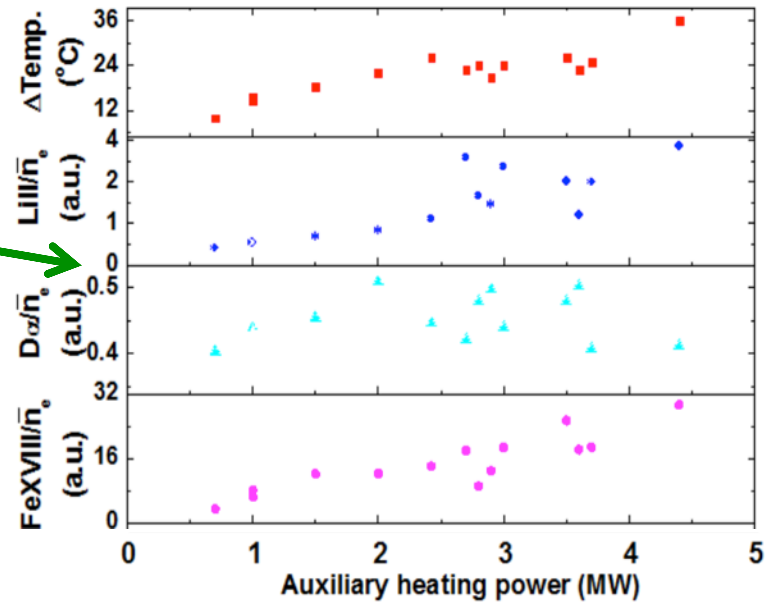


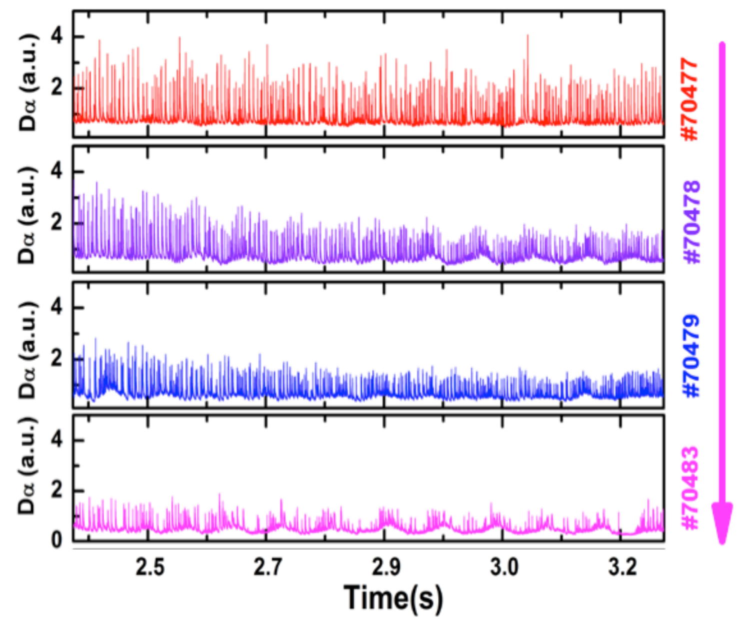
- Additional upgrades: two parallel paths for jxB pumps to pump liquid Li up the back side, and 5x thicker stainless steel protective layer

G. Zuo, *Rev. Sci. Instrum.* **88** (2017) 123506

2nd Generation FLiLi lithium limiter performed well in auxiliary heated discharges in EAST

- Limiter placed within 1 cm of separatrix in RF-heated H-modes
- FLiLi exposed to $P_{aux} \leq 4.5$ MW
  - $q_{peak} \sim 4$ MW/m^2
  - No limiter damage observed after first plasma exposure
  - Limiter re-exposed and flow re-started a week after first experiment
- Progressive conditioning and ELM mitigation with limiter inserted at midplane
- Concern over Li – Cu reactivity underpins Gen. 3, made out of TZM, a Mo alloy

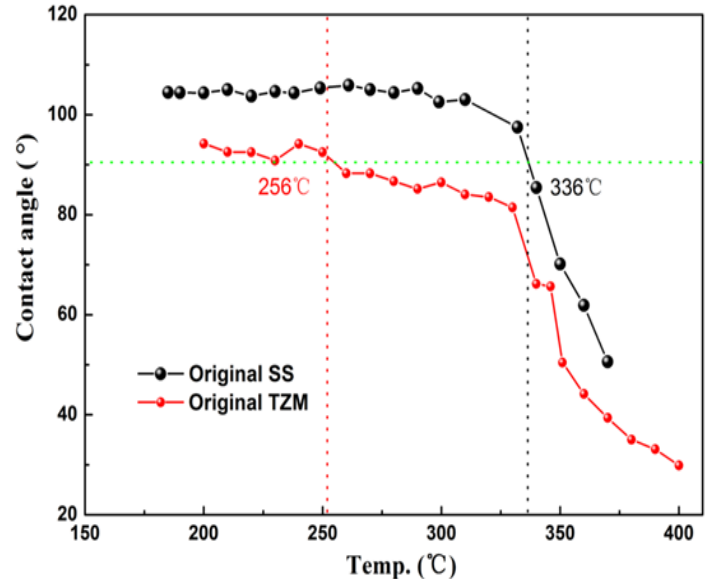




G. Zuo, *Nucl. Fusion* (2018) submitted

Wetting and sputtering of Mo more attractive than stainless steel

- Wetting of TZM with Li ~ 90 °C lower with TZM relative to stainless steel
  - Gen. 3: TZM; Gen. 1 & 2: SS



- Sputtering threshold of Mo ~ 1 keV for 1% yield
  - Sputtering threshold of SS ~ 100 eV for 1% yield, i.e. 90% lower
  - SS sputtering peaks ~ 3%, rx higher than Mo
  - Consistent with high-Z metals being more resilient

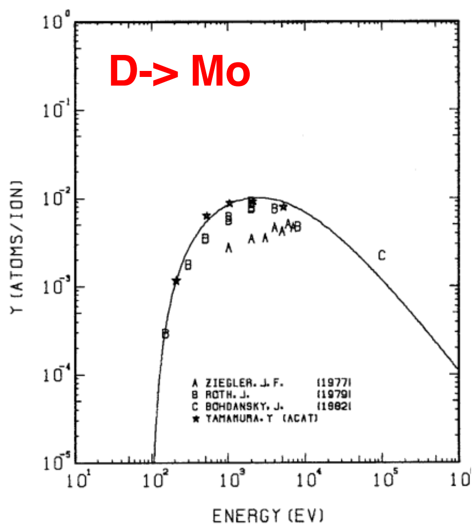


FIG. 165 ENERGY DEPENDENCE OF THE SPUTTERING YIELD OF MO WITH D+.
A= 47.64, Q= 0.85, Us= 6.82EV, s= 2.80, W= 0.45Us.

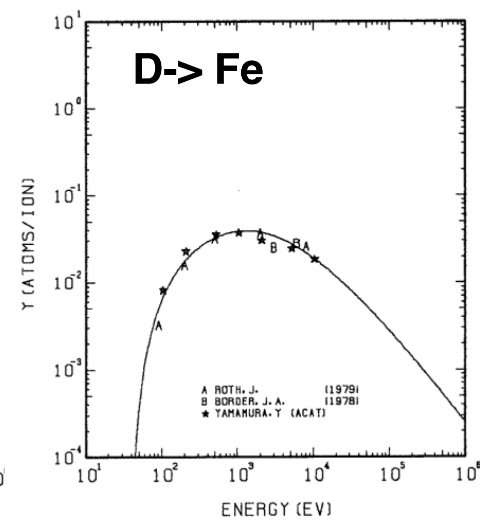
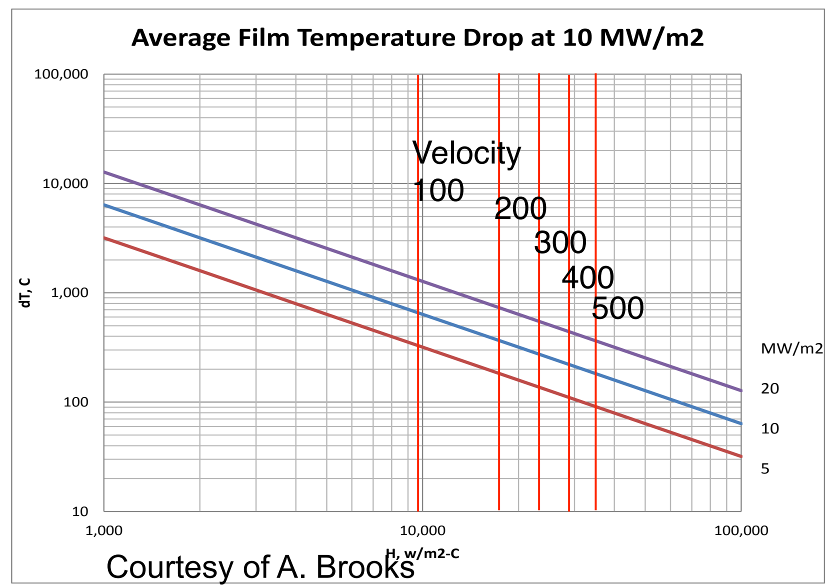


FIG. 79 ENERGY DEPENDENCE OF THE SPUTTERING YIELD OF FE WITH D+.
A= 27.73, Q= 0.75, Us= 4.28EV, s= 2.50, W= 0.28Us.

Mo limiter designed to handle high heat flux with He cooling

- Made of Mo for Li compatibility
  - One plate sent to EAST, second plate sent to UI-UC for testing in HIDRA
  - Extensive heater testing at UI-UC
  - Stainless steel distributor and collector brazed onto plate

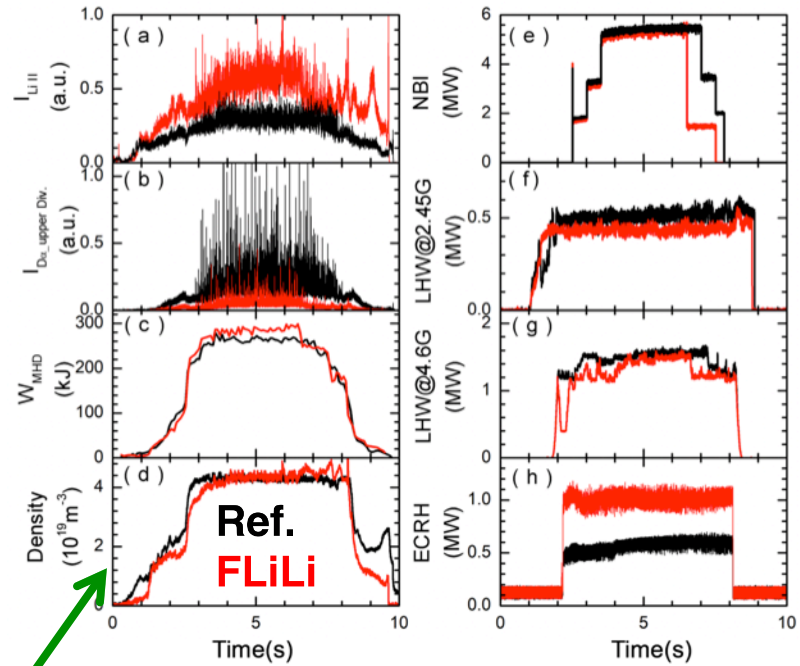
- Cooling tubes designed to remove 10 MW/m^2 with high He velocity and low temperature rise
  - Exhausted heat flux increases with He velocity
  - Temperature rise decreases with He velocity

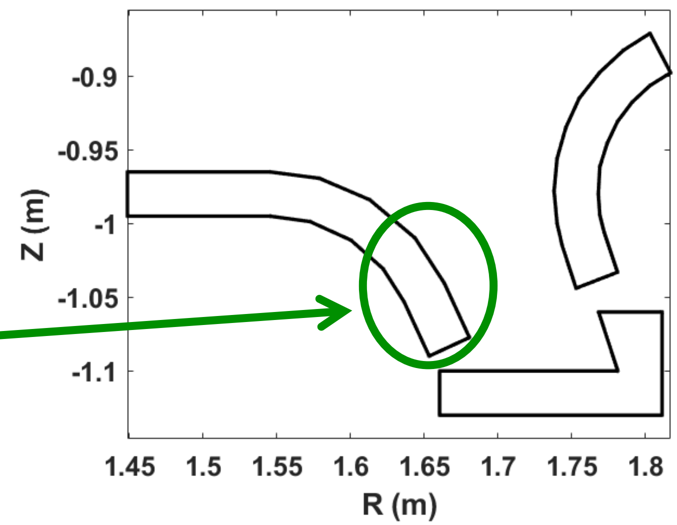


Courtesy of A. Brooks

EAST: 3rd generation flowing liquid Li limiter fabricated; shipped to EAST 6/18 and exposed to plasma 8/18

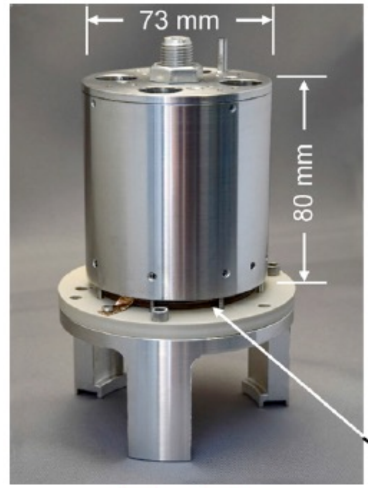
- Made of Mo for Li compatibility
  - One plate sent to EAST, second plate sent to UI-UC for testing in HIDRA
  - Extensive heater testing at UI-UC
  - Stainless steel distributor and collector brazed onto plate
- Experiment in 8/18 exposed FLiLi limiter to plasmas with P_{aux}=8.3 MW @ 3cm from separatrix
  - Reduced recycling, slightly higher stored energy, (ELM mitigation)
  - Future versions: 3D printed W PFC, limiter and/or divertor sector(s)?

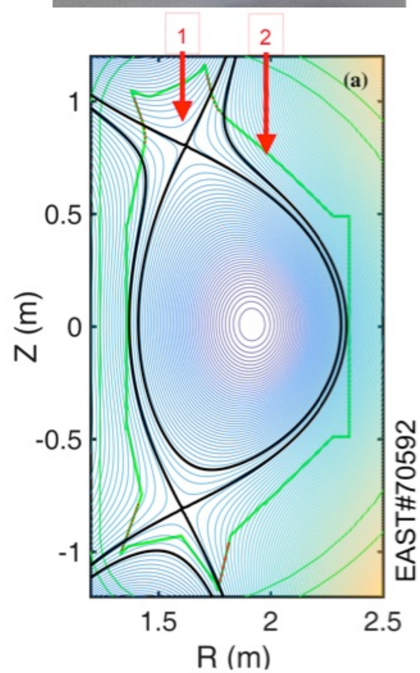


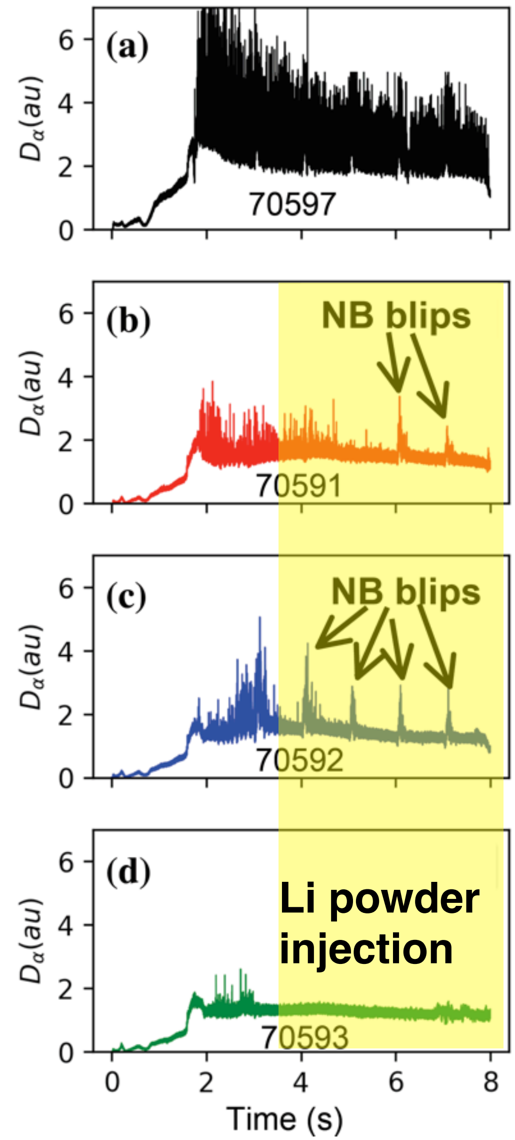


ELMs eliminated with real-time Li powder injection into the W upper divertor in EAST

- Powder injected outboard of X-point in upper SOL
  - Injector uses vibrating piezo-electric disk to inject controlled amounts of powder
  - Similar technology used for B injection in AUG (Lunsford, FIP/2-4)
- Progressive reduction of recycling and elimination of ELMs
  - Stored energy reduced by < 10%, because injection rate was higher than needed

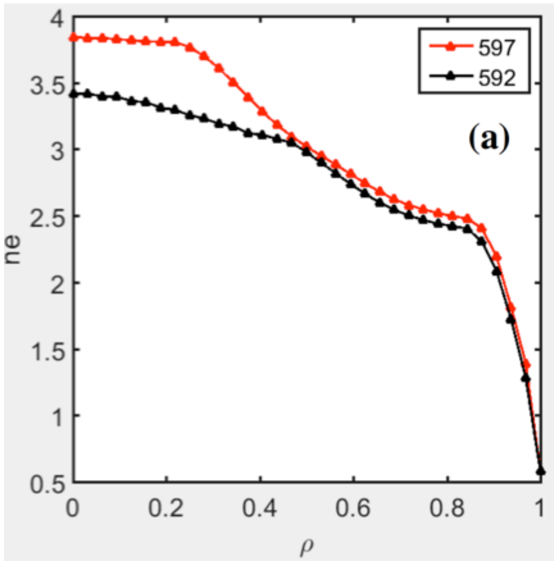


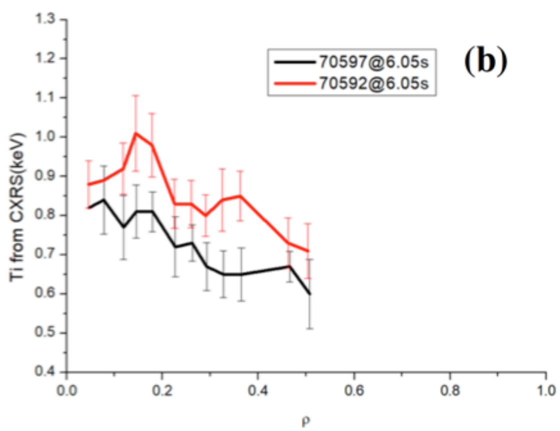


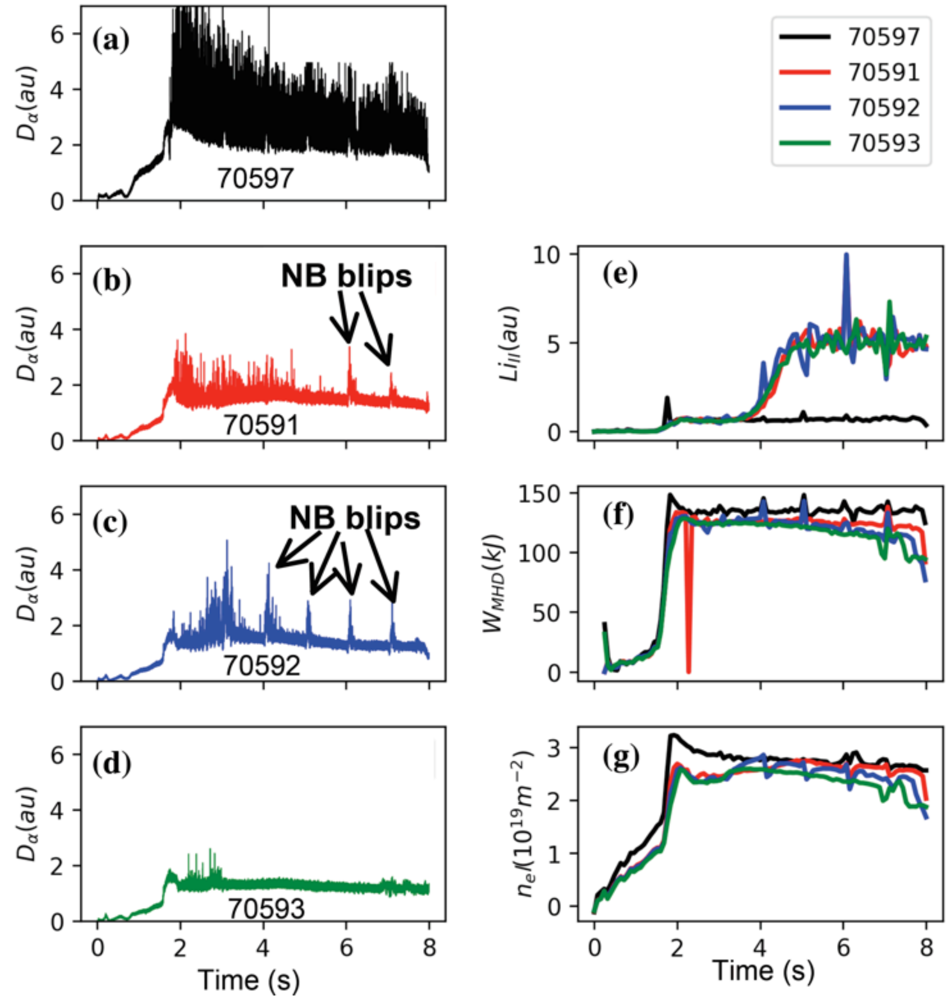


R. Maingi, Nucl. Fusion **58** (2018) 024003; builds on J.S. Hu, Phys. *Rev. Letts.* ***114*** *(2015) 055001*

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

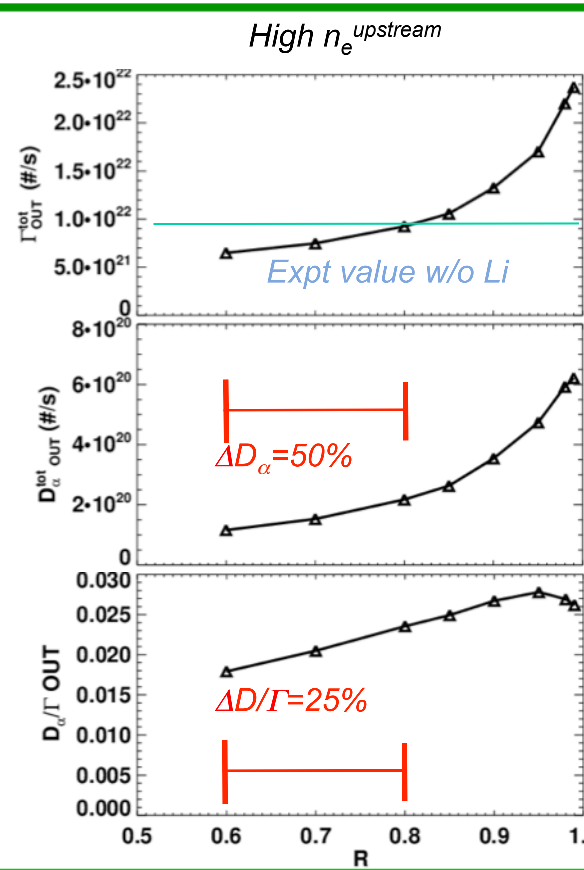
- SOLPS analysis shows local divertor recycling coefficient drops by 20%
- J. Canik, *IEEE Trans. Plasma Sci.* **46** (2018) 1081; builds on J. Canik, *Phys. Plasmas* **18** (2011) 056118

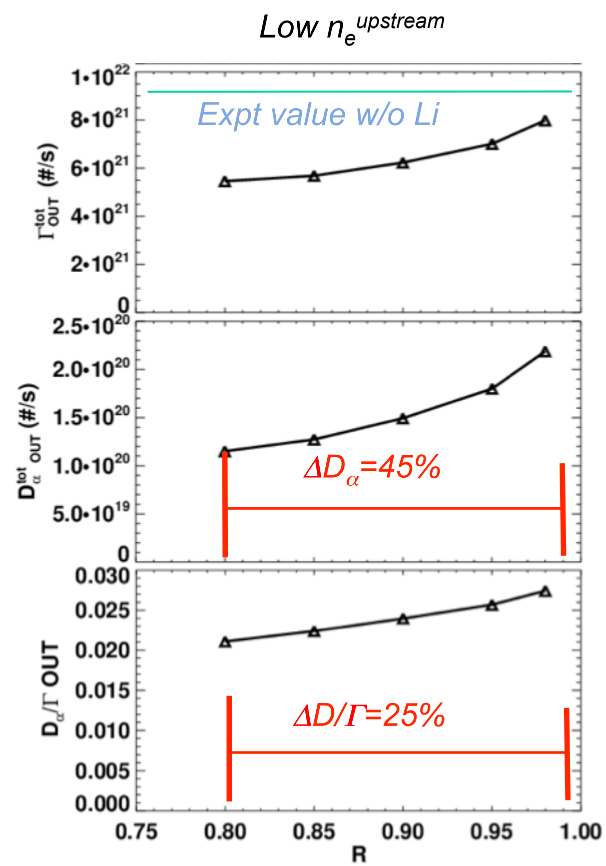
SOLPS modeling of D_α,Γ changes indicate level of D removal with Li powder injection

- 2D plasma/neutrals modeling performed, based on measured upstream n_e profiles before and during Li injection for active recycling control
- For ion fluxes near measured values, SOLPS recycling scans for multiple assumed upstream conditions are consistent with measured D_α, Γ trends

- ΔR ~ 20% is consistent with magnitude of D_α, Γ with Li
  - High $n_e^{upstream}$: R ~ 0.99->0.8
  - Low $n_e^{upstream}$: R ~0.8->0.6

- Implied range of particle removal rates due to Li injection: 1-1.5x10^{21} #/s

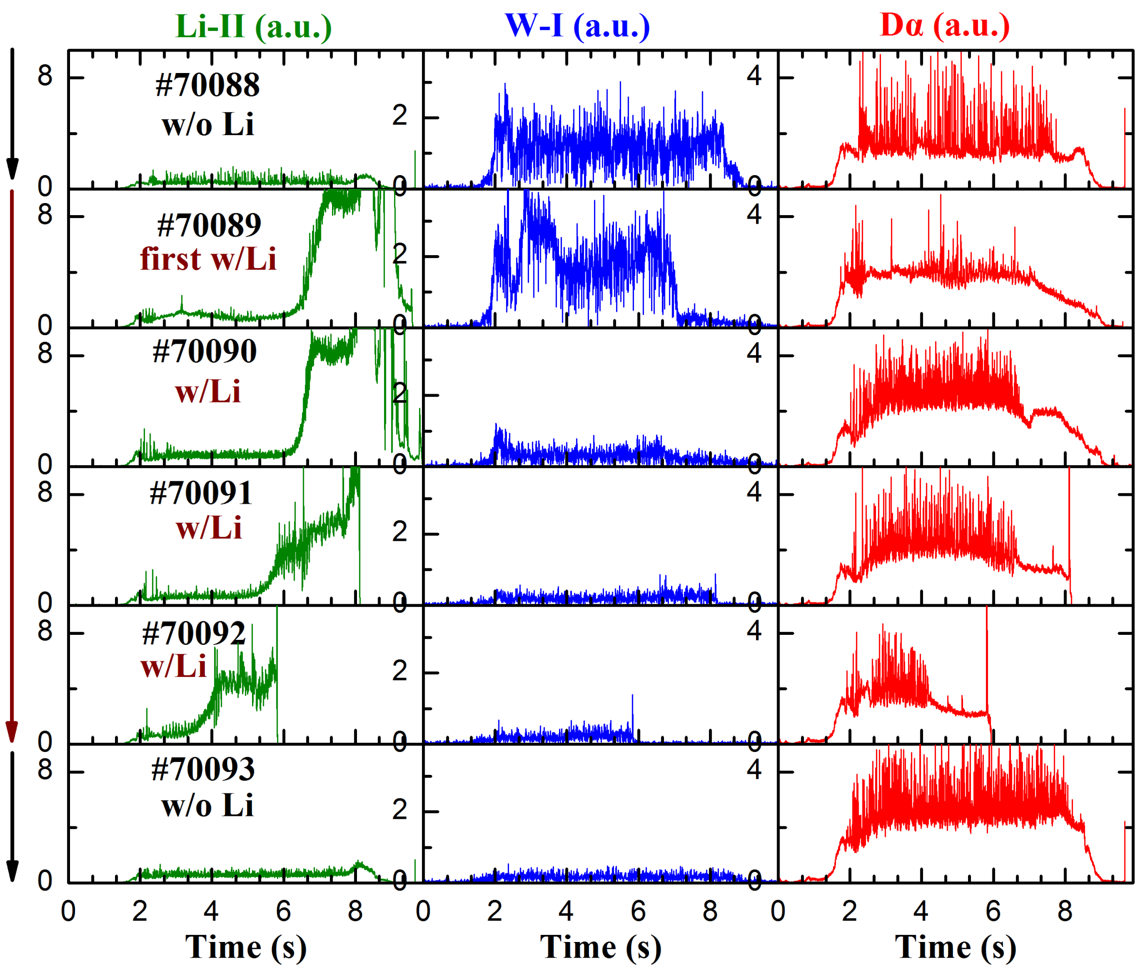




J. Canik, *IEEE Trans. Plasma Sci.* **46** (2018) 1081

Real-time Li powder injection also suppressed W influx on EAST

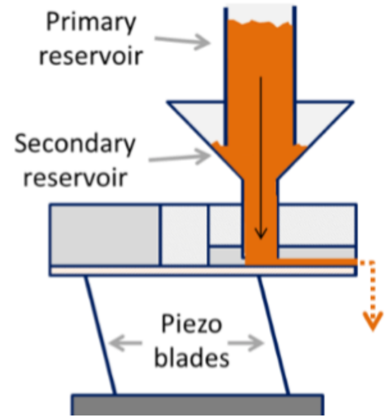
- Control of high-z influx a need for devices with metallic PFCs
  - Often need D or impurity gas puffing to reduce target temperature and sputtering
- Real-time Li injection reduced W-I line emission
  - Effect persists for some time after Li injection stopped

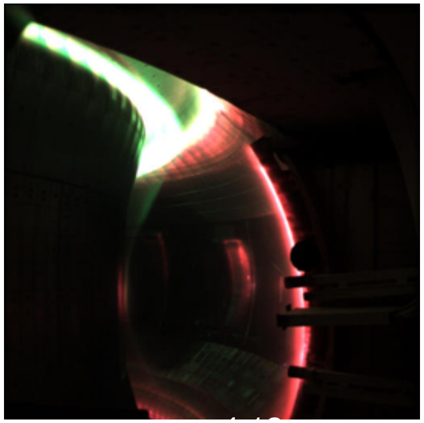


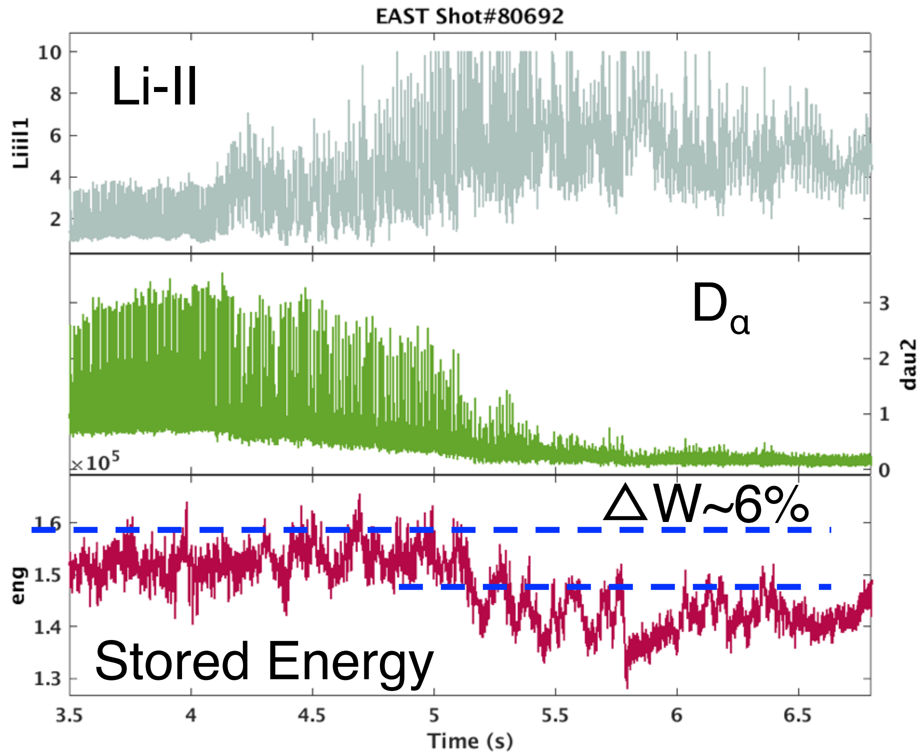
W. Xu, *Fusion Eng. Design* **137** (2018) 202

ELMs mitigated (eliminated?) with new Li granule dropper injection on EAST (8/18)

- Powder (50 μm) injection shown to eliminate ELMs
  - Issue: powder has limited penetration depth through the SOL at high power
- Granule dropper (700 μm) deployed for first time and shown to eliminate ELMs
  - Most likely due to ne profile control via wall conditioning: desire SOL ablation
  - Penetration of granules can be easily controlled, i.e. use impeller to hit granules in at tangential angles to target ablation profile







Flowing liquid metal PFCs performing well in plasmas with increasingly challenging PMI

- Three generations of flowing liquid lithium limiters exposed in EAST
  - Plasma performance was good
  - PMI damage avoidance and improved flow uniformity needed
  - A future step may be a divertor sector using FLiLi and/or LIMIT tile technology to insure flow

- Lithium powder and granule dropper successful at mtigating ELMs and reducing W influx using USN W PFCs

- Concepts and designs for liquid metals PFCs for next step devices and reactors needed