# Amelioration of PMI and improvement of plasma performance with a flowing liquid Li limiter and Li conditioning on EAST (FIP/3-5Ra)

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

# Experiments on FTU with a Liquid Tin Limiter (FIP/3-5Rb)

G. Mazzitelli, M.L. Apicella, M. Iafrati, G. Apruzzese, and the FTU Team

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

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

# 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

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- 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 $P_{aux}$, $I_p$
  - Also new results on lithium powder injection for ELM control
- FTU: comparing liquid tin and liquid lithium limiters
  - Good performance for liquid tin with $q_{peak}$ ~ 18 $MW/m^2$

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

PMI

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

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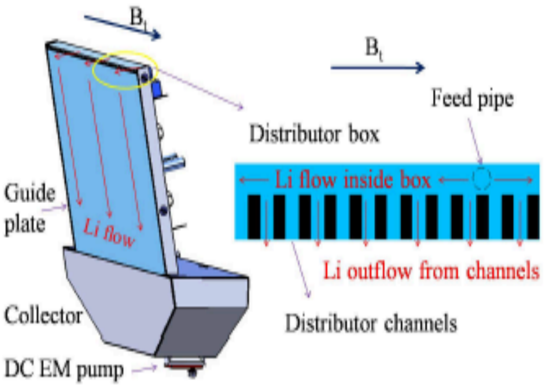
ASIPP

OAK RIDGE National Laboratory

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

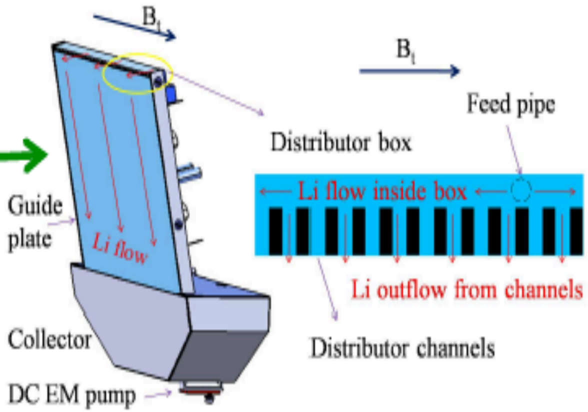
- Three generations of liquid lithium limiters tested in EAST
  - Prototype SS plate tested in HT-7
  - Gen. 1 (12/2014) tested in EAST
  - Gen. 2 (12/2016) tested in EAST
  - Gen. 3 (8/2018) tested at UI-UC and PPPL and then EAST




| 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 |

# 1st 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




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

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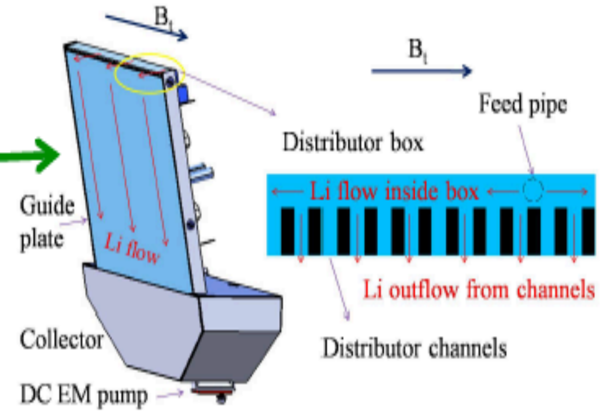


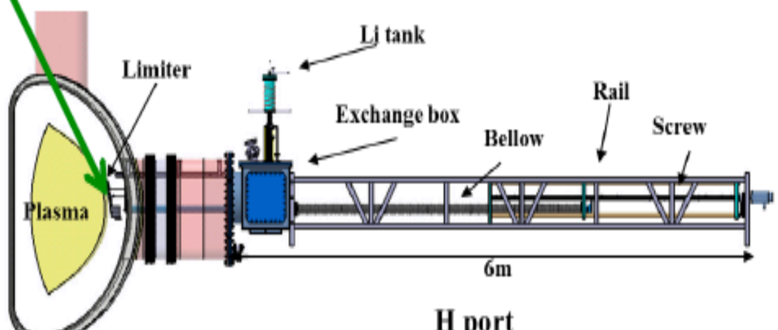


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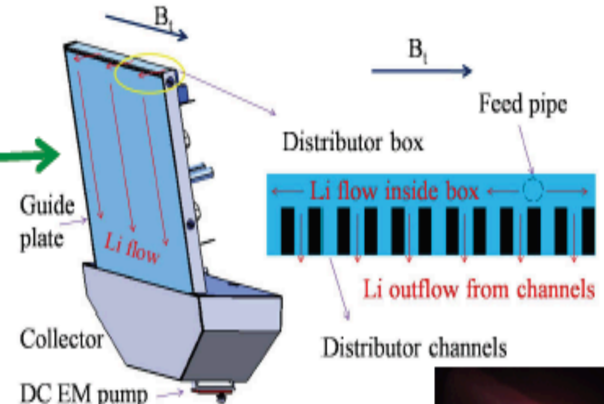
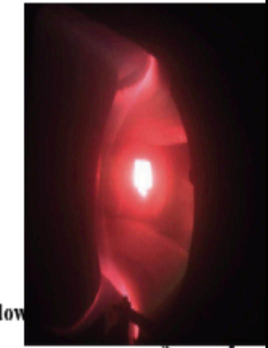
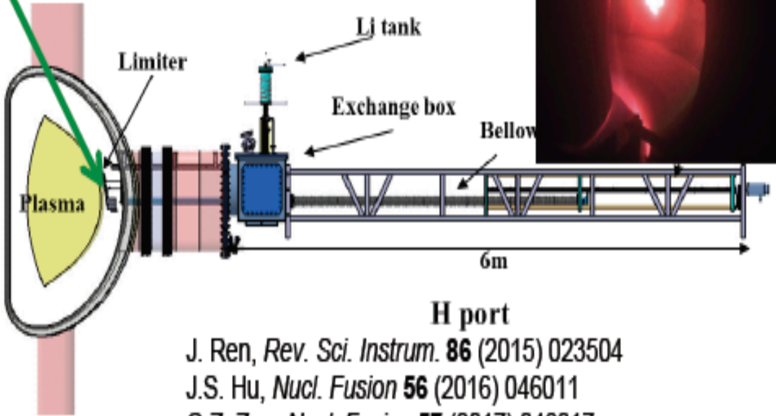
- *H-modes and ohmic discharges compatible with flowing Li limiter*
  - $q_{peak}^{limiter}$ ~ 3.5 MW/m$^2$
- Limiter and distributor damaged during operations, so new design implemented for Gen. 2



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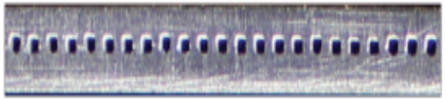
# 2nd Generation flowing liquid lithium limiter (2016) had design upgrades compared to 1st generation limiter (2014)

- Improved distributor manufacturing resilient to cracking, plus
  - Two parallel paths for jxB pumps to pump liquid Li up the back side
  - 5x thicker stainless steel protective layer

Distributor before Li operation in 2014



Distributor before Li operation in 2016

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

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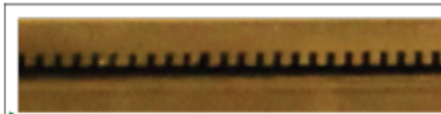
  - Two parallel paths for jxB pumps to pump liquid Li up the back side
  - 5x thicker stainless steel protective layer
- Improved surface texturing led to improved wetting and surface coverage
  - < 30% in 2014
  - > 80% in 2016



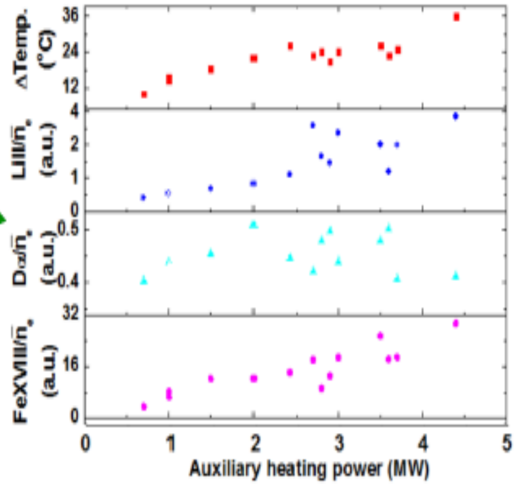
Distributor before Li operation in 2014

Distributor before Li operation in 2016


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

# $2^{nd}$ 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



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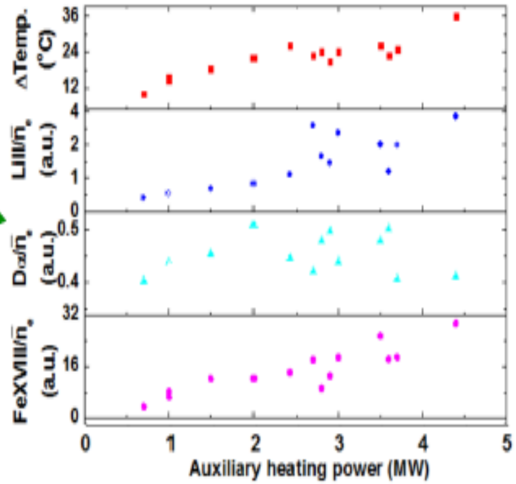
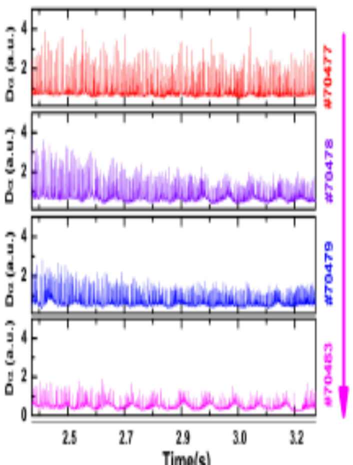



- Progressive conditioning and ELM mitigation with limiter inserted at midplane



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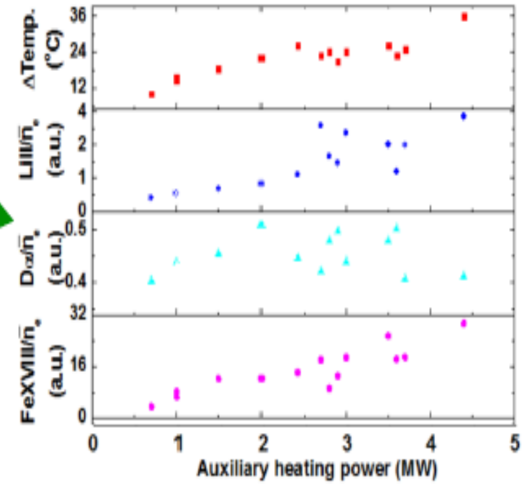
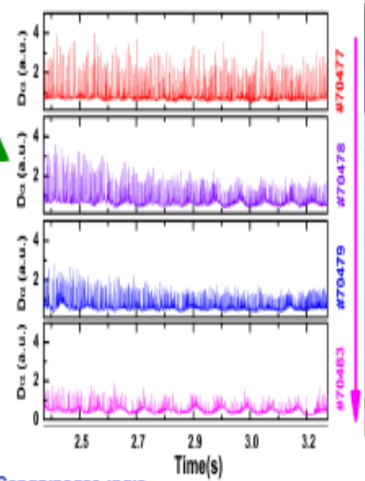
- Progressive conditioning and ELM mitigation with limiter inserted at midplane
- Concern over Li – Cu reactivity underpins Gen. 3, made out of TZM, a Mo alloy




G. Zuo, *Nucl. Fusion* submitted

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

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  - One plate sent to EAST, second plate sent to UI-UC for testing in HIDRA
  - Extensive heater testing at UI-UC
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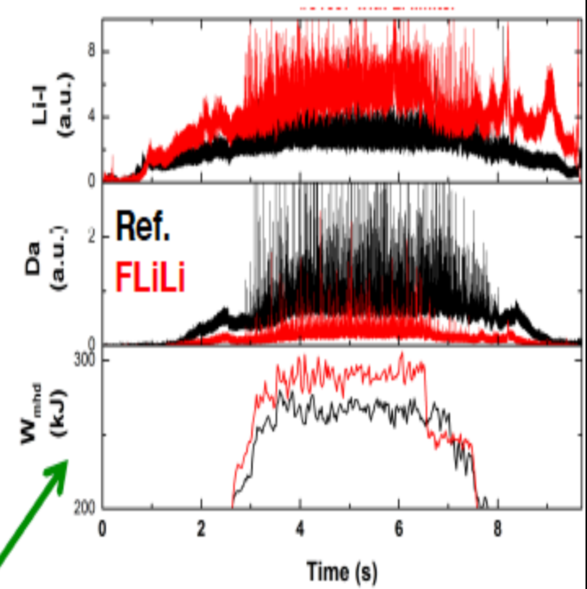
  - Reduced recycling, slightly higher stored energy, (ELM mitigation)



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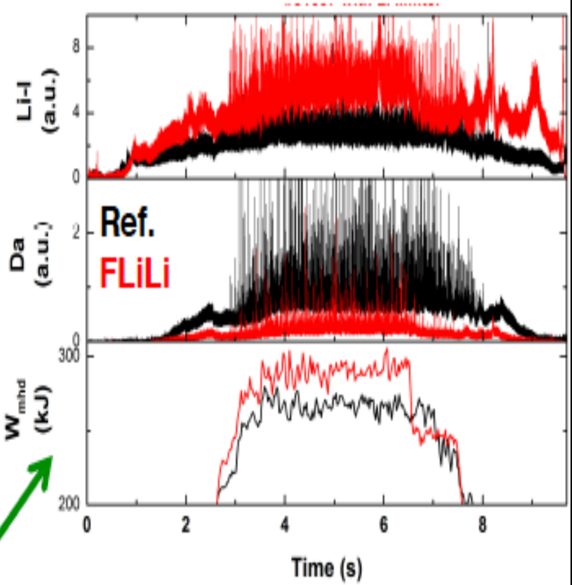
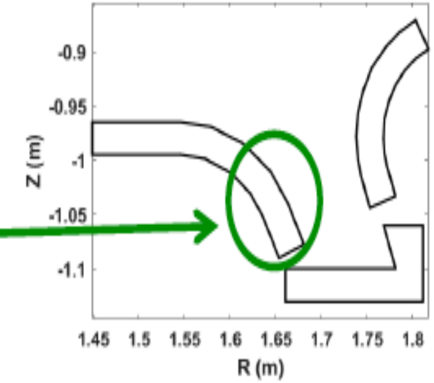
  - Future versions: 3D printed W PFC, limiter and/or divertor sector(s)?

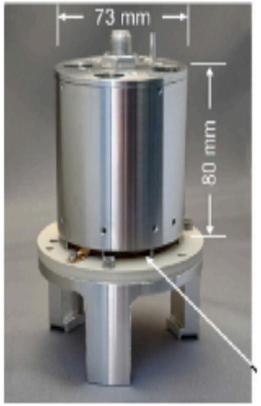


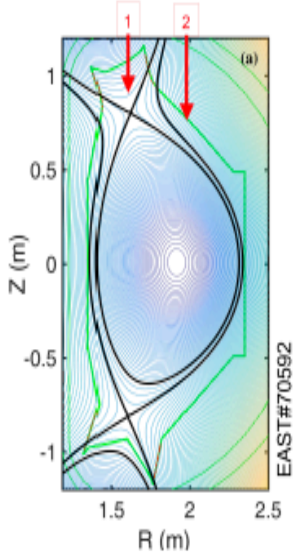




R. Maingi, IAEA FEC 2018

# 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)




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

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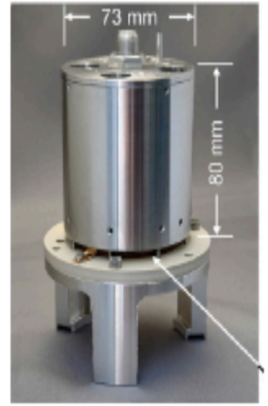
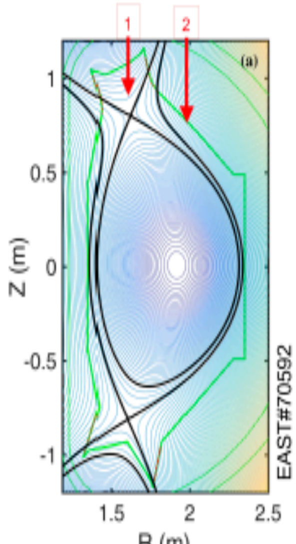
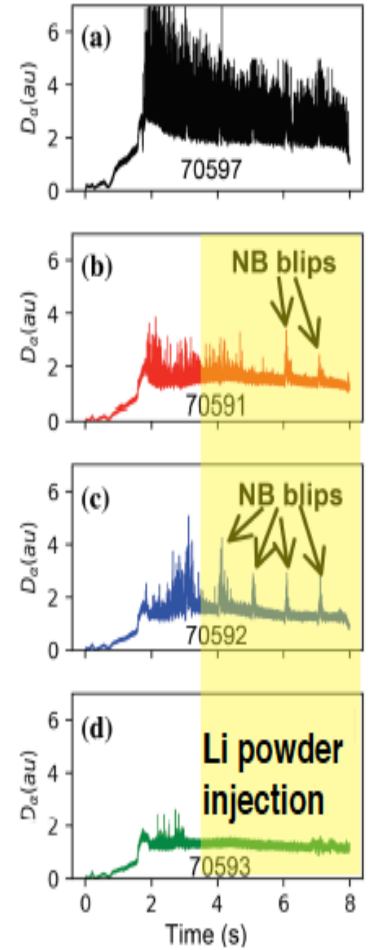
  - Similar technology used for B injection in AUG (Lunsford, FIP/2-4)
- Progressive reduction of recycling and elimination of ELMs
  - Stored energy reduced by < 10%, because injection rate was higher than needed



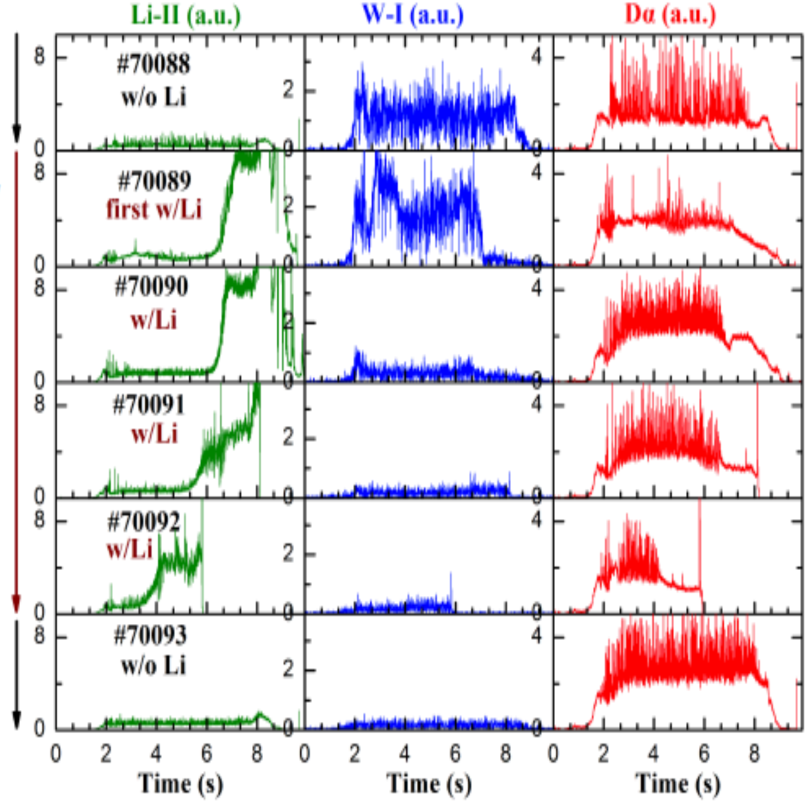




R. Maingi, Nucl. Fusion **58** (2018) 024003; builds on J.S. Hu, Phys. *Rev. Letts.* ***114*** *(2015) 055001*

# 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

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

# Experiments on FTU with a Liquid Tin Limiter

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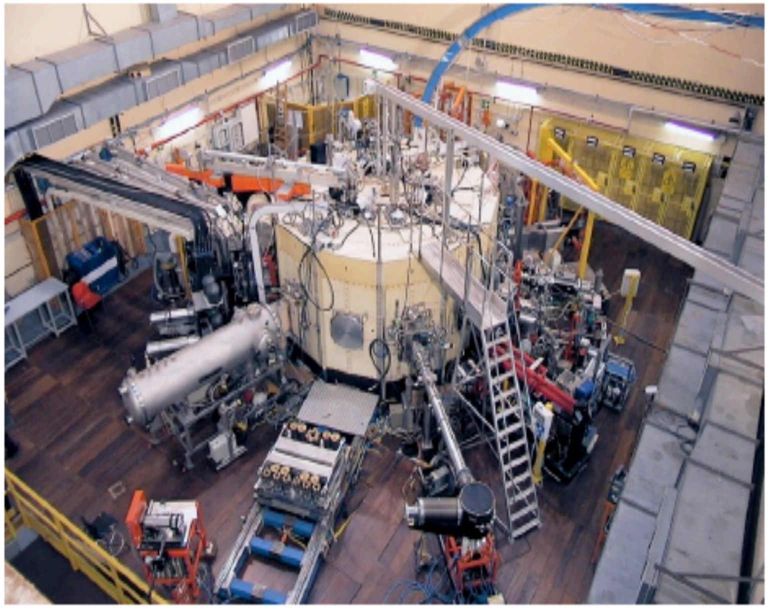
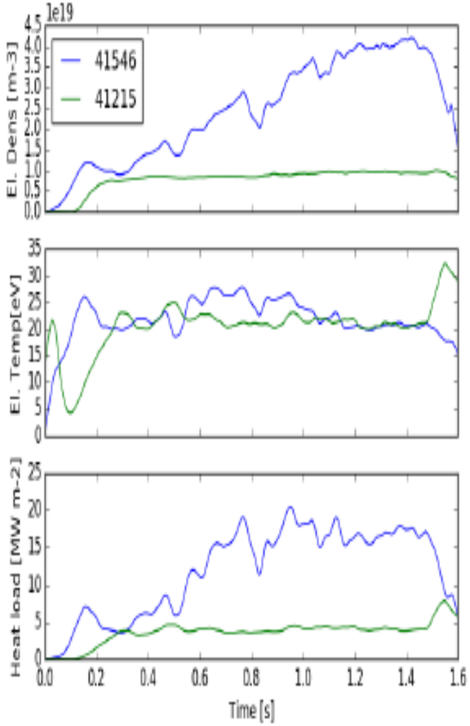
*This work has been partially carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The viewsand opinions expressed herein do not necessarily reflect those of the European Commission.*

# Liquid metal limiters tested in FTU since 2006

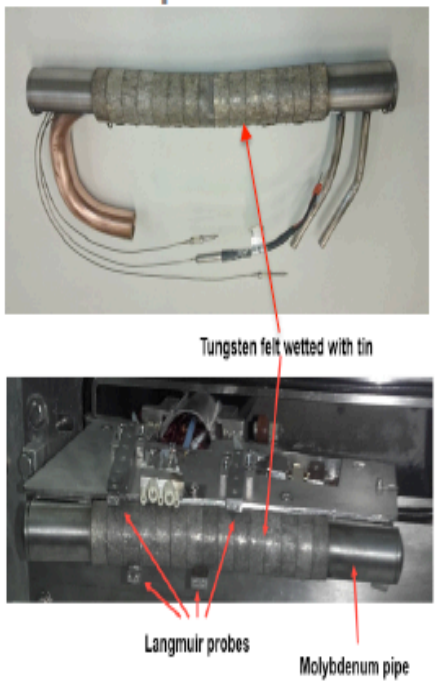
## Performance with tin liquid limiter

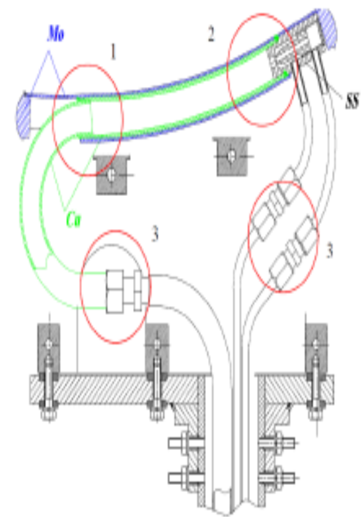




# Liquid Tin Limiter - TLL

## A tin liquid limiter has been used for the first time in a tokamak



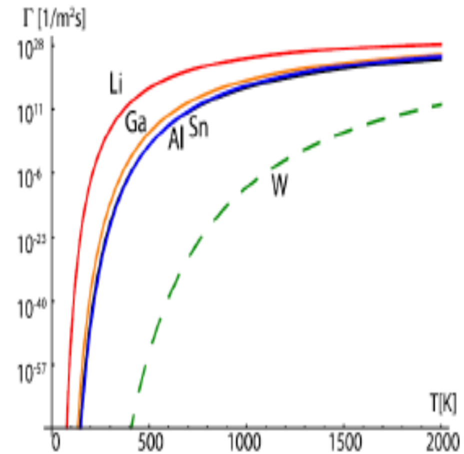



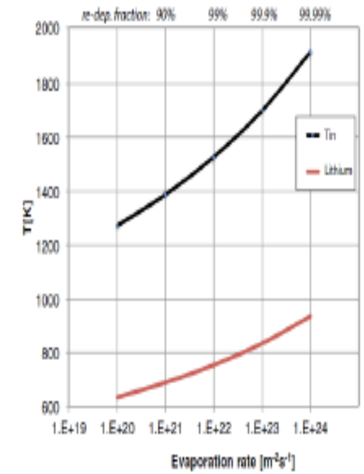

- Capillary porous system used to contain Sn
- Very flexible and versatile layout: the limiter head can be easily changed
- At high temperature tin is very corrosive: the liquid tin limiter layout prevents copper corrosion

- Tin allows a wide temperature operational window with low vapor pressure

# Tin has a wide operational temperature window

- Evaporative flux is one of the main issue for steady state operation
- One of the aim of the experiments in FTU  is to investigate the operational window both for tin and lithium



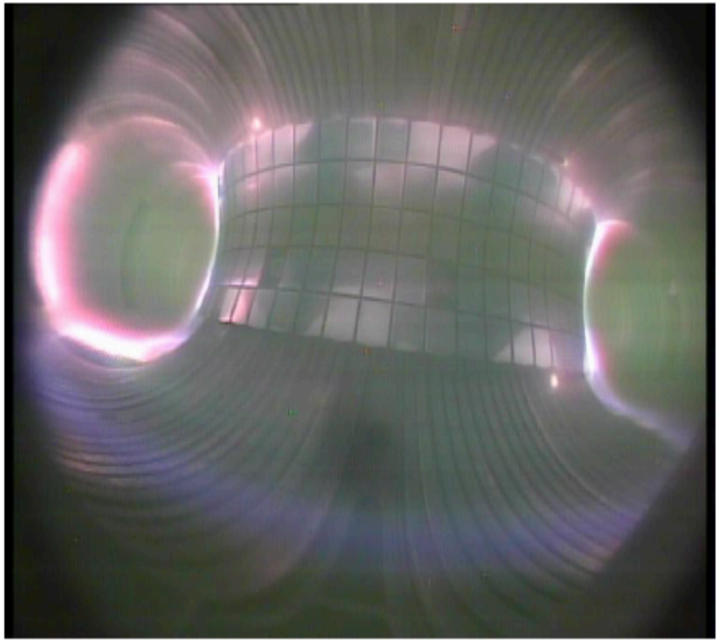



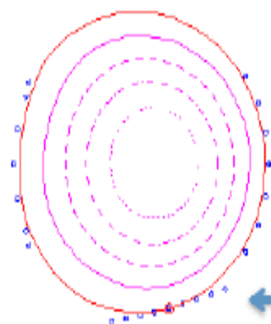

[J.W. Coenen *et al.* Phys. Scr. T159 (2014) 014037]

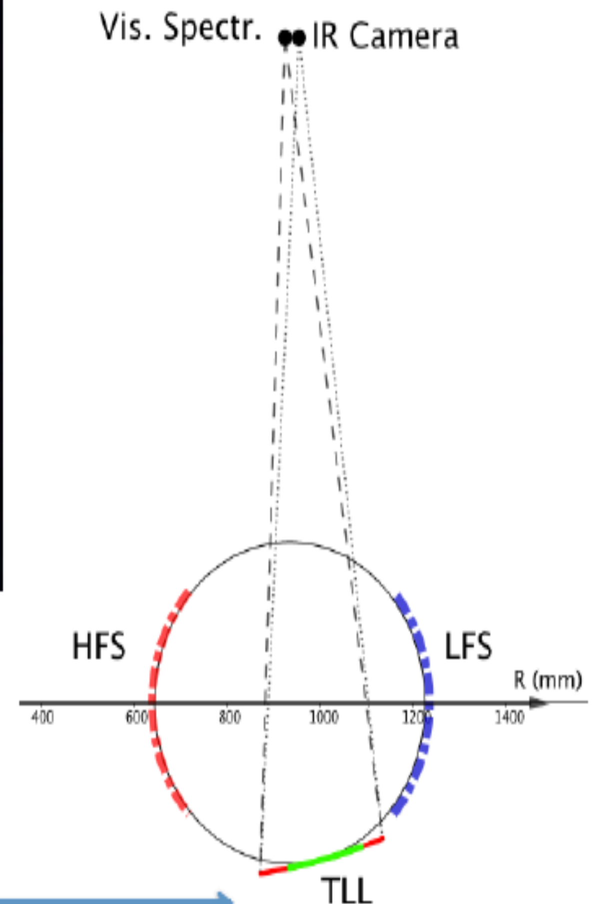
# Characteristics of TLL compared with previous LLL

| Parameter | Lithium limiter | Tin limiter |
|---|---|---|
| Initial surface temp. | ≈ 190-200 °C | ≥ 290 °C |
| Plasma interacting area | 80 | 100 |
| Liquid metal amount | 80 g | 30 g |
| Reservoir | Yes | No |
| Curvature radius | 29 cm | 130 cm |

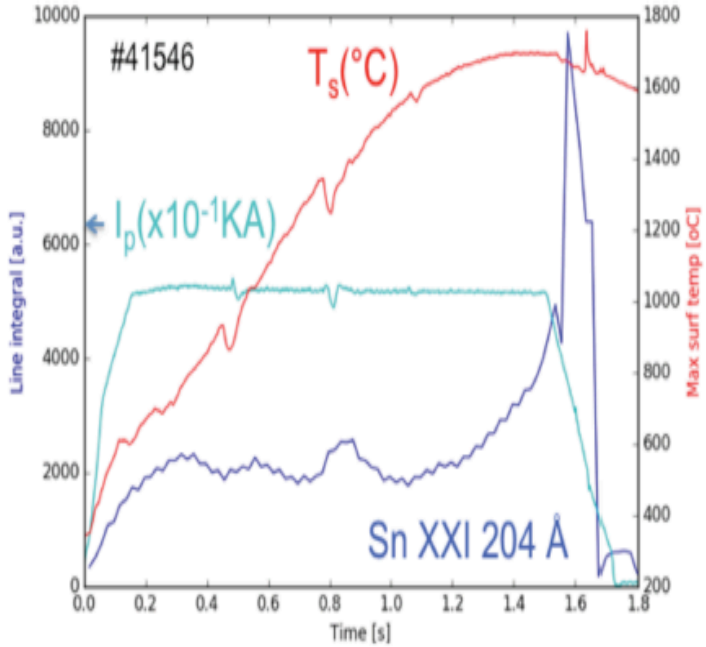
# TLL was operated at the last closed flux surface







# Temperature window with TLL up to 1700 ºC; high vapor pressure only near upper end



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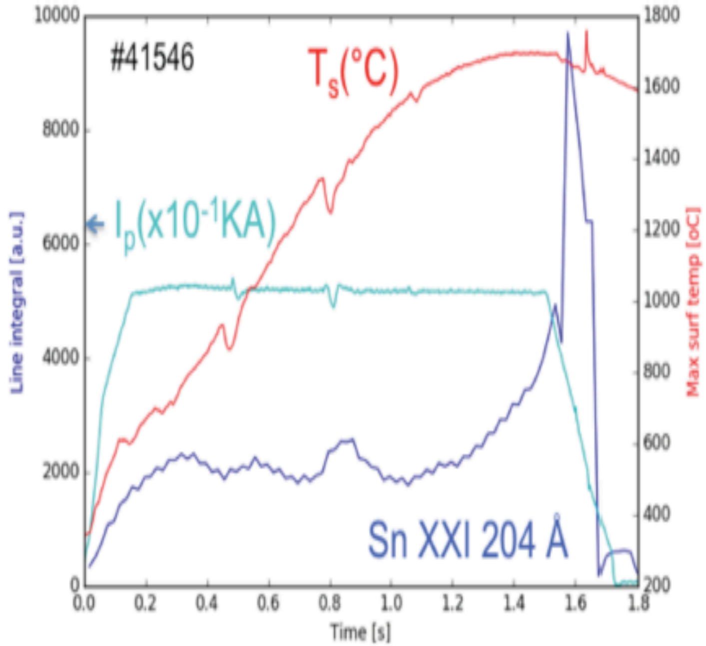
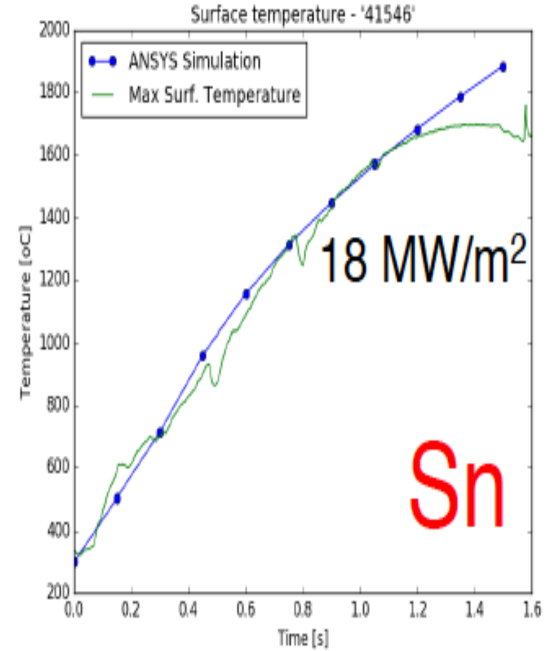
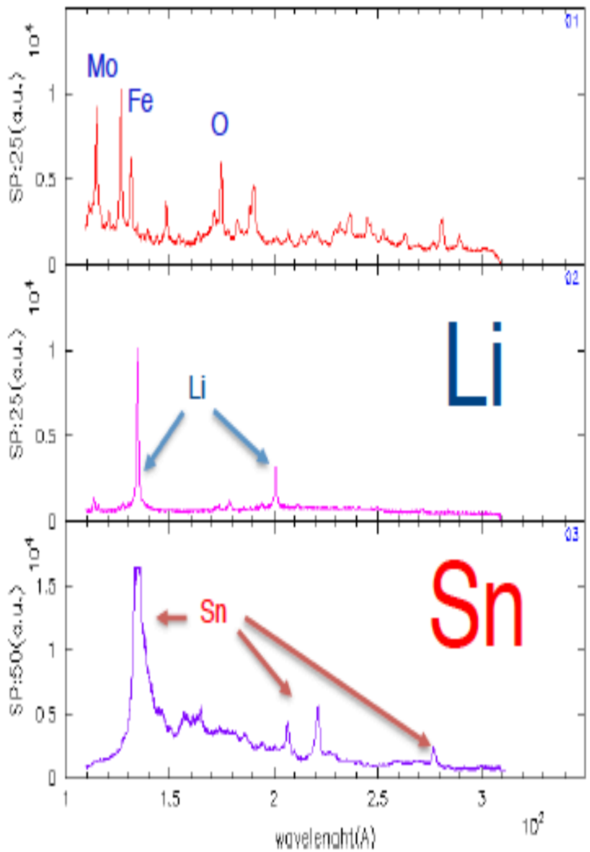



- The difference, after 1s, between ANSYS calculation and experimental surface temperature could be explained by "vapour shield" phenomena

# Core impurity concentrations obtained from UV spectroscopic analysis

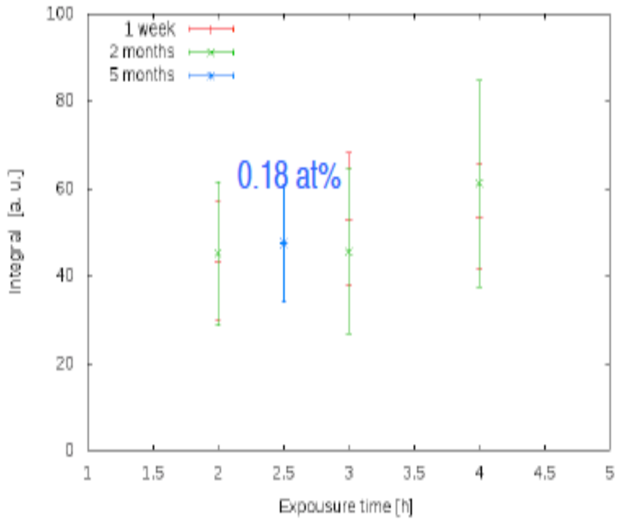



When evaporation becomes dominant the UV spectrum is dominated by Li or Sn lines. From the Zeff measurements we can respectively infer a concentration of

- $n_{Sn}/n_e \sim 0.05\%$
- $n_{Li}/n_e \sim 1\%$

# D retention in Sn low

- Tin samples exposed in GyM facility ($10^{24}$ $m^{-2}$) and analyzed by ion beams
- D concentration of 0.18 at% detected only in first few hundred nm of sample surface
- No time dependences has been observed on sample stored in air at room temperature (one week - two months)
- Comparing with previous measurements [1], despite the fluence being 50x higher, the D content is greater by only 2x in at%. Not far from saturation ?




* Carried out in collaboration with E. Vassallo -Piero Caldirola Institute –CNR Milano , E.Alves and R. Mateus IPFN IST University of Lisbon- Portuga


[1] J. Louriero et al., JNM **12** (2017) 709

# 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
  - *Lithium powder dropper successful at eliminating ELMs and reducing W influx in USN with W PFCs*

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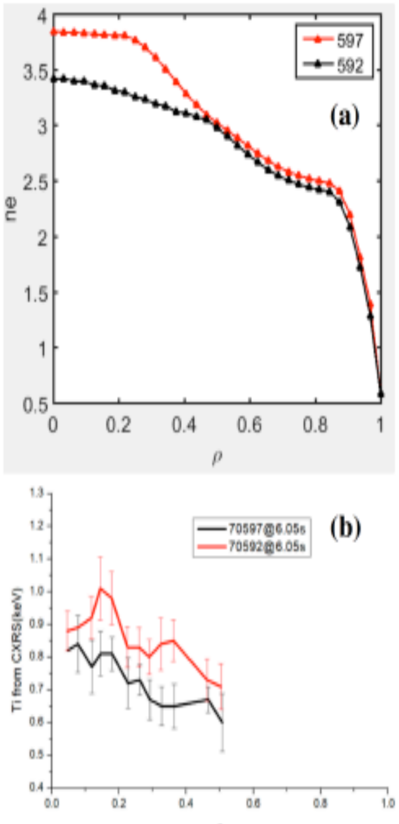
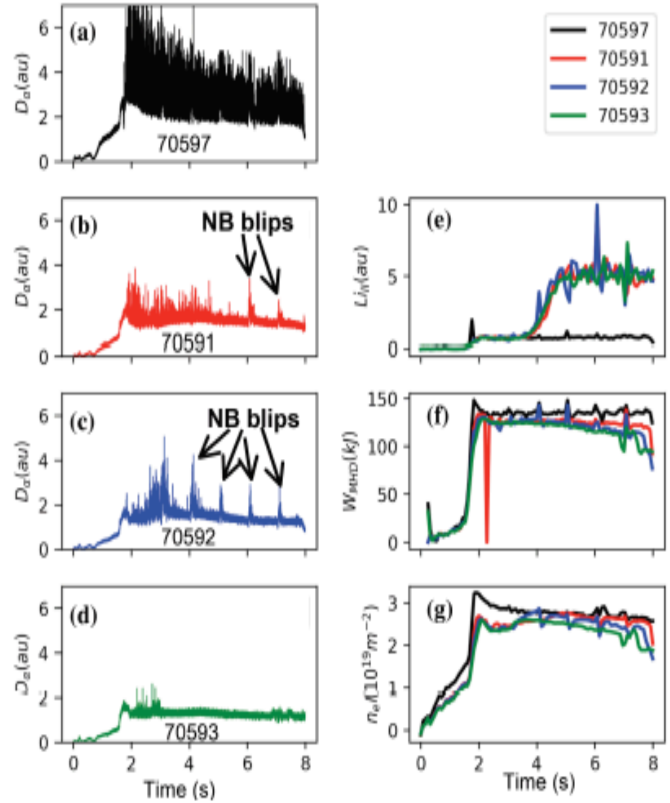
  - *Lithium powder dropper successful at eliminating ELMs and reducing W influx in USN with W PFCs*
- Liquid tin limiters exposed in FTU
  - No performance degradation with TLL
  - High heat flux ~ 18 $MW/m^2$ exhausted
  - Low core Sn concentration and low D retention in Sn confirmed
- Concepts and designs for liquid metals PFCs for next step devices and reactors needed

# Thank you for this opportunity

# 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

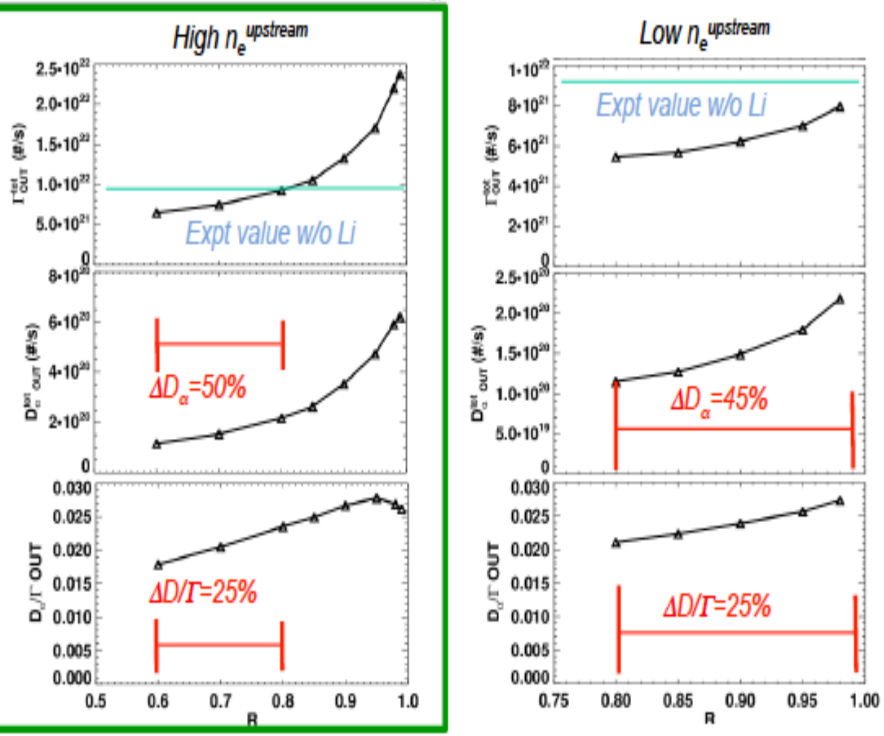



- SOLPS analysis shows local divertor recycling coefficient drops by 20%
- J. Canik, *IEEE Trans. Plasma Sci.* **46** (2018) 1081; builds on J. Canik, *Phys. Plasmas* **18** (2011) 056118

# SOLPS modeling of $D_\alpha$,$\Gamma$ 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 $D_\alpha$, $\Gamma$ trends

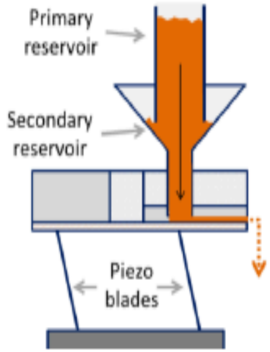
- $\Delta R$ ~ 20% is consistent with magnitude of $D_\alpha$, $\Gamma$ with Li
  - High $n_e^{upstream}$: R ~ 0.99->0.8
  - Low $n_e^{upstream}$: R ~0.8->0.6

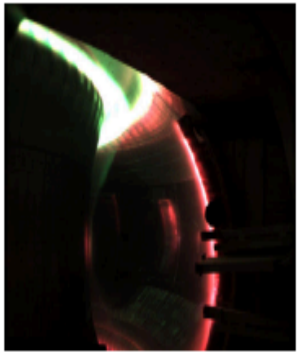


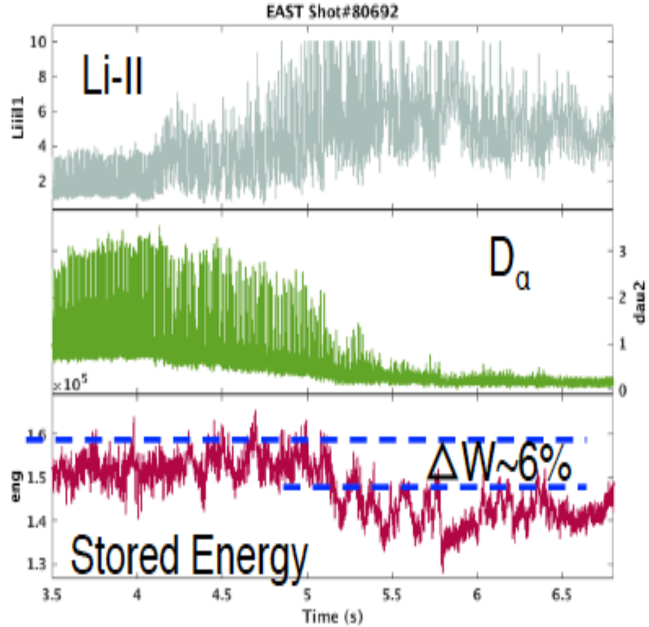

J. Canik, *IEEE Trans. Plasma Sci.* **46** (2018) 1081

# 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

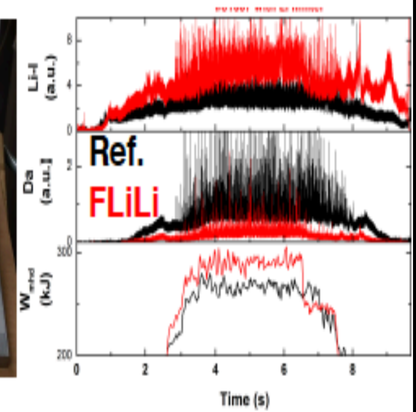


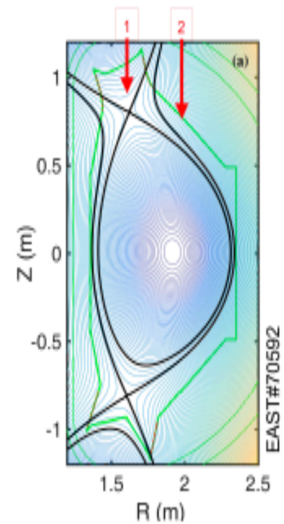



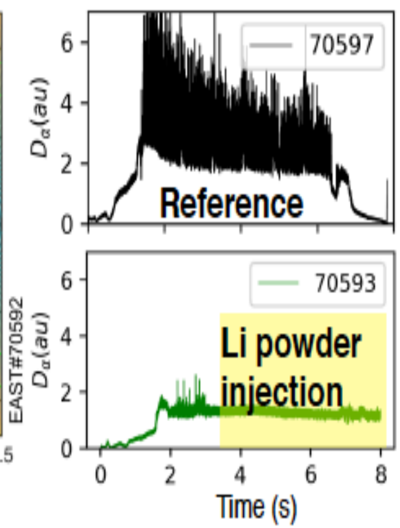


# ELMs and plasma-materials interactions mitigated with flowing lithium PFCs and active lithium injection in EAST

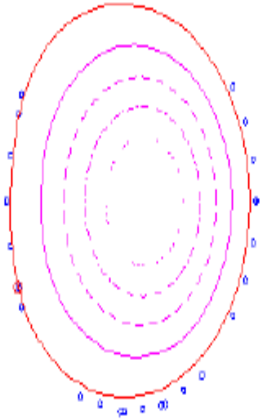
- 3rd generation flowing liquid lithium (FLiLi) limiter inserted into EAST H-modes
  - Made of a Moybdenum alloy
  - Recycling reduced and PMI mitigated with limiter inserted
  - *Brought HIDRA online to test limiter designs*
- ELMs eliminated with real time lithium powder injection into the upper W divertor
  - Progressive conditioning
  - *New imaging diagnostics: camera & dual filter technique*



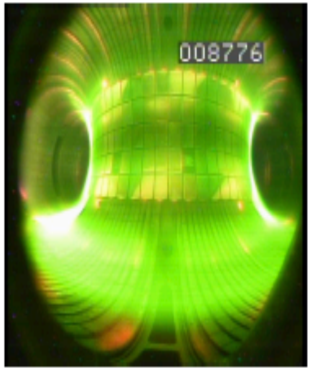
# The liquid metal limiters during the FTU pulse



Equi Psi

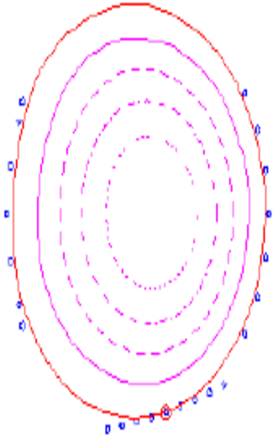
( from "ODINB" )

/Ip/ = 497. kA
/Bt/ = 5.822 T
q_edge = 6.44

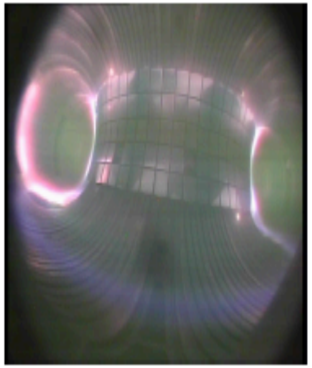



**Li**

*Up to 1.5cm from the LCMS*



/Ip/ = 494. kA
/Bt/ = 4.019 T
q_edge = 4.21



**Sn**

*Closed the LCMS*