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

PMI

ENEA
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

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
  - 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

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

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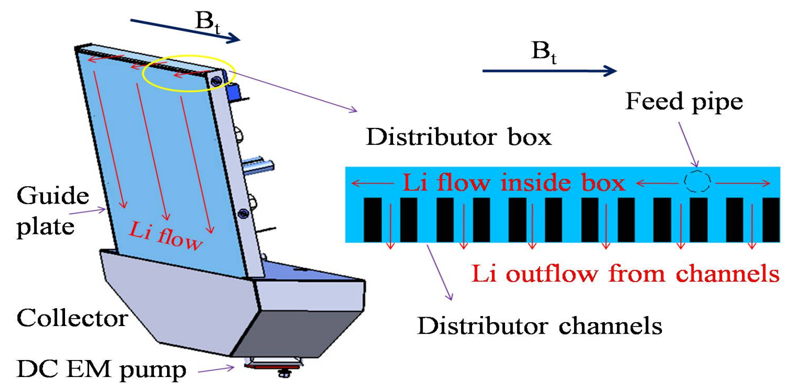
The science and technology of flowing liquid lithium limiters has been advanced via US-PRC PMI collaboration on EAST

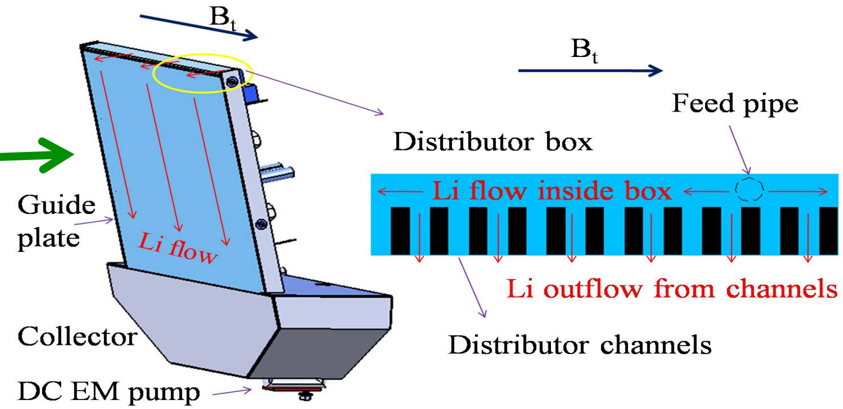
- Three generations of liquid lithium limiters tested in EAST
  - Prototype SS plate tested in HT-7
  - Gen. 1 (12/2014) tested in EAST
  - Gen. 2 (12/2016) tested in EAST
  - Gen. 3 (8/2018) tested at UI-UC and PPPL and then EAST



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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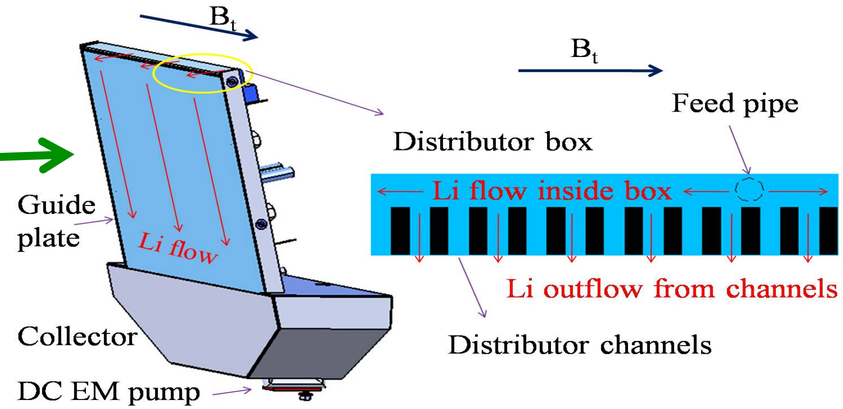

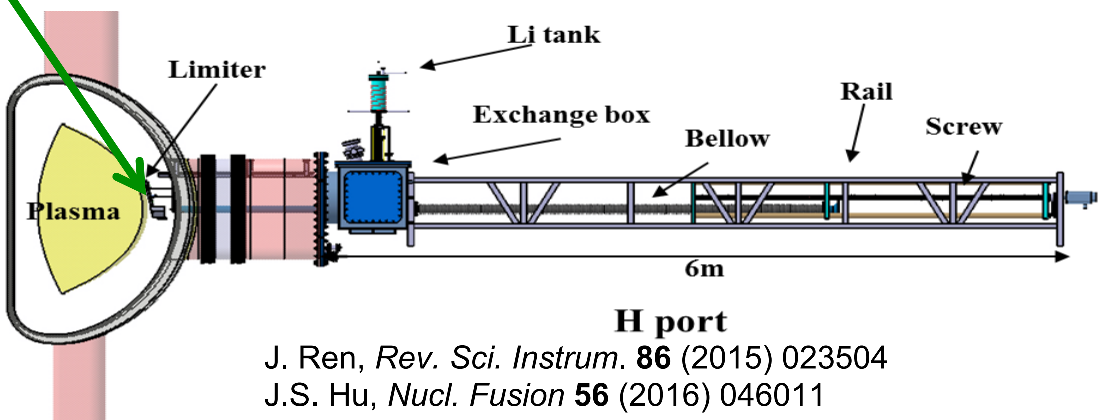

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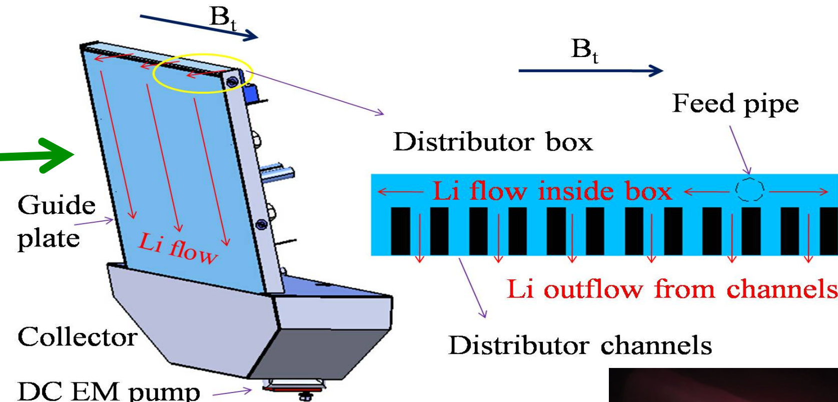
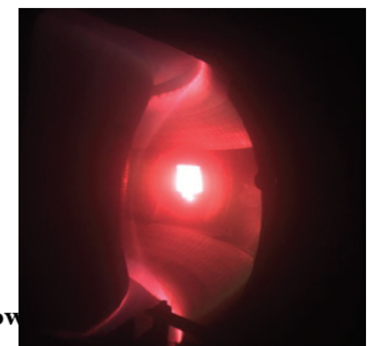
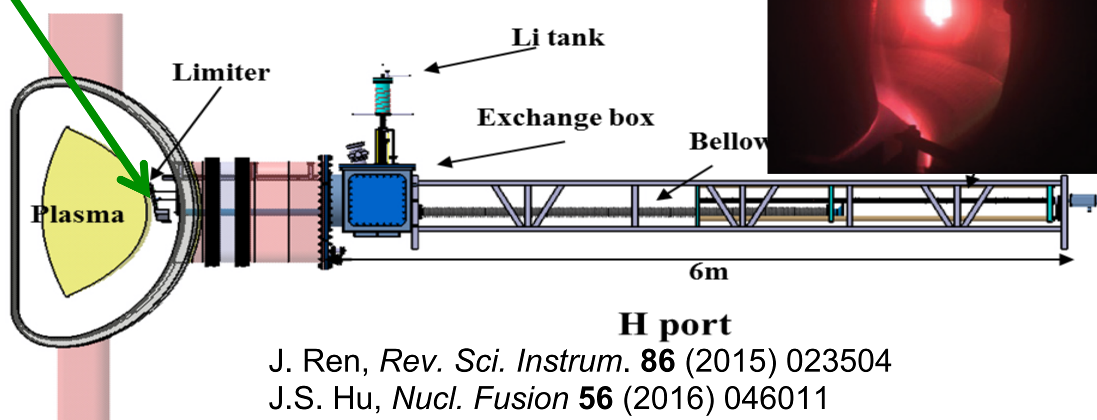
- Inserted at midplane on MAPES system
- *H-modes and ohmic discharges compatible with flowing Li limiter*
  - $q_{peak}^{limiter} \sim 3.5\ MW/m^2$
- Limiter and distributor damaged during operations, so new design implemented for Gen. 2







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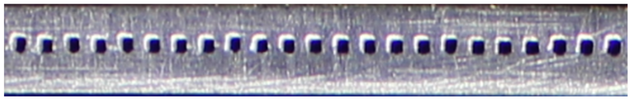
2^{nd} Generation flowing liquid lithium limiter (2016) had design upgrades compared to 1^{st} generation limiter (2014)

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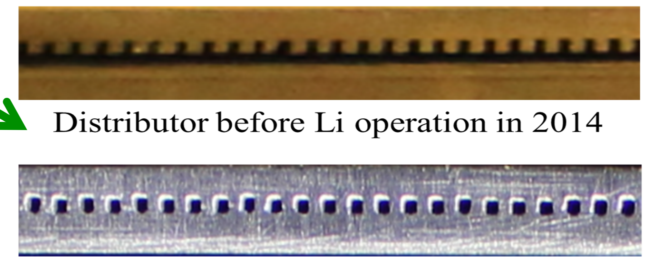
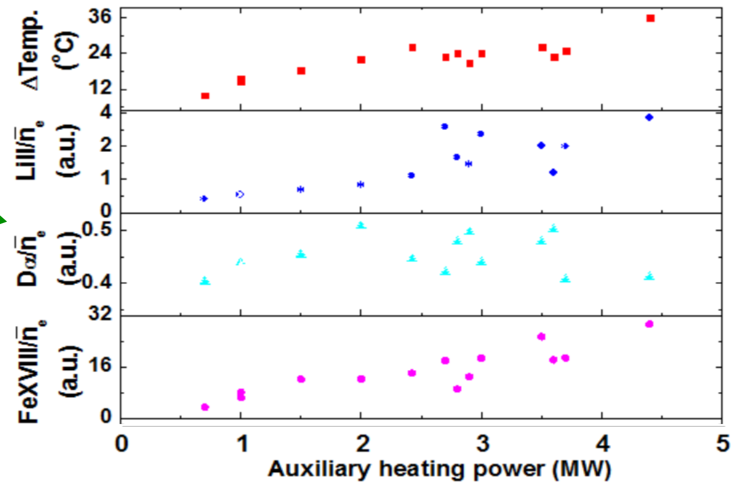
- Improved distributor manufacturing resilient to cracking, plus
  - Two parallel paths for jxB pumps to pump liquid Li up the back side
  - 5x thicker stainless steel protective layer
- Improved surface texturing led to improved wetting and surface coverage
  - < 30% in 2014
  - > 80% in 2016


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} ~ 4 MW/m^2
  - No limiter damage observed after first plasma exposure
  - Limiter re-exposed and flow re-started a week after first experiment



G. Zuo, *Nucl. Fusion* submitted

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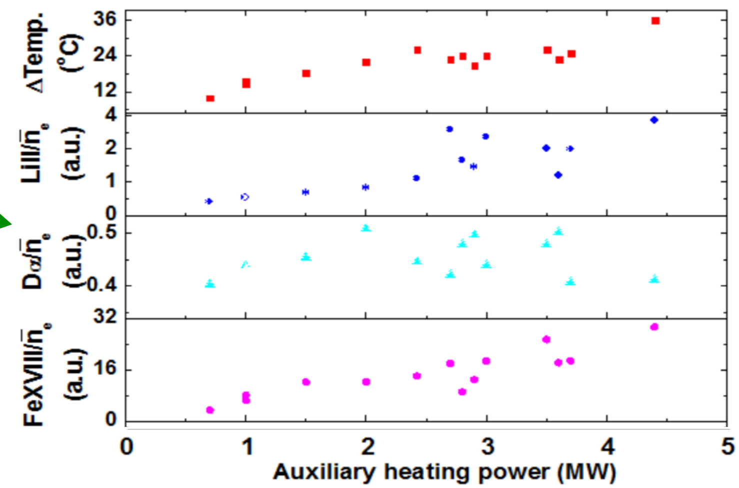

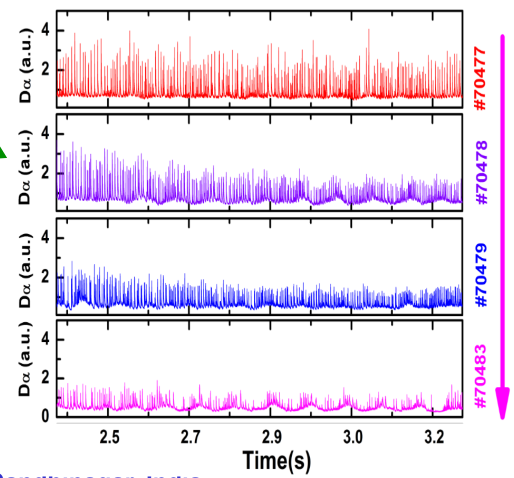

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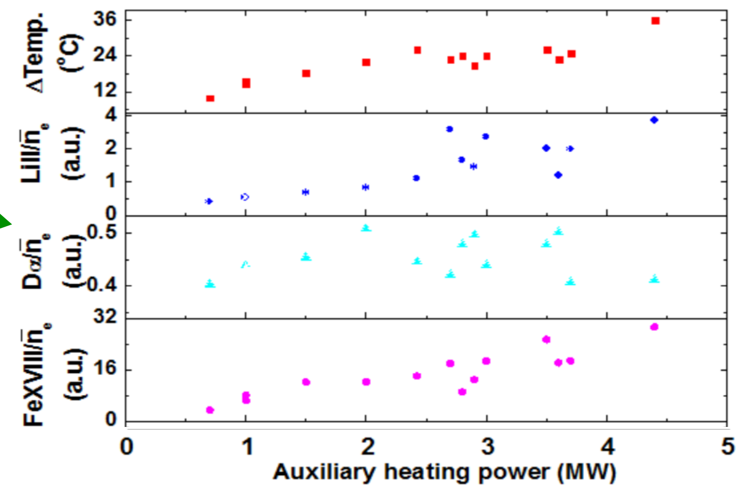
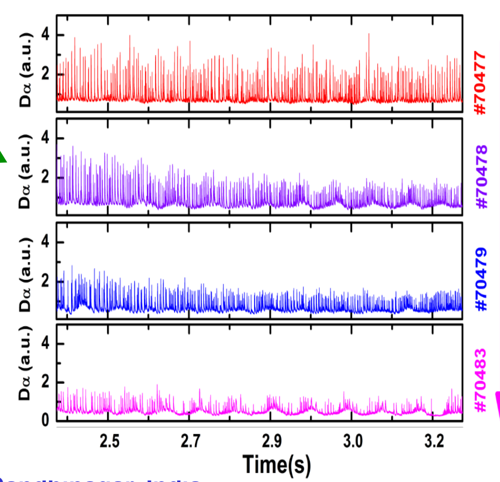
- Concern over Li – Cu reactivity underpins Gen. 3, made out of TZM, a Mo alloy

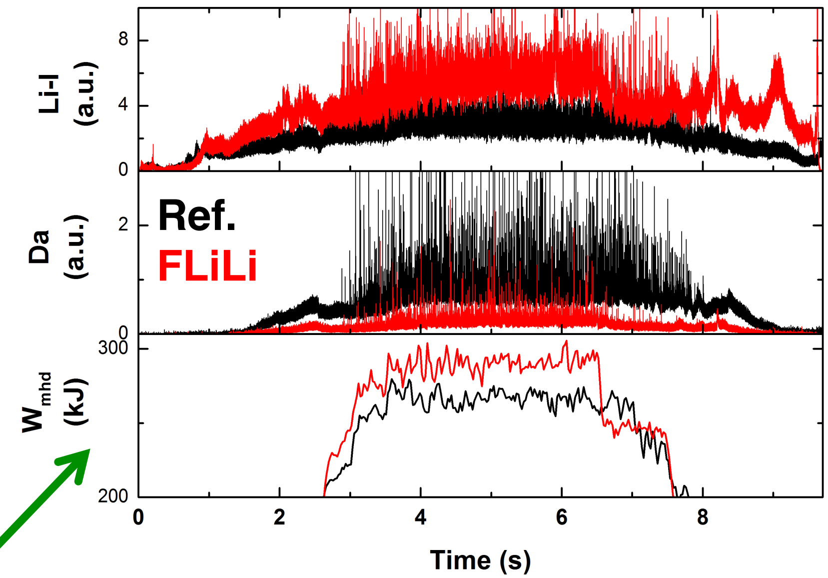




G. Zuo, *Nucl. Fusion* submitted

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

- 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)



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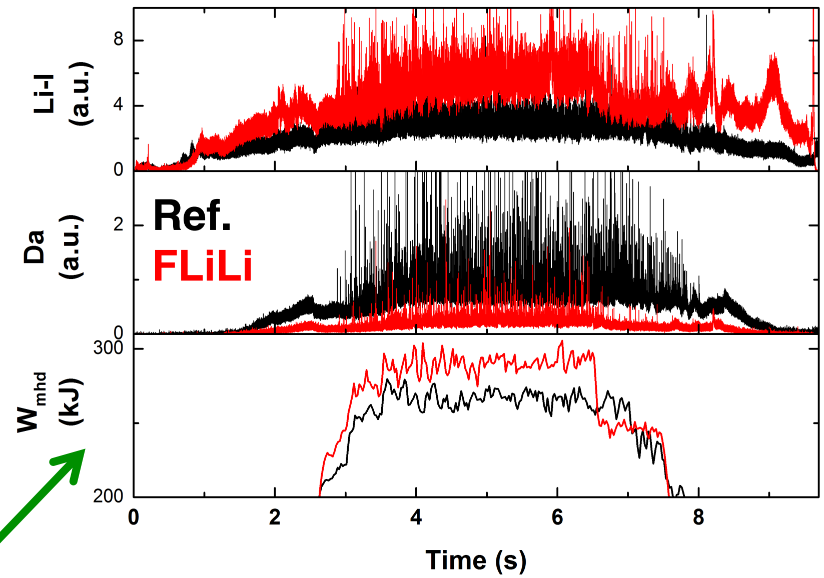
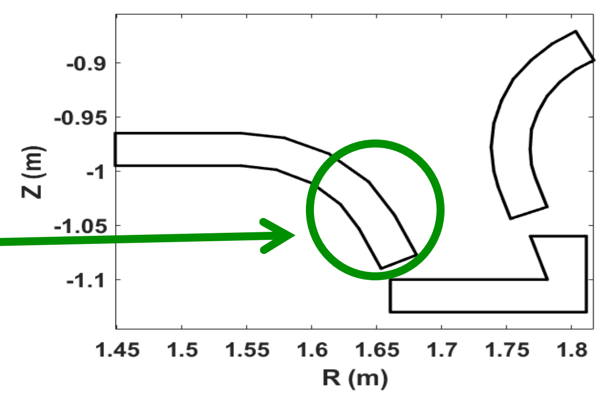
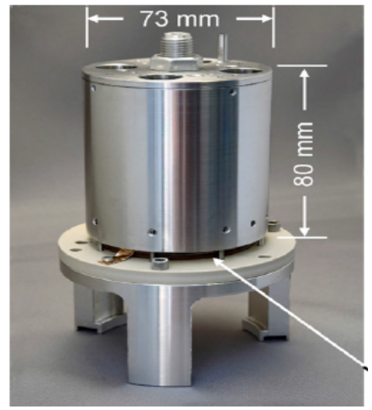
  - Future versions: 3D printed W PFC, limiter and/or divertor sector(s)?

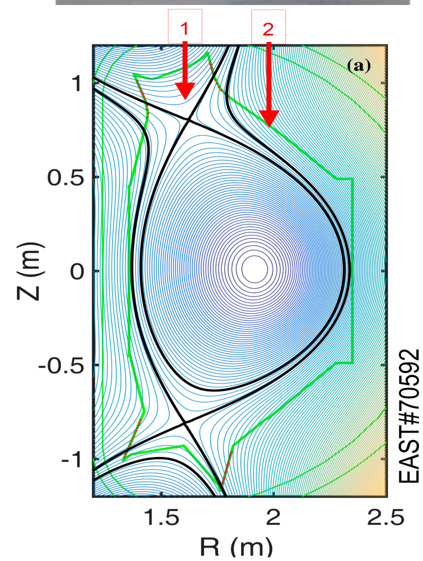




ELMs eliminated with real-time Li powder injection into the W upper divertor in EAST

- 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)





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

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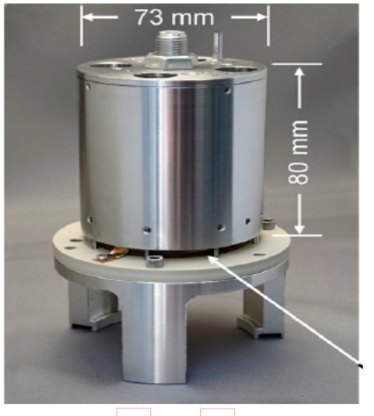
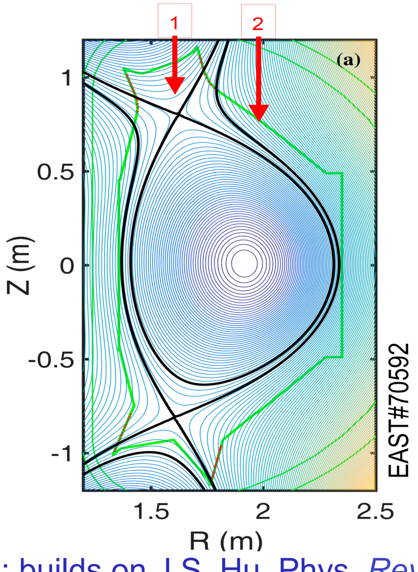
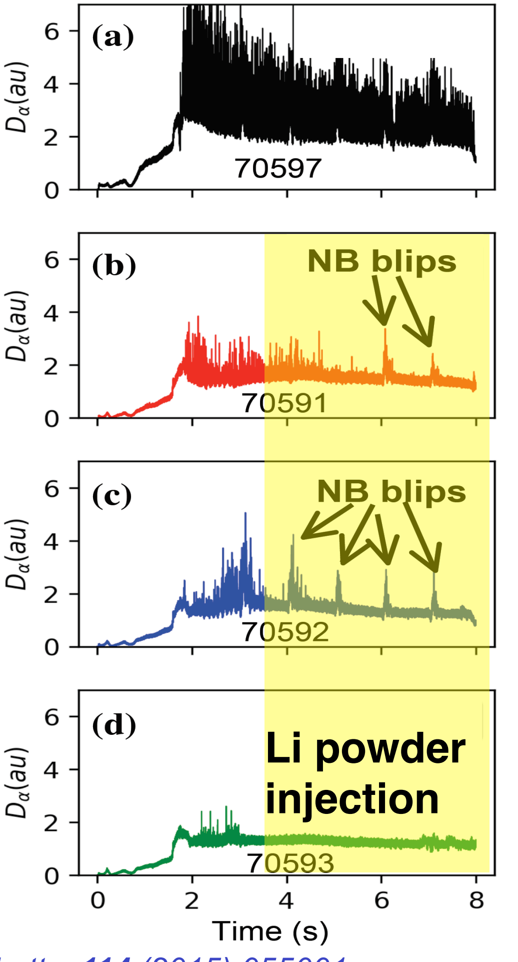
  - Injector uses vibrating piezo-electric disk to inject controlled amounts of powder
  - Similar technology used for B injection in AUG (Lunsford, FIP/2-4)
- Progressive reduction of recycling and elimination of ELMs
  - Stored energy reduced by < 10%, because injection rate was higher than needed



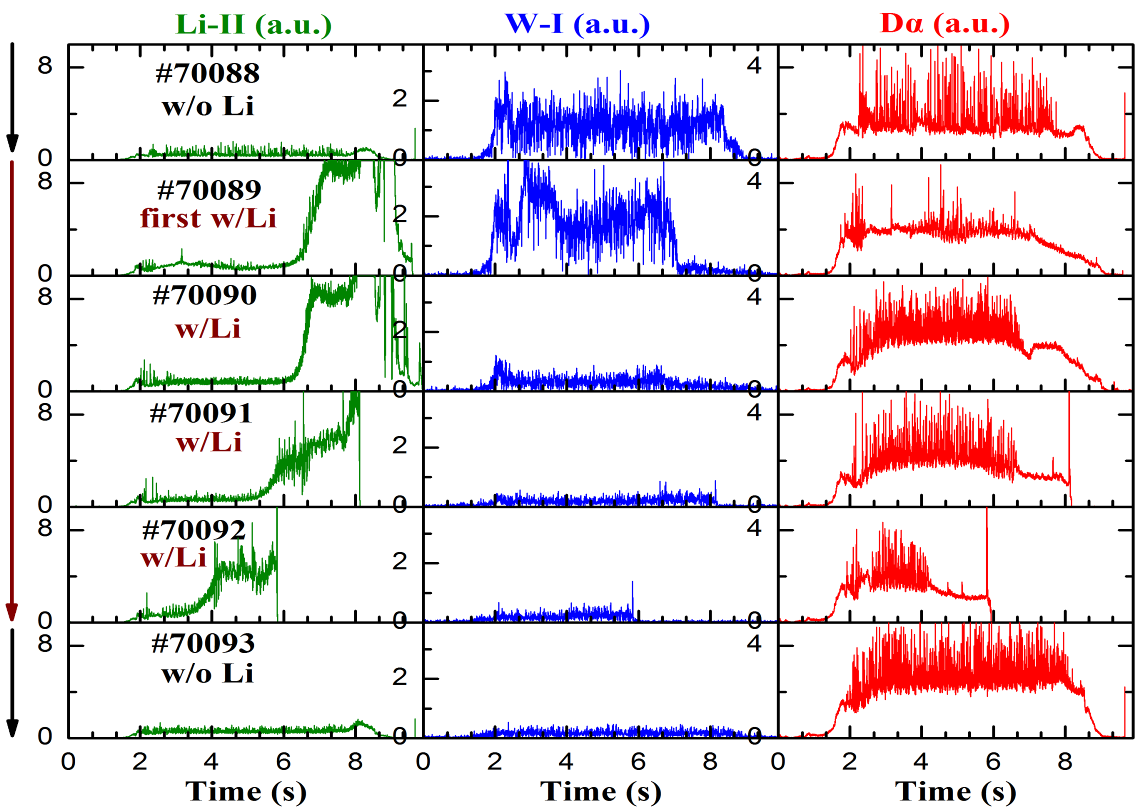




R. Maingi, Nucl. Fusion **58** (2018) 024003; builds on J.S. Hu, Phys. *Rev. Letts.* ***114*** *(2015) 055001*

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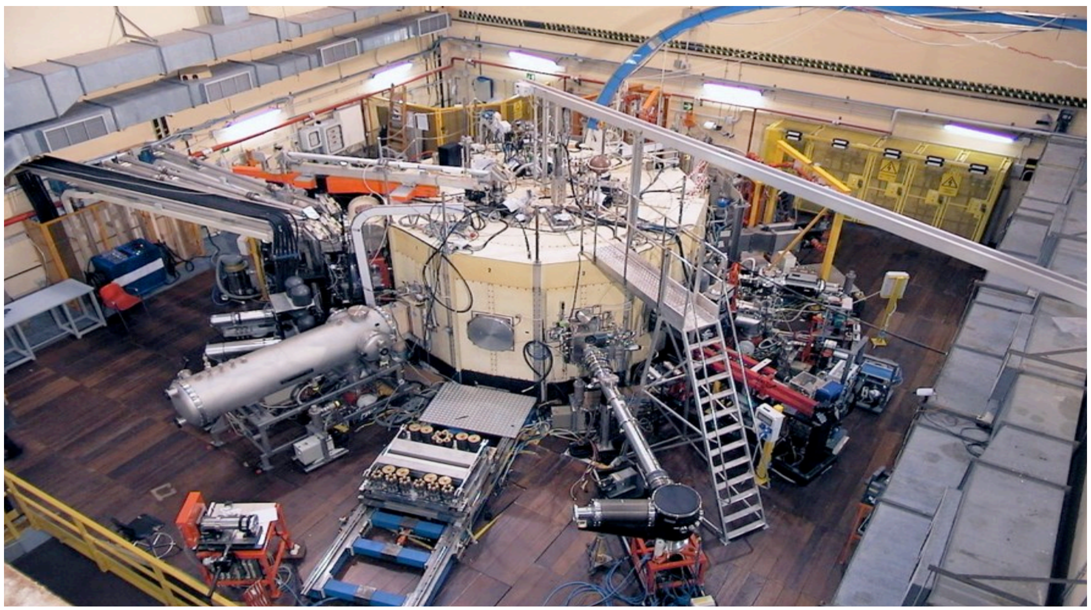
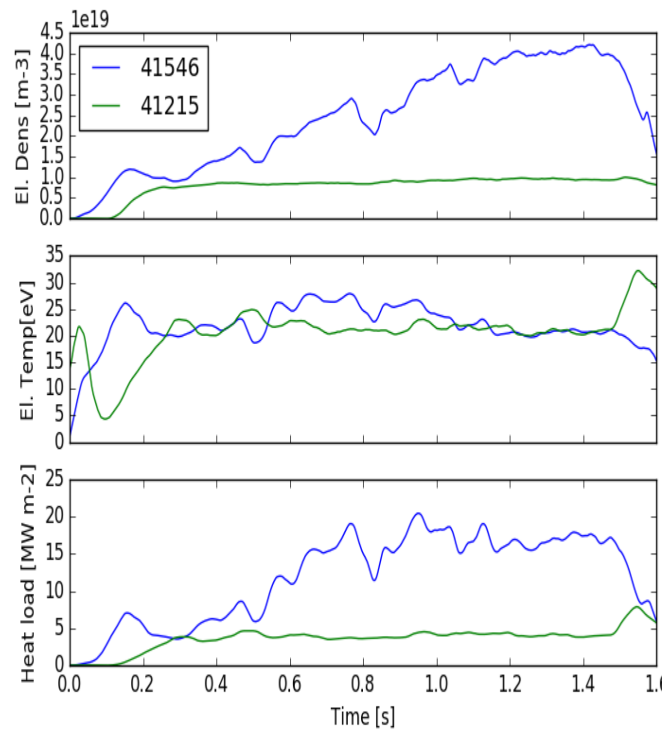
This work has been partially carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The viewsand opinions expressed herein do not necessarily reflect those of the European Commission.

Liquid metal limiters tested in FTU since 2006

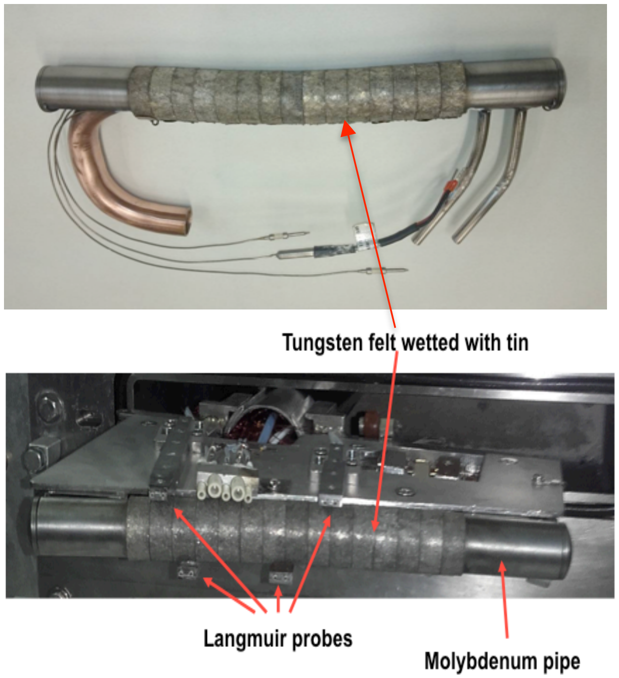
Performance with tin liquid limiter

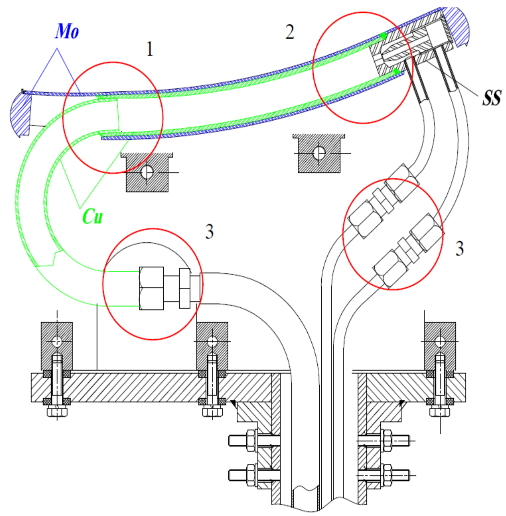




Liquid Tin Limiter - TLL

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





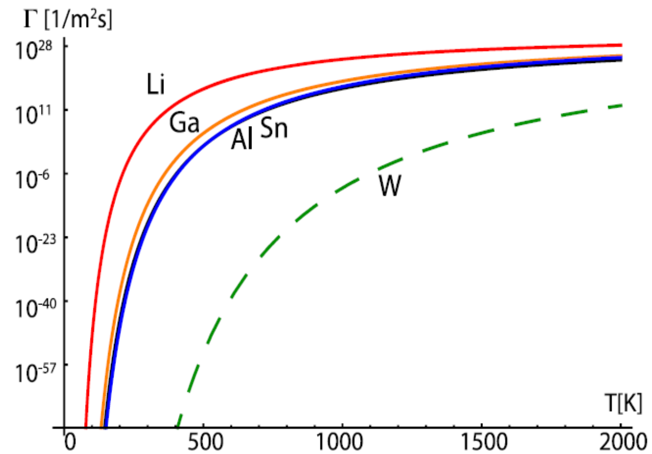
- Capillary porous system used to contain Sn
- Very flexible and versatile layout: the limiter head can be easily changed
- At high temperature tin is very corrosive: the liquid tin limiter layout prevents copper corrosion

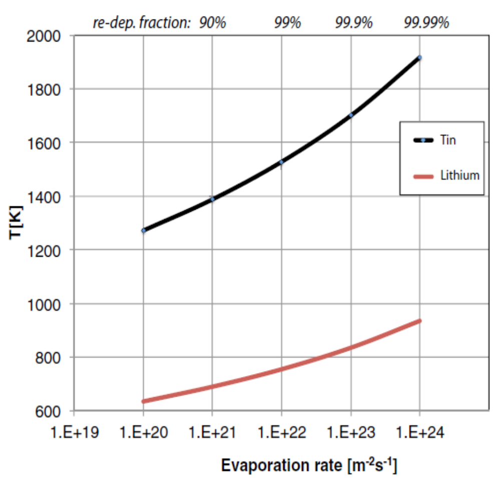
- Tin allows a wide temperature operational window with low vapor pressure

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



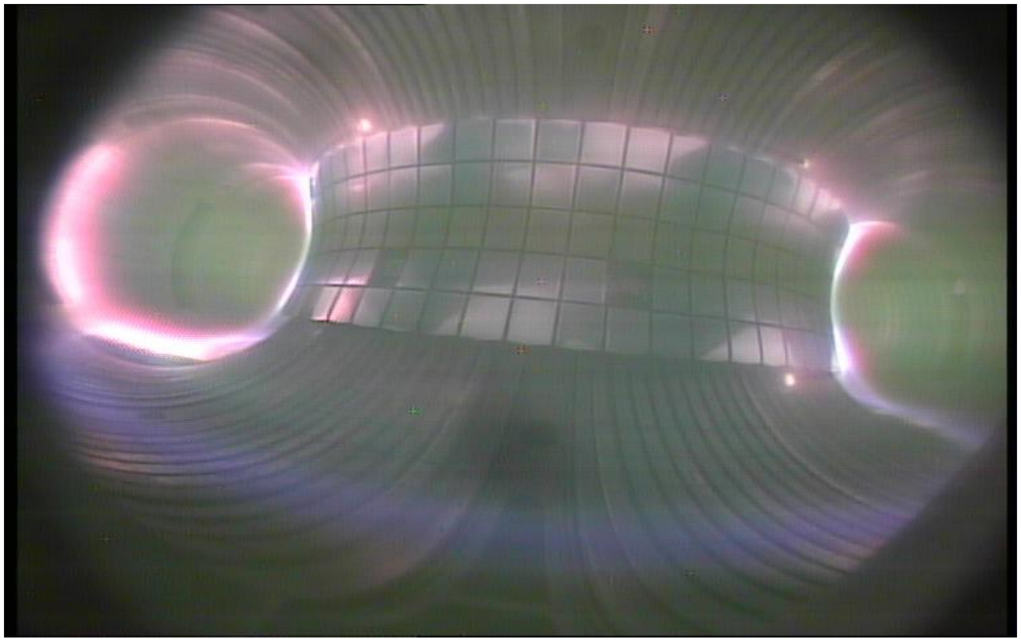


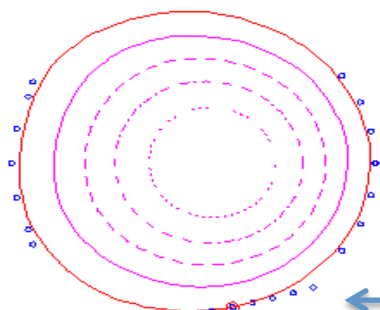
[J.W. Coenen *et al.*
Phys. Scr. **T159** (2014) 014037]

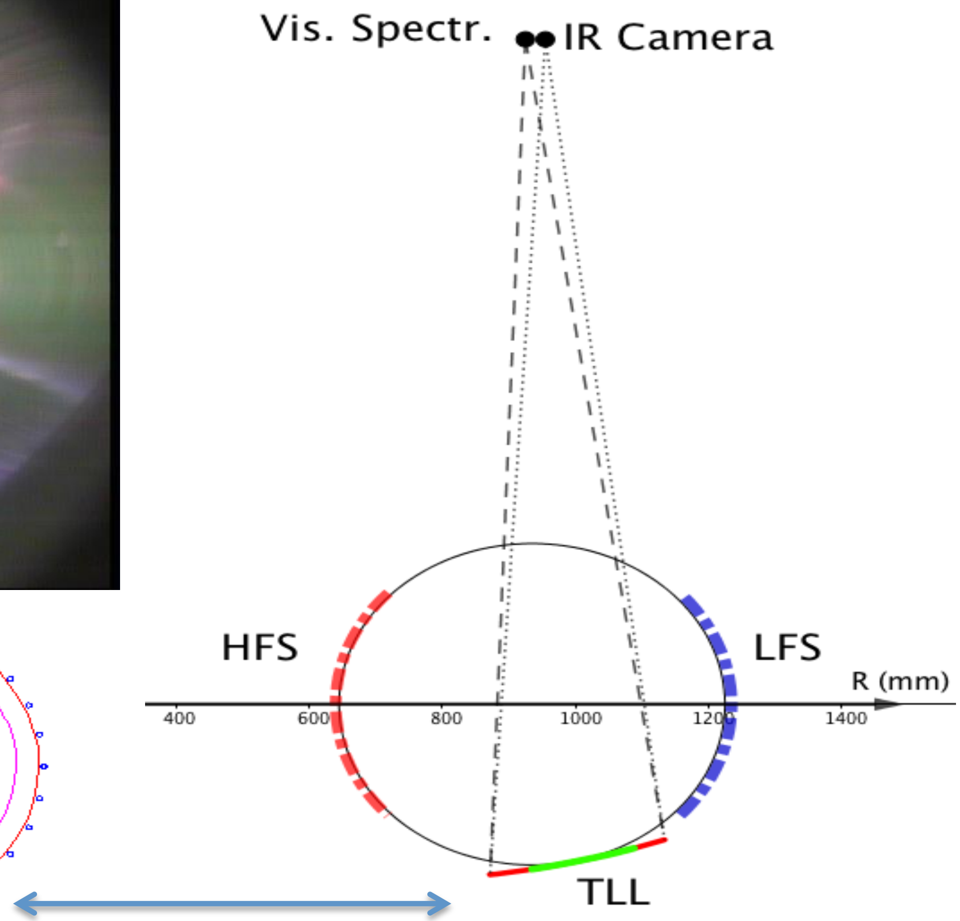
Characteristics of TLL compared with previous LLL

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

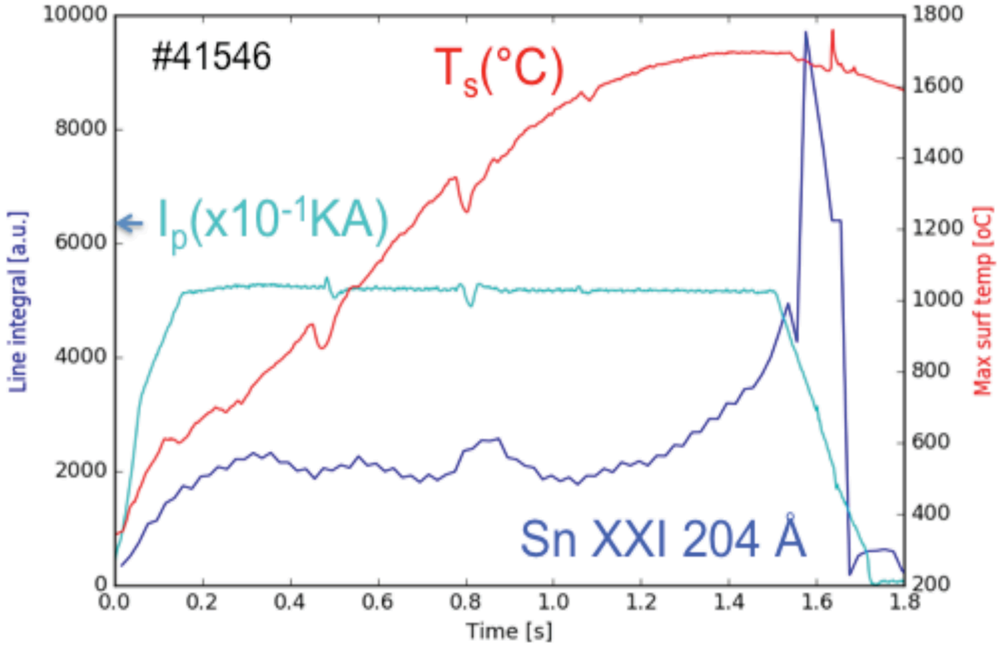
TLL was operated at the last closed flux surface







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



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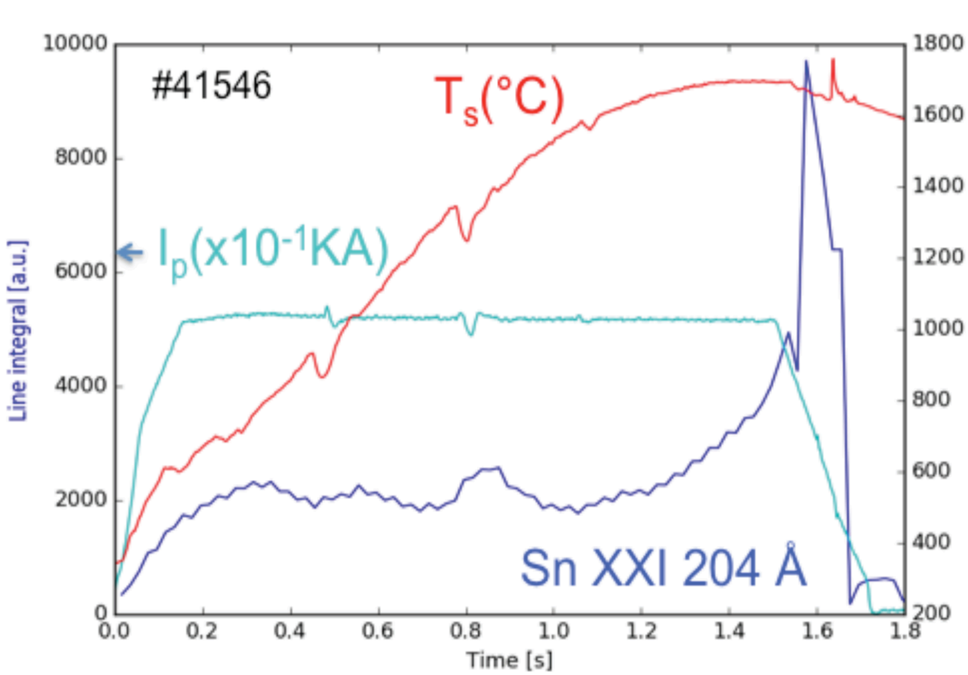
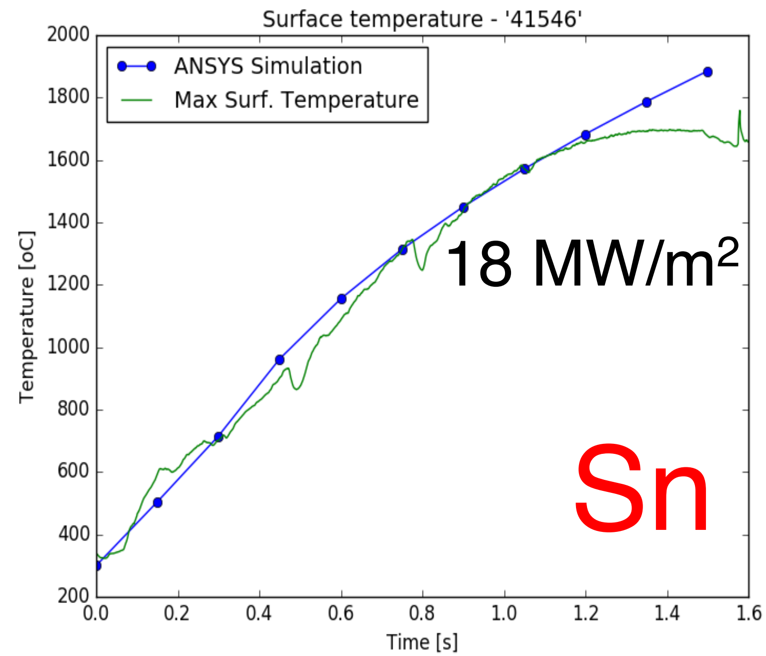
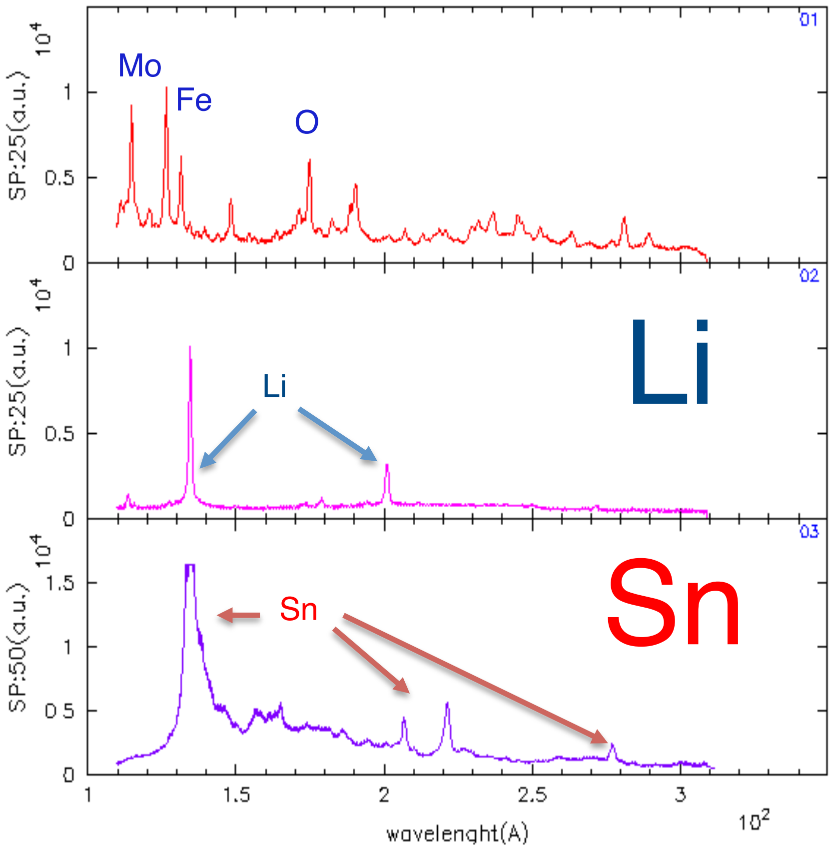




- The difference, after 1s, between ANSYS calculation and experimental surface temperature could be explained by “vapour shield” phenomena

Core impurity concentrations obtained from UV spectroscopic analysis

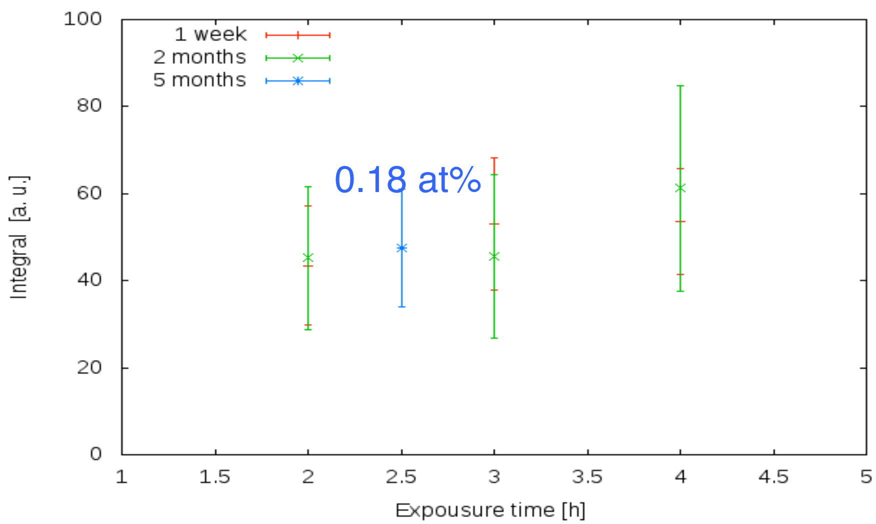


When evaporation becomes dominant the UV spectrum is dominated by Li or Sn lines. From the Zeff measurements we can respectively infer a concentration of

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

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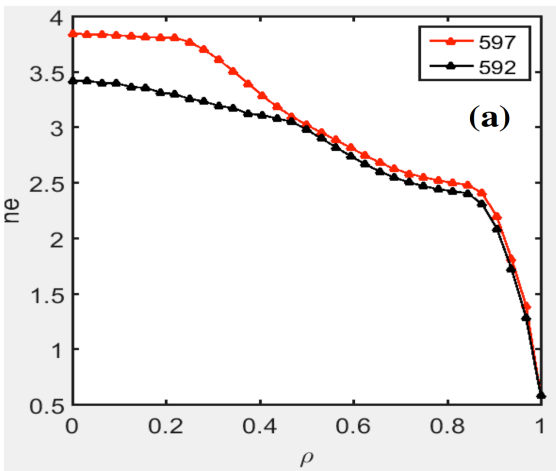
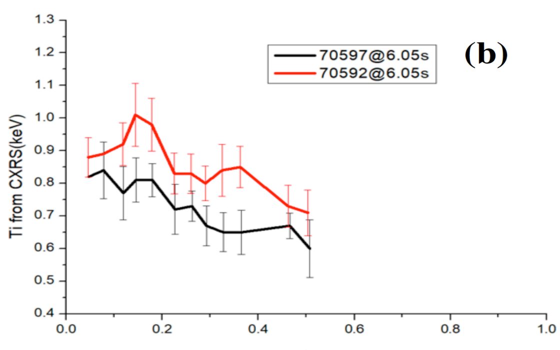
  - *Lithium powder dropper successful at eliminating ELMs and reducing W influx in USN with W PFCs*
- Liquid tin limiters exposed in FTU
  - No performance degradation with TLL
  - High heat flux ~ 18 MW/m^2 exhausted
  - Low core Sn concentration and low D retention in Sn confirmed
- Concepts and designs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

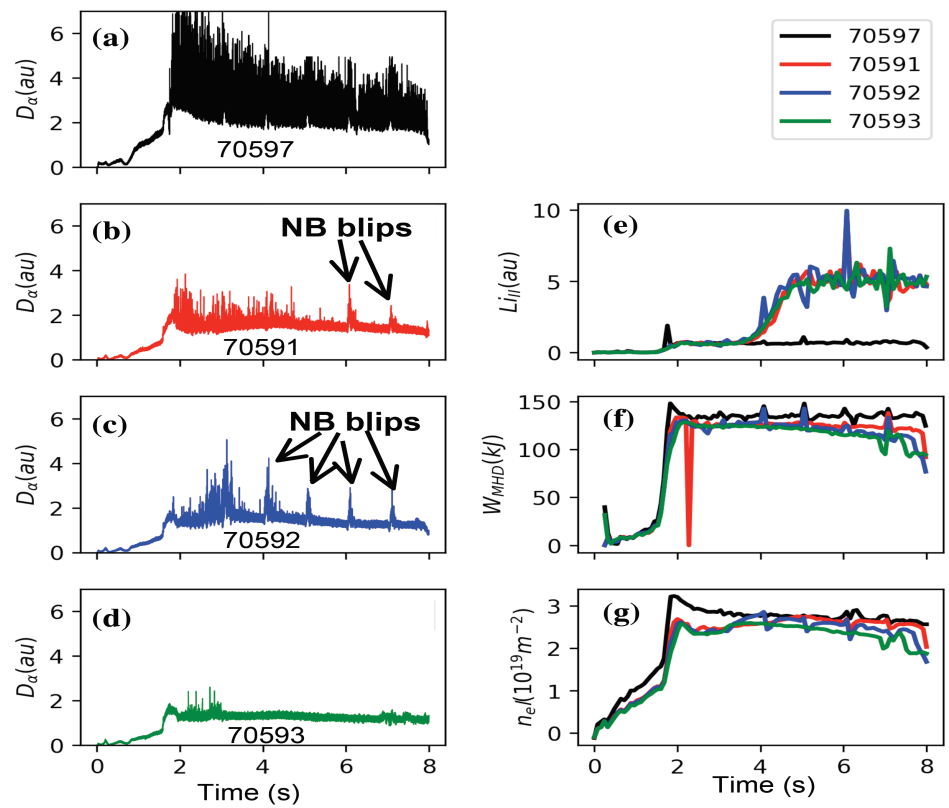
Thank you for this opportunity

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

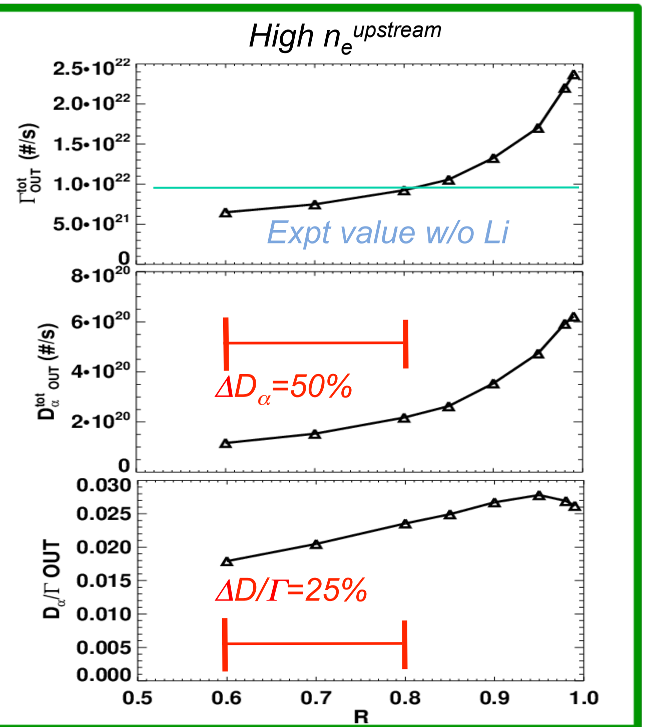


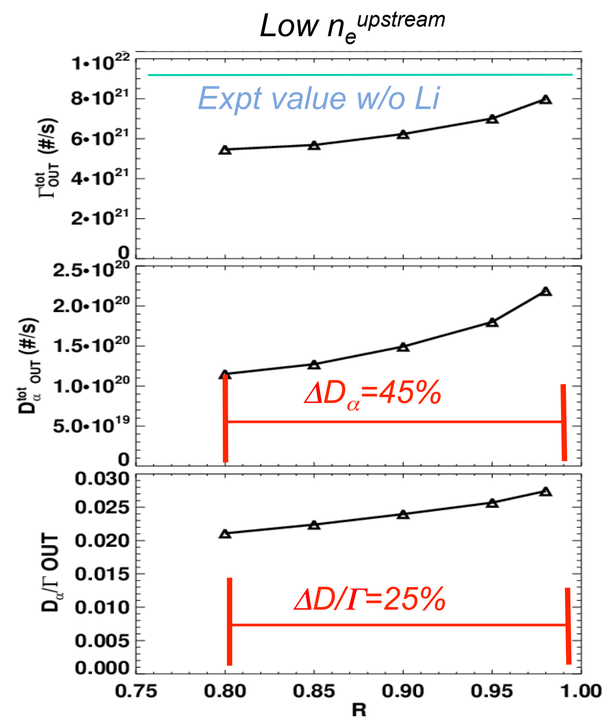
- SOLPS analysis shows local divertor recycling coefficient drops by 20%
- J. Canik, *IEEE Trans. Plasma Sci.* **46** (2018) 1081; builds on J. Canik, *Phys. Plasmas* **18** (2011) 056118

SOLPS modeling of D_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

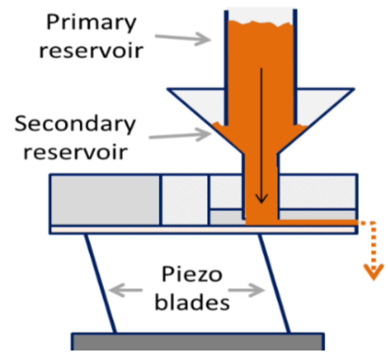


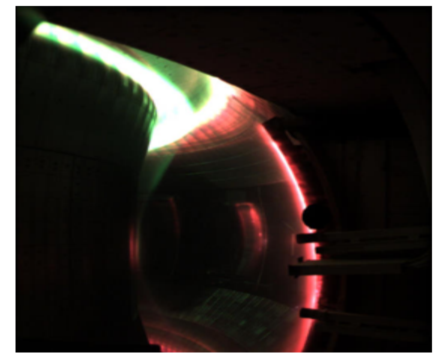


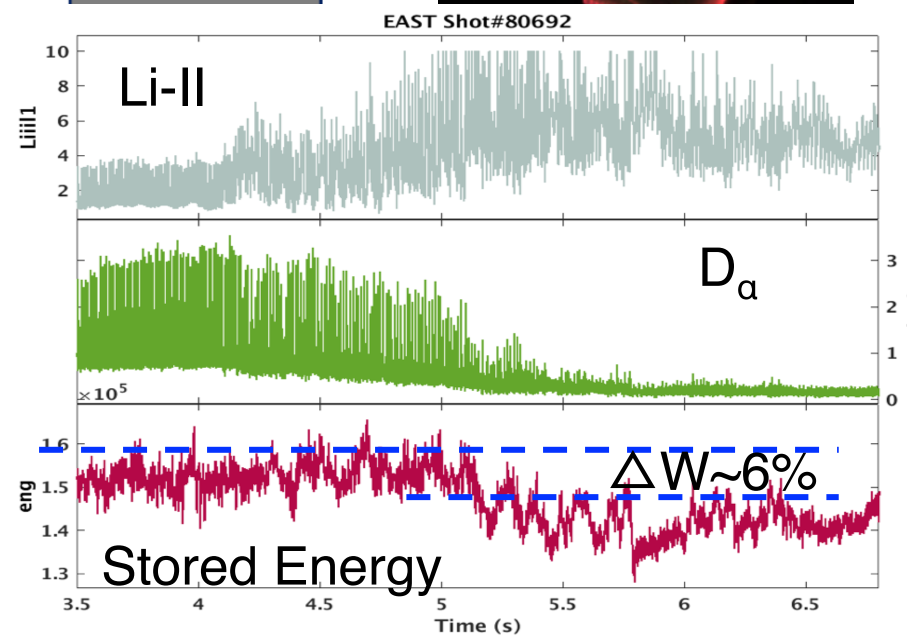
J. Canik, *IEEE Trans. Plasma Sci.* **46** (2018) 1081

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

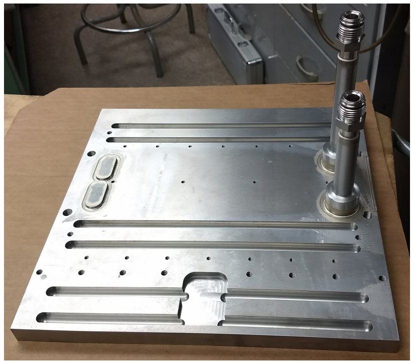


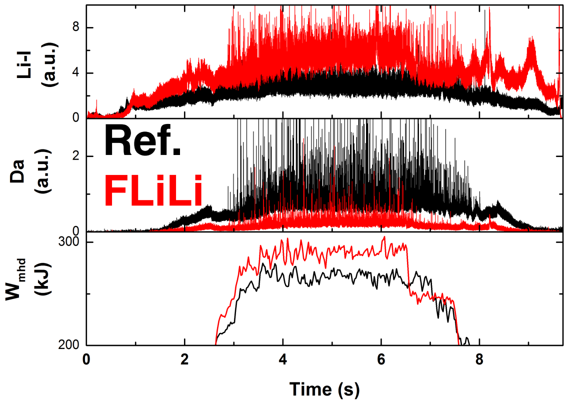


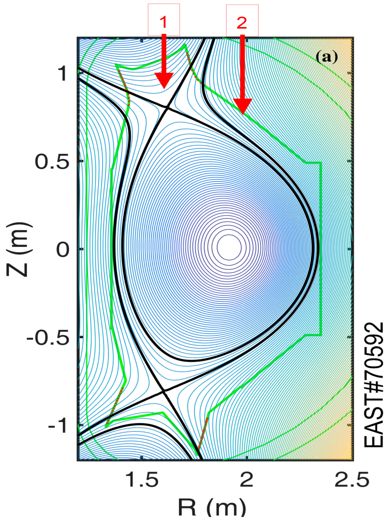


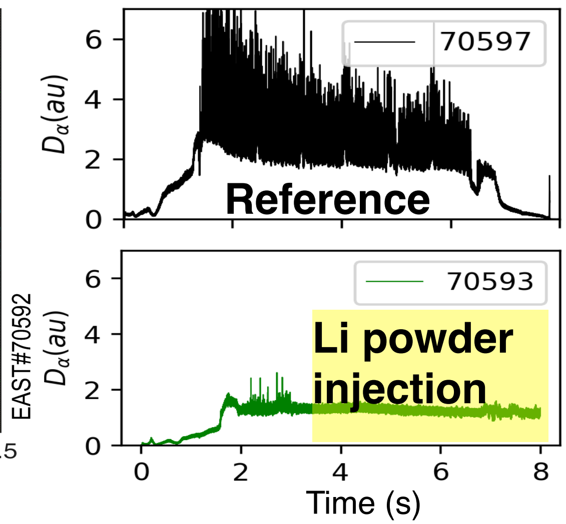
ELMs and plasma-materials interactions mitigated with flowing lithium PFCs and active lithium injection in EAST

- 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*

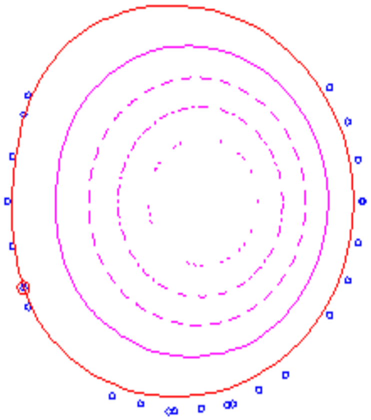








The liquid metal limiters during the FTU pulse



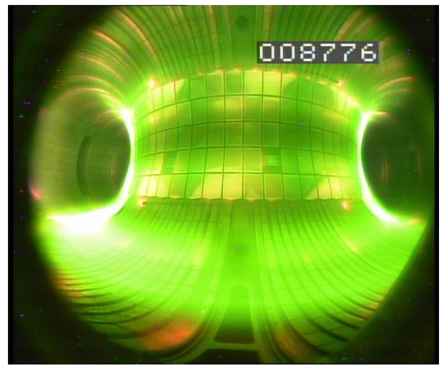
Equi Psi

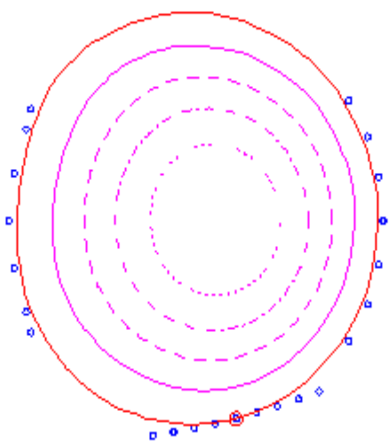
(from "ODINB")

/Ip/ = 497. kA
/Bt/ = 5.822 T
q_edge = 6 44

Li

Up to 1.5cm from the LCMS

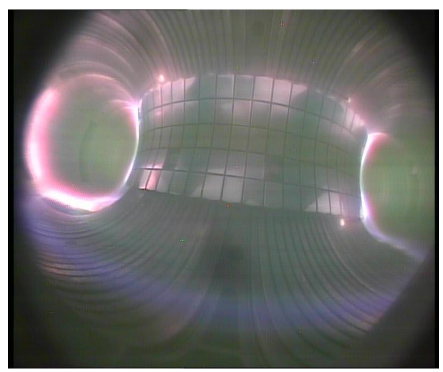


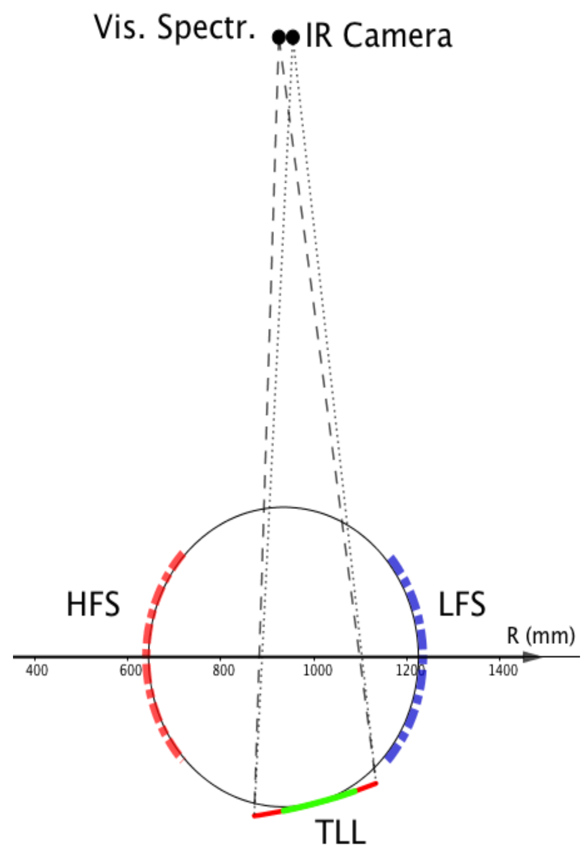


/Ip/ = 494. kA
/Bt/ = 4.019 T
q_edge = 4 21

Sn

Closed the LCMS





Tin surface temperature simulation with ANSYS