Lithium PFCs and Lithiated Edge Control at DIII-D

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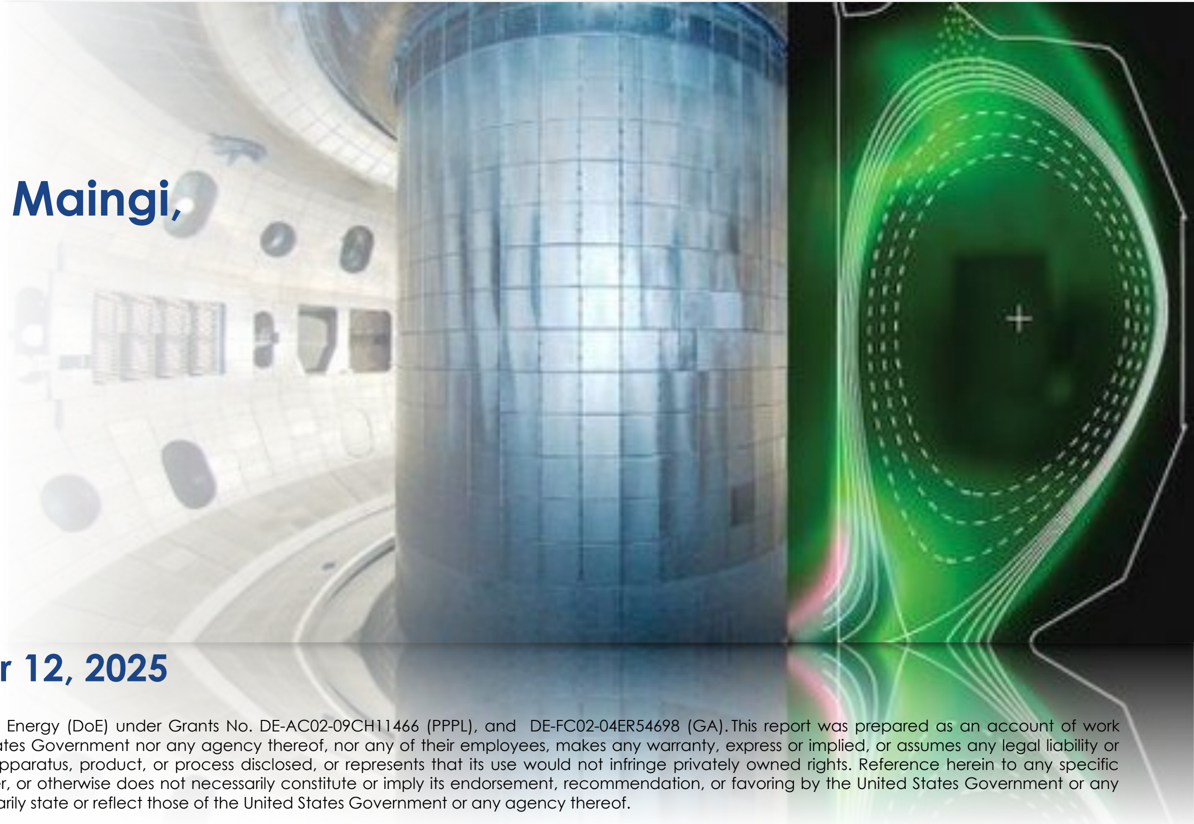

DIII-D Industry Day Event, November 12, 2025

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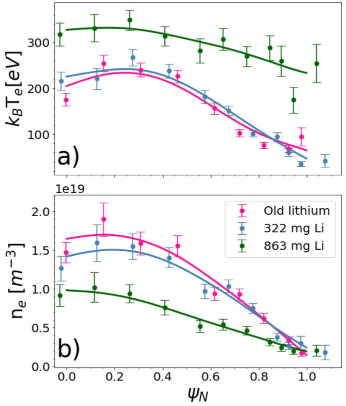
Why lithium walls?

Flatter Te profiles enable higher stable edge pressure with reduced turbulence, allowing higher fusion power density in smaller, more compact devices

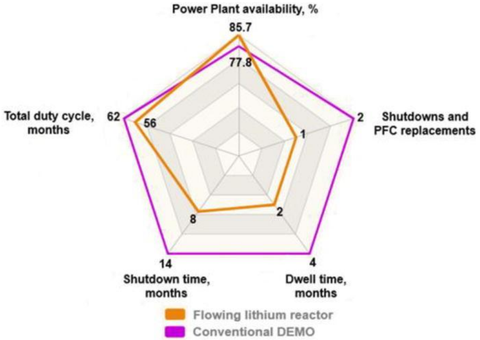
- Reduced recycling and a hotter edge improve H-factor and β
- Improved divertor power exhaust via hot, low-density SOL and wider λ_q

Flowing liquid lithium PFCs provide self-healing, high-heat-flux capability

- Strong D/T uptake and He pumping support integrated fuel and ash handling



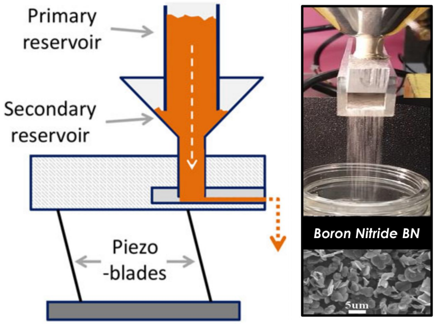
A. Maan et al 2023 Nucl. Mat. and Energy 35 101408



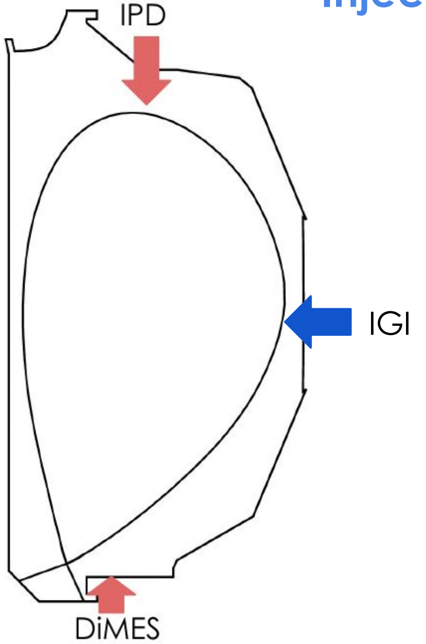
A. de Castro et al 2021 Phys. Plasmas 28, 050901

Enabling capability for Li studies: multi-species material injectors for lithium in powder and granule injection

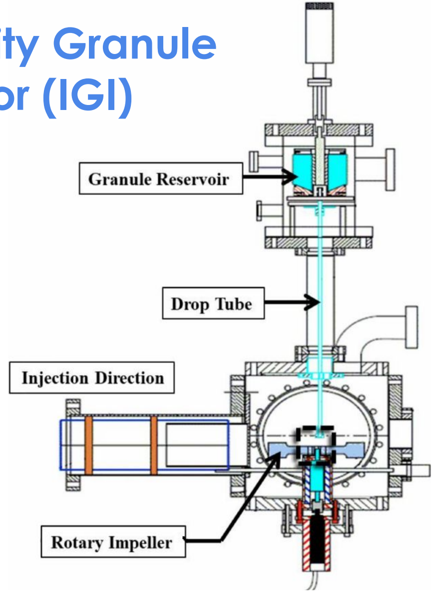
Impurity Powder Dropper (IPD)



- Particle size 5 - 900 μm
- Mass flow 1-200 mg/s
- Speed 5-6 m/s



Impurity Granule Injector (IGI)



- Particle size 0.7 - 2 mm
- Mass flow 1-100 mg/s
- Speed 60-180 m/s

A. Nagy et al 2018, Rev. of Sci. Instr. 89 (10) 10K121

M. S. Vorenkamp et al 2017, Fusion Sci. and Techn. 72, 488-495

Outline

Lithium-divertor power exhaust

Effect of lithium on edge stability and fuel recycling

Performance of liquid lithium plasma-facing components

Conclusions

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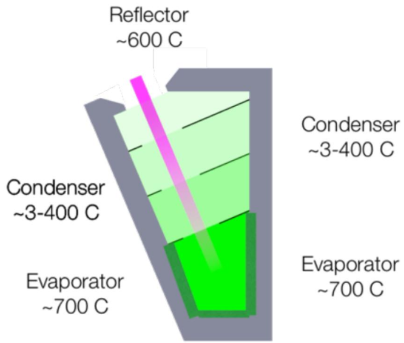
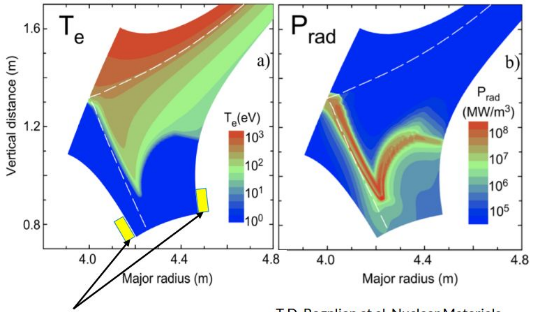
Opportunity to test a lithium divertor in DIII-D: lithium vapor box concept





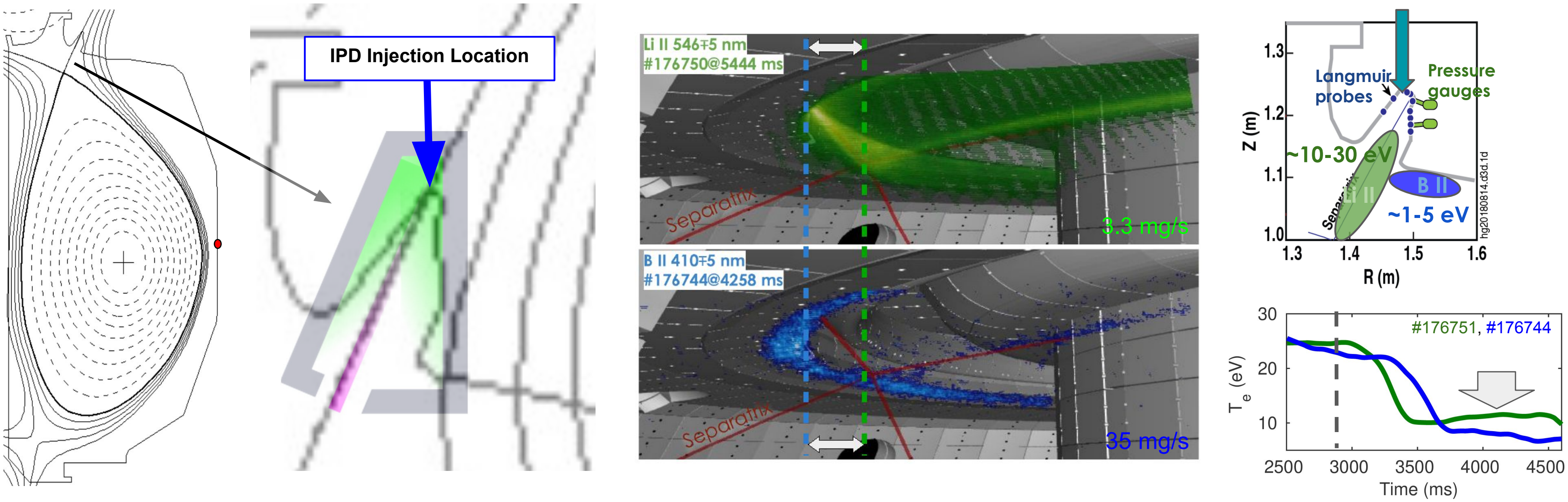
T.D. Rognlien et al. Nuclear Materials and Energy 18 (2019) 233–238

- **Strong local radiative cooling from lithium vapor can reduce peak divertor heat flux and protect solid PFCs**
- **Stable, near-target detachment mitigates X-point MARFEs**
- **Good core performance is preserved by effective Li screening through closed divertor geometry**

Directly testable at DIII-D using the small-angle-slot divertor with near-target Li injection for power exhaust and core-edge integration studies

R.J. Goldston et al 2017 Nucl. Mat. and Energy 12 1118-1121
E.D. Emdee et al 2019 Nucl. Fusion 59 086043
E.D. Emdee et al 2024 Nucl. Fusion 64 086047

Lithium powder in the small-angle-slot divertor as a proxy for a lithium vapor box



Li powder injection into the small-angle-slot divertor produced strong divertor cooling at relatively low mass flow rates (3–5 mg/s) while maintaining good H-mode confinement; B achieved similar effect at higher mass flow rates

F. Effenberg et al 2022 Nucl. Fusion 62 106015

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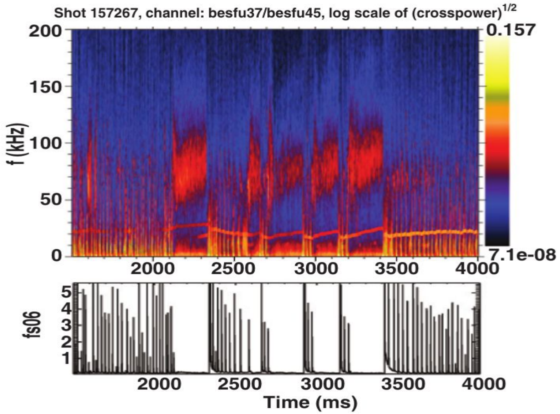
Lithium conditioning facilitates access to ELM-suppressed scenarios

Lithiated walls pump deuterium and reduce recycling, lowering edge density and collisionality

- The pedestal remains further from the peeling–ballooning ELM stability boundary
- Li dilution and modified edge current profiles weaken peeling–ballooning drive, so small continuous edge fluctuations can relax the gradient without large ELMs

In DIII-D, real-time lithium conditioning is used to map ELM suppression across a wide range of scenarios by scanning injected power, q_{95}, and I-coil current while measuring pedestal modes



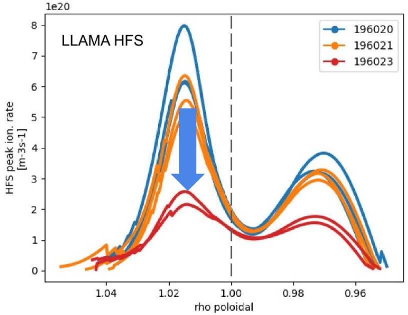
ELM-free periods of enhanced pedestal caused by Li injection in potential DIII-D reference shot
T.H. Osborne et al 2015 Nucl. Fusion 55 063018

Bursty Chirp modes correlated to increase in Te and reduction in wall fueling during ELM-suppression with Li

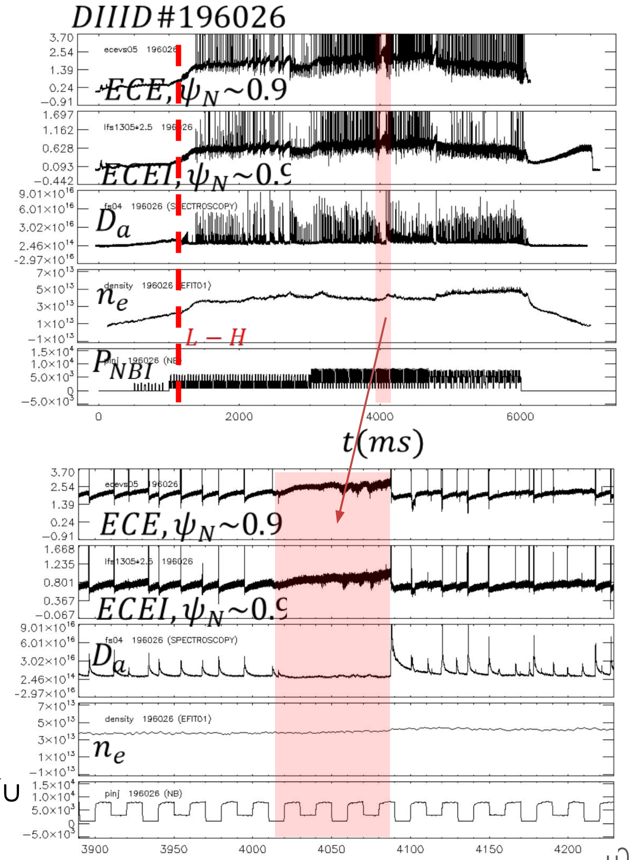
Transient ELM suppression with Li powder injection in H-mode is accompanied by Bursty Chirp Modes

- These modes correlate with increased Te and reduced Da emission
  - Low frequency mode: n<5
  - BCM: n~10-15

Wall-fueling reduced based on LLAMA & gas analysis

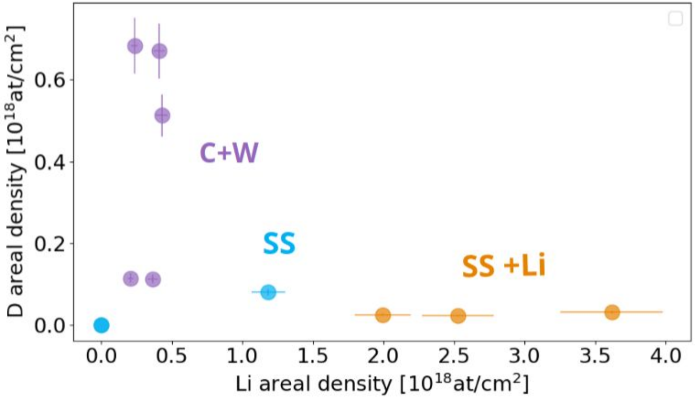


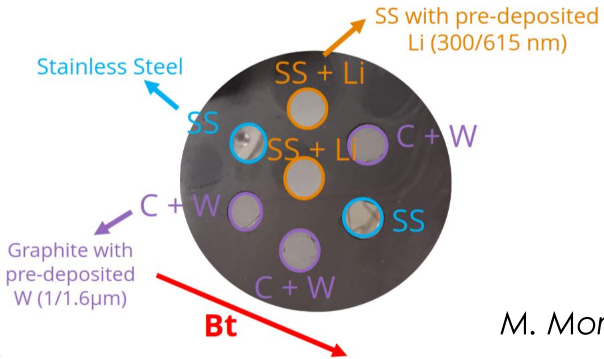
L. Horvath



G. Yu

Fuel retention in Li–D co-deposits vs. pre-deposited Li films confirms role of co-deposition during Li powder injection





DiMES sample exposures enable detailed Li PMI studies of erosion, deposition, and fuel retention

- With the DiMES head at room temperature, D retention is dominated by Li–D co-deposits
- D retention shows no clear dependence on the initial pre-deposited Li thickness
- Carbon increases overall fuel retention in the Li–D layers

M. Morbey et al 2025 Nucl. Mat. and Energy 43 101915

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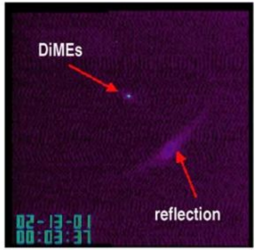
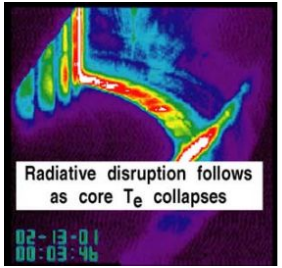
Previous Li material exposure to DIII-D strike point led to a radiative disruption caused by material ejection

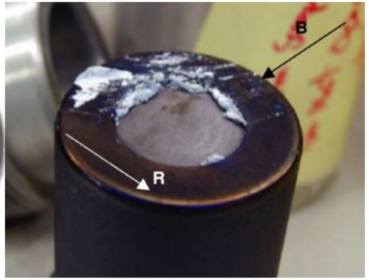
Before exposure

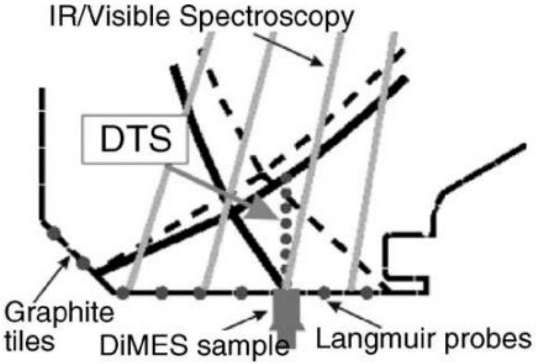
Li ejection leads to radiative disruption





After plasma exposure





Experiments demonstrated need for PFC concepts that stabilize lithium under high heat flux and control its migration

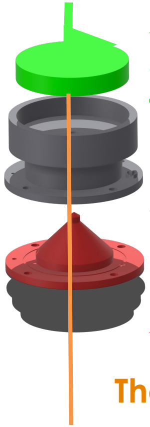
D.G. Whyte et al 2004 Fusion engineering and design 72.1-3 133-147

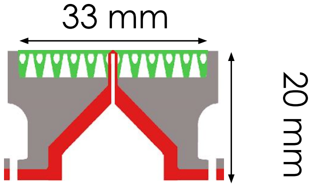
New approach: lithium in additively manufactured tungsten capillary porous structure (CPS)

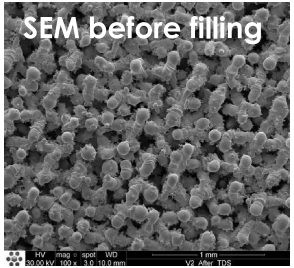
Addressed stability under high heat flux and control of Li migration in stationary, high-power ELM-ing H-mode

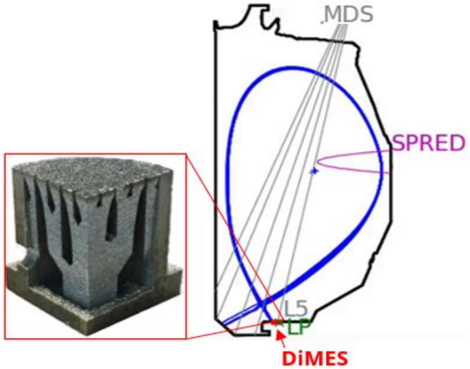
- Uniform spatial evaporation for heated CPS (350 ℃) observed via fast-camera
- $\Gamma_{evap} = 2 * 10^{20} cm^{-2} s^{-1}$
- No Li detected in core
- Rapid toroidal dispersion of evaporated Li
- Minimal displacement of Li outside of DiMES

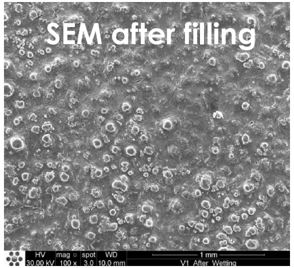
M. Morbey APS-DPP 2025





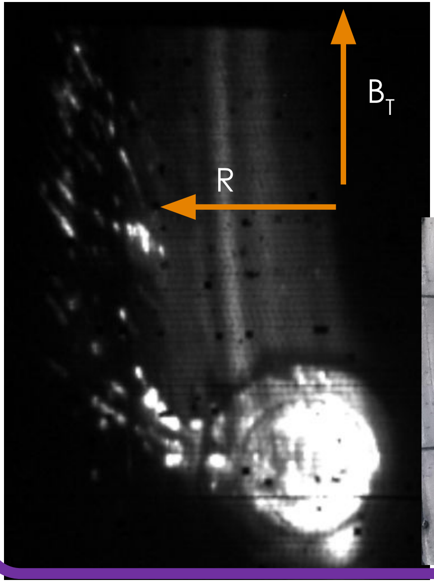




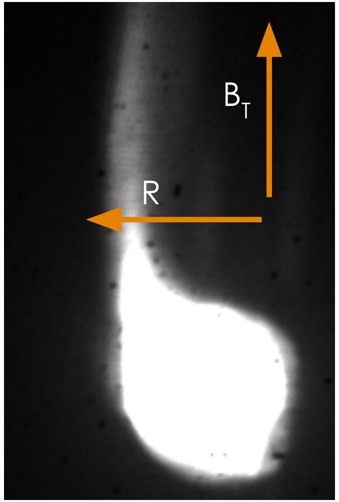


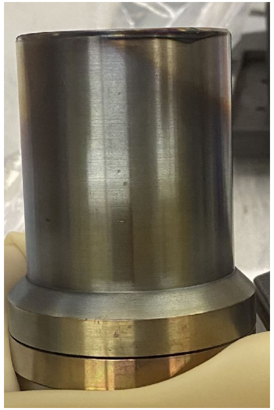
Stable operation without ejection has been demonstrated for CPS with lithium in liquid state during H-mode

Non-heated CPS



Heated CPS





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DIII-D NATIONAL FUSION FACILITY

DIFFER

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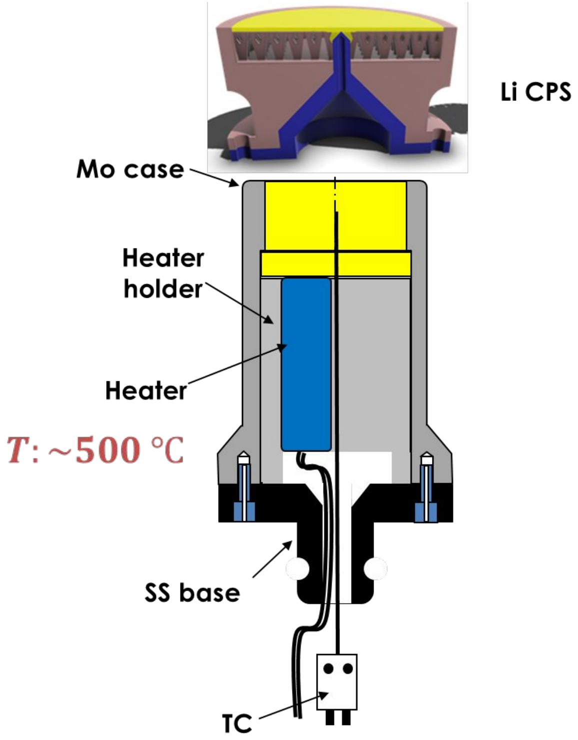
Multi-species material injectors and material sample manipulators at DIII-D enable systematic studies of lithium PFC performance and core-edge integrability

- Lithium wall behavior for power exhaust, edge stability, and surface conditioning has been demonstrated in DIII-D with both powder injection and wall conditioning
- Liquid lithium concepts have been tested via DiMES heads with CPS-based samples

Next: lithium divertorlets, temperature dependent fuel retention, and effect of D gas puff on Li divertor leakage, lithium conditioning in negative triangularity …

Appendix

Lithium CPS DiMES holder with heating capability

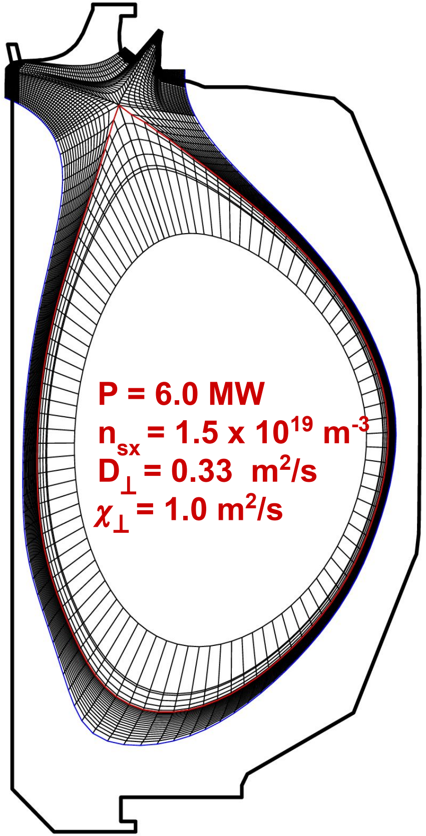


3D plasma fluid and kinetic edge transport (EMC3-EIRENE) was coupled to dust transport (Dust Injection Simulator)

- **EMC3**: **3D edge transport Monte Carlo code**
  - Braginski plasma-fluid model for D, T, H
  - Trace impurity fluid model
- **EIRENE**: **kinetic neutral transport code**

- **Dust Injection Simulator** (DIS):

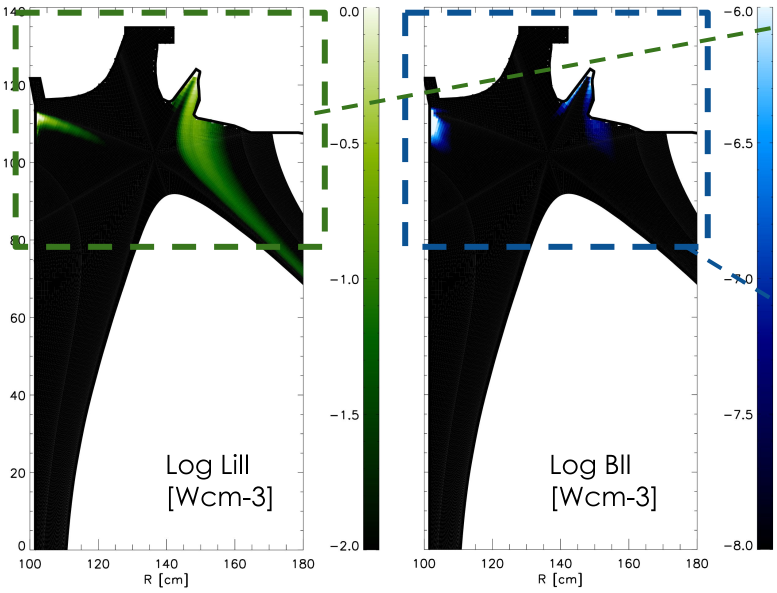
$$R_f = \sum F_{drag,nZ} + F_{drag,n0} + F_E + F_{grav} + F_{centr.}$$



Y. Feng et al, Contrib. Plasma Phys. 54 (4-6) 2014
F. Nespoli et al, PoP 28, 073704 2021
F. Effenberg et al, NME 26, 100900 2021

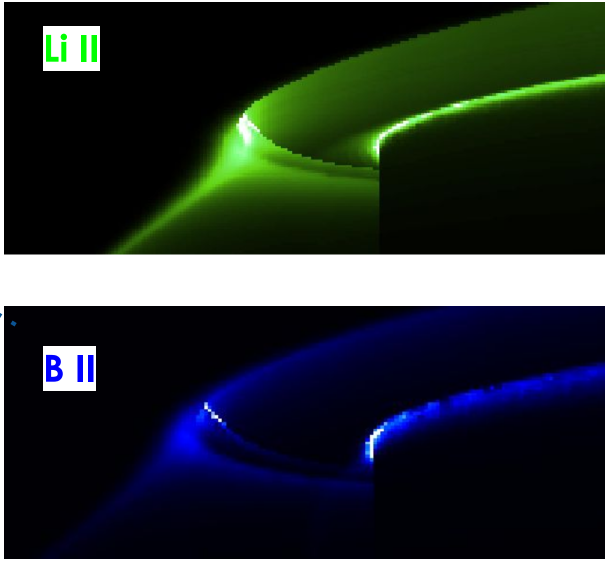
First modeling: Li II emission enhanced in in main SOL and at the separatrix, B II strongest near targets

2D line emission distribution (losses)



F. Effenberg et al IAEA FEC 2020

Synthetic camera diagnostic



EMC3-EIRENE

- B an Li: sourced as atomic trace impurities
- Simplifying assumptions: comparable loss fraction f_{rad}=40%, carbon neglected
- Line emission: based on ADAS atomic data