U.S. Domestic Liquid Metal Plasma Facing Components Development Program

Final Technical Report
DE-SC0020642
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LMPFC

Liquid Metal PFC Program Report for the University of Illinois Urbana-Champaign

Daniel Andruczyk

Research Associate Professor

Suite 100 Talbot Laboratory

104 South Wright St

Urbana IL,

61801 USA

Email: andruczy@illinois.edu

CPMI
Center for Plasma-Material Interactions
cpmi.illinois.edu

ILLINOIS
Nuclear, Plasma & Radiological Engineering
GRAINGER COLLEGE OF ENGINEERING

Outline

- Goals
- Distribution and Wetting
  - MEME
  - Lithium Distribution
    - Loop setup
    - Initial tests
    - Capped Distributor
  - Stream Formation
  - Velocity measurements
- Vapor Shielding
  - DIFFER experiments
  - ZAPDOS-CRANE Model
- Helium retention and low recycling operation
- Summary and Conclusions

Goals

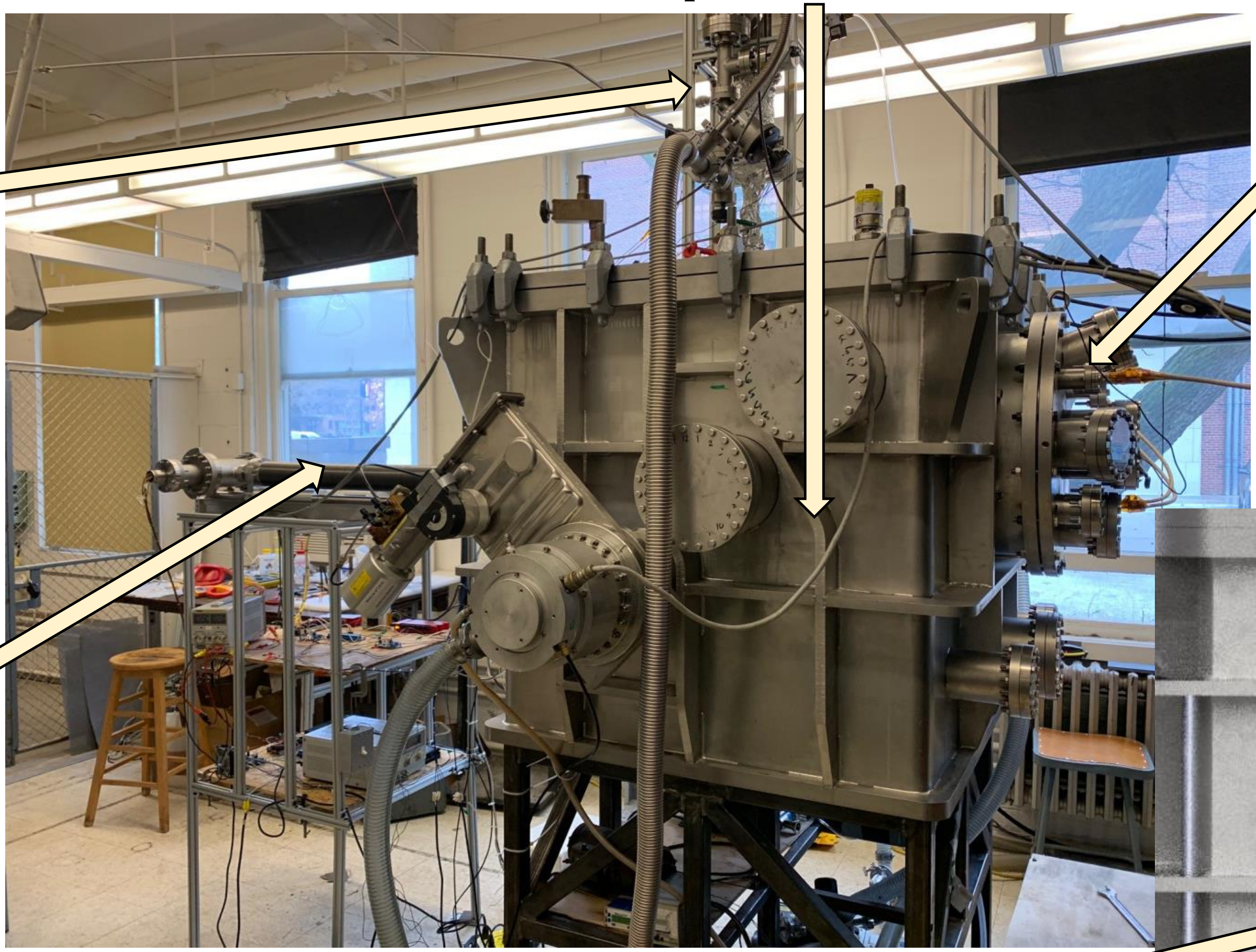
- Single effect experiments being undertaken by UIUC
- Liquid lithium loop and wetting of surfaces
  - Development of loading systems
  - EM pumps for loop
  - Flow velocity
  - Wetting of surfaces
  - Distribution design
- Vapor Shielding in the presence of impurities
  - Performed on MAGNUM-PSI
  - Helium
  - Neon
- If there was time
  - Compatibility testing of different materials
  - Helium and hydrogen retention and pumping by lithium

Mock-up Entry Module in EAST (MEME): Flowing liquid lithium wetting experiments

1 m^3 cubed volume: Base pressure $\sim 10^{-8}$ *torr*

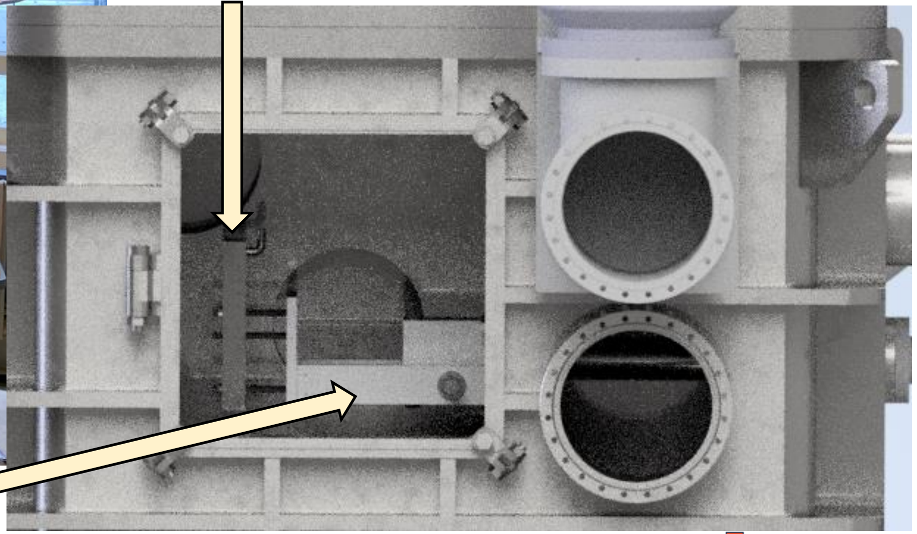
Lithium loader: equipped with load lock to allow for reloading under vacuum. Reservoir volume 1650 cm^3

50 *cm* circular flange: 9 flanges for front-on plate diagnostics (CCD, IR cameras)



PFC: modularly designed components allow for easy swap out. Attached to TA for easy maintenance/installation

1 *m* stroke transfer arm



TA attachment: allows for rotation of PFC.

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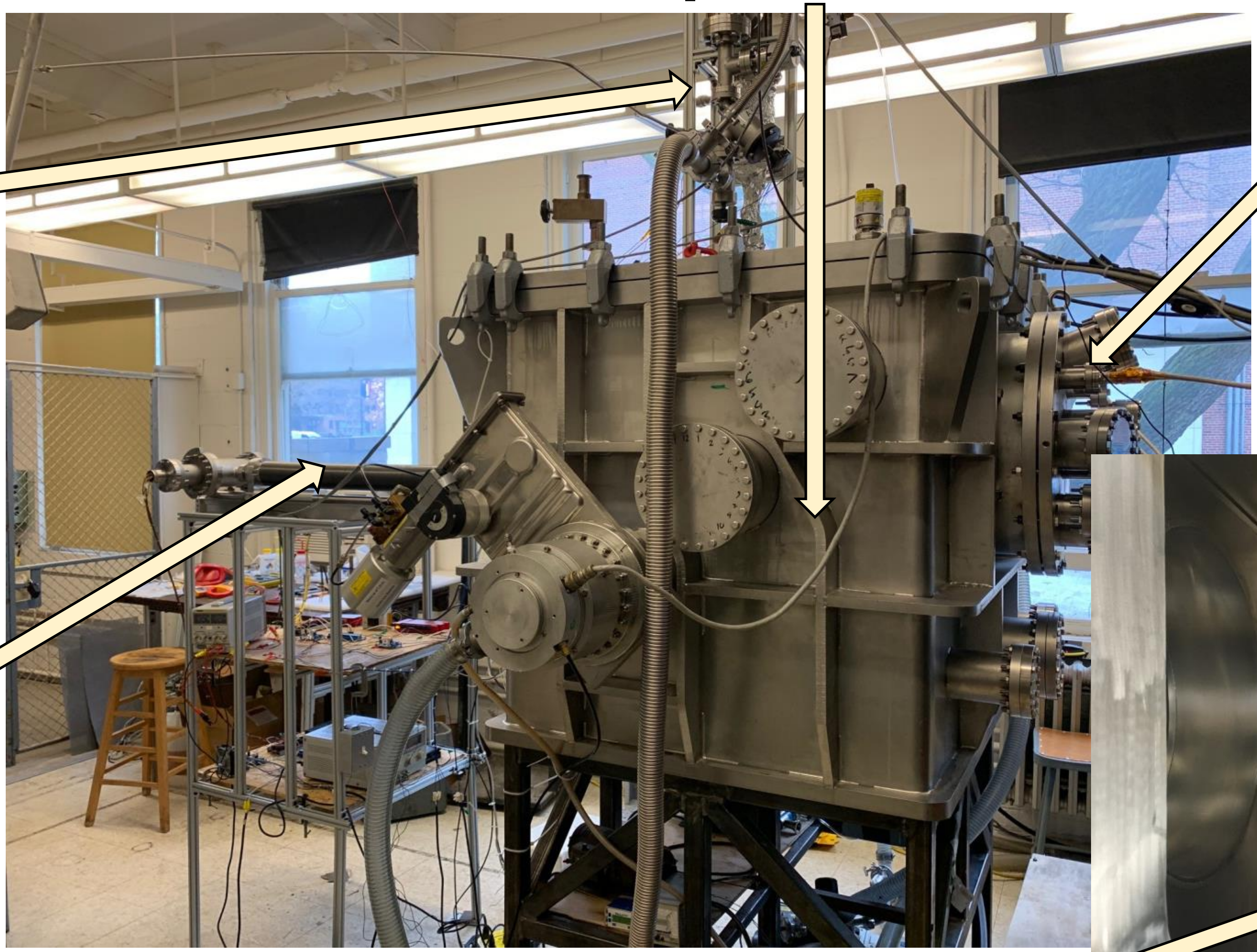

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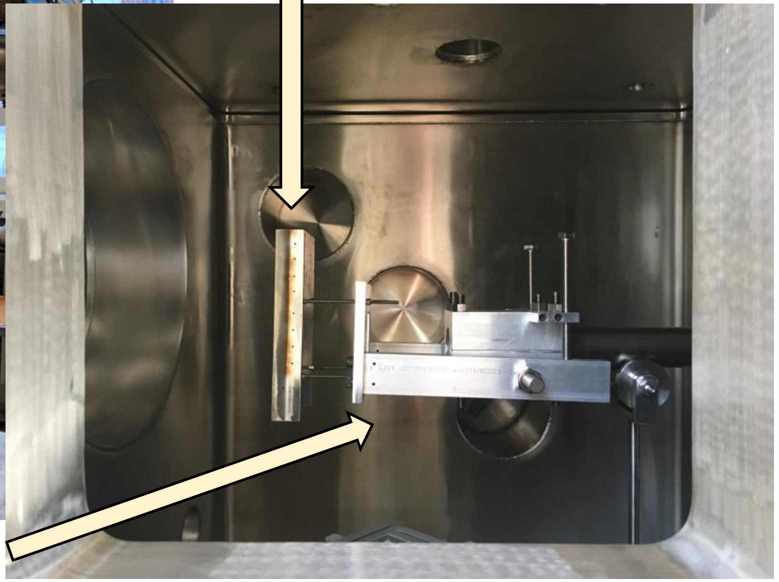

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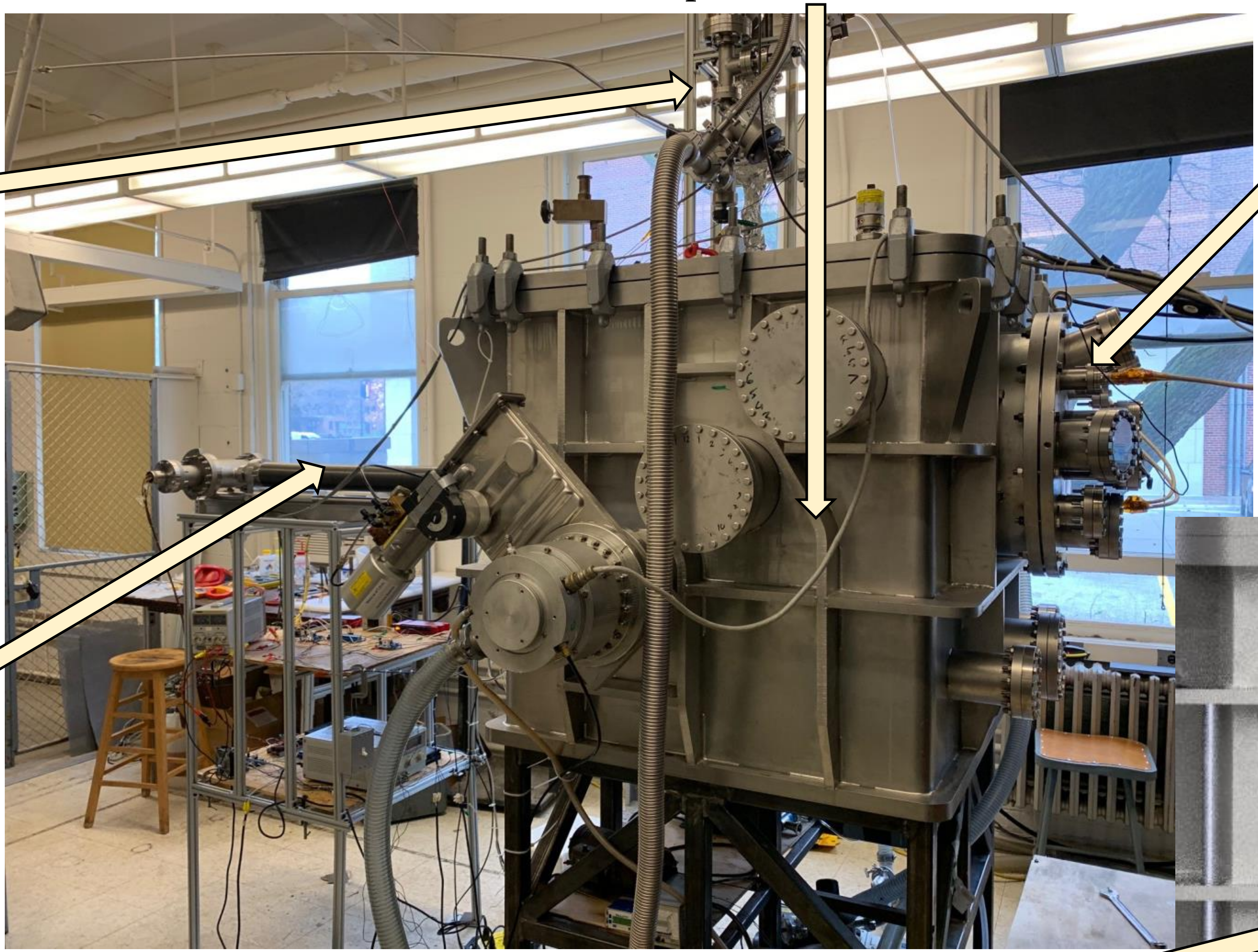

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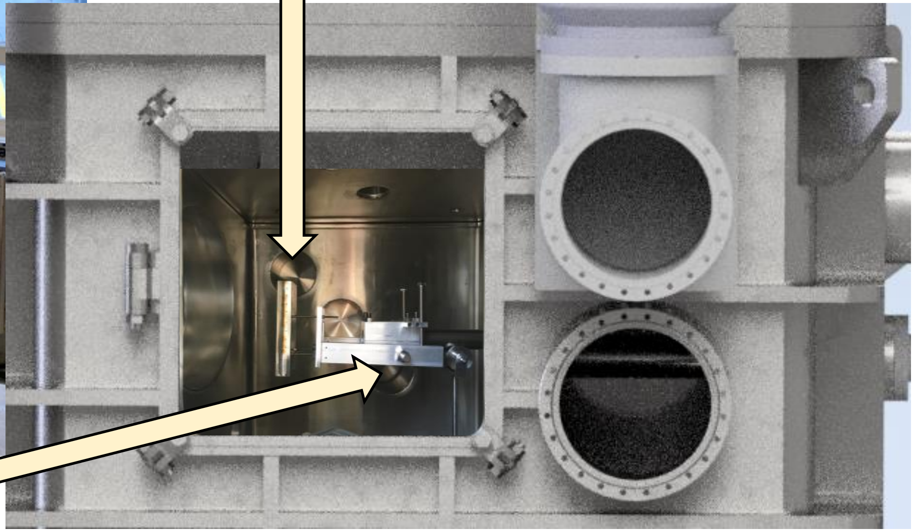
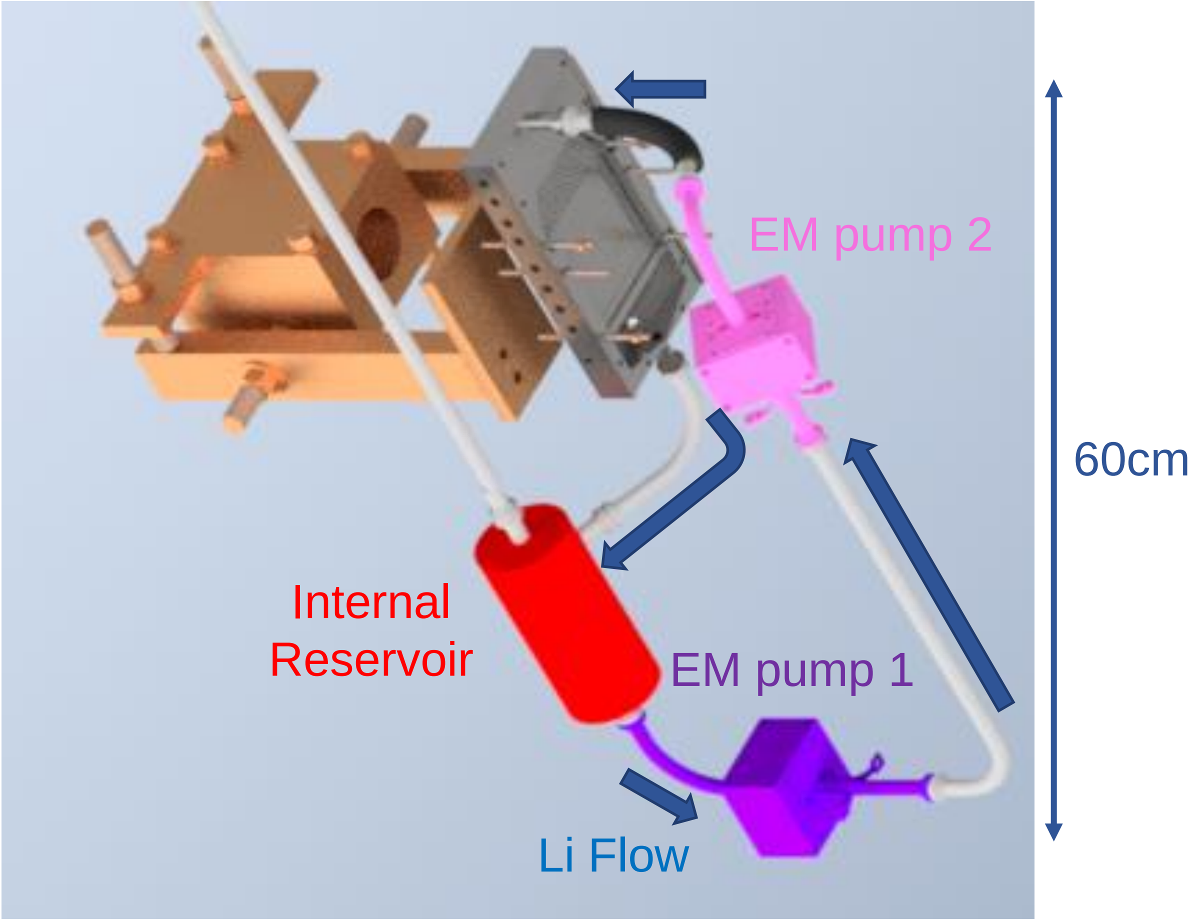


TA attachment: allows for rotation of PFC.

Lithium Distribution: Loop Setup

- Properties:
  - Base pressure: $\sim 9x10^{-8}$ Torr
  - Chamber Pressure molten lithium: $\sim 9x10^{-7}$ Torr
- Added second EM pump
  - Pumping requirements higher than expected
  - Lack of wetting in pipes
    - Max achievable temperature $270^{o}C$
  - Possible impurities within lithium
  - Current required to drive flow:
    - Pump1 : 129 Amps
    - Pump2 : 100 Amps
- Plate angled at 13^{o}
  - Maximum allowed by current design
- 300g lithium loaded into an argon environment
  - Purity maintained by load lock
- Diagnostics:
  - 7 TCs on loop
  - 6 TCs on plate



Lithium Distribution: Initial Tests

- Initial test produced a lithium droplet above the distributor
  - No wetting to distributor
  - Assumed lithium was wicking on bottom surface of cap
    - 5mm gap between surface and base of plate
- Second test ran with a cooler plate temperature ($220^0 C$)
  - Below lithium wetting to subdue wetting
- Second test produced similar behavior
  - Lithium already wetted to bottom surface?
  - Flow driven due to gravity to large?
- Capped distributor to attempt to force lithium to wet to posts

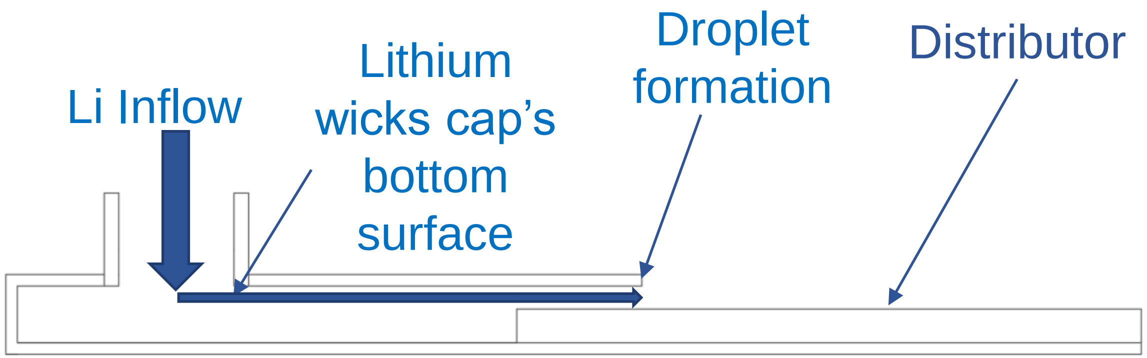


Plate at $320^o C$

Plate at $220^o C$

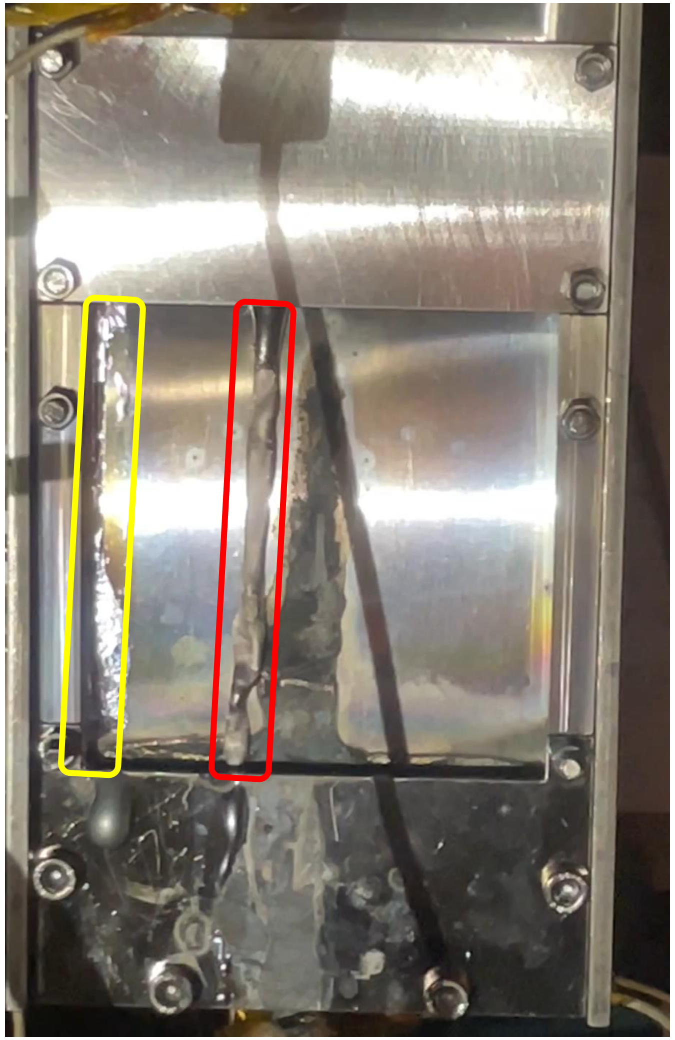
Lithium Distribution: Capped Distributor

- Capped Distributor produced flow upon plate
  - Sustained flow down middle of plate for $\sim 30 mins$
  - TCs on loop highlighted lithium recirculation

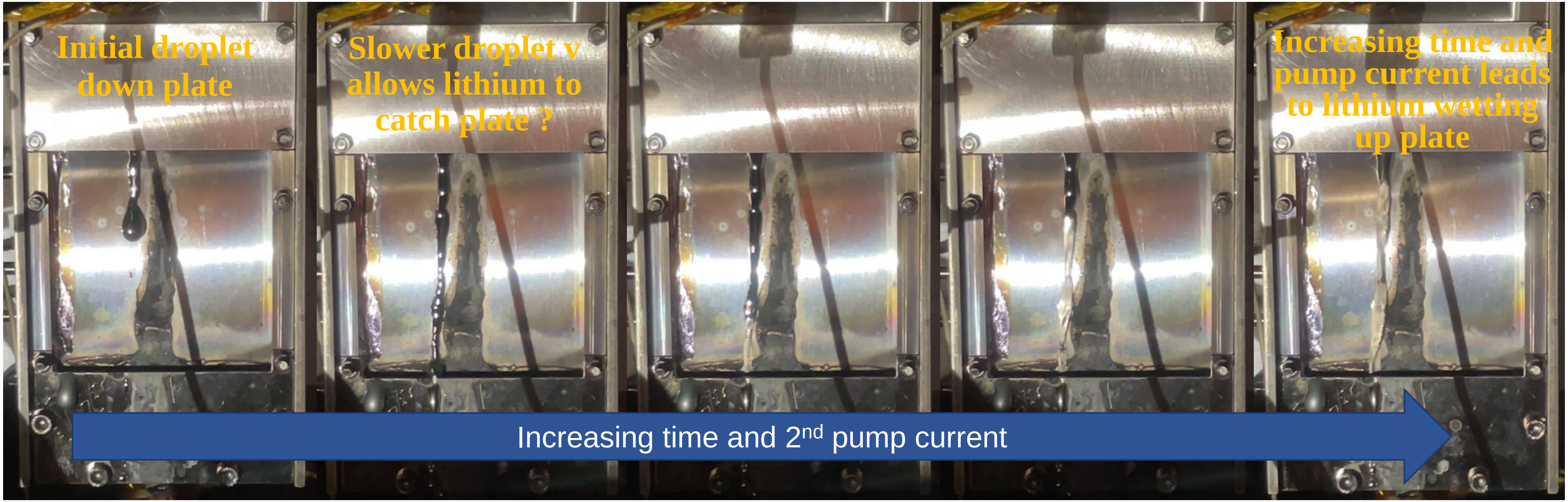
- Initial flow on the right edge of the plate
  - Initial blockage in distributor from previous runs
  - Wetted the right-hand wall

- However, still appears distributor isn't wetting
  - Lithium running along distributor top and dropping onto plate
    - Gap of 2mm between post and cap
  - No post-mortem of distributor yet

- Plan to machine wedge piece to fill gap between cap and posts
  - Suppress lithium flow and lead to build-up in distributor



Frame by Frame of Stream Formation

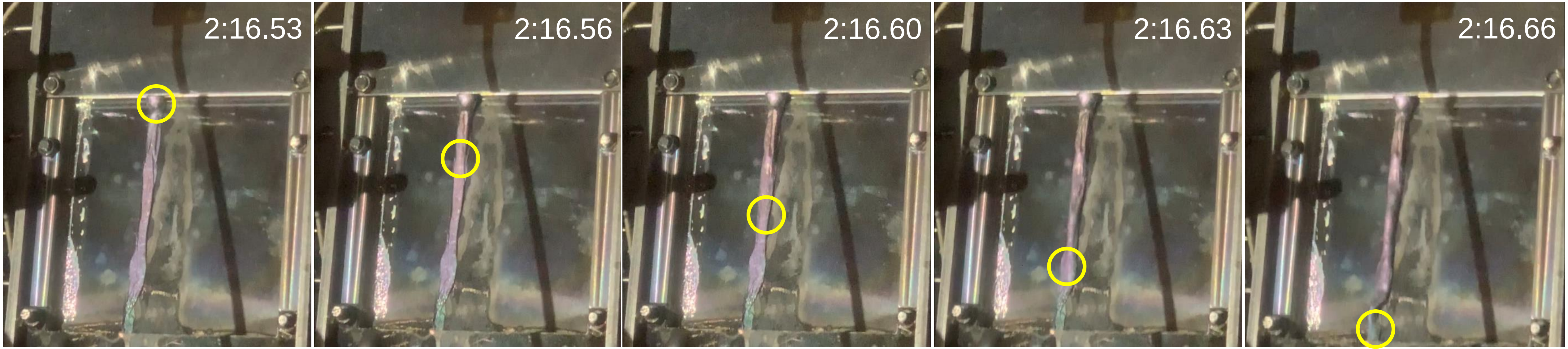


Results of the Flowing Liquid Lithium Loop in MEME

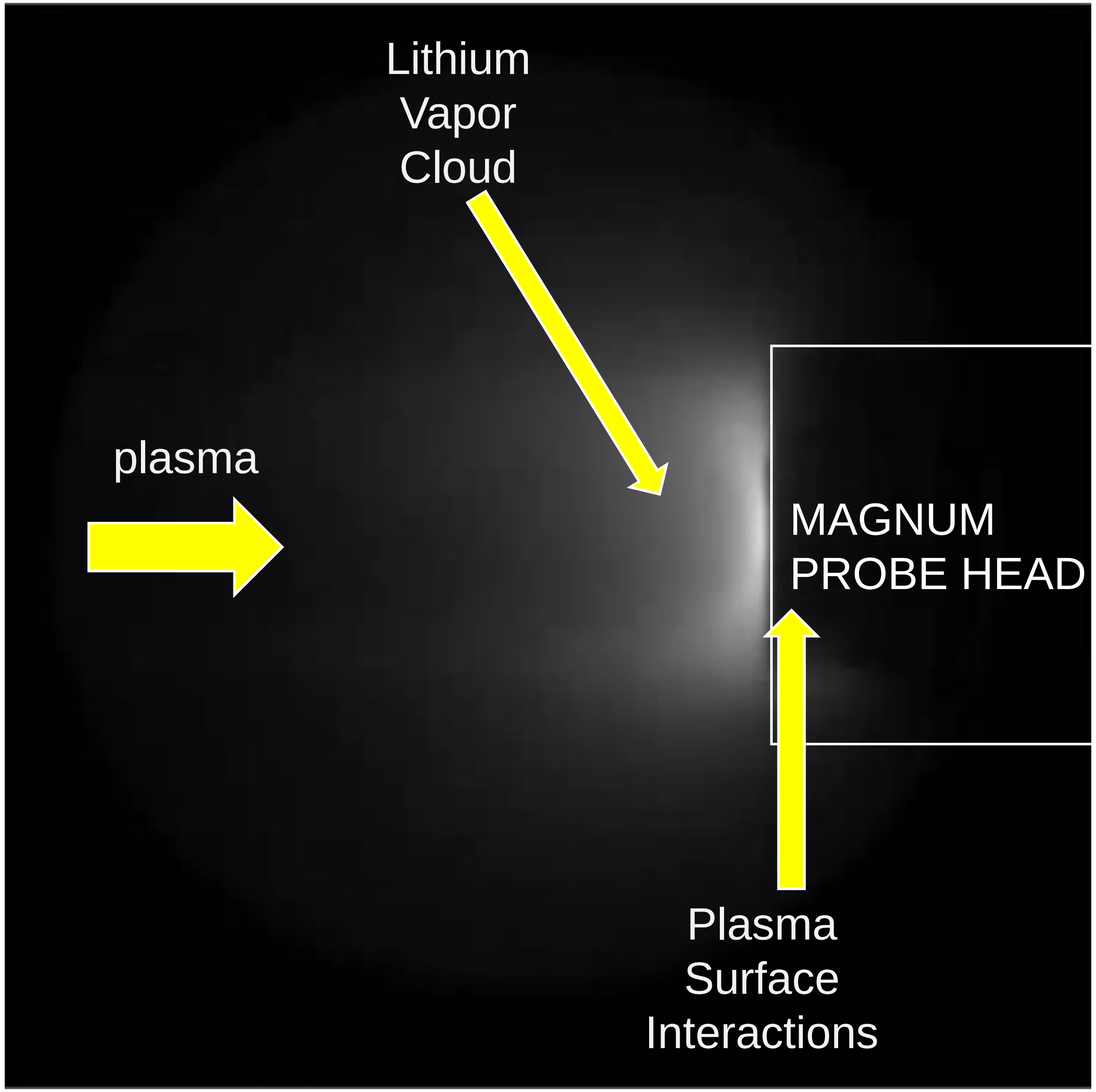
- Plate at 13.5^{o} from the normal
- 15 cm length
- With 100 A into the EM pump get a velocity of

$$v = 1 \text{ m/s}$$

- Need to fix a design feature in the plate distributor.
  - A gap between the posts and plate allows the Li to flow down the plate rather than wick into the posts.
  - See an initial flow of Li down the edge of plate and good wetting
  - Thing flow.
  - See the big bulk, laminar flow, more indicative of what is seen probably in the loop itself.
- Still analysis of results being done and new distributor to be tested next week to try for full wetting.

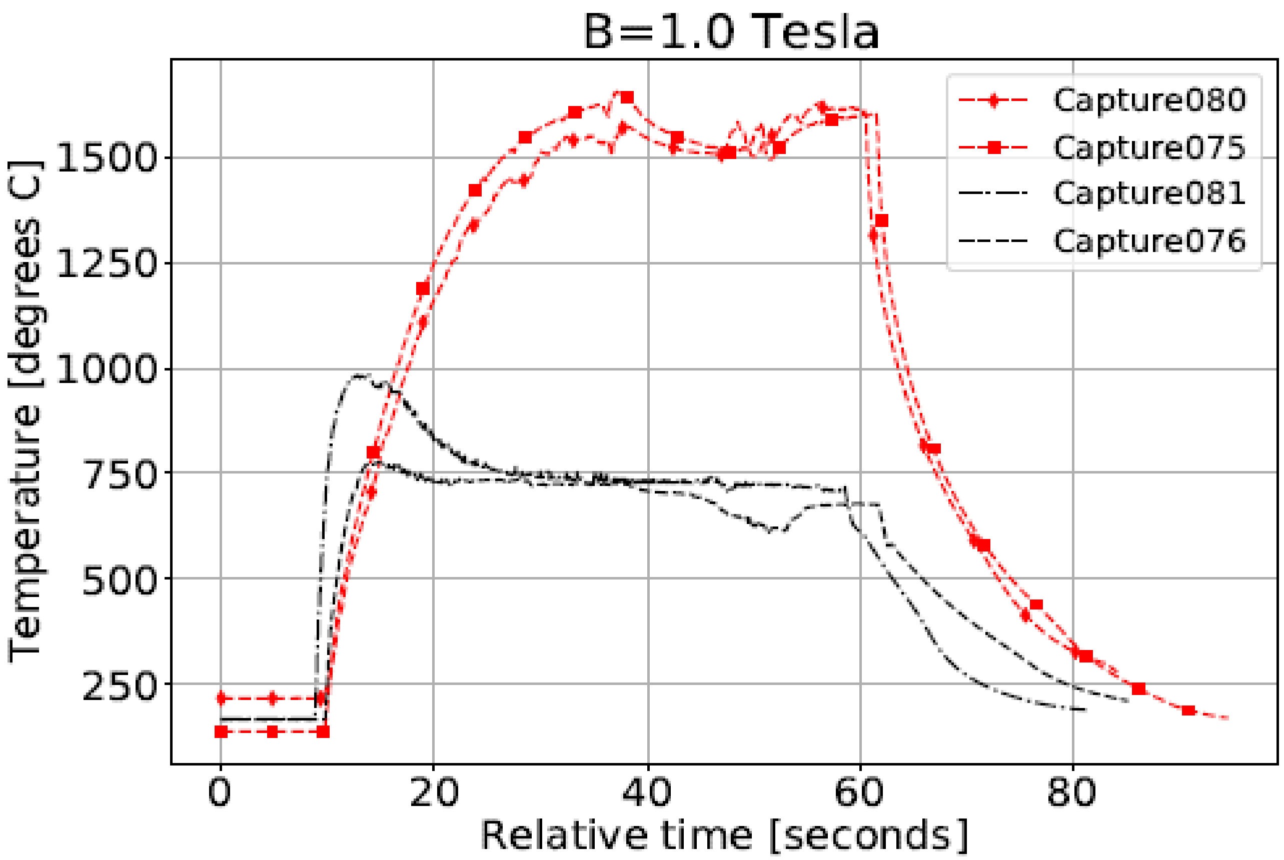


Power Dissipation in Li Vapor Shielding Experiments



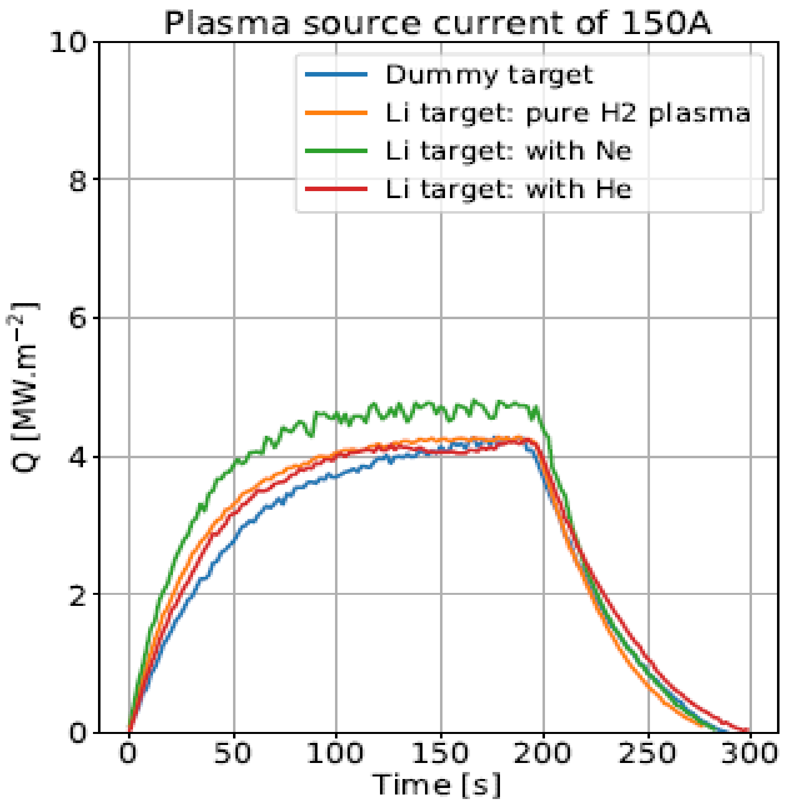
Background

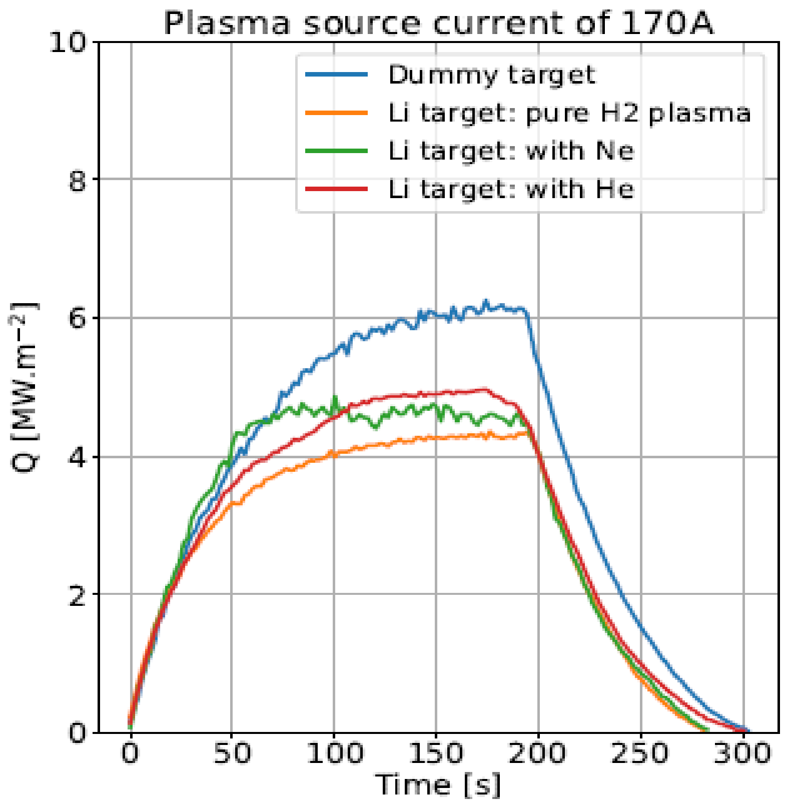
- Li vapor shielding experiments performed on MAGNUM PSI have shown that when in vapor shielding regime:
  - A locking temperature is attained
  - Around 750 ºC – 800 ºC attained at about 6.0 MWm^{-2}
  - Holds at least up to 20.0 MWm^{-2}
- The picture on the right shows 15 – 20 MWm-2 shots on solid (red) and Li (black) targets
- The incident heat flux is therefore reduced by a certain amount which equilibrates to yield that locking temperature

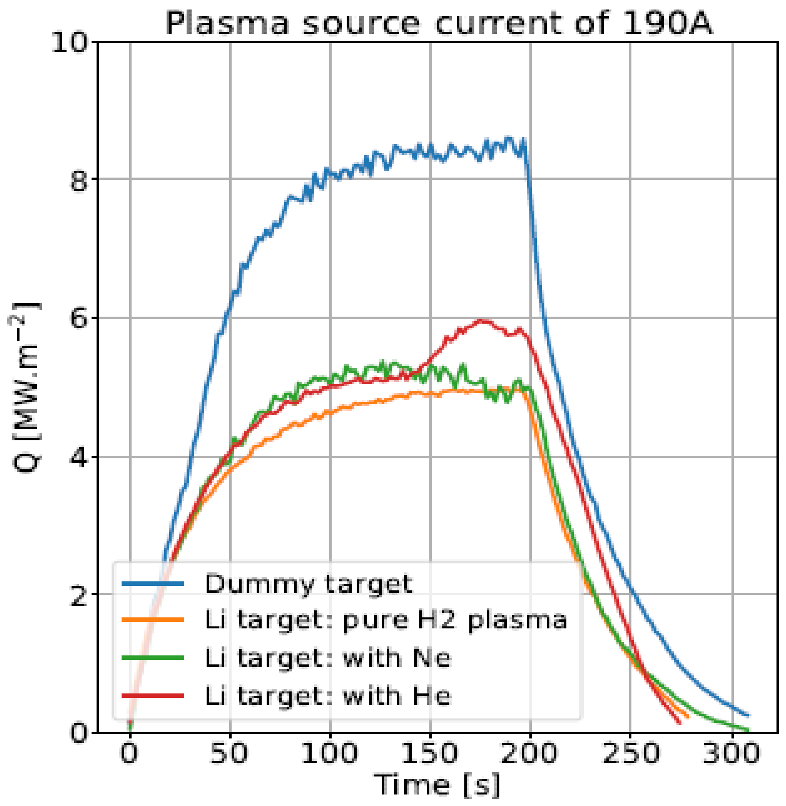


Calorimetry Data from MAGNUM-PSI Shots

- Steady state calorimetry data clearly shows the effect of Li vapor shielding for increasing plasma power
  - At low enough powers, there's no noticeable difference between the solid and Li target profiles
  - Once the heat flux is high enough, the vapor shielding effect starts to be felt

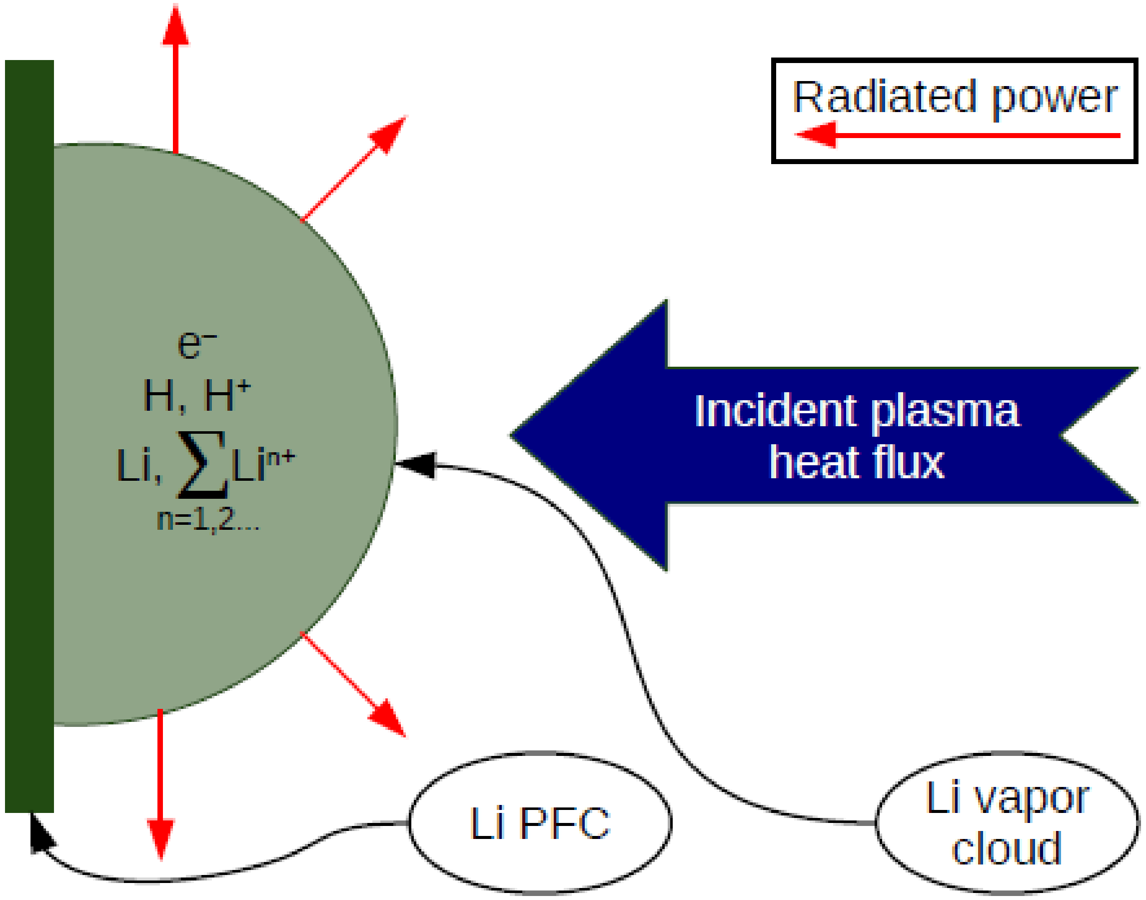






Contributing Factors

- The plasma heat flux to the target is increasingly reduced until it saturates at some equilibrium, translating into the observed surface locking temperature
- A couple of factors contribute to the heat dissipation:
  - The Li evaporative heat flux
  - The Li vapor cloud itself, radiating power away from the target via plasma chemistry



Modeling Q_{Li}^{vap}

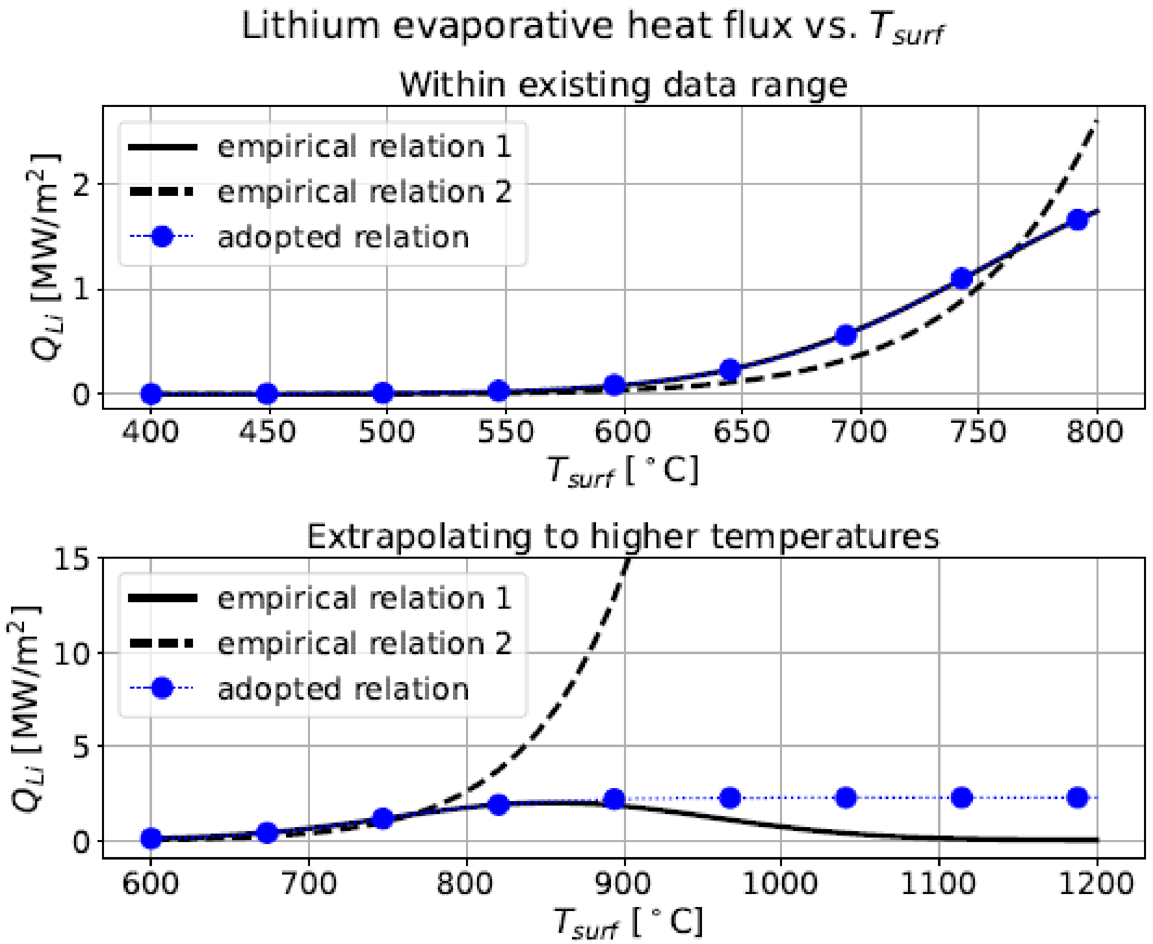
- The evaporative Li particle flux J_{Li} can be modeled from existing data and empirical relations as:

$$J_{Li}(T_{surf}) = e^{-T_{surf}} + A\left[1 - \frac{1}{1 + e^{\left(\frac{T_{surf}-c}{s}\right)}}\right]$$

- T_{surf} is the Li surface temperature and A, c and s are fitting parameters

- The evaporative heat flux is Q_{Li}^{vap} is obtained from J_{Li}, the Li heat of vaporization h_{Li} and Avogadro's number N_A as:

$$Q_{Li}^{vap} = \frac{h_{Li} \times J_{Li}}{N_A}$$

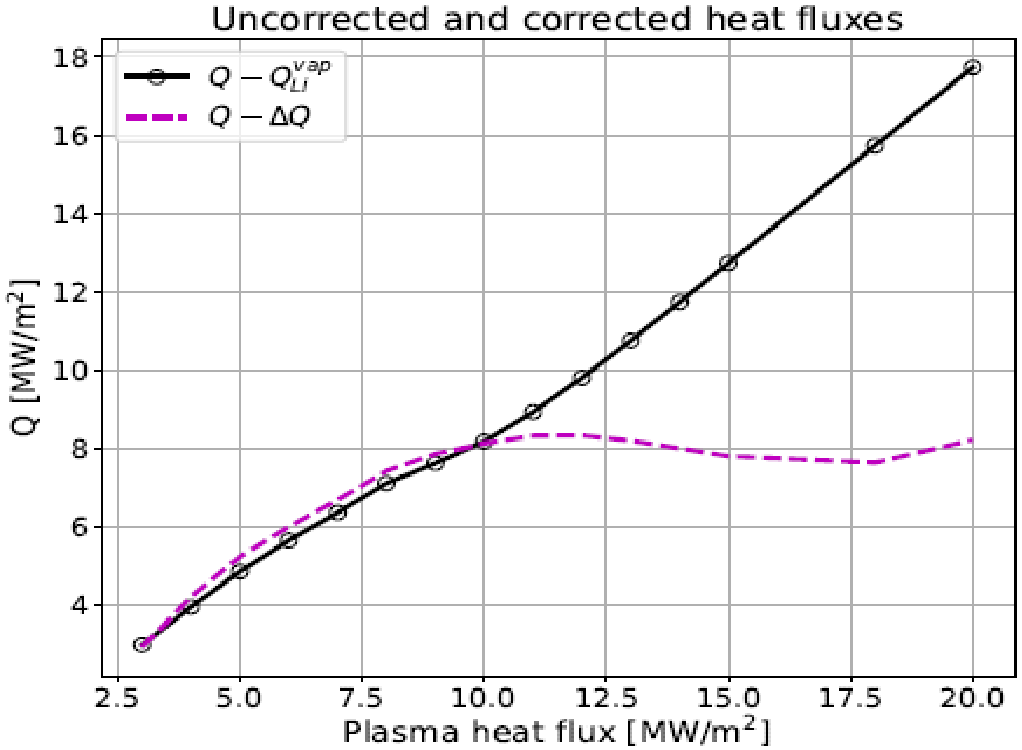


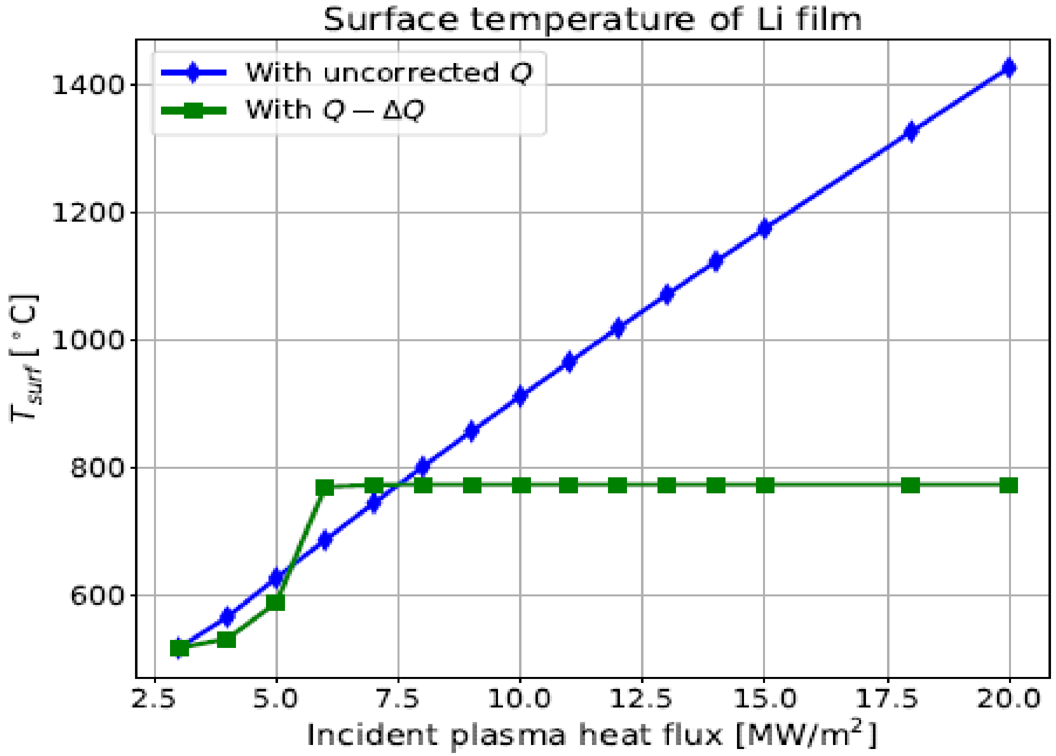
Total Power Dissipation

- The total heat dissipation, accounting for plasma chemistry, can be found by solving a heat diffusion model and correcting the heat flux by ΔQ to achieve the observed locking temperature. This gives

$$\Delta Q(T_{surf}) = A \cdot T_{surf} + B \cdot \left[1 + erf\left(\frac{T_{surf} - \mu}{\sigma_m}\right)\right] + C$$

- With A, B, C, μ and σ_m fitting parameters





Special Case and Considered Reactions

- Taking one of the experimental shots from MAGNUM-PSI with a plasma current of 170 A we have:
  - $Q \approx 6.0$ MWm^{-2} on a solid target
  - $Q \approx 4.0$ MWm^{-2} on a Li target
  - Li locking temperature of $T_{surf} \approx 650$ ^{o}C

- This results in dissipation of 1.5 MWm^{-2} or $\Delta Q = 265\ W$ (from the surface area of the used samples) divided in:
  - $Q_{Li}^{vap} = 45\ W$
  - 220 W from plasma chemistry

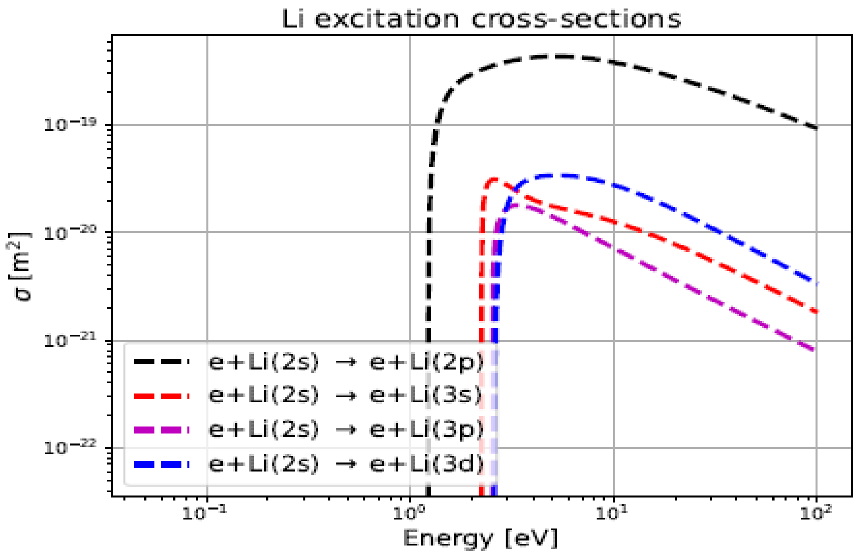
- Excitation and ionization of Li atoms are accounted for as the most plausible dissipation mechanisms inside the vapor cloud
  - These reactions are driven by collisions with electrons

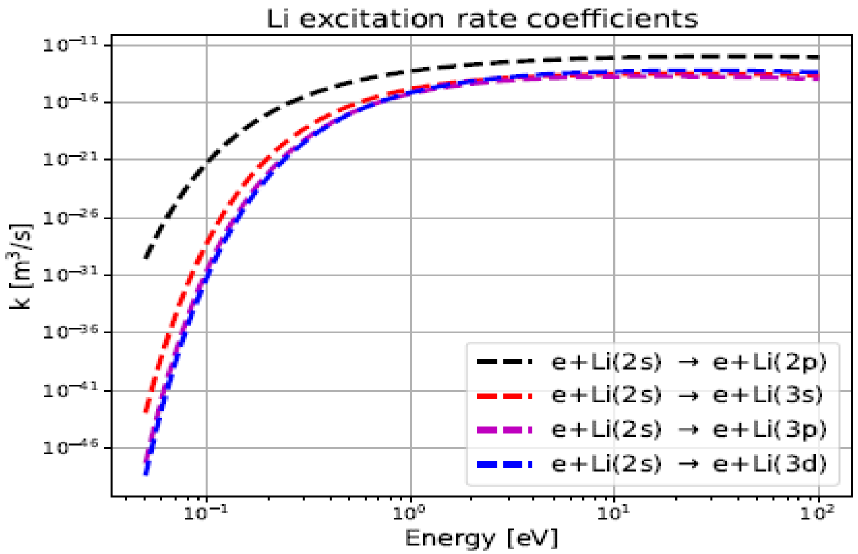
- Rate coefficients are obtained via integrating the cross-section over a Maxwellian

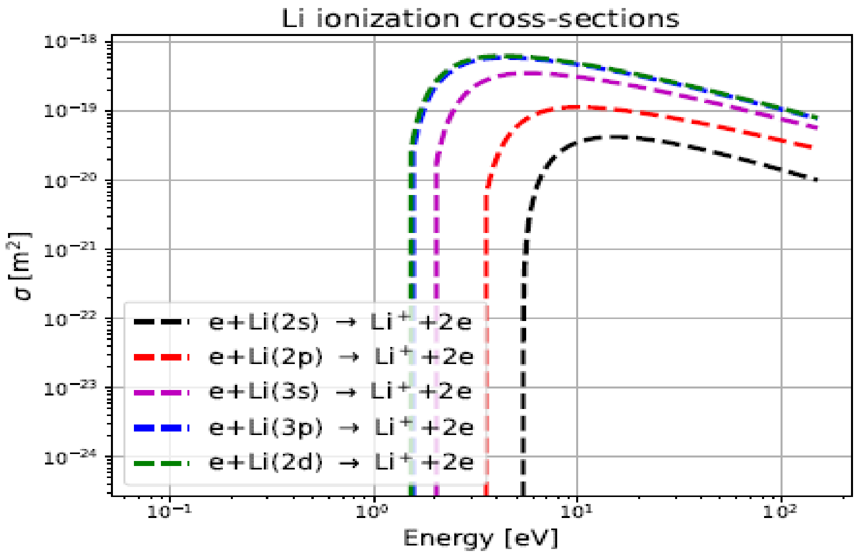
$$k = \int_E \sigma(E) \sqrt{\frac{2E}{\mu_m}} y(E) dE$$

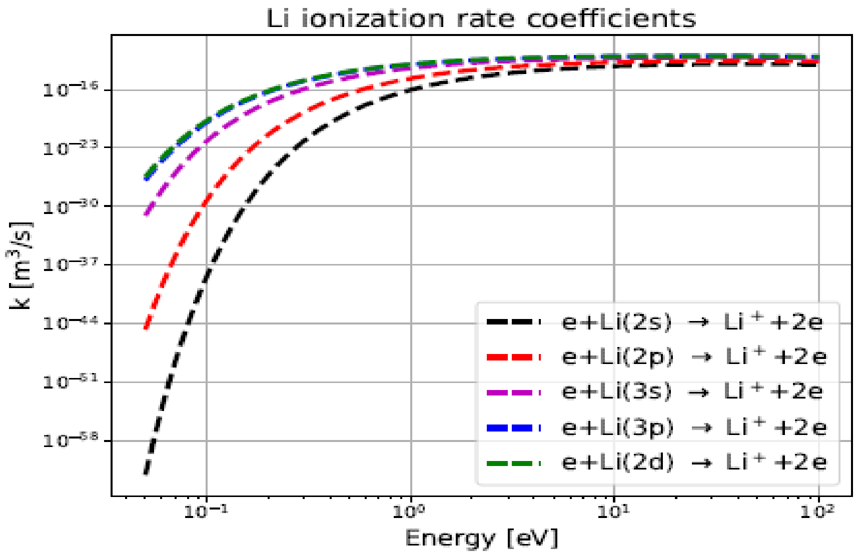
- With σ the cross-section, μ_m the reduced mass and *y(E)* the Maxwellian distribution

Obtained k [m^3s^{-1}]









Dissipation per atom

- The power loss per Li atoms can be found for a certain electron energy via

$$P_{loss} = k[m^3 s^{-1}] \cdot n_e[m^{-3}] \cdot \Delta E[eV]$$

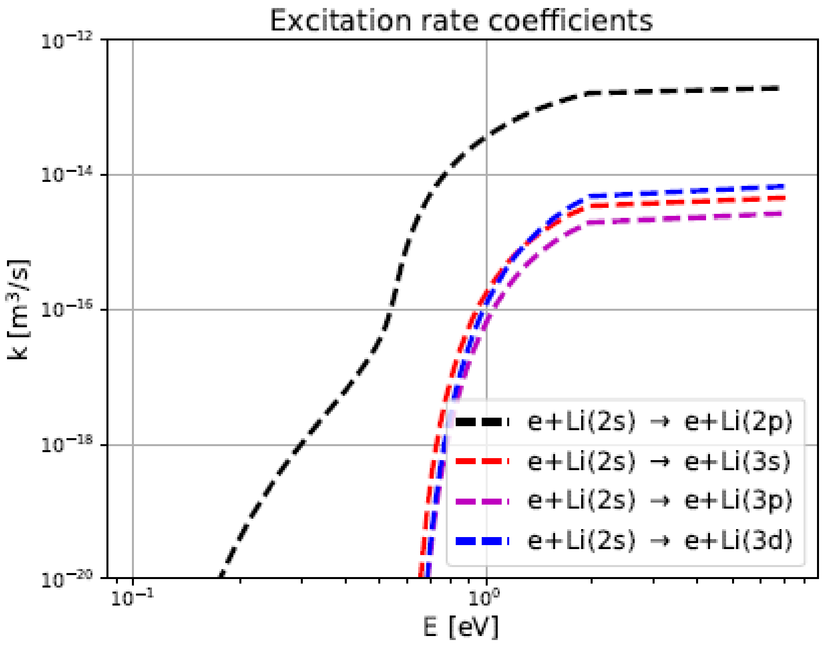
- For the MAGNUM-PSI experiments, the electrons were around 1.2 eV, which leads to the following table

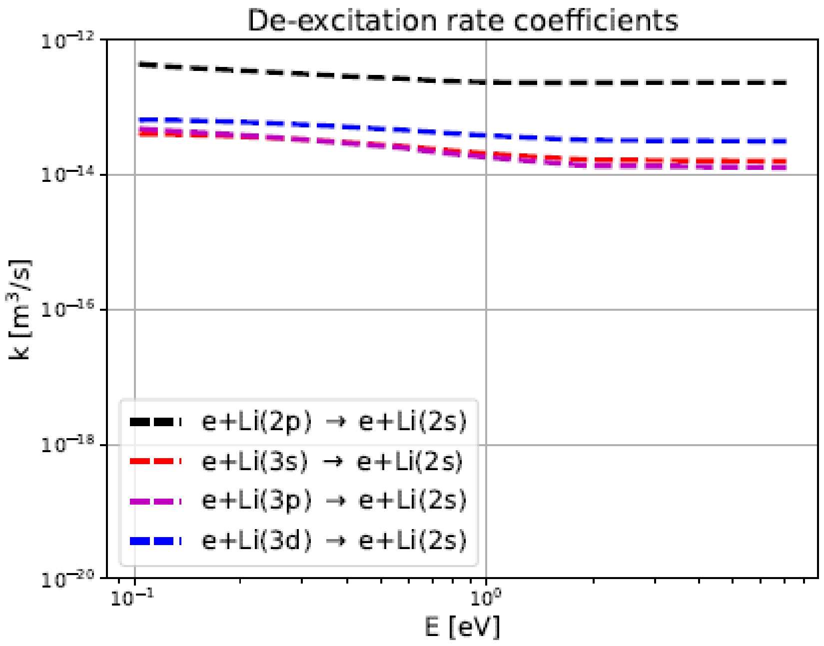
Excitation power loss		Ionization power loss	
Reaction	P_{loss} [MeV/s]	Reaction	P_{loss} [MeV/s]
$e + Li(2s) \rightarrow e + Li(2p)$	73.6914	$e + Li(2s) \rightarrow Li^+ + 2e$	0.7229
$e + Li(2s) \rightarrow e + Li(3s)$	4.4306	$e + Li(2p) \rightarrow Li^+ + 2e$	7.8615
$e + Li(2s) \rightarrow e + Li(3p)$	2.1462	$e + Li(3s) \rightarrow Li^+ + 2e$	56.4405
$e + Li(2s) \rightarrow e + Li(3d)$	2.9590	$e + Li(3p) \rightarrow Li^+ + 2e$	111.1002
		$e + Li(2d) \rightarrow Li^+ + 2e$	118.9097

Main Dissipation Mechanism

- The obtained power loss per Li atom suggests that the power dissipation is mainly achieved by
  - Excitation of ground state Li atoms
  - Ionization of excited Li atoms

- However, the de-excitation reaction rates are much higher than the excitation ones for the experimental plasma parameters





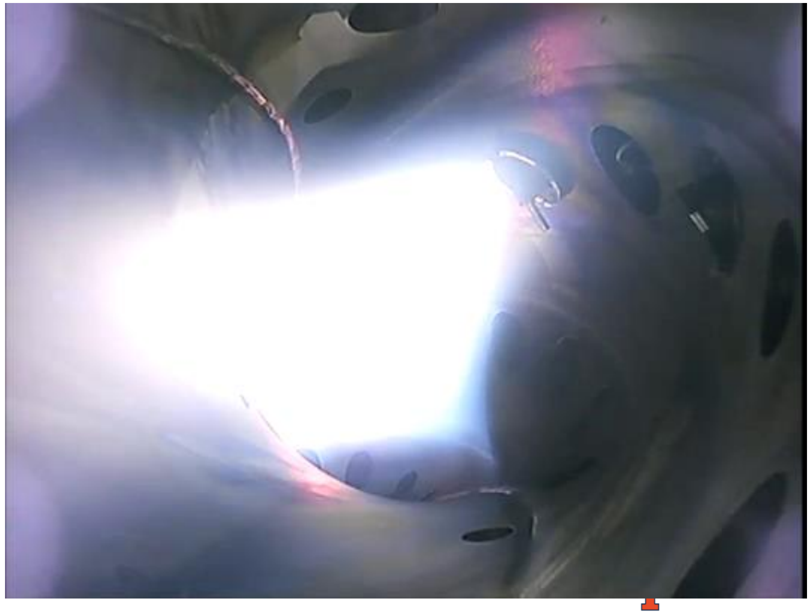
Helium Pumping by Lithium in HIDRA

- HIDRA
  - R_o = 0.72 m
  - r = 0.19 m
  - a = 0.1 m

Distance from the plasma edge ($D = a$ – 0.045m)

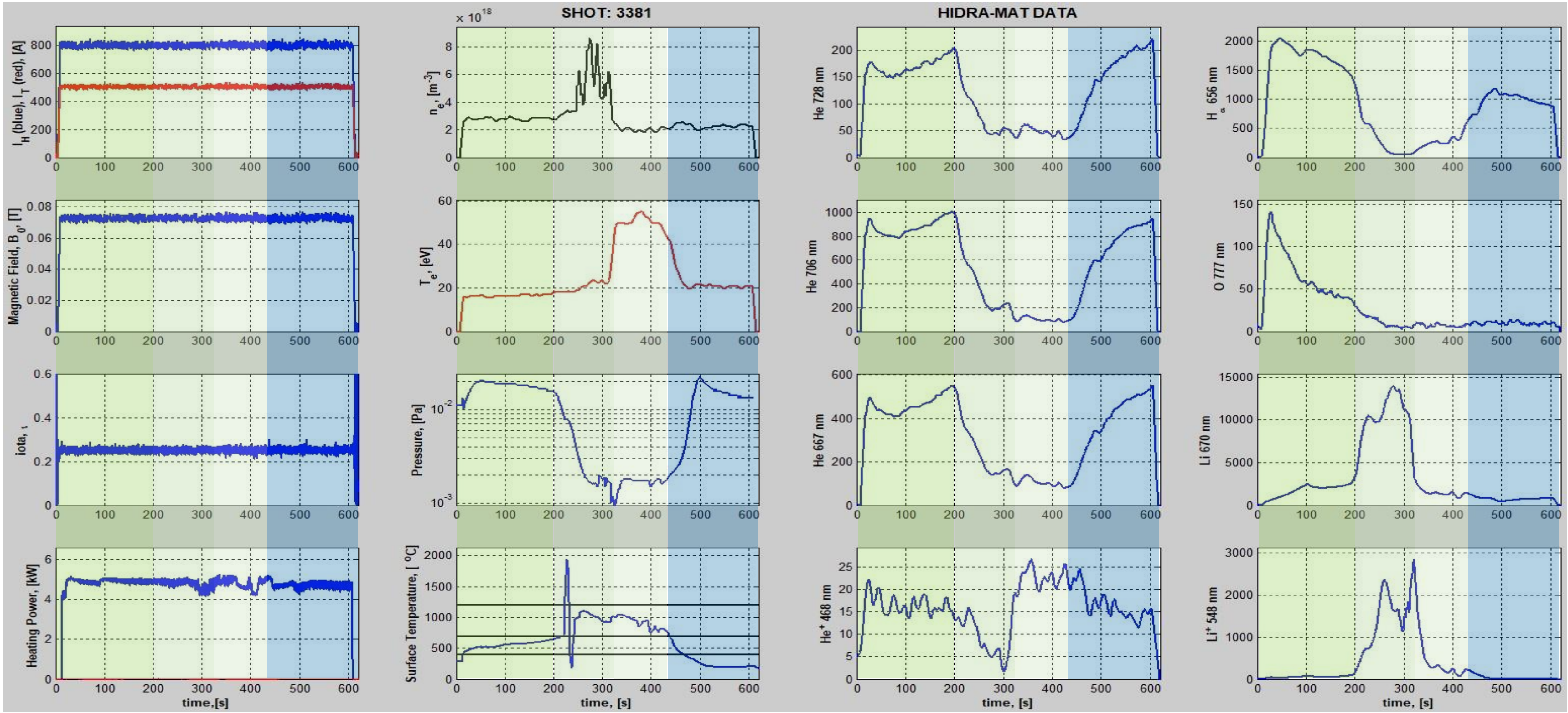
S_{HIDRA} = 5.400 m^2
V_{HIDRA} = 0.513 m^3
V_{plasma} = 0.142 m^3

- HIDRA is a ***"dirty machine"***
  - Due to HIDRA's design, we cannot bake the machine, we do discharge cleaning, however it still in not perfect.
    - Base pressure 5 – 9×10^{-7} torr
    - Main impurities will be air and water vapor (plus some hydrocarbons) on the SS surface of the vessel.
  - This means that the **impurity atoms/elements are hydrogen and oxygen** due to water vapor
    - **H_α – 656 nm**
    - **O – 777 nm**
    - **Other lines too**

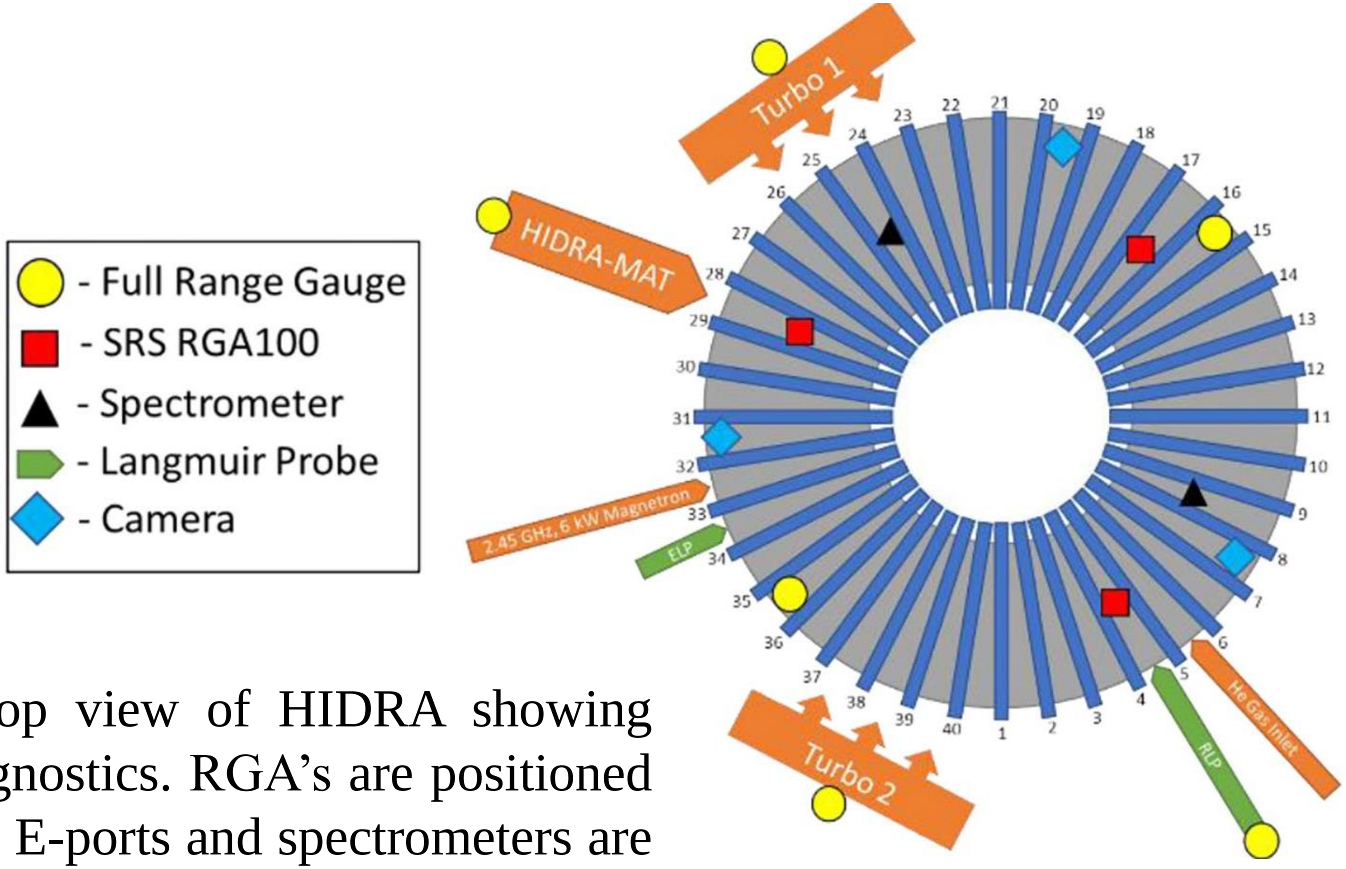


- What will be shown here are helium experiments
  - Helium is flowing at a constant rate throughout the discharge.
    - Range of flow rates 0.50 – 1.00 sccm
    - The MFC has been calibrated to helium (this was done at the factory, in fact it has 10 separate calibrated gas settings, including H_2 and D_2)
  - This means that in this case **the recycling atom is helium!**

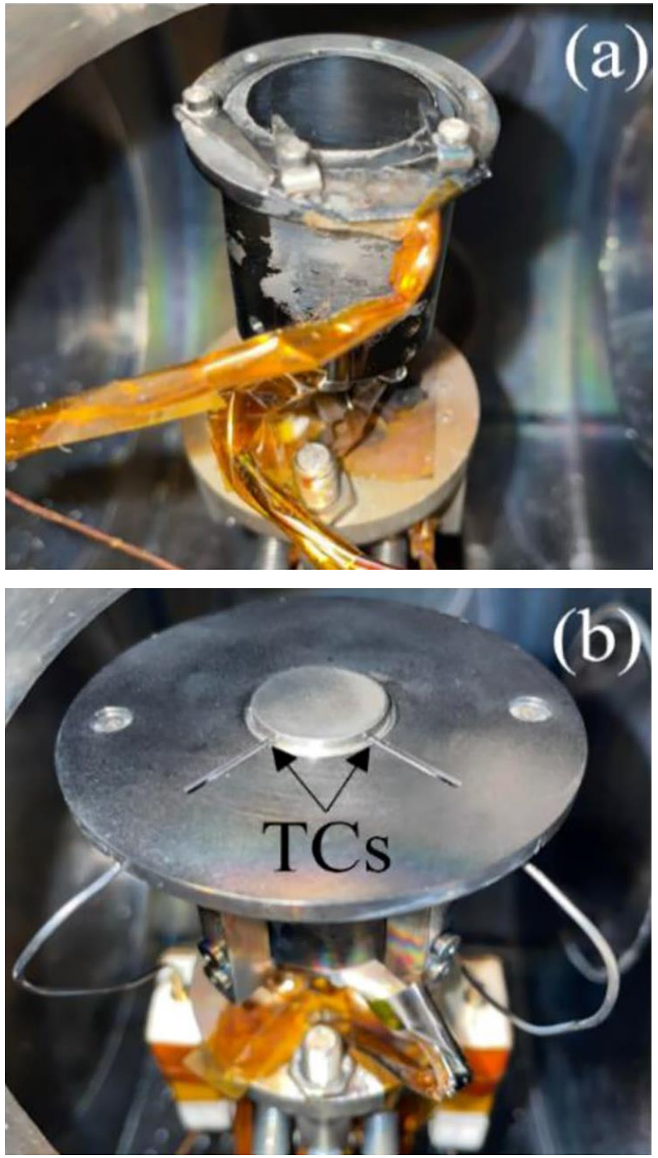
SHOT# 3381: The Original "ZEUS" Shot



Upgrade in Diagnostics and sample holder/heater

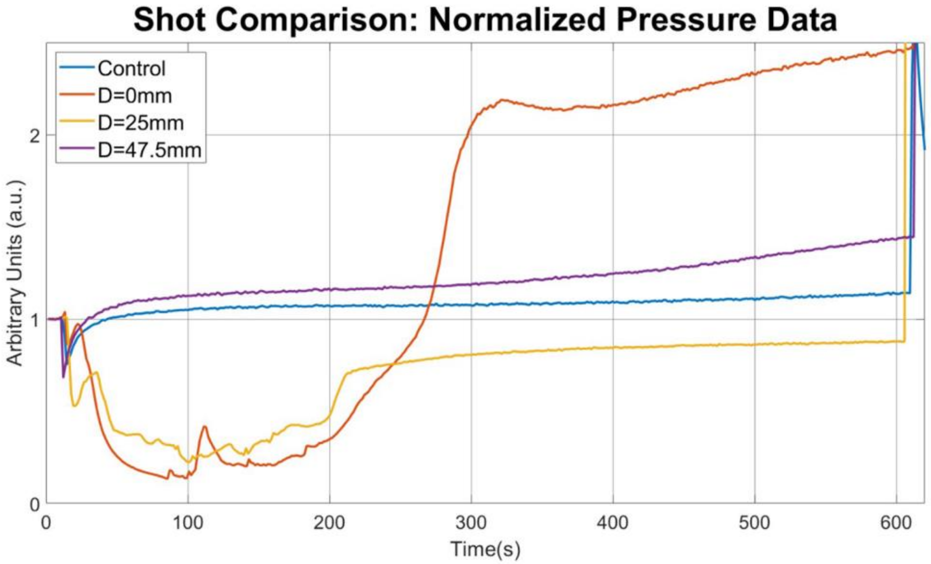


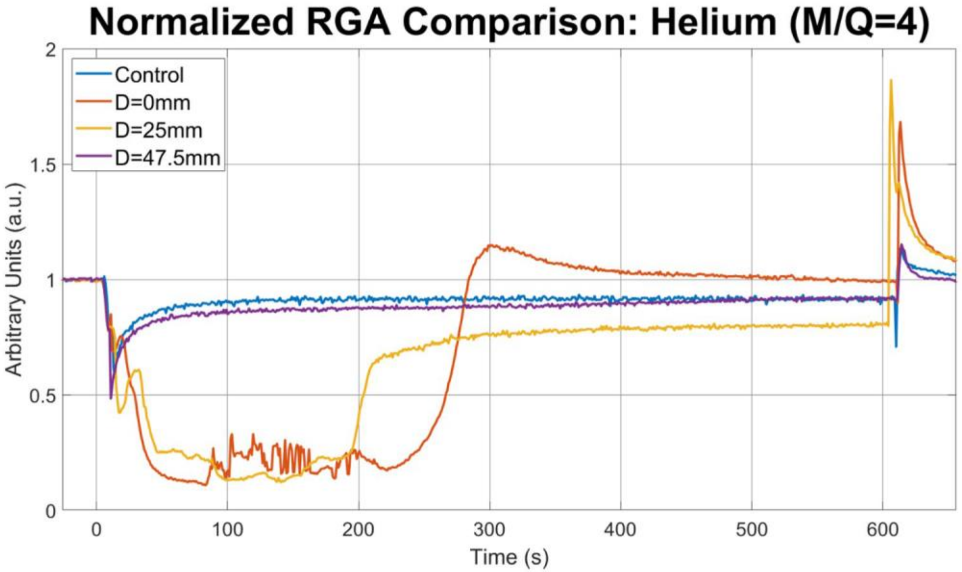
Schematic top view of HIDRA showing LEEX's diagnostics. RGA's are positioned on the upper E-ports and spectrometers are positioned on the lower E-ports. Other diagnostics and pumps are connected to other HIDRA ports.



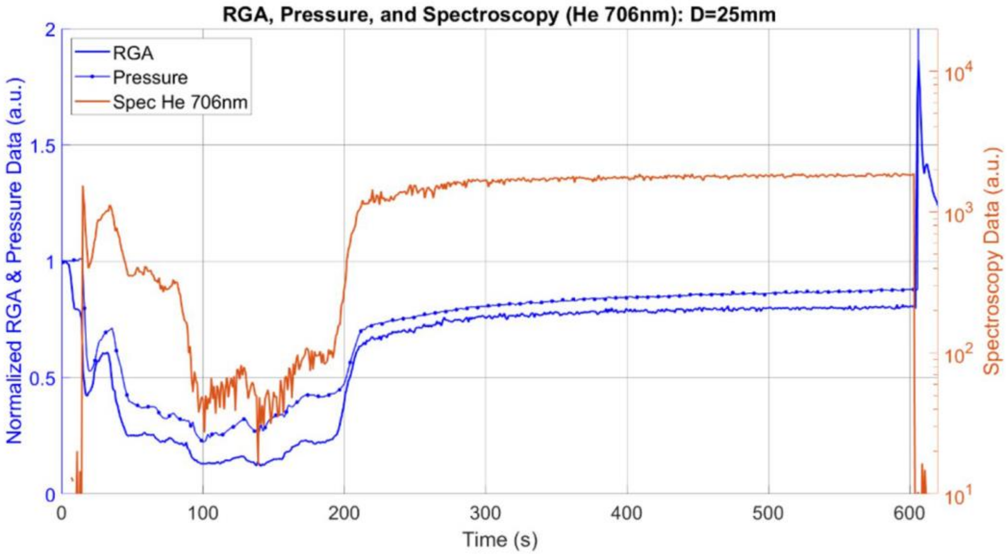
The heater and sample holder configuration for the (a) Zeus shots and (b) LEEX campaign

Up to an 85% drop reduction in recycling

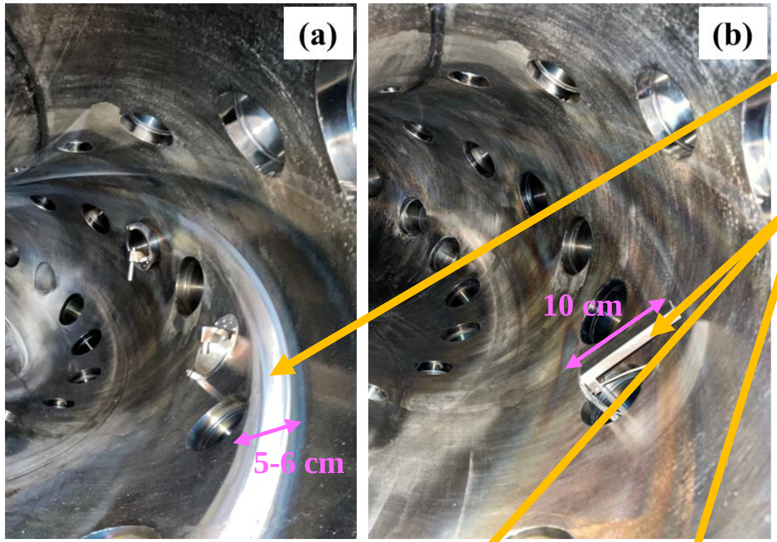




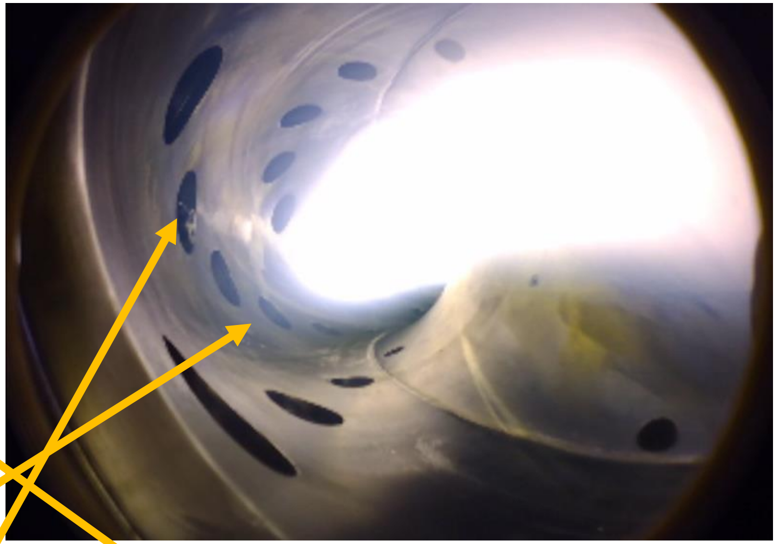
- Three different diagnostics
  - Pressure
  - RGA's
  - Spectroscopy
- All show the same behavior
- We know now that this is a real effect
- This re-confirms that what we saw in the "Zeus" shots and LERE is a real effect!

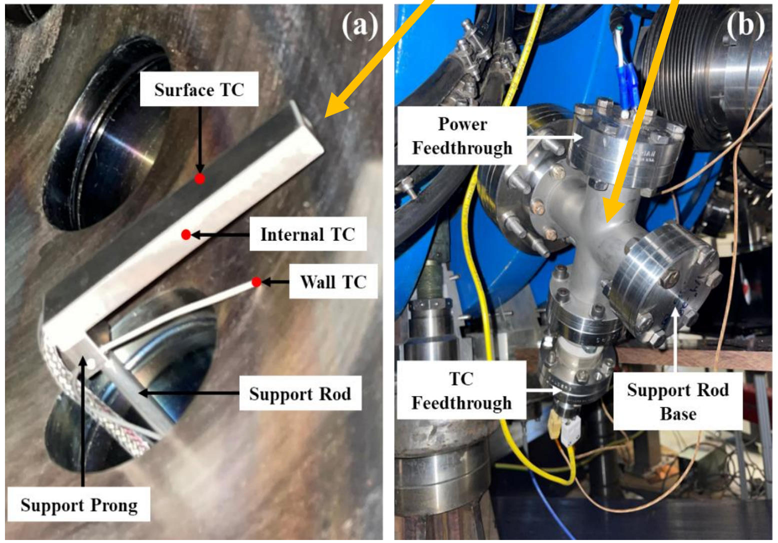


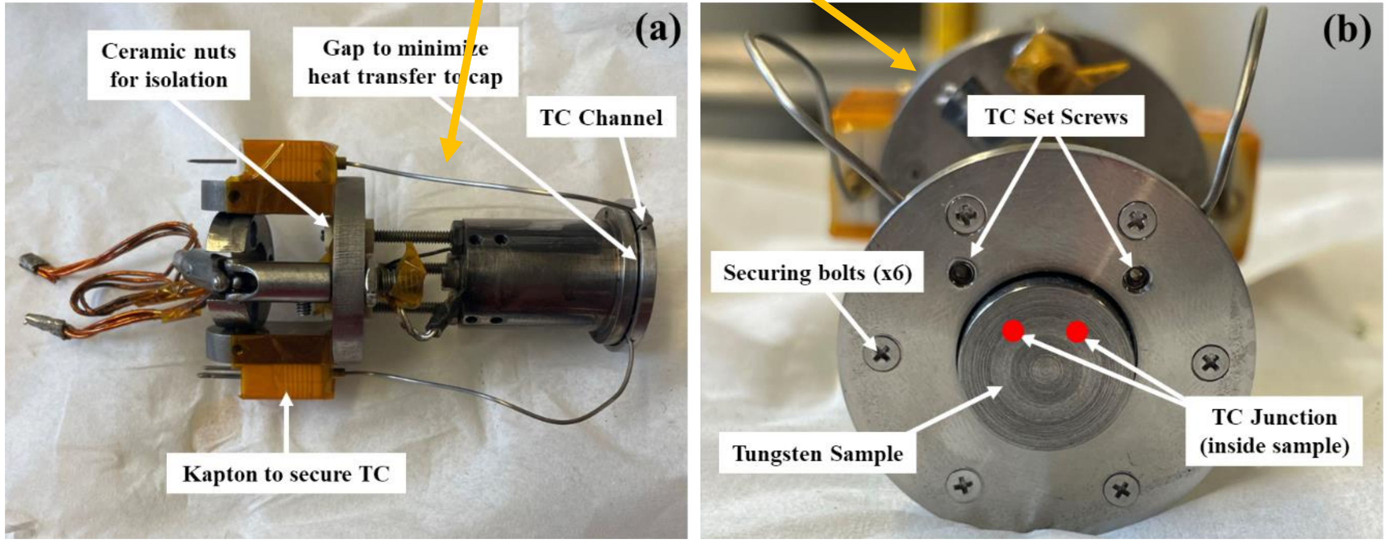
HIDRA was Opened up for Cleaning, Equipment Upgrades and Installation



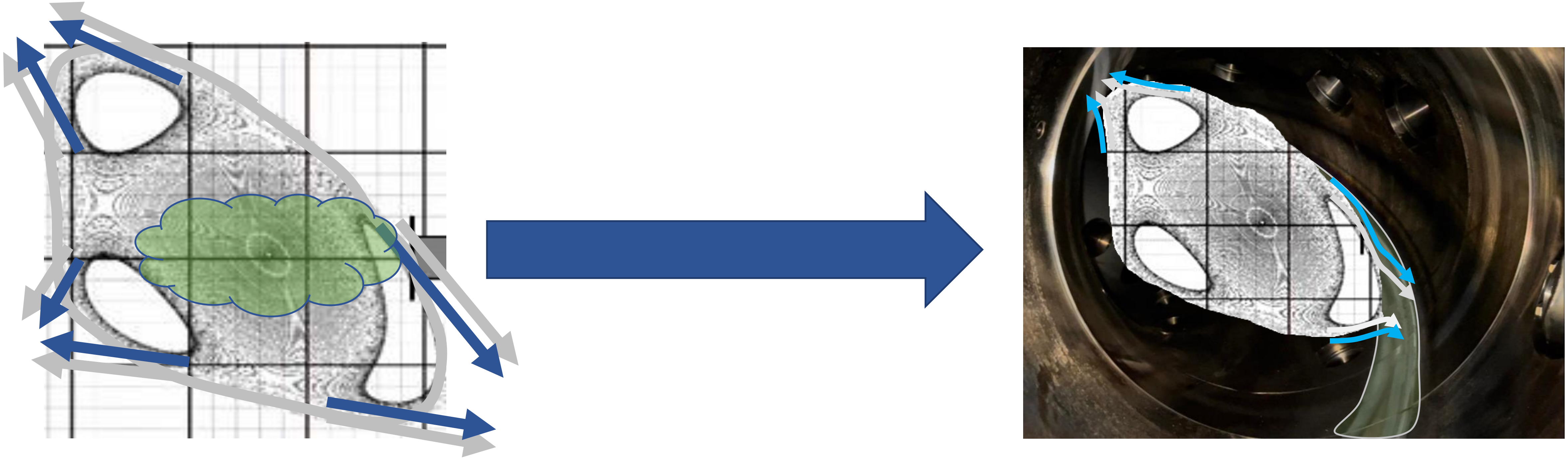
- Lithium Follows the Magnetic Field Lines, Does not go "Everywhere"!
- Addition of a Wall Heater for Desorption Experiments. This is to show if the Helium is Being Trapped at the Wall
- Material Analysis Tool (HIDRA-MAT) Also received an Upgrade.
- Beautiful first plasma after cleaning.
- Can see new HIDRA-MAT head at edge



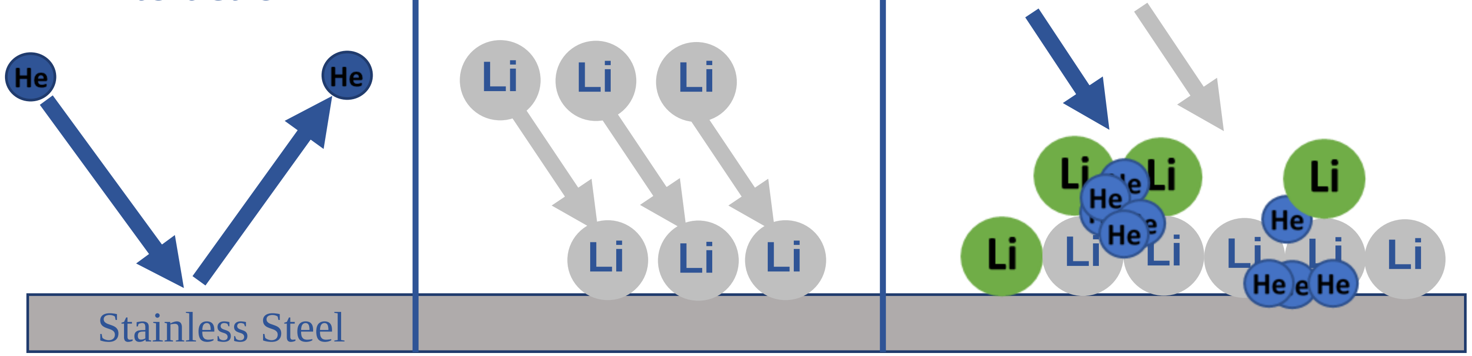




Retention Mechanism: Helium Retention at the Walls by co-deposition



Regular He wall interaction	Regular Li wall interaction[14,15]	He trapped in Li[16]



Literature suggests that helium can cluster at vacancy and interstitial sites in the lithium lattice

[7] H. Kleine, M. Eckhardt, and D. Fick, Surf. Sci. 329, 71 (1995).
[8] H. Sugai et al., J. Nucl. Mater. 222, 254 (1995).
[9] A. R. M. Iasir and K. D. Hammond, Comput. Mater. Sci. 204, (2022).

Summary and Conclusions

- Flowing liquid lithium loop is now in operation at UIUC
- Flow measurements of around 1 m/s have been measured and wetting experiments are currently underway.
  - Distributor design using posts and a "pachinko" style method being tested.
  - Surface designs will also be tested.
- From the analysis, it is therefore found that the main dissipation channel inside the Li vapor cloud is the excitation of the ground state Li atoms
  - This is true for lower electron temperatures
  - Higher T_e will naturally add to the contribution of ionization reactions as excited species live longer
- From the observed size of Li vapor cloud in the experiments and the expected dissipation of 220 W, a Li density can be inferred with $n_{Li} \approx 1.0545 \times 10^{19}$ m^{-3}
- Helium retention with lithium has been observed in HIDRA with Lin operation
  - Low recycling regime
  - Plasma temperature increased form ~25 eV to over 50 eV
  - This seems to back-up FLIRE results from 2005
- Note on the Future of the program
  - Continues surface wetting
  - New LM material corrosion
  - Vapor cloud in toroidal conditions
  - Hydrogen and helium pumping and retention