Liquid metal plasma-material interaction science and component development

MA Jaworski on behalf of the Liquid Metal Plasma-Facing Component working group

FESAC Meeting, Washington DC – July 8-10, 2014

PRINCETON PLASMA PHYSICS LABORATORY

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

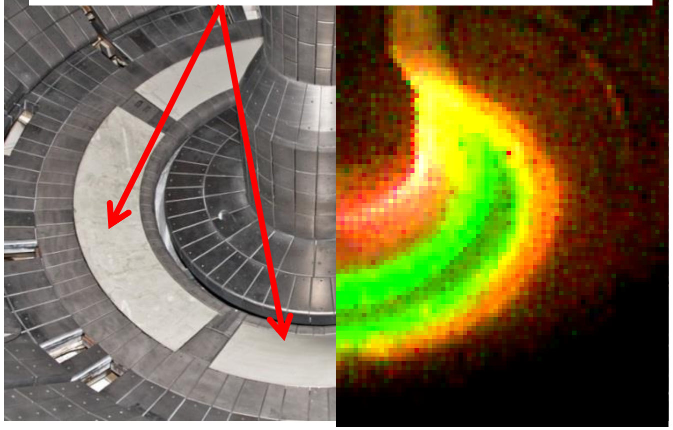
UCLA

Liquid metals may be the only material for FNSF and economical reactors

- Liquid metal plasma-facing components (LM-PFCs) are a revolutionary approach (see Maingi, Majeski talks):
  - No permanent damage
  - Increased power loading, relaxed design constraints
  - Enhanced confinement regimes
- LM-PFCs are poised for breakout to leadership in plasma-facing materials
- We propose **to enable** high-power confinement device testing via
  - Dedicated "test-stand" facilities
  - Providing fundamental physics and engineering data on LM-PFC plasma-surface interactions

Coenen, et al., JNM 2013

NSTX Liquid Li Divertor



In 10 years, our initiative will advance LM-PFCs along two fronts

1. Conduction-cooled targets: with thin liquid layers need to demonstrate integrated performance in a high-power device.
   - **We propose** to upgrade high-power confinement devices and complete a demonstration within 10 years via accelerated R&D on a linear device

2. Convection-cooled (self-cooled) targets: have been proposed as a means to greatly increase the power-handling capabilities of the liquid metals.
   - **We propose** to demonstrate the feasibility in a toroidal device and inform on research goals for the following 10 years

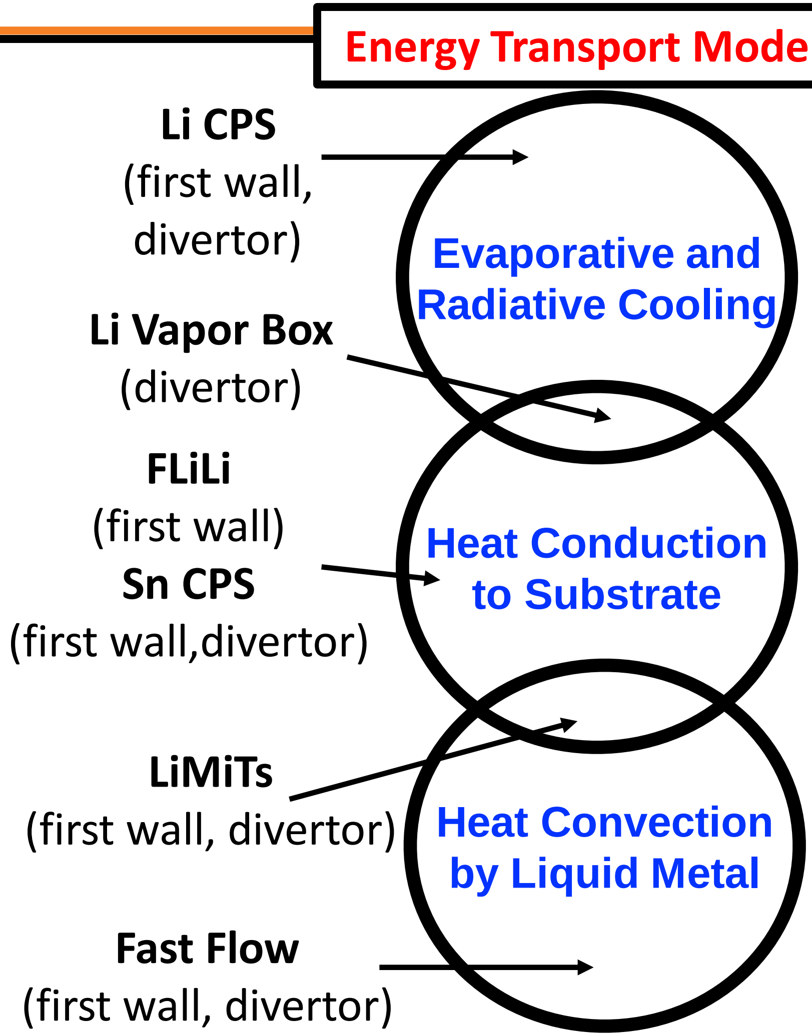
Science-driven program will address critical physics unknowns and guide technology

Energy Transport Mode

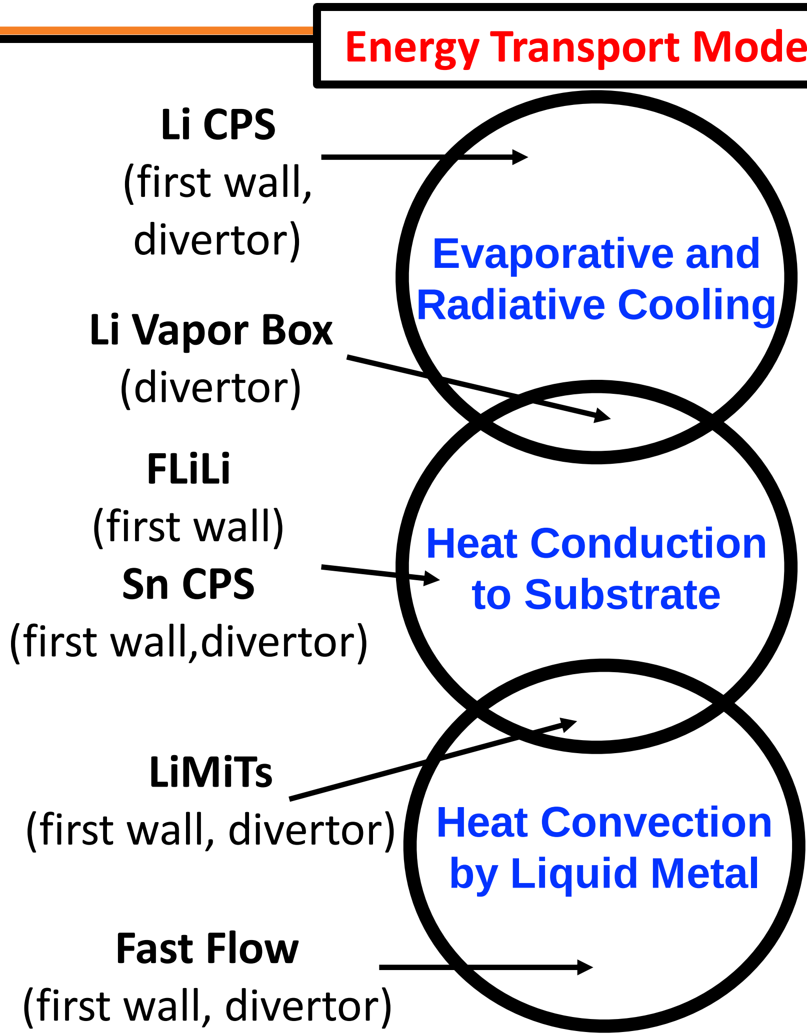
Heat Conduction to Substrate

Solid PFCs

Science-driven program will address critical physics unknowns and guide technology



Science-driven program will address critical physics unknowns and guide technology



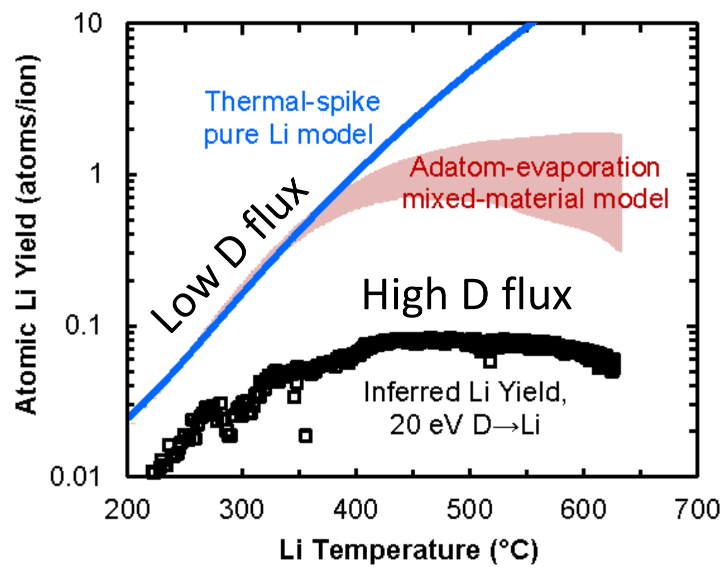
- High-power density on slow-flow lithium leads to vapor-shielded targets for extreme heat-flux mitigation

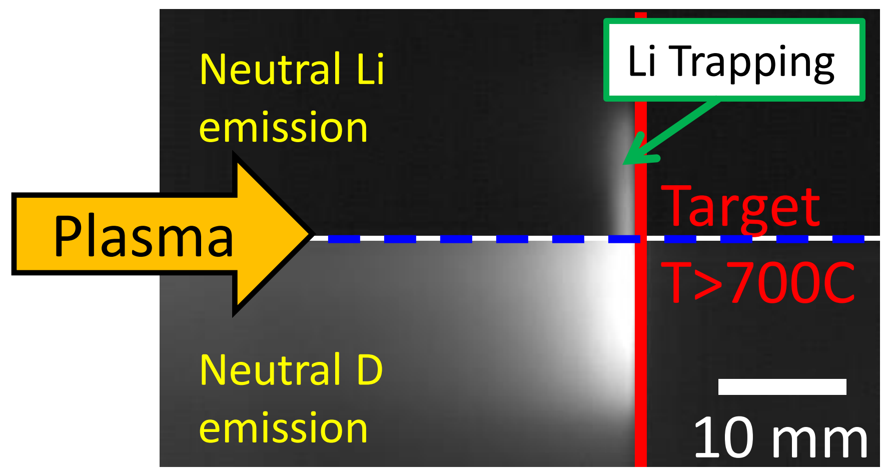
- Fast-flow concepts can exhaust extreme amounts of power via convection

All the concepts share similar physics and engineering unknowns…

Enabling research on test stands provides central connection between thrusts

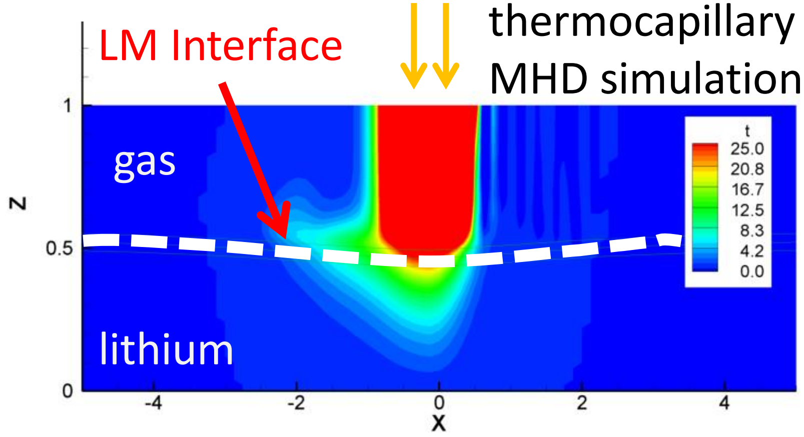
- Steady-state, high-flux test stands link surface science and integrated scenario thrusts
  - Temperature-enhanced erosion seen with Li, Sn, Ga, still not understood
  - Observed suppression of erosion needs **surface science thrust (Allain)**
  - Near-surface PMI studies prepare the way for **tokamak scrape-off layer studies (Maingi)** to establish true material temperature limits
- Physics-needs drive facility requirements, for example:
  - Significant lithium through-put enables material transport physics and recapture technology development
  - Steady cooling required for controlled tests at single temperature



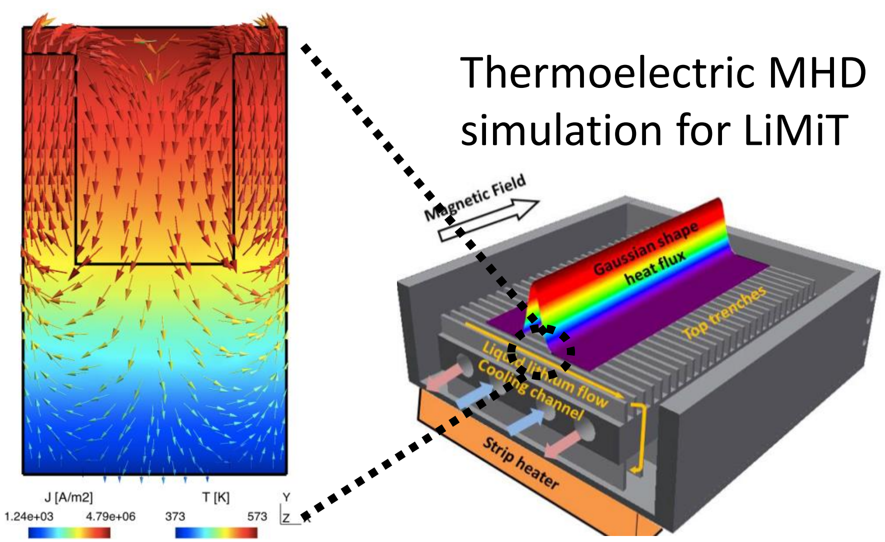


Theory and modeling provide confidence in extrapolation to confinement devices

- Free-surface MHD provides multiple couplings and rich physics
  - **Free-surface deformations** critical for high heat-flux regions
  - Research on liquid metal PFCs is also research on solid metal walls
- Theory and modeling can help refine experiments and identify important features for confinement device PFCs



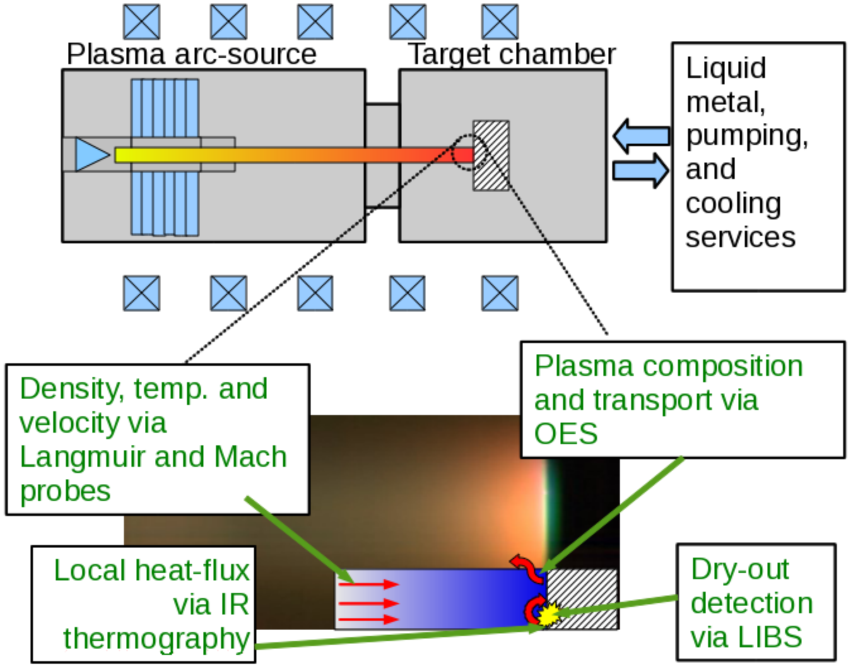
Free-surface thermocapillary MHD simulation



Thermoelectric MHD simulation for LiMiT

Modest investment needed to address facility requirements

- Dedicated linear device with integrated liquid lithium loop can address physics and technology goals
  - Conventional arc-source proposed to provide divertor-relevant heat fluxes
  - Material transport, recapture requires integrated lithium loop
  - **Extensive water cooling incompatible with lithium PFCs**
- Dedicated toroidal devices can demonstration basic stability
  - Similarity experiments with GaInSn could be restarted quickly
  - Dedicated lithium facilities will address low-density fluid and hydrogen cycle aspects directly




UCLA MTOR GaInSn Experiment

Key facilities will address science issues and enable integrated demonstration within 10 years

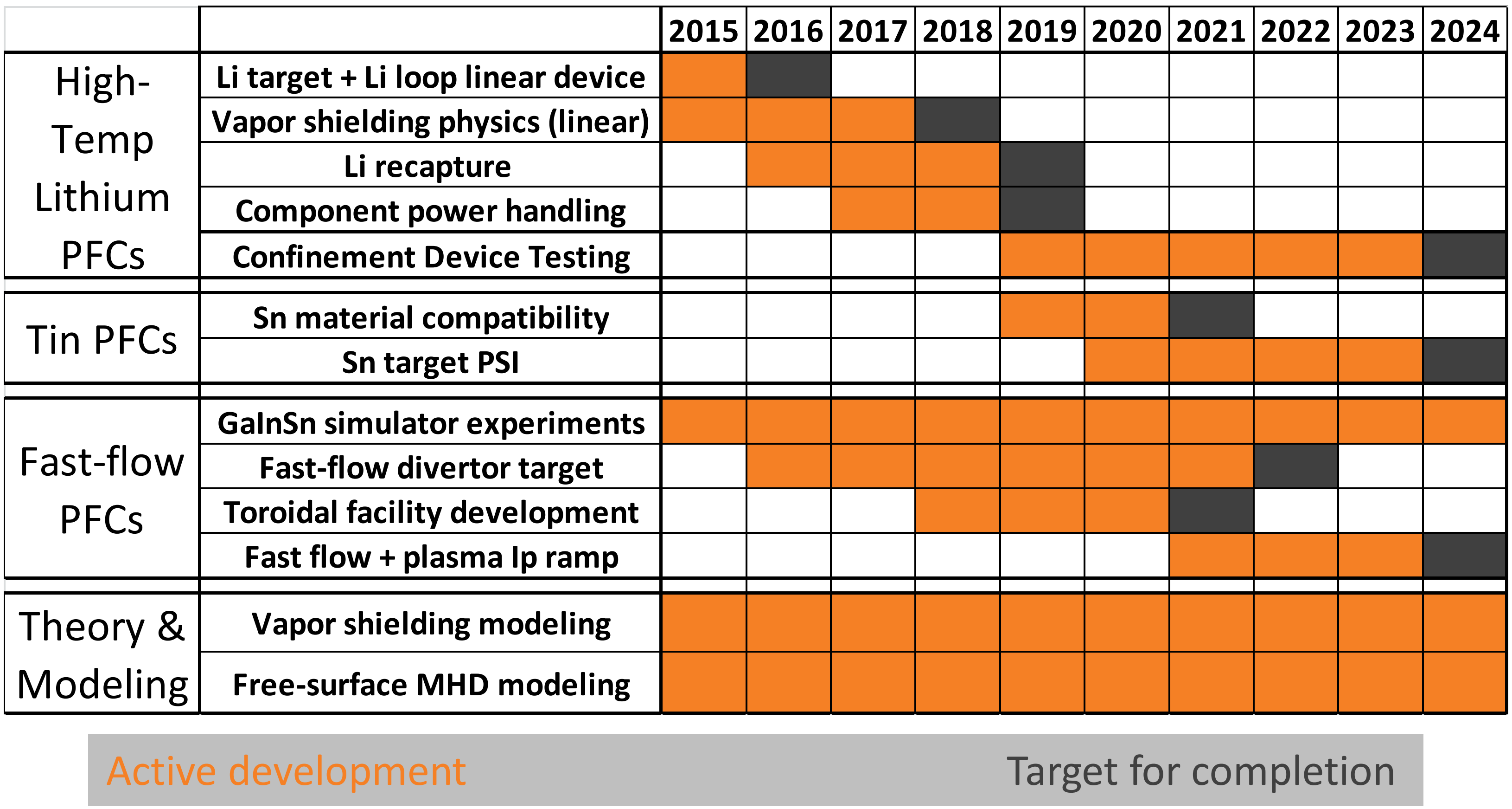
Partial contribution to topic
Major contribution to topic
Full resolution of topic

		Confinement Devices		
	Test Stands	High Power (NSTX-U ADX?)	Long Pulse (EAST)	High-power, high duty-factor, hot walls
Issues				
Power and Momentum Dissipation (PMI)	Linear			
Component technology (PFC)				
Steady power handling	Linear			
Free-surface stability (toroidal)	Fast-flow			

10-year goal: Competitive PFM with W

- Dedicated test stands provide fundamental physics and engineering demonstrations prior to implementation on confinement device
- NSTX-U has demonstrated high heat-fluxes and leverages PPPL Li expertise

Dedicated facilities can achieve aggressive timeline for confinement device demonstrations



Summary

- Large-scale flowing liquid metal PFCs are nearly ready to break-out with dedicated confinement device testing

- Dedicated test-stand facilities will advance the science and component technology to enable these demonstrations

- **The US can lead the world in liquid metal PFCs with an aggressive program to upgrade NSTX-U and address the open questions directly**

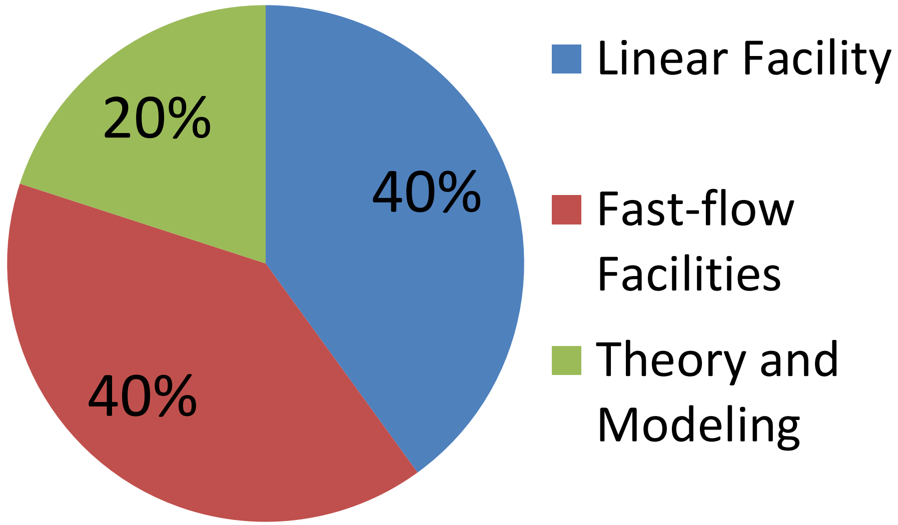
Backup

Enabling research on test-stands will maintain US leadership in LM PFCs

- Experience with liquid metal experiments and plasma devices enables rapid startup
- Staging enables continuous progress in all thrusts
  - Test-stands ramp-down after initial investment enables confinement device thrust
  - Growing program in late-decade to support Sn studies
- **US poised to outpace world programs with NSTX-U and possibly ADX liquid metal programs**

Notional Test-stand thrust budget breakdown

$5-6M/year



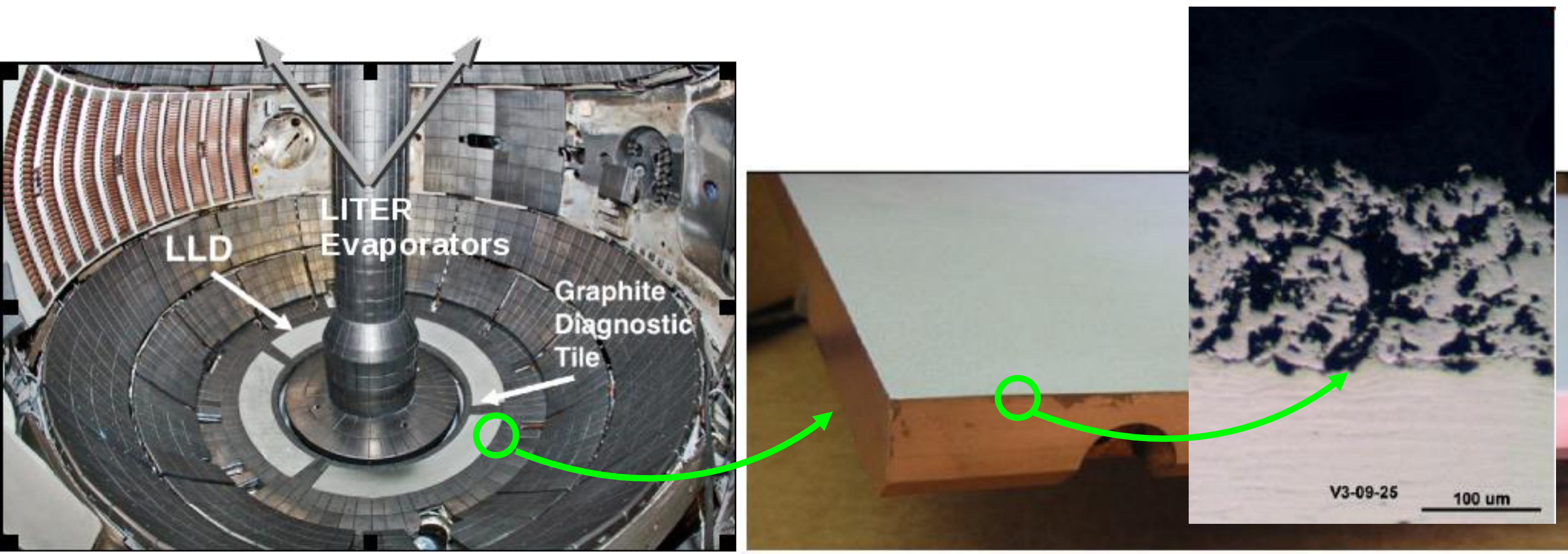
Facility requirements for liquid metal linear device studies

- Similar plasma-physics regimes with divertor match atomic physics parameters at target ← **High-density arc-source & RF-source ok**
- Divertor-like heat flux enable emission/recapture studies and appropriate surface-temperature profiles ← **High-density arc-source & RF-source ok**
- Long-pulse/steady-state operation enable controlled single-temperature and material recapture demonstrations ← **Arc-source & RF-source ok; No device has liquid metal loop**
- Gas-cooling required for safety considerations and DEMO-relevance ← **No present or planned plasma device**
- Contamination-tolerant plasma-source required for erosion-tolerant PFCs ← **Arc-source ok, dielectric windows for RF not ok**

NSTX LLD demonstrates stable operation

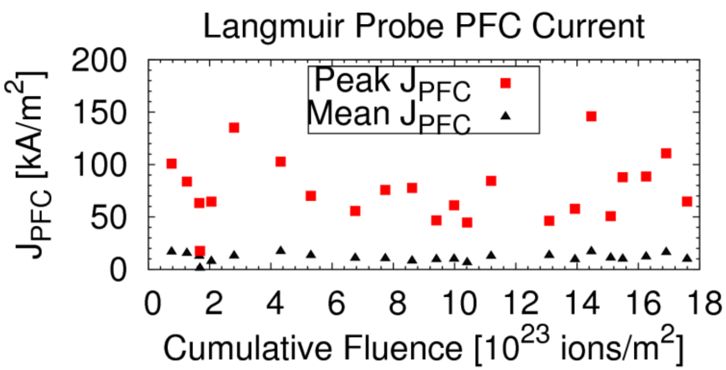
NSTX performed liquid-metal PFC experiments with the Liquid Lithium Divertor (LLD)

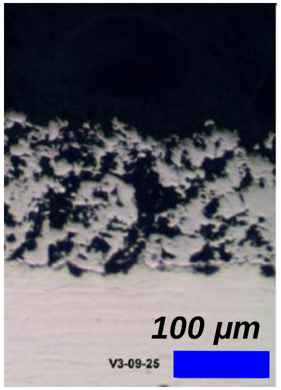
- Liquid lithium divertor installed for FY2010 run campaign
- 2.2cm copper substrate, 250um SS 316, ~150um flame-sprayed molybdenum porous layer; LITER loaded
- 37g estimated capacity, 60g loaded by end of run



Stable liquid metal PFC operation demonstrated with NSTX Liquid Lithium Divertor

- Up to 10x more current measured with Langmuir probes; LLD porous geometry limits droplet size

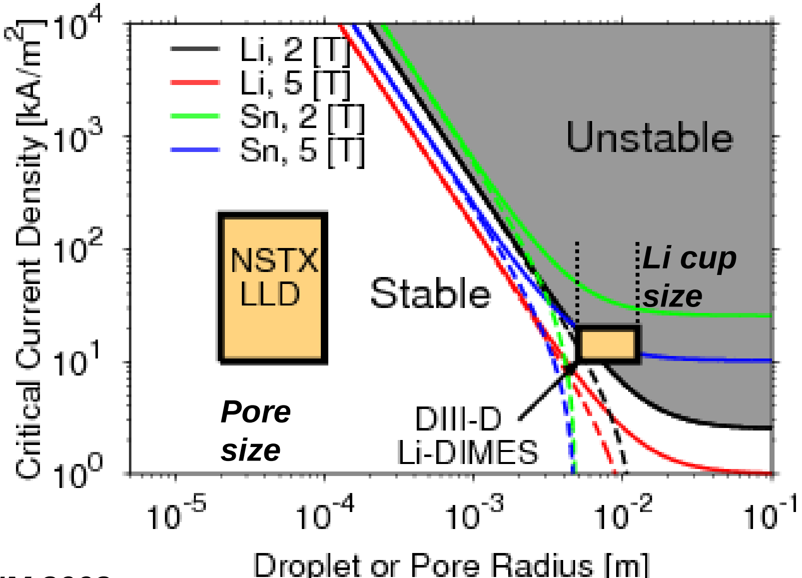




- Rayleigh-Taylor analysis provides marginal stability curves; NSTX LLD stable

$$j_{cr} = \frac{1}{B}\left(\frac{4\pi^2}{\lambda^2}\Sigma + \rho g\right)$$

For the fastest growing modes



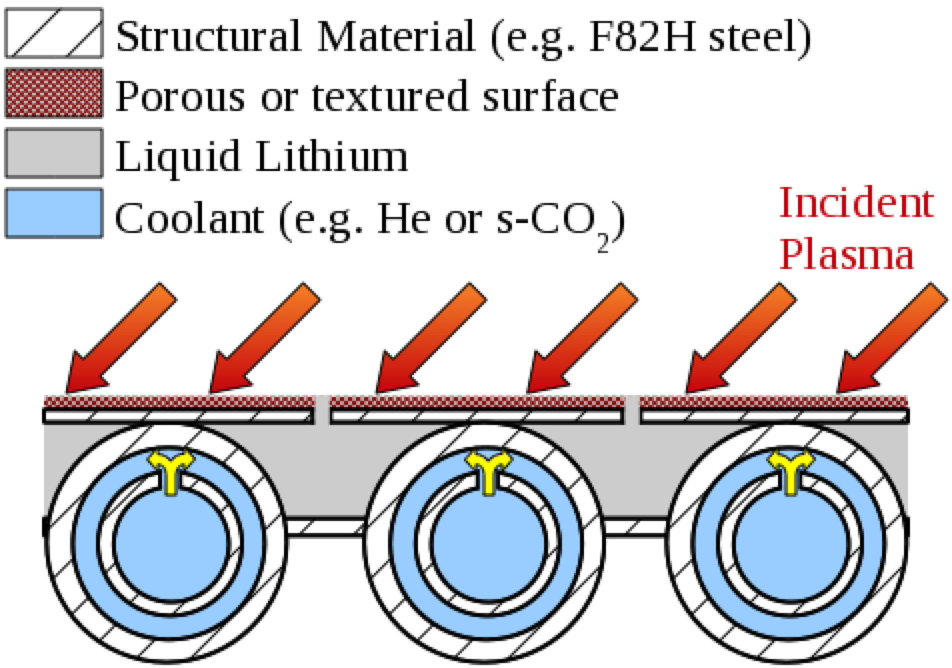
- CPS tests also reduced droplet ejection with smaller pore sizes*

Jaworski JNM 2011, Jaworski NF 2013 , Whyte FED 2004, *Evtikhin JNM 2002

Design studies indicate need for high-temperature lithium surface research

An approach to a liquid-metal PFC: Actively-supplied, capillary-restrained systems

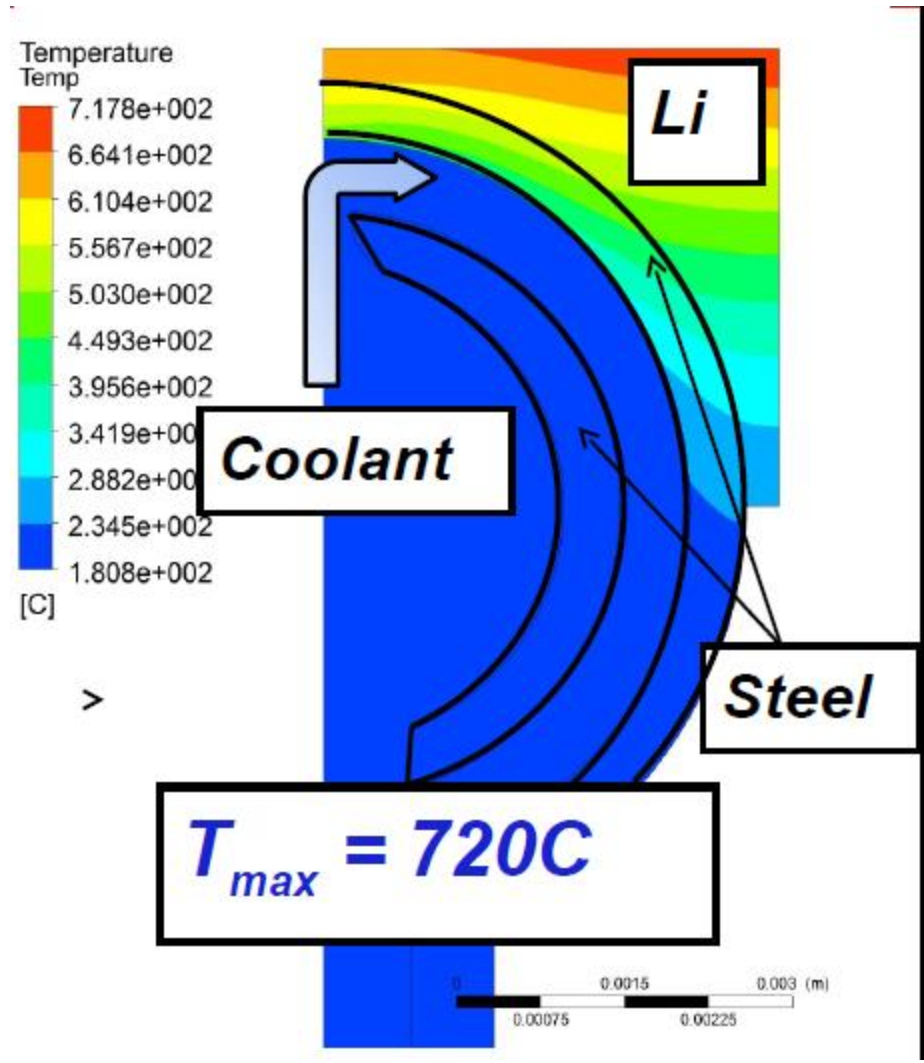
- Closely connected primary coolant and liquid lithium reservoir/supply structure
- Continuous flow to the surface to flush gettered material and maintain wetted surfaces (substrate protection)
- Multiple coolant options exist (T-tube impinging jets shown as example)



Jaworski PPCF 2013

Advanced cooling techniques can be optimized for LM-PFCs for steady-state cooling

- T-tube[1] uses impinging gas jets to increase local heat transfer coefficient
- Altered T-tube for these simulations to have:
  - Smaller radius
  - Steel structure, s-CO2 coolant **(No tungsten)**
  - 10 MW/m^2 incident
  - Consistent with strength limits of ODS-RAFM steel
- Previous studies considered <400C as limit for hydrogen retention



[1]Abdel-Khalik FST 2008.

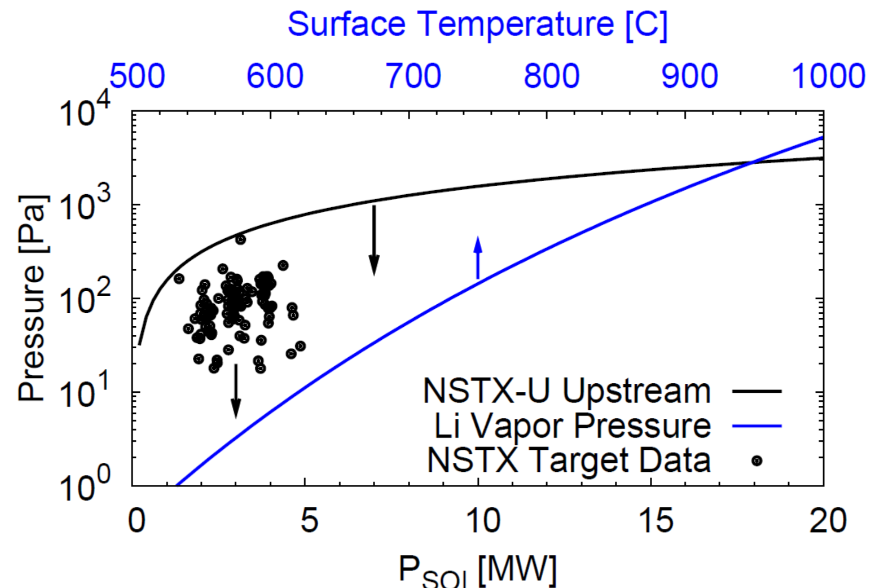
What are the physics ramifications of high temperature liquid lithium PFCs? What will an integrated scenario look like?

- Lithium vapor cloud can potentially provide effective power and pressure loss ***(continuous vapor-shielding)***
  - Non-coronal Li radiation
  - Li vapor pressure vs. plasma pressure
- Capillary-Porous System(CPS) targets have dissipated large incident heat fluxes: e-beam tested to 25MW/m^2 limited by Li inventory (Evtikhin JNM 2002)
- CPS limiter in FTU able to operate above 550C (Apicella PPCF 2012)
- **What is $T_{max,surf}$ for a lithium PFC in the divertor?**
- Preliminary experiments being performed on Magnum-PSI plasma device

$$p_u = p_t(1 + M_t^2) + p_{Li}$$

$$q_t^{plasma} = \gamma \Gamma_{sat}^{+} T_e = \gamma n_{es} c_s T_e = \gamma c_s p_t$$

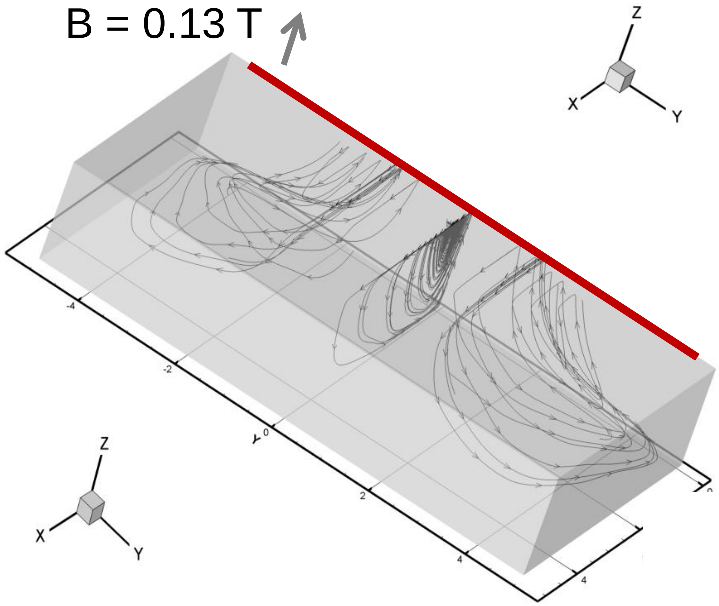
$$P_{SOL} = 4\pi^2 R_0 a \kappa^{1/2} \frac{\chi_\perp}{\lambda_T} n_u T_u = 4\pi^2 R_0 a \kappa^{1/2} \frac{\chi_\perp}{\lambda_T} p_u$$



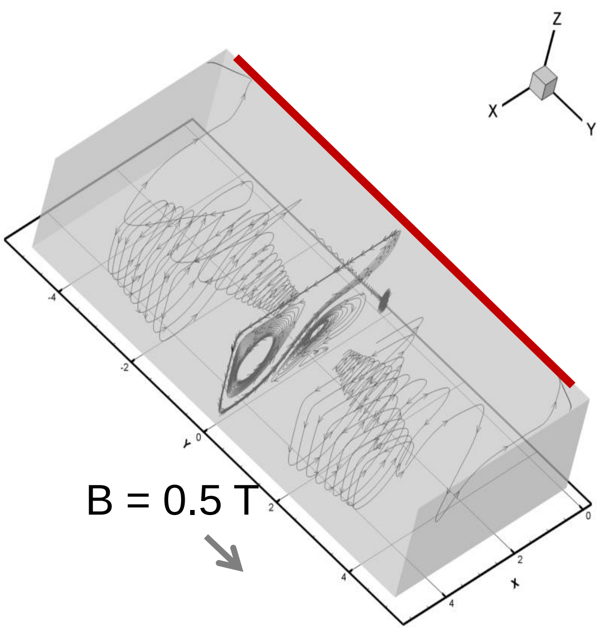
Jaworski PPCF 2013

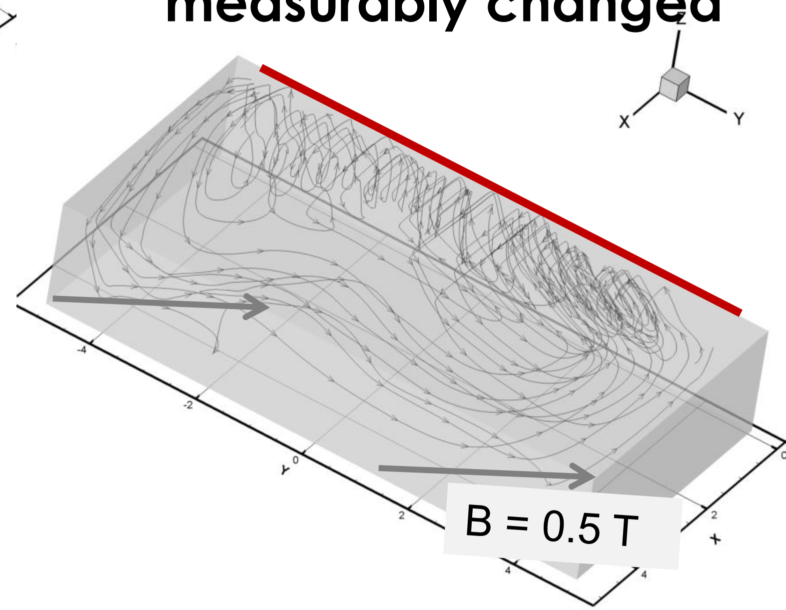
Thermocapillary MHD modeling from UCLA

Study of impact of field direction on Marangoni recirculation velocity



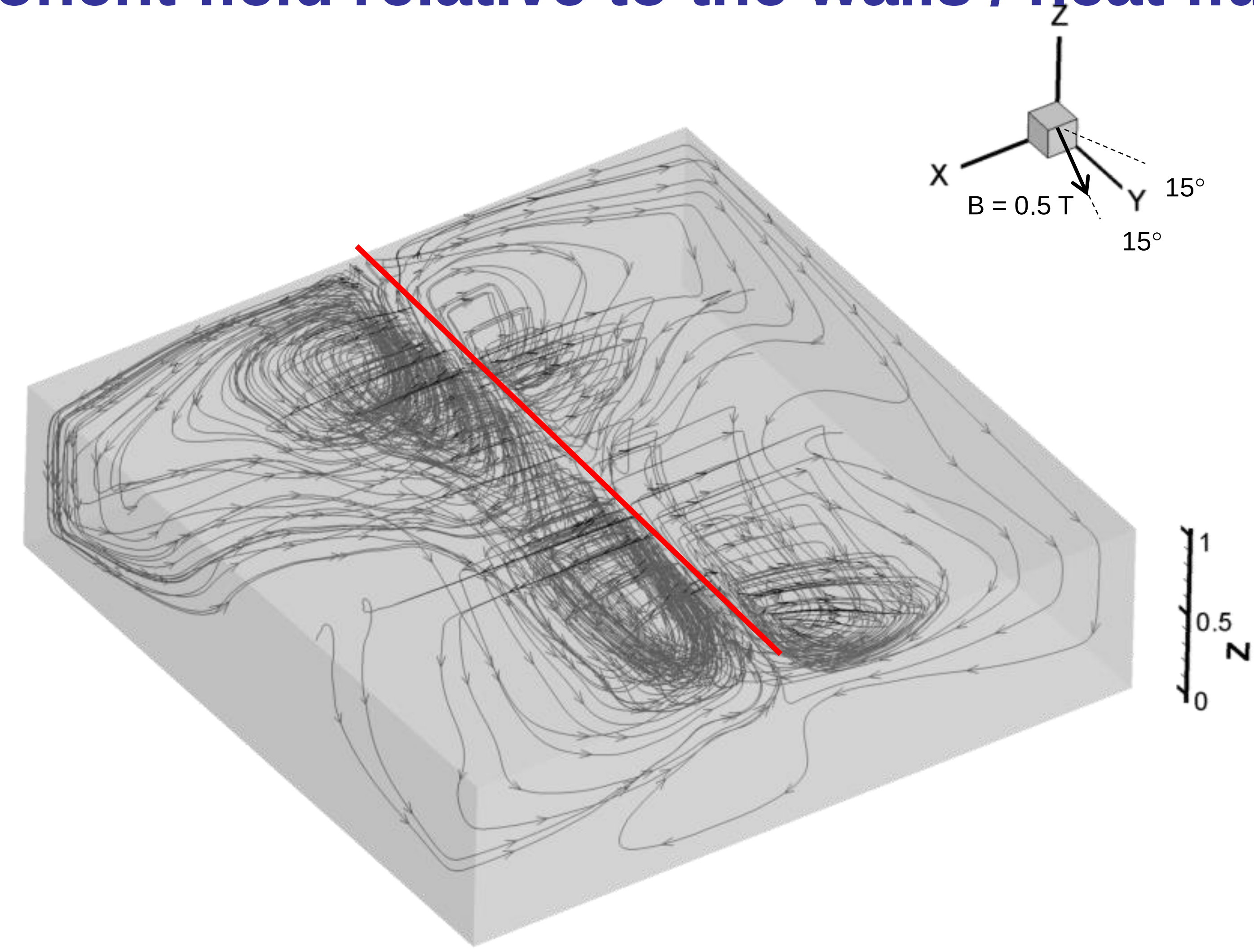
- **Surface temperature profiles not dramatically changed with field direction changes**
- **Heat flux into the bottom wall was measurably changed**



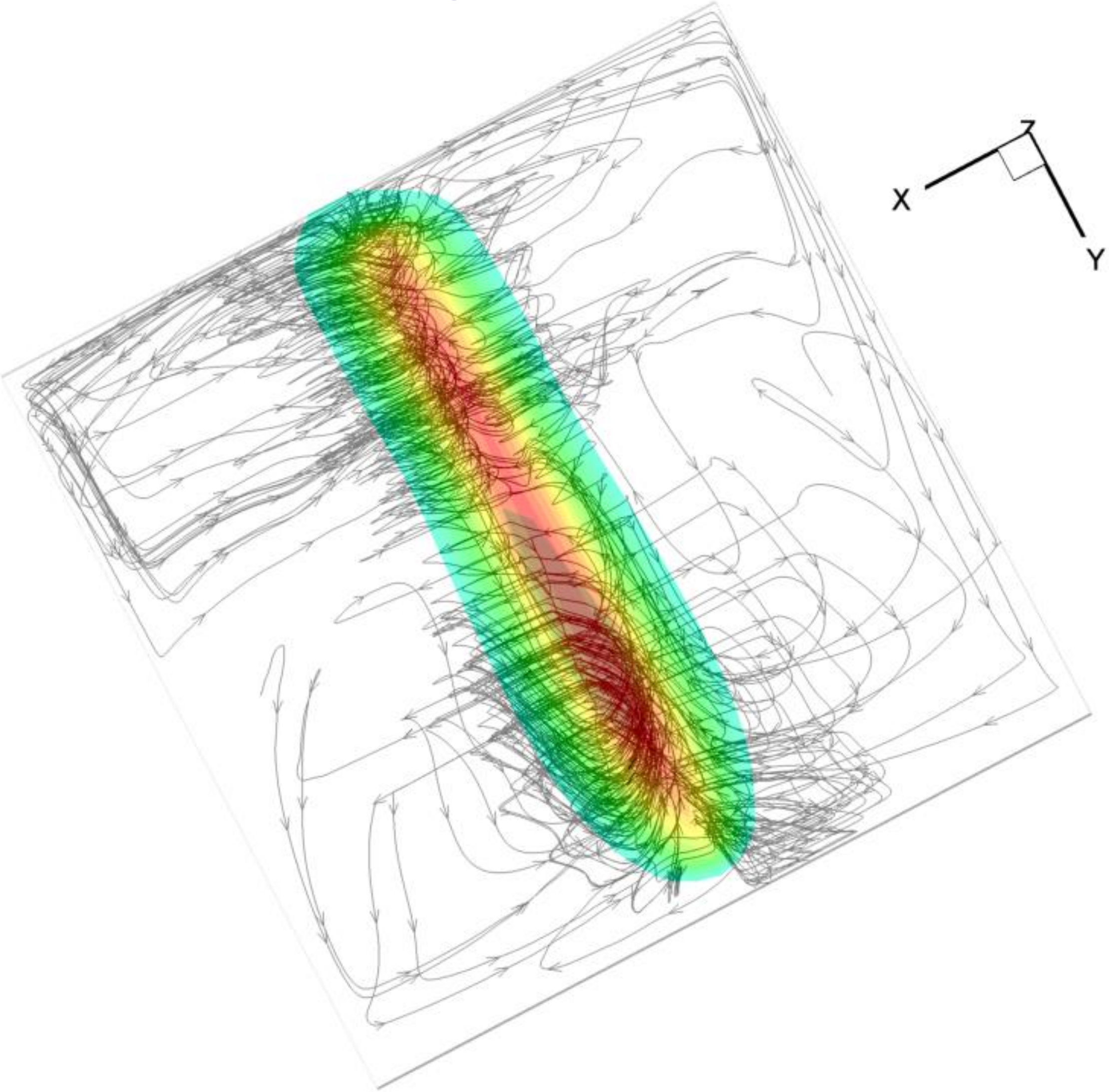


UCLA

New rigidlid results – no symmetry and 3 component field relative to the walls / heat flux



Looking from the top, the heated spot appears to be pulled slightly off center line by strong lateral velocity



UCLA

Parameter bγ/ρgh (~Bond No.) provides estimate of the change in surface height

- **dh/dx varies from 1.5x to 1x the dimensionless parameter** bγ/ρgh **with increasing field**
- **Surface deformation becomes important for SLIDE (~1 cm) when q'' approaches 10 MW/m^2**
- **Surface deformation becomes important for 1 mm when q'' approaches 100 kW/m^2**

Bond No. for 1 cm thick lithium film

b	bγ/ρgh	~q''
10^3 K/m	.03 mm/cm	10^5 W/m2
10^4 K/m	.3 mm/cm	10^6 W/m2
10^5 K/m	3 mm/cm	10^7 W/m2

Bond No. for 1 mm thick lithium film

b	bγ/ρgh	~q''
10^3 K/m	.3 mm/cm	10^5 W/m2
10^4 K/m	3 mm/cm	10^6 W/m2
10^5 K/m	30 mm/cm	10^7 W/m2

UCLA