Lithium-Infused Trenches

How to use molten lithium to remove high heat fluxes in a fusion device

David N. Ruzic, Wenyu Xu, Daniel Andruczyk,

Vijay Surla[#], Michael Jaworski[&]

[#] on assignment at PPPL, [&]PPPL

UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Nuclear, Plasma, and Radiological Engineering
Center for Plasma-Material Interactions

Contact: druzic@illinois.edu

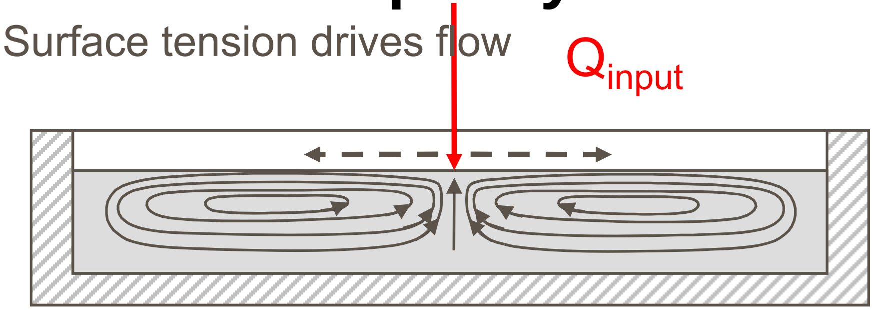
Outline

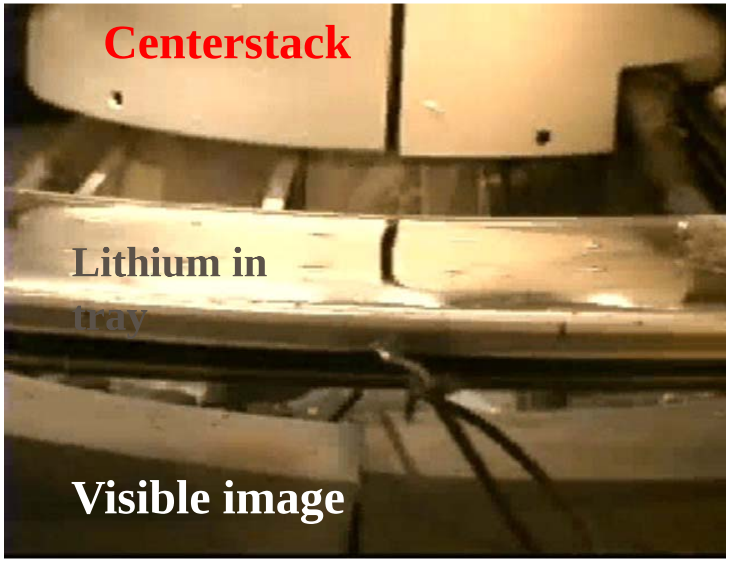
- Introduction
- Thermo-Electric MHD seen in SLiDE (Solid/Liquid Divertor Experiment)
- Lithium/Metal Infused Trenches (LiMIT concept)
  - Concept
  - Proof-of-Principle experiments
  - Velocity Measurements
- Analytical Formulation
- Limits on LiMIT
- Conclusion

CDX-U Results - The Unexpected Happened

- Trying to melt lithium in CDX-U:
  - - 60 MW/m^2 heat flux redistributed from spot heat
  - - No evaporation despite lithium's tendency to do so (and purpose of e-beam run!)
- Why did the lithium melt the entire tray and not evaporate?
  - - First explanation was thermocapillary phenomena
  - - Temperature dependent surface tension resulted in flow and strong convection away from hot spot
  - - If true, will this work in a divertor without over heating the Li ?

Thermo-Capillary Effect?

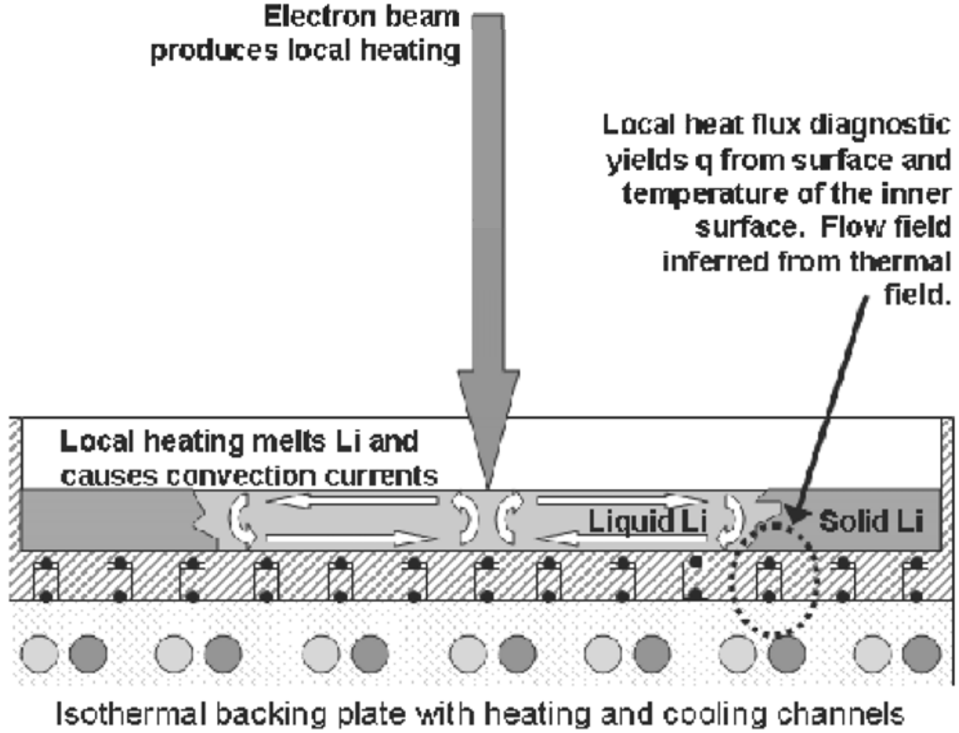


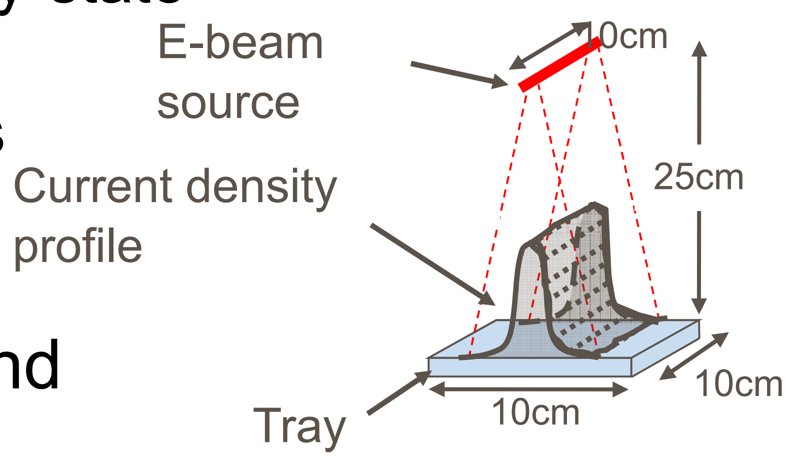


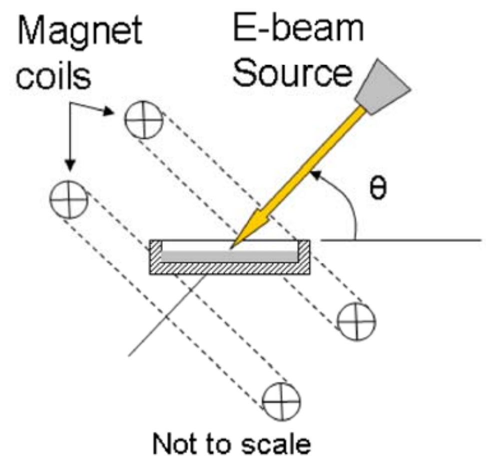
R. Majeski et al., "Final results from the CDX-U lithium program," *Presentation at 47th Annual Meeting of the Division of Plasma Physics (APS-DPP), Denver, Colorado, October, 2005.*

SLiDE at Illinois - Overview

- Solid/Liquid Lithium Divertor Experiment (SLiDE)
  - - Produces temperature gradients with an electron beam
  - - Creates magnetic field with external magnet system (these tests at normal incidence)
  - - Measures temperature distribution in tray containing lithium
  - - Active cooling for steady-state operation
  - Camera system monitors surface velocity
- Designed, constructed and operated for this work

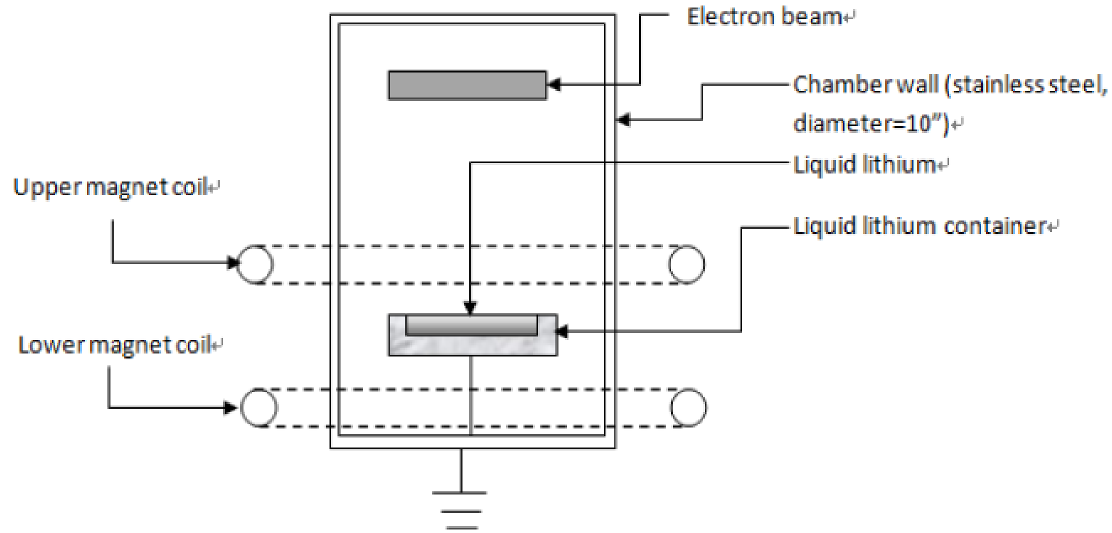


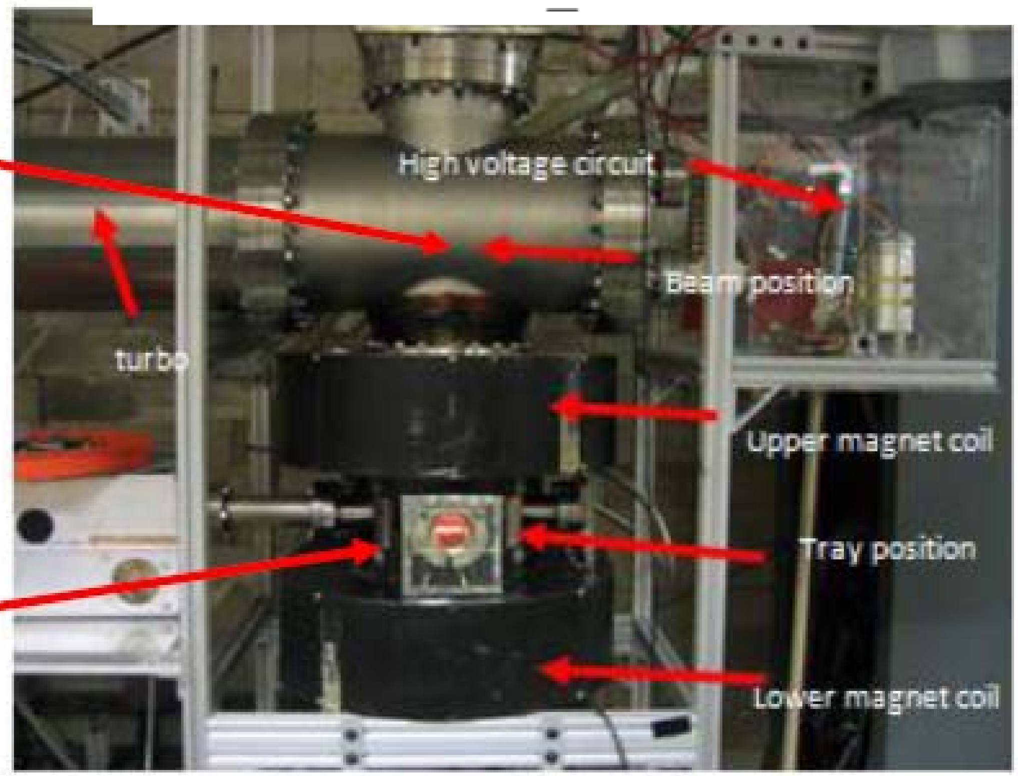




Machine Layout

- A sheet electron beam hits an instrumented tray filled with lithium in a magnetic field.
- Present version allows the tray to tilt so the angle between the heat flux and the field can be like in a tokamak – almost parallel.





Thermoelectric MHD, Basics

- Thermoelectric effect
  - - Causes thermocouple junction voltages
  - - Thermoelectric power present in most materials
  - - Electromotive force generated by temperature gradients
  - - Requires different material (or TE power) to provide current return path and generate current
- Replace one material with a liquid in magnetic field
  - - TE current and B-field generate Lorentz force

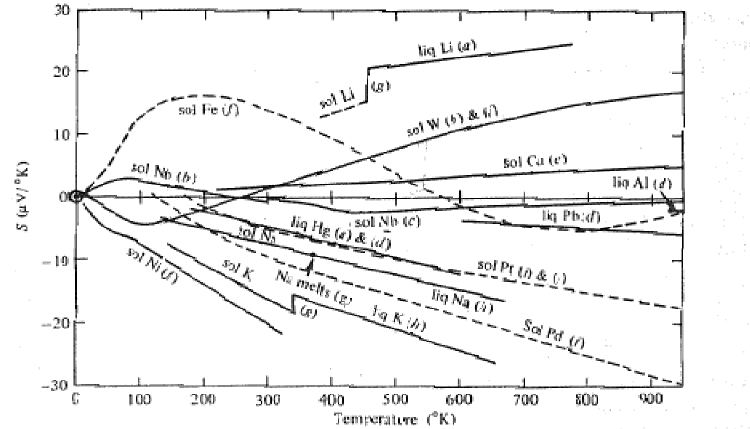
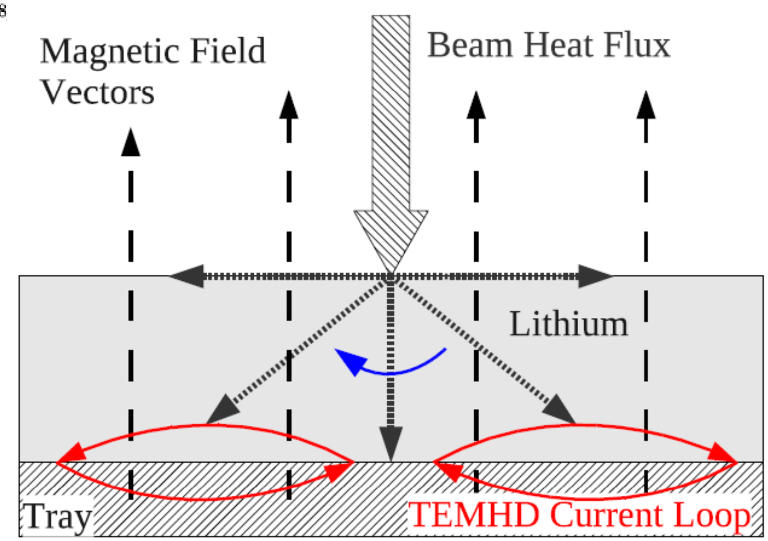


FIGURE 3. Some absolute thermoelectric powers for pure metals. (N.B. Small amounts of additives can produce large changes.) sol = solid; liq = liquid; Al = aluminium; Cu = copper; Fe = iron; Hg = mercury; K = potassium; Li = lithium; Na = sodium; Nb = niobium; Ni = nickel; Pb = palladium; Pt = platinum; W = tungsten. Sources: (a) Ioannides et al. (1975); (b) Carter et al. (1970); (c) Rang & Kowger (1965); (d) Marwaha (1967); (e) Marwaha & Cusack (1966); (f) B
(1958



(b) Thermo-electric Currents.

Force is out of page on left side – into page on right side. It should rotate!


0000.000

Qualitative Tests for TEMHD

- Magnetic field reversal
  - - Flow direction reverses upon reversal of field
  - - Flow is consistent and steady in swirl
- Flow direction consistent with TEMHD source
  - - Mirror system reverses apparent sense of rotation
  - - Magnets measured to determine direction
  - - E-beam and TE have opposite rotation senses
- Addition of insulator halts any swirling flow
  - - Quartz slides added between tray and lithium
  - - No flow observed at all in these cases

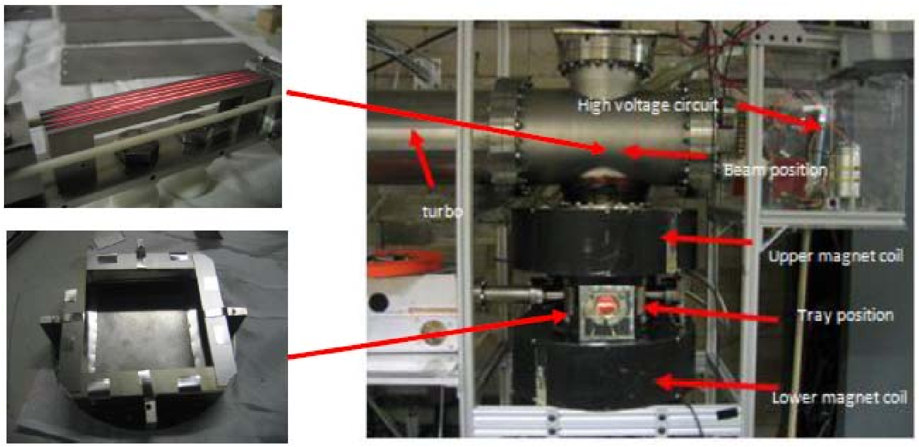
- Test based on the time required for the lithium to come to a stop
  - Viscous damping brings fluid to a rest without additional forces to maintain flow (seconds)
  - If thermoelectric currents exist, these will decay at the thermal time constant of the lithium-tray system (minutes). Minutes was observed.
  - Maintaining the magnetic field will sustain the flow, as opposed to damping it. Flow stays on without e-beam.
  - Turning magnetic field back on after a viscous spin-down should induce motion once more. Restarts when field is turned on.

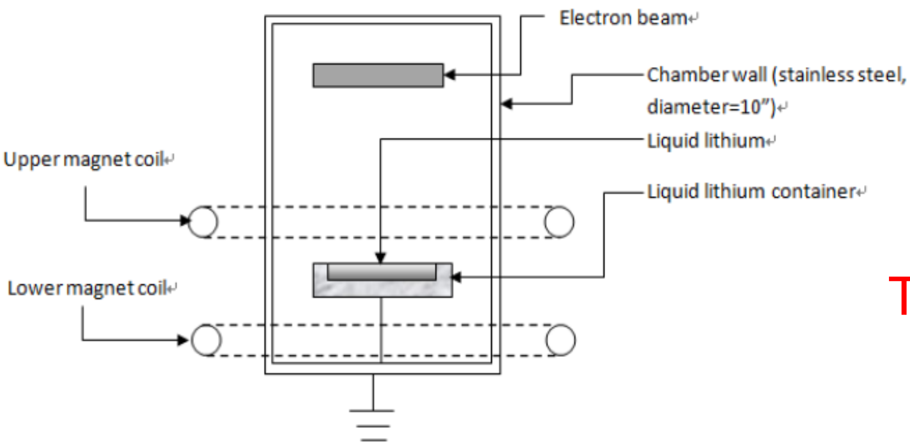
All tests showed TEMHD was responsible for flow

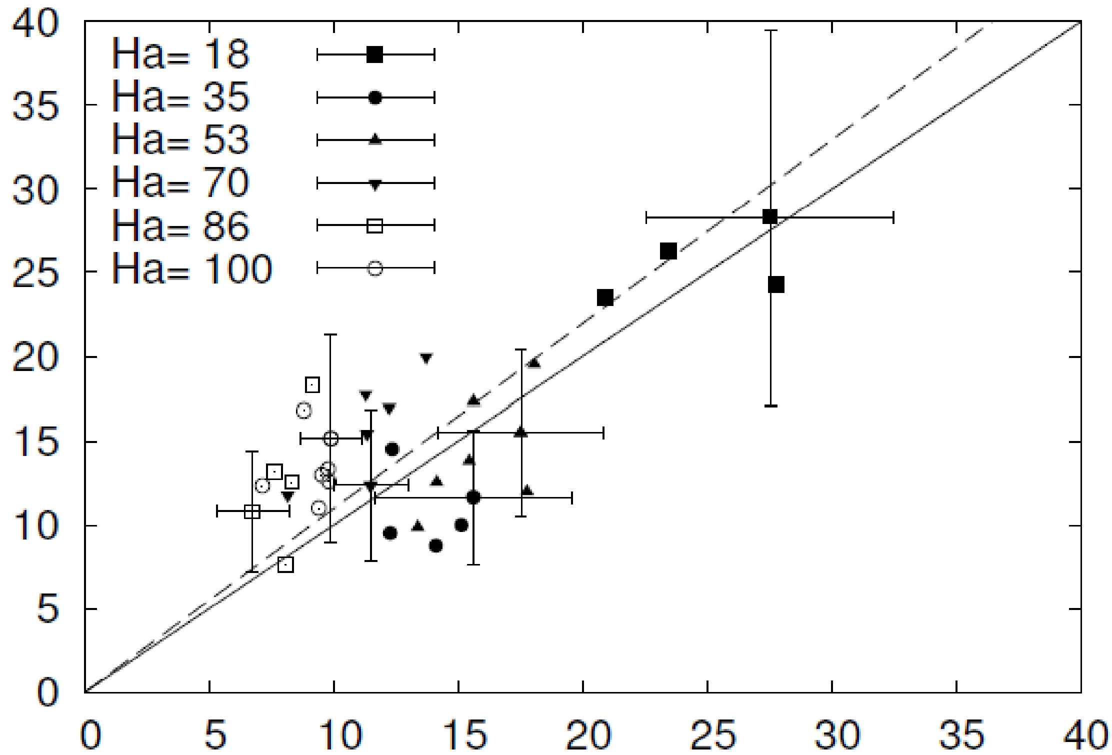
Qualitative SLiDE Results: Velocity

- TEMHD dominated in these cases and moves lithium at predictable velocities.

M.A. Jaworski, et al. Phys. Rev. Lett. 104, 094503 (2010)







Theoretical vs Experimental velocities in cm/s.

Theory matches at all Ha numbers tested

Ratio of TEMHD to TC in SLiDE

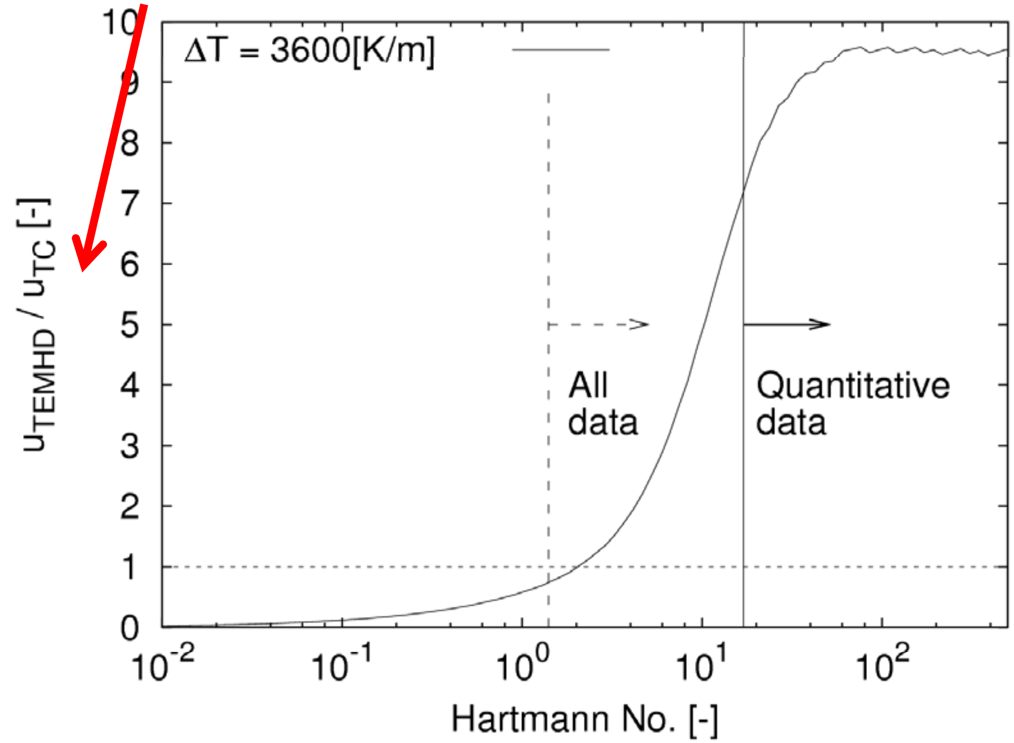
- All quantitative data cases show evidence of swirling flow.
- However, TC was capable of being seen in an oscillatory flow behavior.
  - TEMHD flow distributes heat and smooths out the gradient along the Li – steel interface
  - With no gradient there, only the surface temperature gradient exists, therefore TCMHD until interface gradient builds up again

When the Jaworski number is near 1 and TEMHD and TCMHD (Maragoni effect) are balanced, so flow oscillates between swirling and splitting.

$$\frac{u_{TEMHD}}{u_{TC}} = \frac{P(\sigma\rho\nu)^{1/2}}{\gamma} F(\mathfrak{H})$$

$$\text{where} \quad F(\mathfrak{H}) = \frac{\mathfrak{H} - \tanh(\mathfrak{H})}{\mathfrak{H}\tanh(\mathfrak{H}) + C\tanh^2(\mathfrak{H})}$$

Jaworski Number was always greater than 1 !



Jaworski Number: $\zeta = \frac{P(\sigma\rho\nu)^{1/2}}{\gamma}$

So, What Can You Do With TEMHD ??

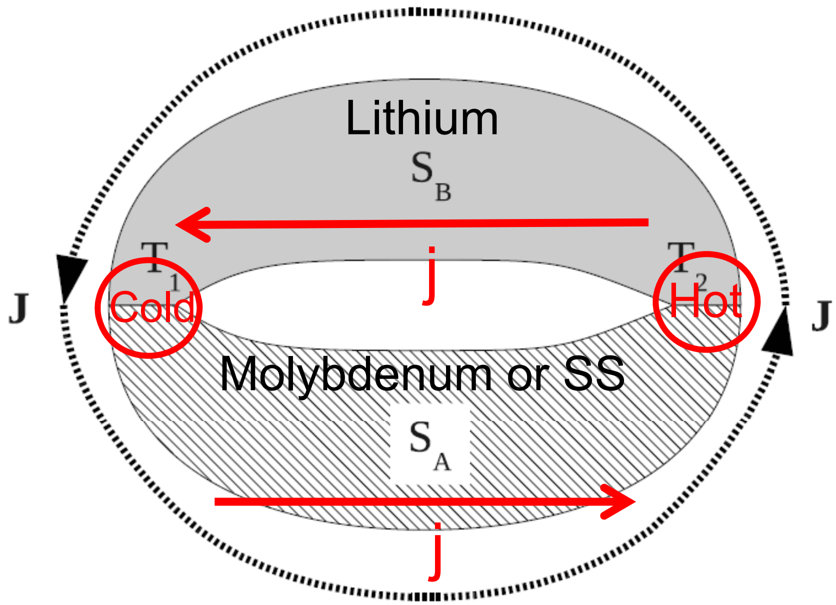
I will show that you can use a lithium PFC to cool something without the lithium evaporating and without a pump.

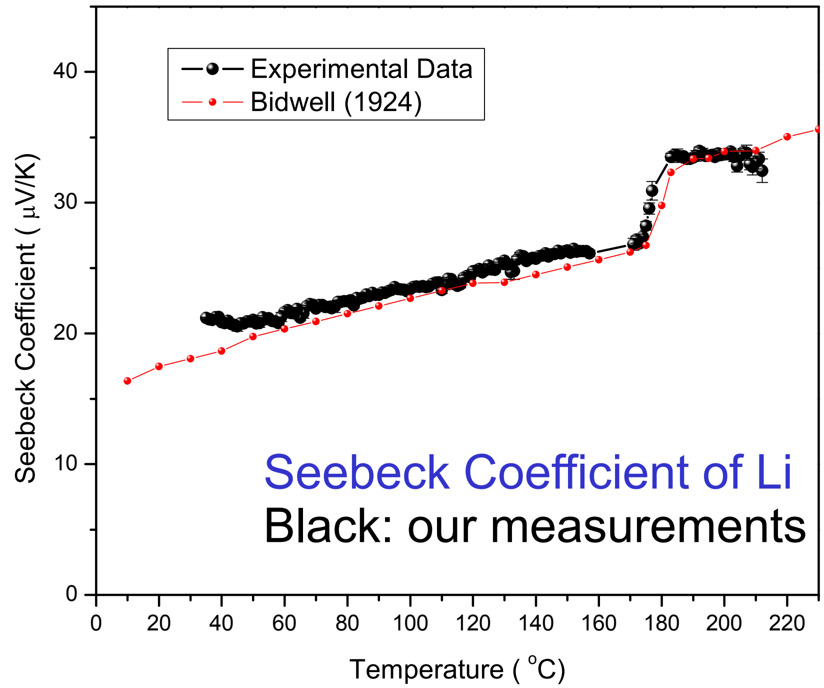
LiMIT: Lithium / Metal Infused Trenches

Outline

- Introduction
- Thermo-Electric MHD seen in SLiDE (Solid/Liquid Divertor Experiment)
- Lithium/Metal Infused Trenches (LiMIT concept)
  - Concept
  - Proof-of-Principle experiments
  - Velocity Measurements
- Analytical Formulation
- Limits on LiMIT
- Conclusion

Thermoelectric effect

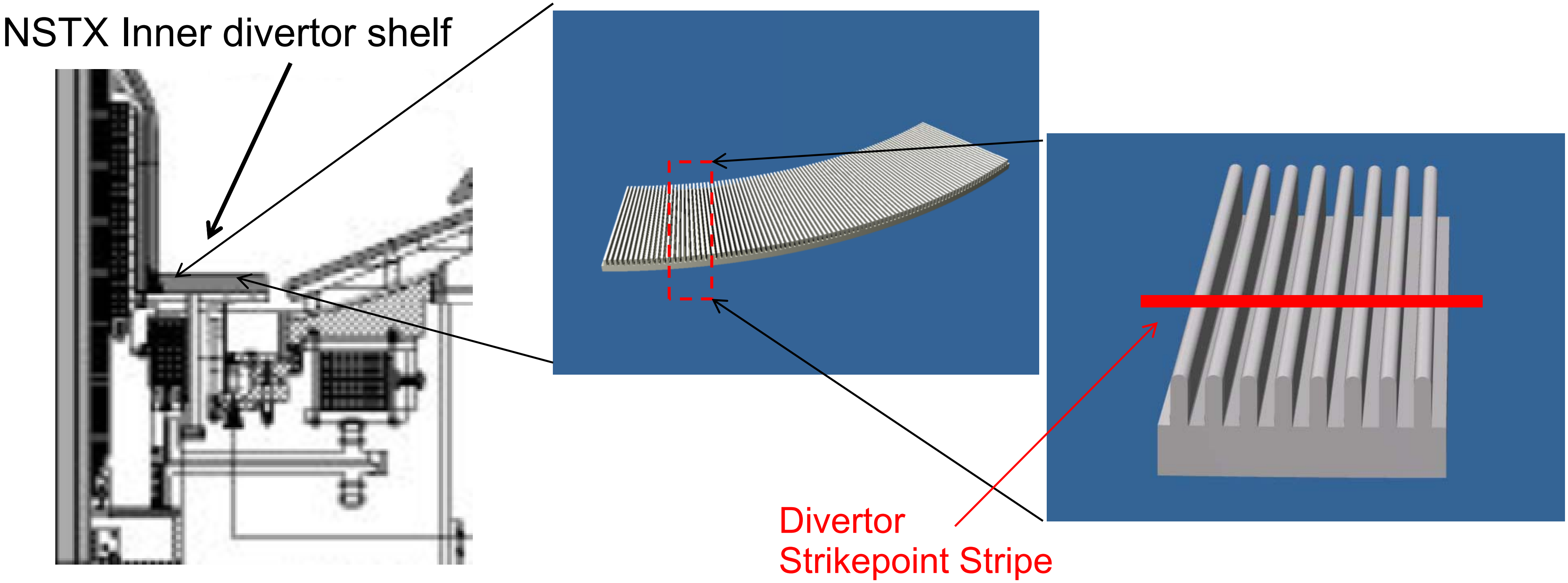




- Like a thermocouple, a voltage is created at a junction of two metals dependent on the temperature.
- A current will flow based on that voltage difference: $j = \sigma \Delta S \Delta T$

where σ is the conductivity, and ΔS is the difference in Seebeck coefficients. There is a large difference in S between Li and most other metals and it increases with T.

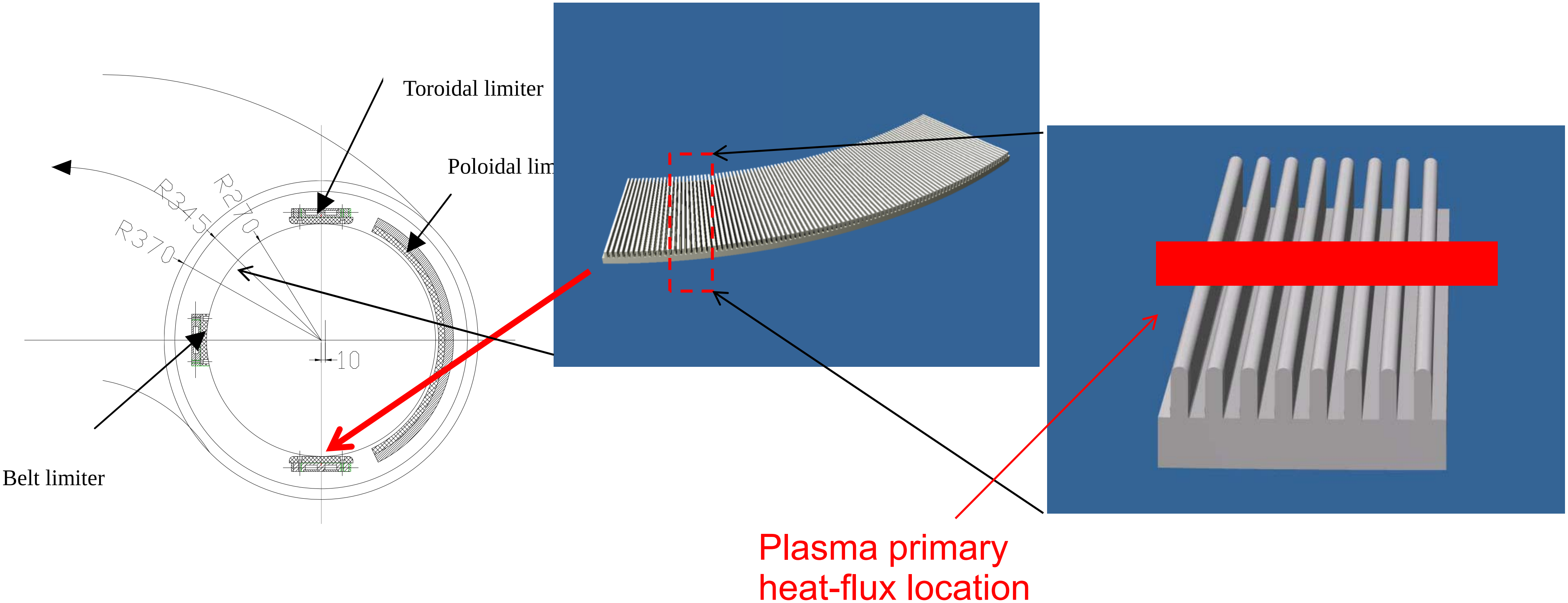
The Idea: "LiMIT" Design in NSTX



- Left is a cross-section of NSTX showing the "shelf-like" inner divertor plates.
- Right is the LiMIT concept: molybdenum tiles with radial trenches containing lithium. The trenches run in the radial (polodial) direction such that they lie primarily perpendicular to the torroidal magnetic field.

The Idea: “LiMIT” Design in HT-7

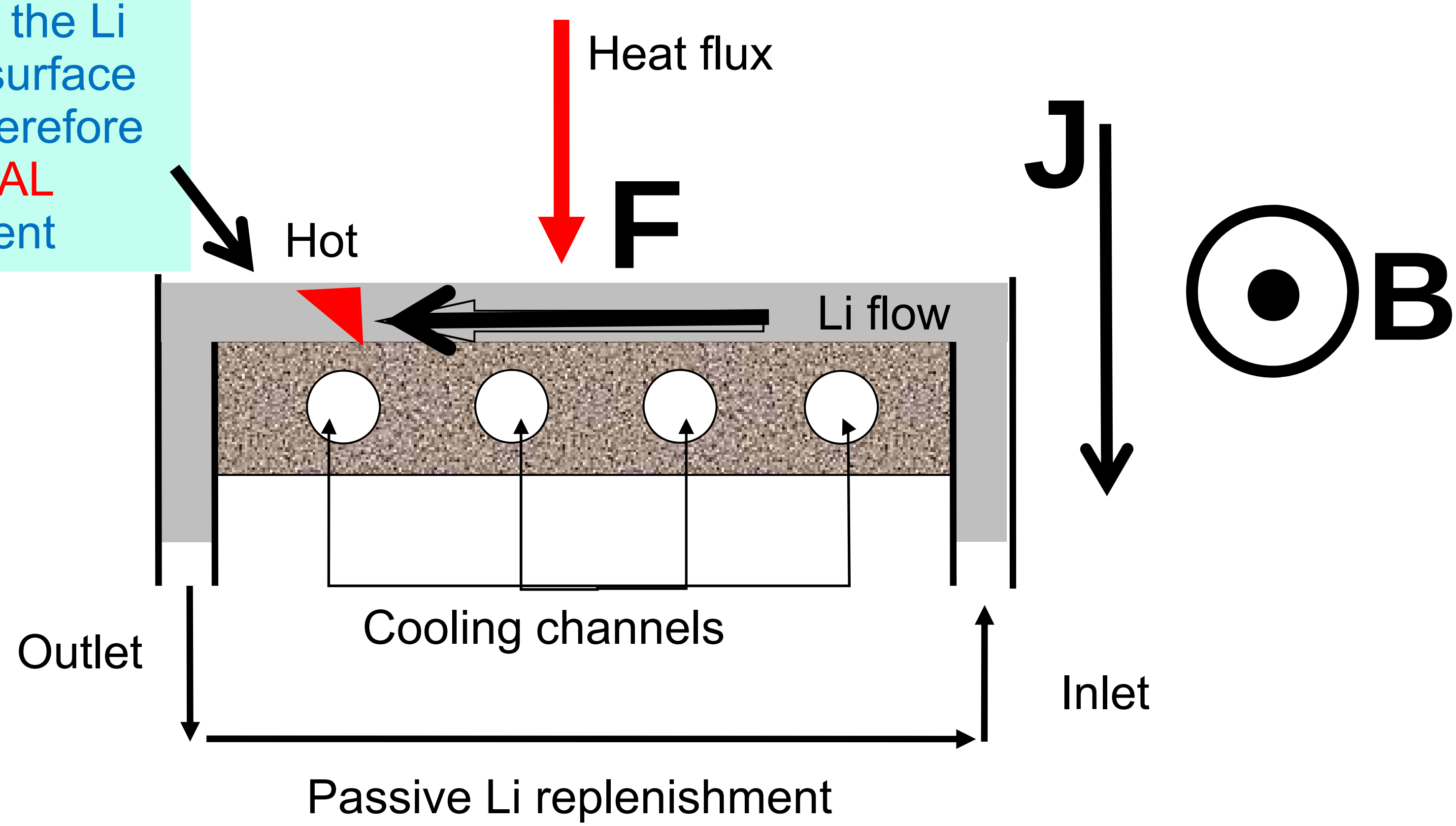
HT-7 Cross-section:



- Left is a cross-section of HT-7 showing the toroidal limiter.
- Right is the LiMIT concept: molybdenum tiles with radial trenches containing lithium. The trenches run in the radial (polodial) direction such that they lie primarily perpendicular to the torroidal magnetic field.

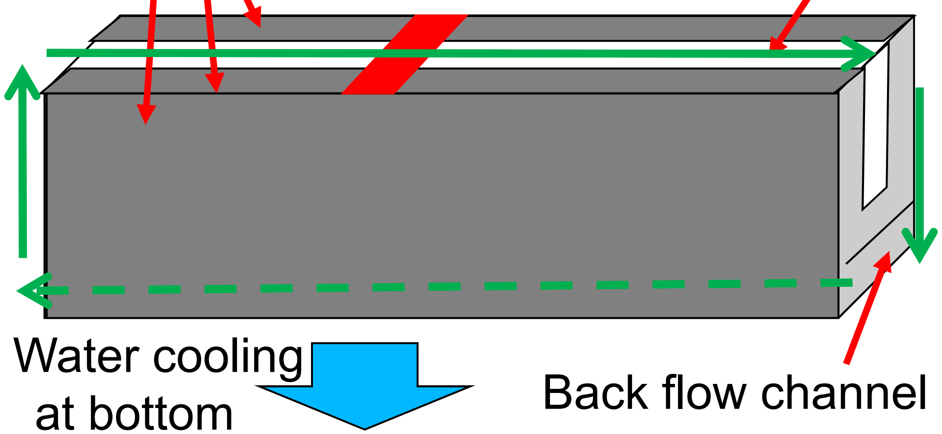
Lithium Flow in the Trenches is Self-Pumping

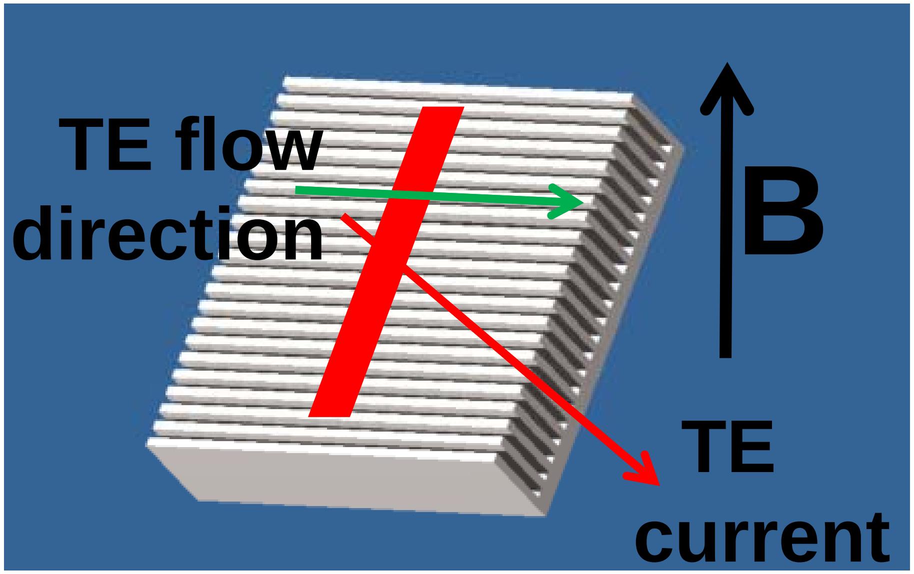
The top surface of the Li is hotter than the surface that is deeper. Therefore there is a VERTICAL temperature gradient



- Concept for heat removal using TEMHD. The Li flows in the slots of the Mo plate powered by the vertical temperature gradient. This vertical temperature gradient generates vertical current, which when "crossed" by the torroidal magnetic field, will create a radial force on the Li driving it along the slot. This flow will transfer the heat from the strike point to other portions of the divertor plate. The bulk of the Mo plate could be actively cooled for a long-pulsed device or passively cooled for something like NSTX. Under the plate the Li flows back naturally.

Initial test in SLiDE

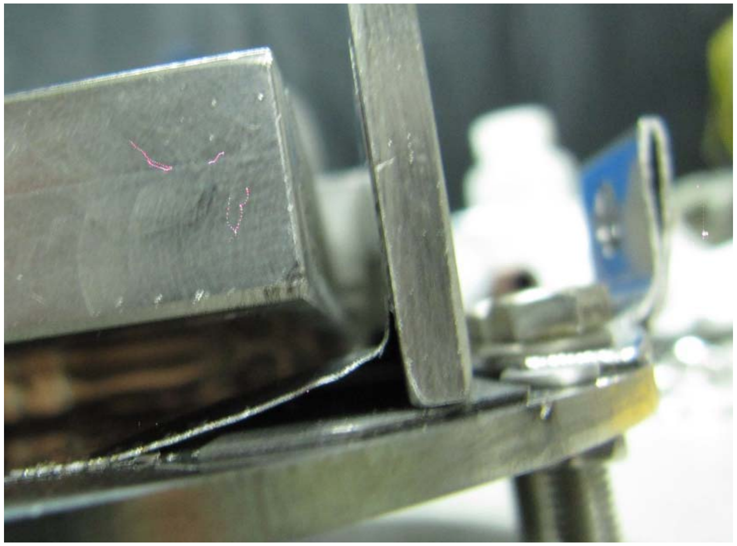




- The SLiDE experiment at Illinois has been reconfigured to test this concept. We expect to be able to show radial flows of Li along radial trenches in a stainless steel plate and measure the flow velocity compared to calculations.
- The lithium tray is tilted to a small angle with the magnetic field. An electron beam is used to provide the heating while the magnet can generate about 600 Gauss magnetic field parallel to the tray surface.
- The trench is 2mm wide, 1cm high and 10 cm long. The back flow channel is 4mm thick.

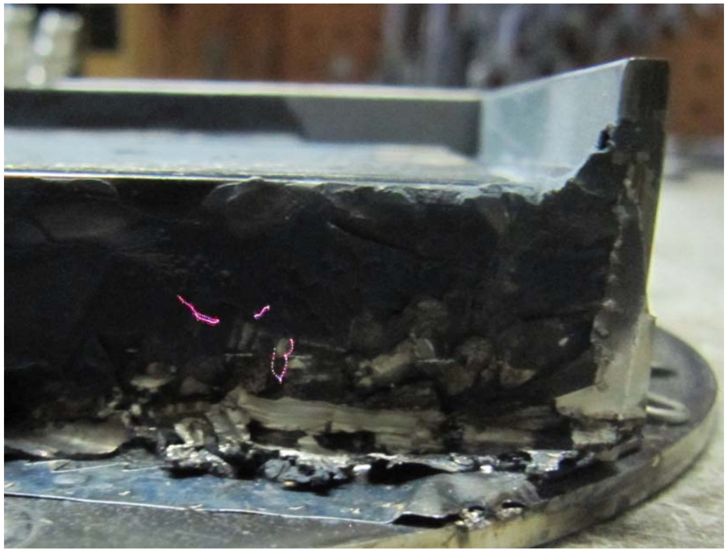
Lithium filled the trench

Stainless Steel “LiMIT” tray trench assembly



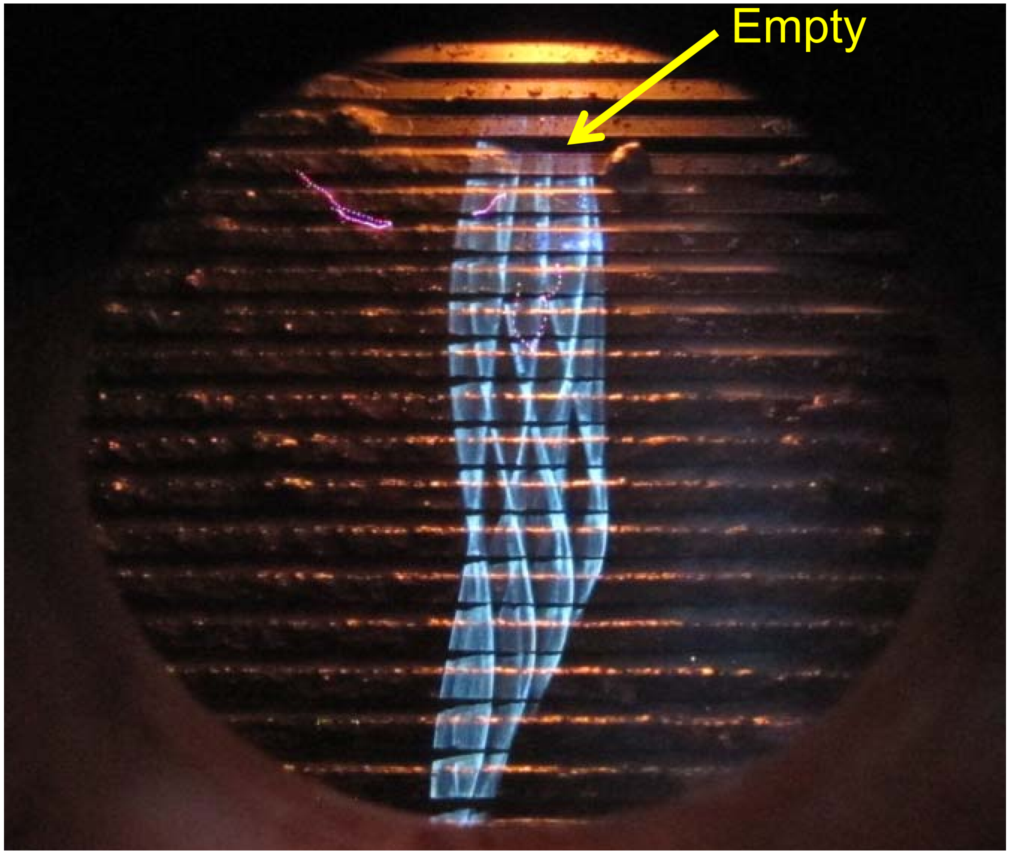
Back flow channel below the trench system

Lithium successfully filled the trenches.

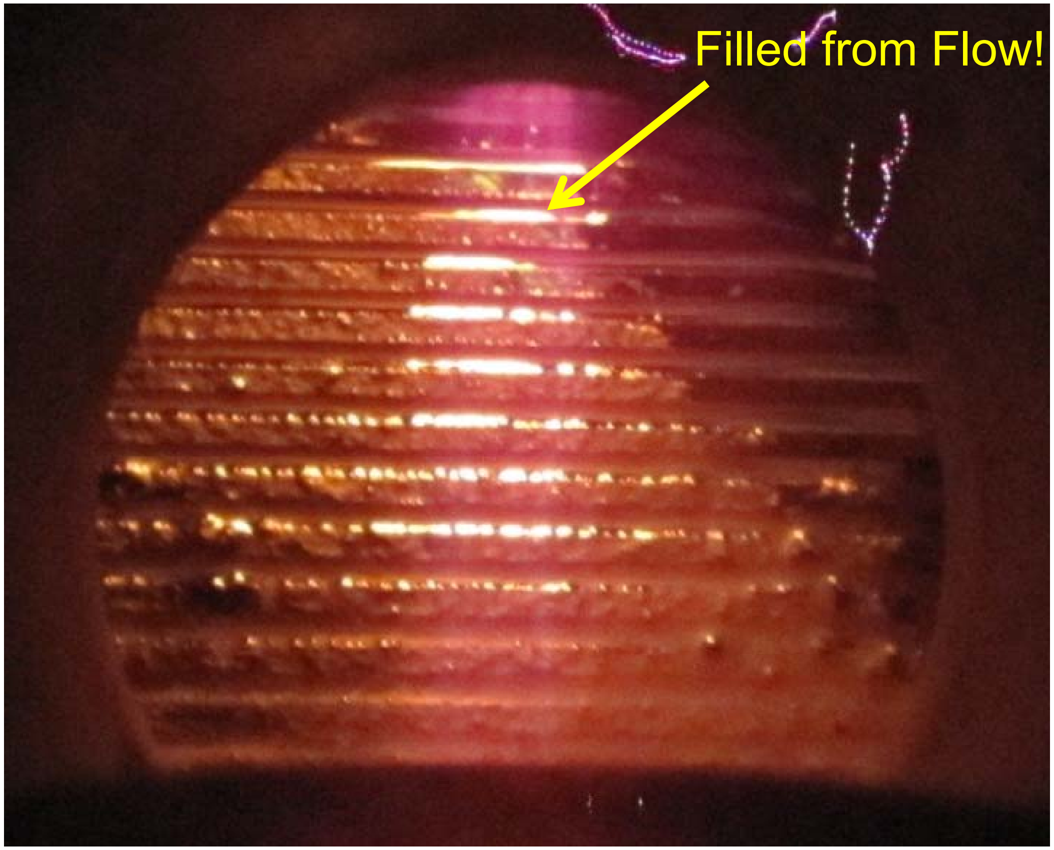


Lithium successfully filled the back flow channel too.

First observation of self-driven flow in the trench



Initial melting of the lithium.
The lines seen are Bremsstrahlung from E-beam.

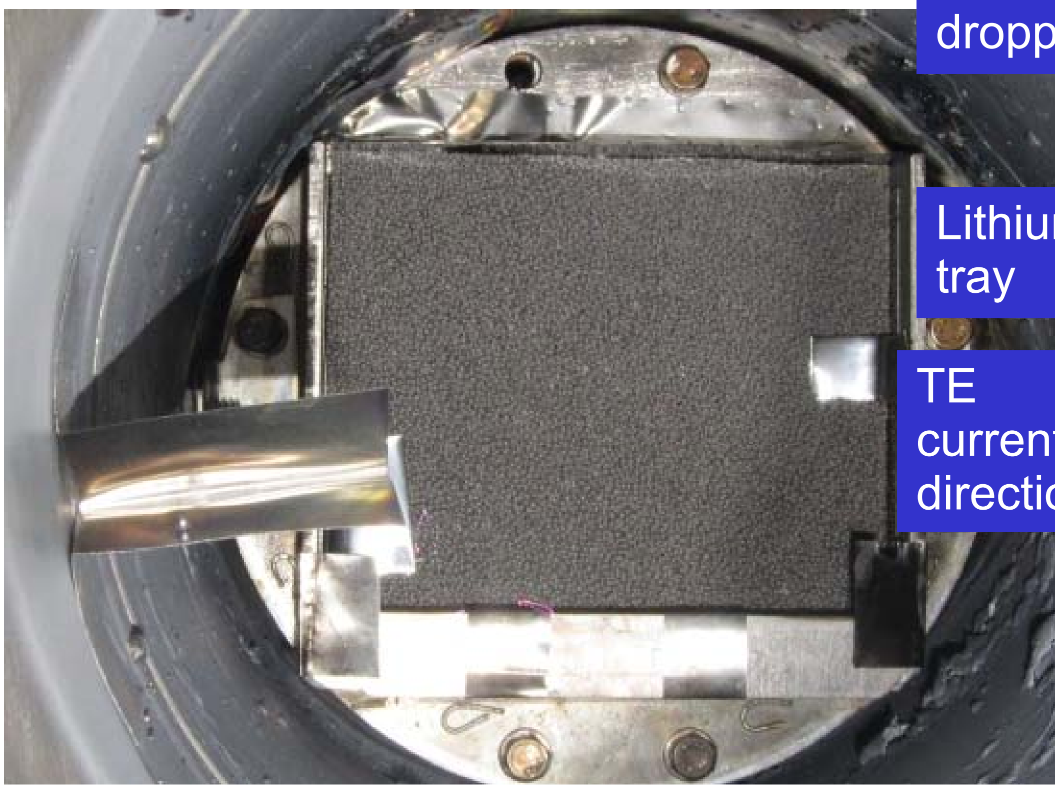


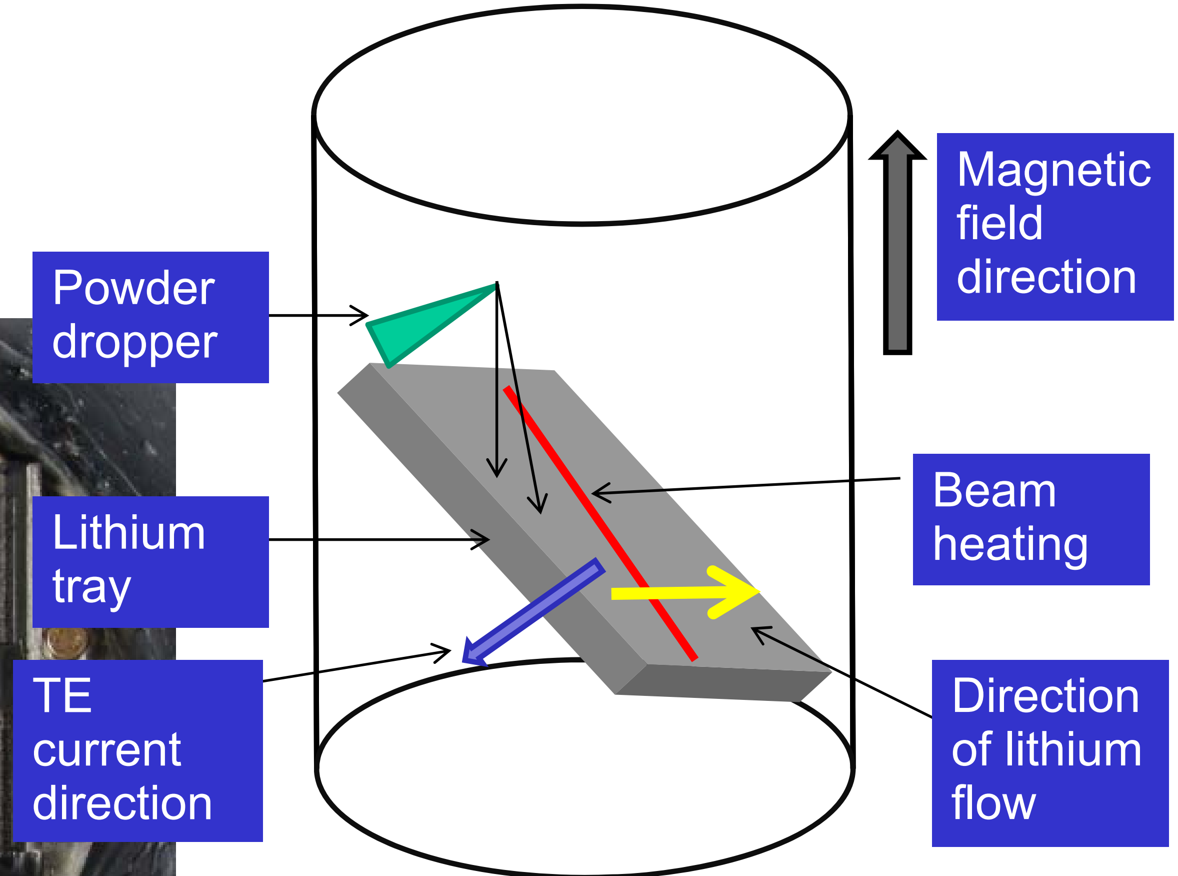
Lithium is totally melted.
Red glow indicative of lithium vapor from heat stripe.

Li flow filled the top trenches

To really observe flow: sprinkle dust on the lithium !

We added a tray to hold some lithiumoxide dust and hit the device with a hammer to knock the dust onto the tray.   It worked !





Show Movie: “moving impurities (top view)”

The top view movies are shot through a mirror, so the flow in these frames is from top to bottom.

[redacted]

Four Frames that Show a Moving Dust Grain

Top-Down view. Due to the mirror, the flow in these pictures is from top to bottom.

This frame by frame video capture allows one particle to be tracked.

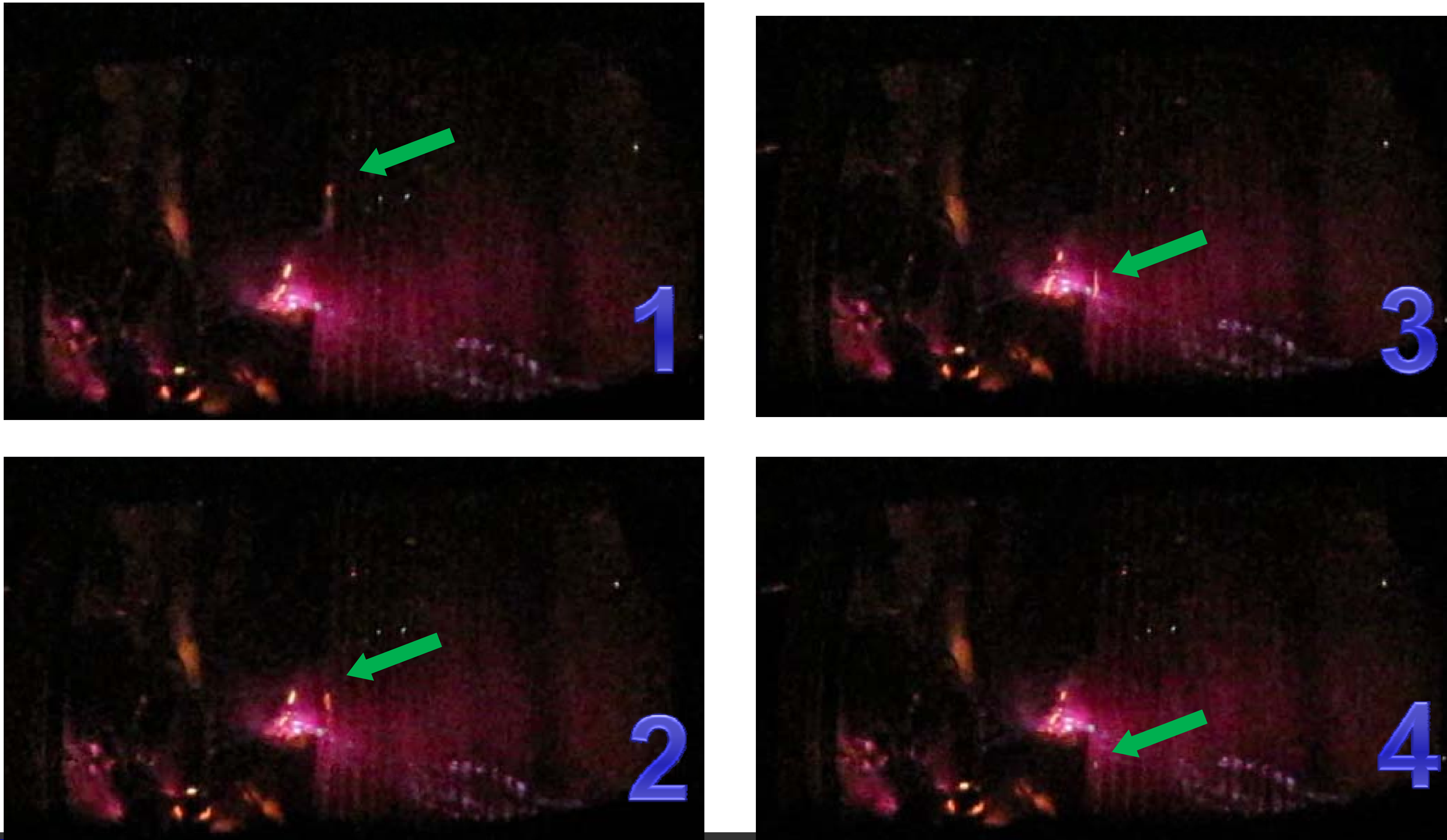
Show Movie: “four-frame sequence (top view)”

The top view movies are shot through a mirror, so the flow in these frames is from top to bottom.

A Different Four-Frame Sequence

This one is first visible even more toward the edge of the tray.

We have movies from the side port as well.



Show Movie: “moving impurities (side view)”

The side view movies are shot looking directly at the tray, so the motion is from left to right.

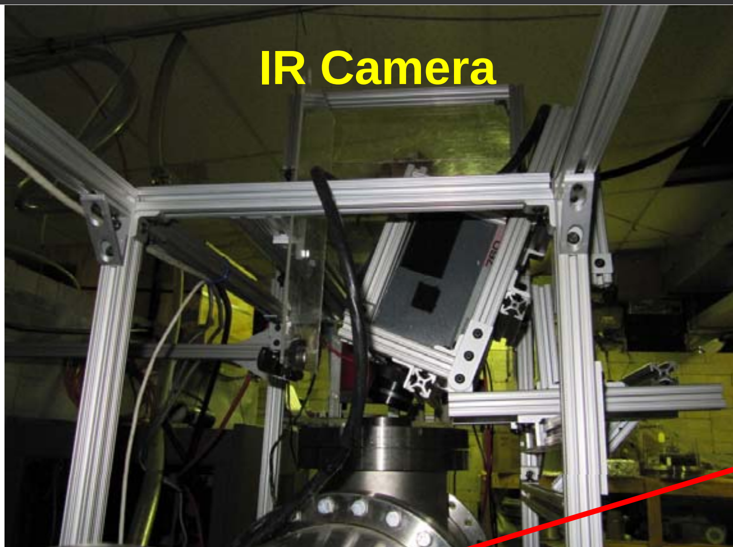
[redacted]

Calculation of the speed of the flow

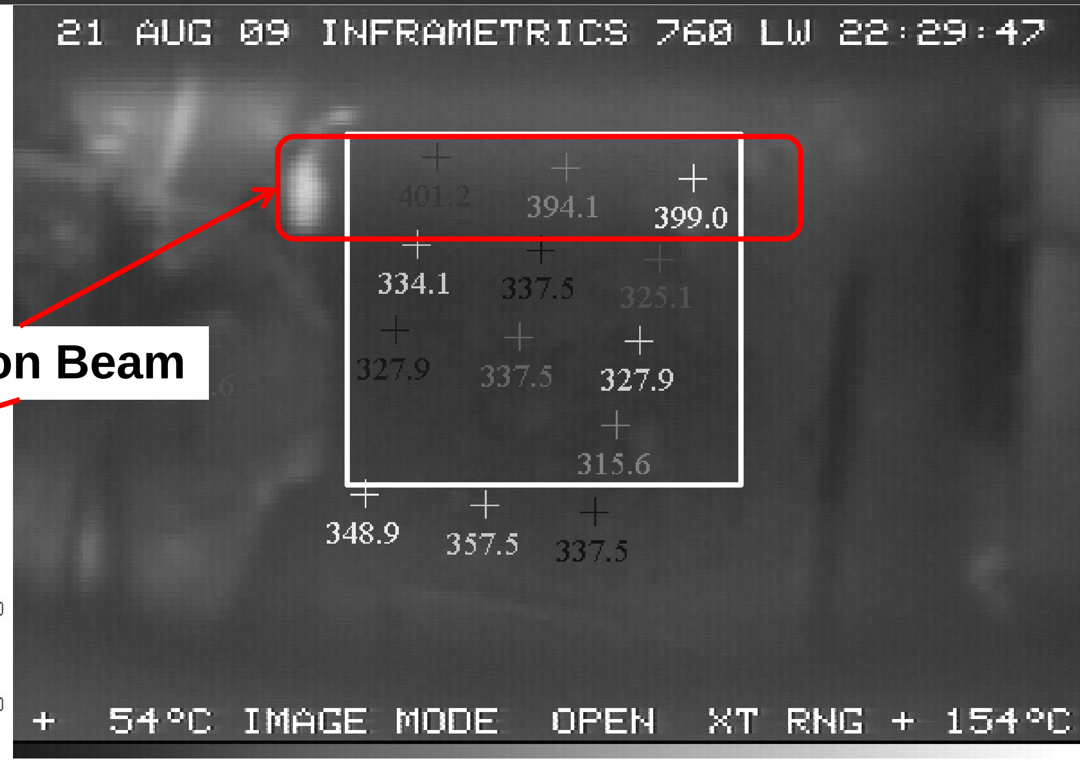
- The time between each frame is 1/25 s. The total length of the moving trace is measured and divided by the time interval.

- From four independent sequences, analyzed by two different methods the flow speed in the channels was determined to be: 22.1 +/- 3.1 cm/s

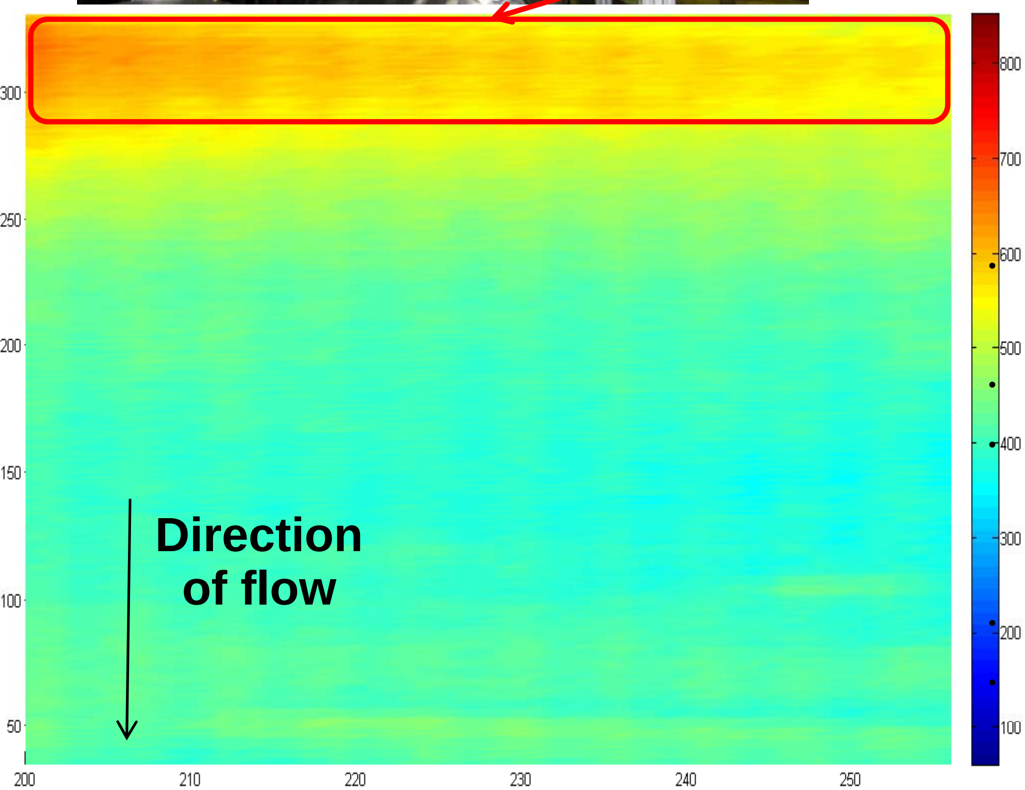
Temperature measurements using IR Camera



Degrees C shown at right



Electron Beam

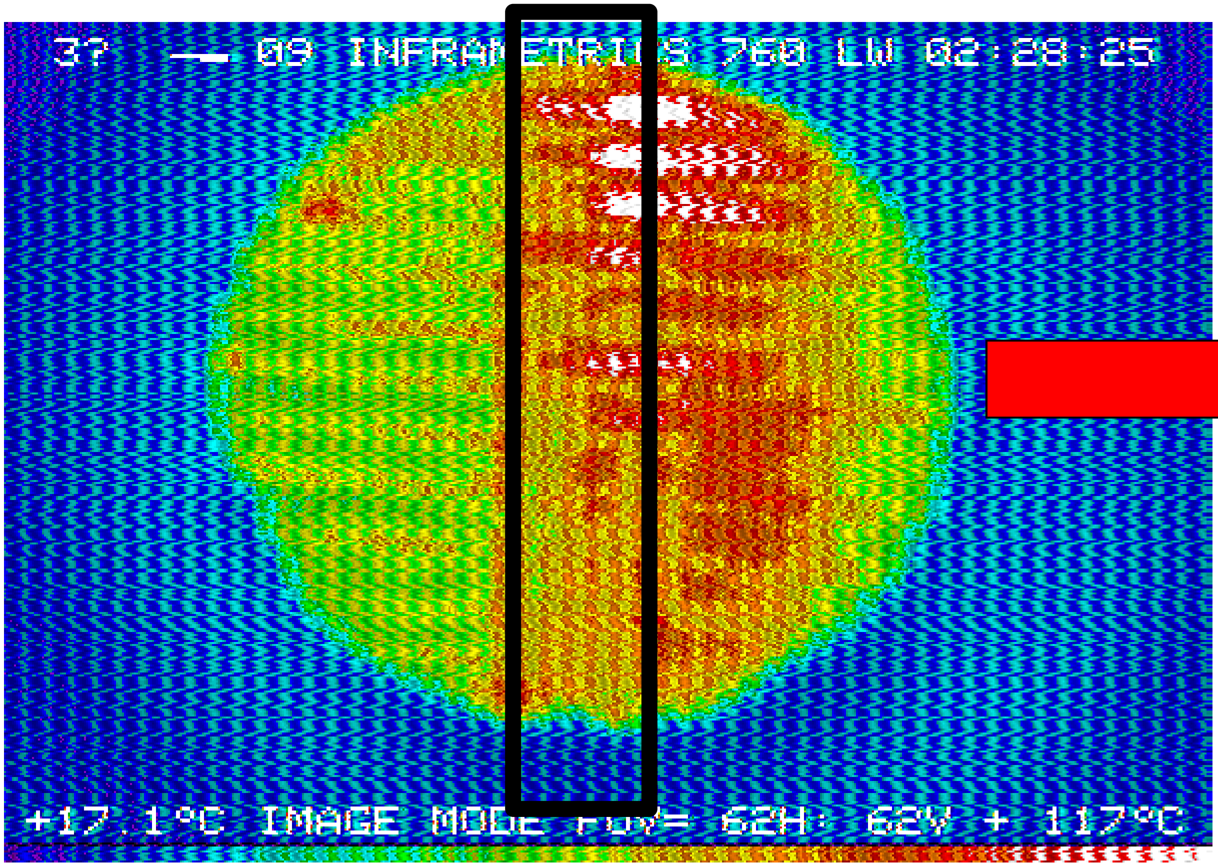


- IR camera used to measure the surface temperature of the trenches
- Above is the raw image seen by camera
- A mask is applied to the region around the trench because of the difference in emissivity of stainless steel and lithium
- Left is a RGB plot from the camera (in K)
- Camera and window from Sandia National Lab- Albuquerque. Thanks Dennis Youchison!

IR pictures of Stainless Steel (400 W)

Note that rf interference in this picture produced the vertical lines and waviness

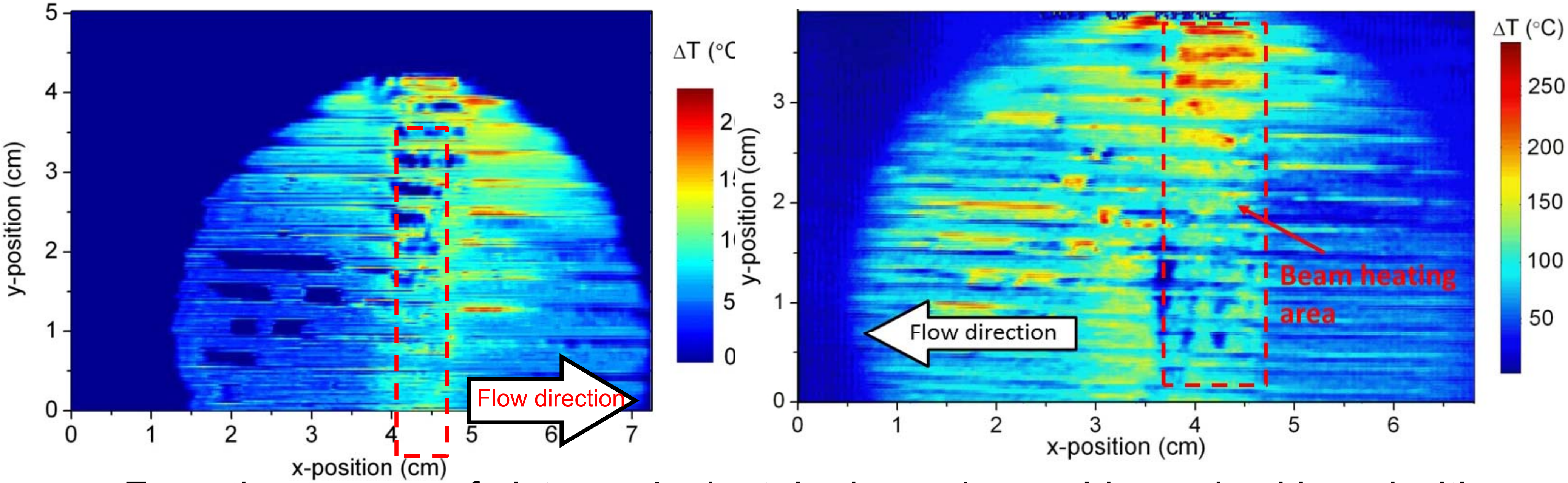
Electron Beam Heat Stipe



Lithium Flow Direction

Heat clearly moves to the right – the direction of the TEMHD lithium flow

IR measurements switching magnetic field



- From these types of pictures, look at the heat along a Li trench with and with out heating then compute the temperature difference.
- Assume that energy is mostly transferred out by convection and use:

$$u = \frac{q}{\rho C_P h w (\frac{\Delta T}{2})}$$

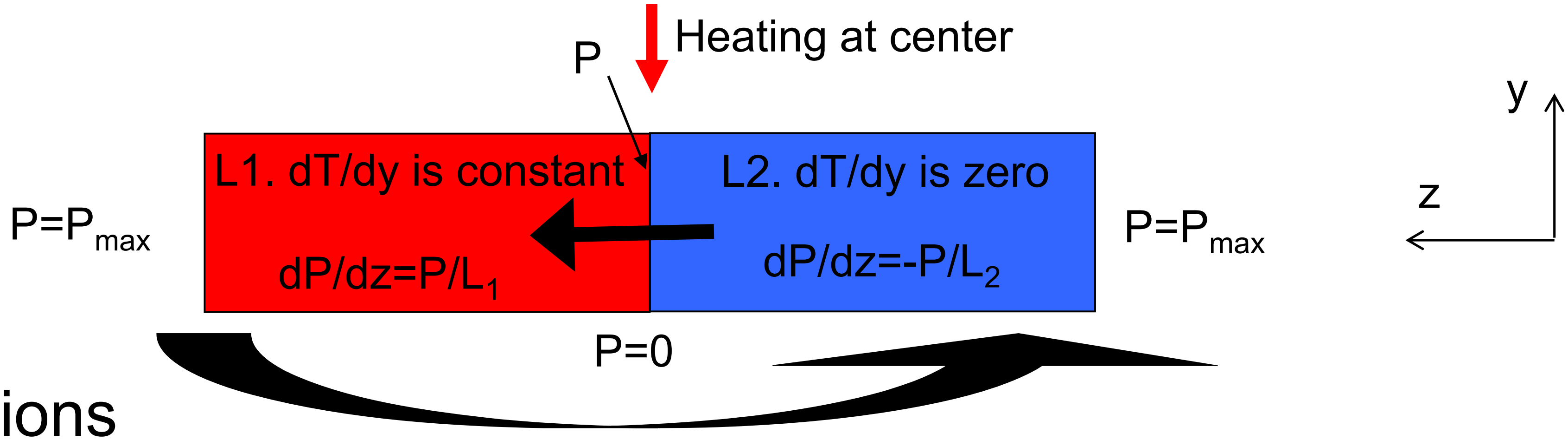
- Here q is the power absorbed by a single trench. ρ is the density of lithium. C_P is the heat capacity of lithium. h is the height of the trench and w is the width of the trench. ΔT is the temperature difference between the inlet and outlet temperature

Result: Velocity: 0.15 +/- 0.07 m/s

Outline

- Introduction
- Thermo-Electric MHD seen in SLiDE (Solid/Liquid Divertor Experiment)
- Lithium/Metal Infused Trenches (LiMIT concept)
  - Concept
  - Proof-of-Principle experiments
  - Velocity Measurements
- Analytical Formulation
- Limits on LiMIT
- Conclusion

2-D Theoretical Model



- Assumptions
  - The velocity, $u(y)$, is constant in z. Pressure P is linear in z.
  - Lithium flows out of the left side outlet and then flows into the right side inlet.
  - After the heating stripe hits at a single point making the temperature gradient along the y direction discontinuous. It is constant on the left hand side will become zero after the lithium flows back to the right inlet.
  - The velocity (averaged over y) are continuous in z.

Guiding Equations

- 1D Navier-Stoakes equation (assume a constant pressure gradient) and Ohm's Law. J_s is the current due to the thermoelectric force. σ is the conductivity of the lithium and μ is its viscosity.

$$\mu \frac{d^2u}{dy^2} - \frac{dP}{dz} = jB \qquad j = \sigma B u + j_s$$

- Boundary conditions
  - At y=0 which is the bottom of the trench, the speed, u is zero. u(0)=0
  - At y=h, the free surface boundary condition requires $\frac{du(h)}{dy} = 0$
- Following Shercliff, from these equations we can get

$$u(y) = -\frac{1}{\sigma B^2}(Bj_s + \frac{dP}{dz})(1 - \frac{\cosh(Ha(1 - y/h))}{\cosh(Ha)})$$

where

$$Ha = hB\sqrt{\sigma/\mu}$$

- Integrating from y=0 to y=h, the mean velocity is: $\bar{u} = -\frac{1}{\sigma B^2}(Bj_s + \frac{dP}{dz})(1 - \frac{\tanh(Ha)}{Ha})$

Solving for the current

- The width of the lithium trench is w. The width of the metal return leg is t. Therefore from conservation of current

$$\sigma B u + j_s = -(t / w)\, j_w$$

- Kirchhoff's Law gives:

$$\frac{j_w}{\sigma_w} - \frac{j_s}{\sigma} = S \frac{dT}{dy}$$

where S is the thermoelectric coefficient

- From above we can express the mean velocity of the TEMHD driven flow without referring to j:

$$\bar{u} = \frac{Ha - \tanh(Ha)}{Ha + C \tanh(Ha)} \left(\frac{S}{B} \frac{dT}{dy}\bigg|_z - \frac{1+C}{\sigma B^2} \frac{dP}{dz} \right)$$

where

$$\mathrm{C} = \frac{w \sigma_{Li}}{t \sigma_{SS}}$$

Finding the Pressure

- Assume the length of the left region is L_1 and that of the right region is L_2. Total length is $L = L_1 + L_2$.
- Assume the pressure changes linearly in each region.
- Based on these assumptions we can get the average velocity in the left region as

$$\bar{u}_{left} = \frac{Ha - \tanh(Ha)}{Ha + C\tanh(Ha)}\left(\frac{S}{B}\frac{dT}{dy}\bigg|_{left} - \frac{1+C}{\sigma B^2}\frac{dP}{dz}\bigg|_{left}\right)$$

- And the average velocity in the right region is

$$\overline{u_{right}} = -\frac{1}{\sigma B^2}\left(\frac{dP}{dz}\bigg|_{right}\right)\left(1 - \frac{\tanh(Ha)}{Ha}\right)$$

- From the continuity average velocity assumption we get

$$\frac{Ha - \tanh(Ha)}{Ha + C\tanh(Ha)}\left(\frac{S}{B}\frac{dT}{dy} - \frac{1+C}{\sigma B^2}\frac{P}{L_1}\right) = \frac{1}{\sigma B^2}\frac{P}{L_2}\left(1 - \frac{\tanh(Ha)}{Ha}\right)$$

- Which can be solved for P_{max}:

$$P_{\max} = \frac{\sigma S B \dfrac{dT}{dy}\bigg|_{left}}{\dfrac{Ha + C\tanh(Ha)}{Ha} * \dfrac{1}{L_2} + \dfrac{1+C}{L_1}}$$

Velocities

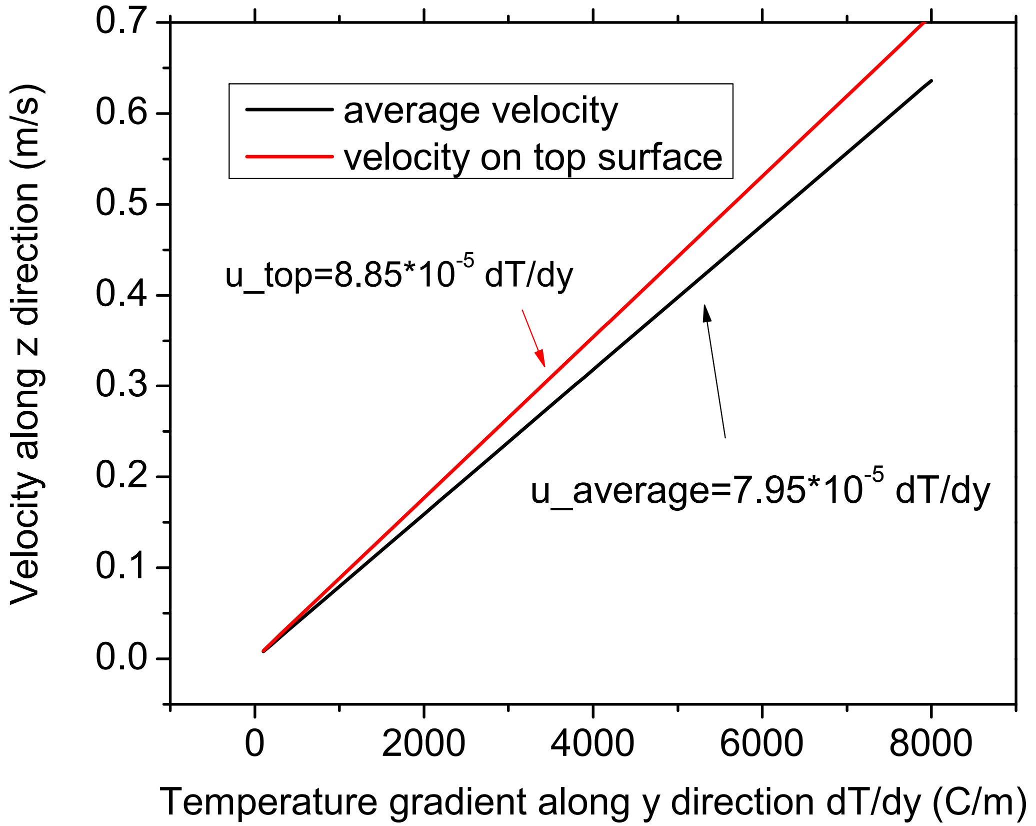
- Substituting P_{max} back into the average velocity gives

$$\bar{u} = \frac{S}{B}\frac{dT}{dy}\frac{1}{\dfrac{Ha + C\tanh(Ha)}{Ha} + \dfrac{(1+C)L_2}{L_1}}\left(1 - \frac{\tanh(Ha)}{Ha}\right)$$

- And the velocity on the top surface

$$u(h) = \frac{S}{B}\frac{dT}{dy}\frac{1}{\dfrac{Ha + C\tanh(Ha)}{Ha} + \dfrac{(1+C)L_2}{L_1}}\left(1 - \frac{1}{\cosh(Ha)}\right)$$

- Using our values of S, B, Ha, w, t, L_1 and L_2, the average and top velocity can be plotted vs the vertical temperature gradient.



How to find the temperature gradient

- A way to estimate the temperature gradient is based on the energy conservation.
- Assume that the absorbed energy could transfer in two ways: 1D heat conduction along y direction in left region and 1D convection along the entire z direction.
- Power balance equation:

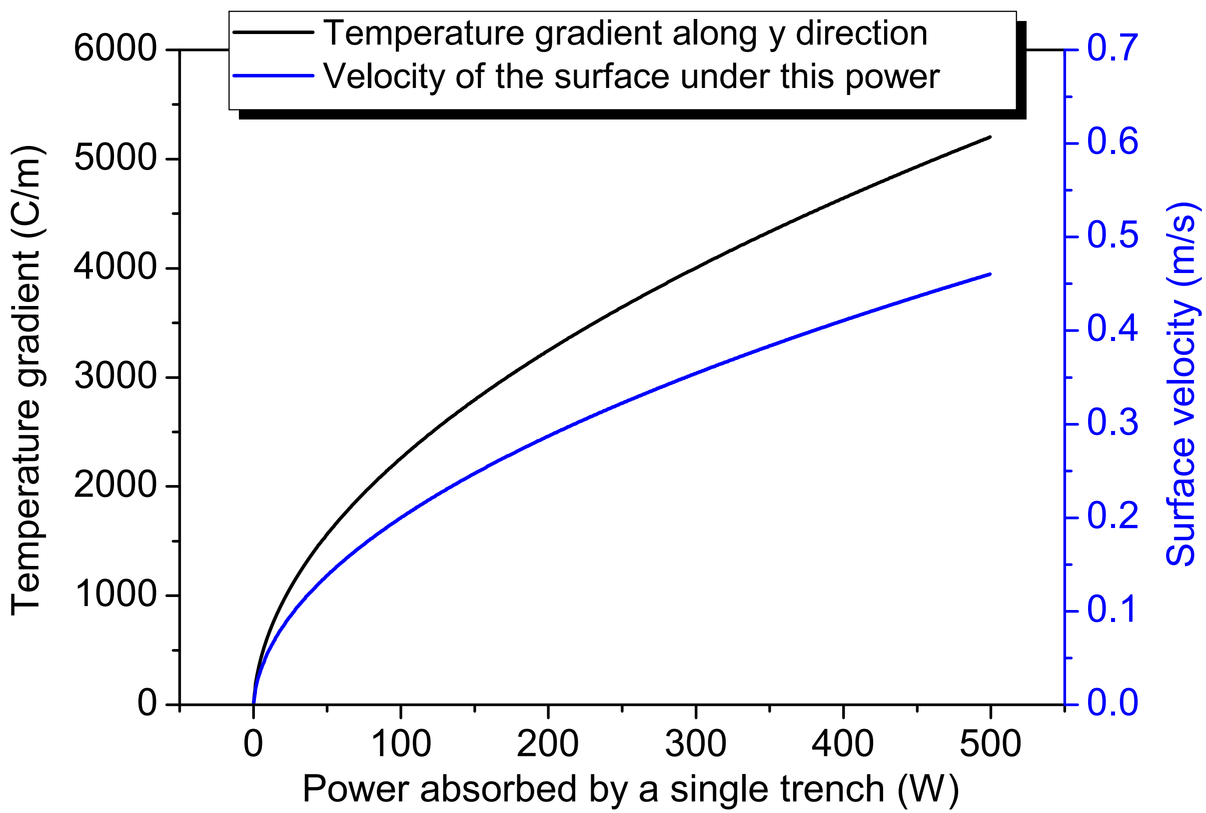
$$Q = k\frac{dT}{dy}L_1 w + \rho C_P\left(\frac{1}{2}\frac{dT}{dy}h\right)\bar{u}hw$$

- Q is the power that is absorbed by a trench and the first term on the right is the heat conduction. The second term on ther right is the convection and $\frac{1}{2}\frac{dT}{dy}h$ is assumed to be the average temperature.

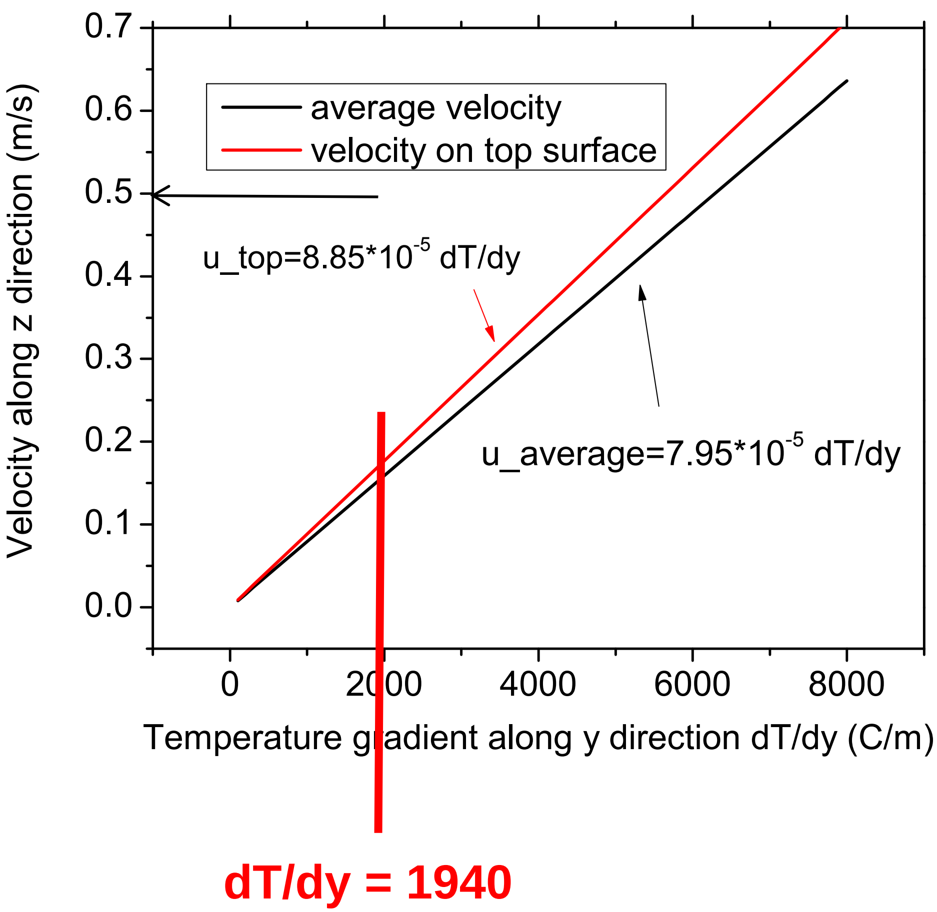
Temperature gradient and velocity vs Power

- After we plug the average velocity into the previous equation we can get a quadratic equation for dT/dy as a function of Q

$$\frac{1}{2}\rho C_P h^2 w\left[\frac{S}{B}\frac{1}{\frac{Ha+C\tanh(Ha)}{Ha}+\frac{(1+C)L_2}{L_1}}\left(1-\frac{\tanh(Ha)}{Ha}\right)\right]\left(\frac{dT}{dy}\right)^2+kL_1 w\frac{dT}{dy}=Q$$

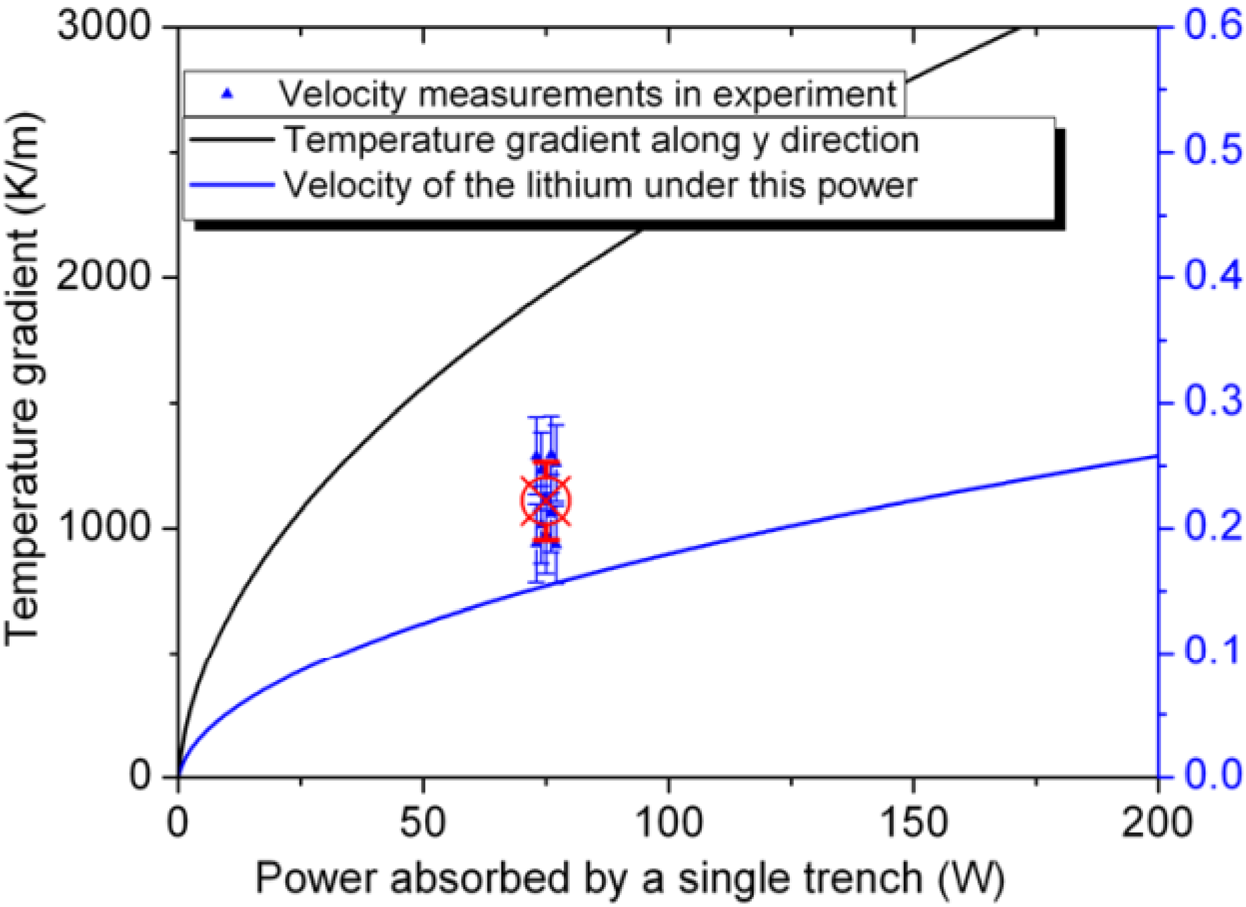


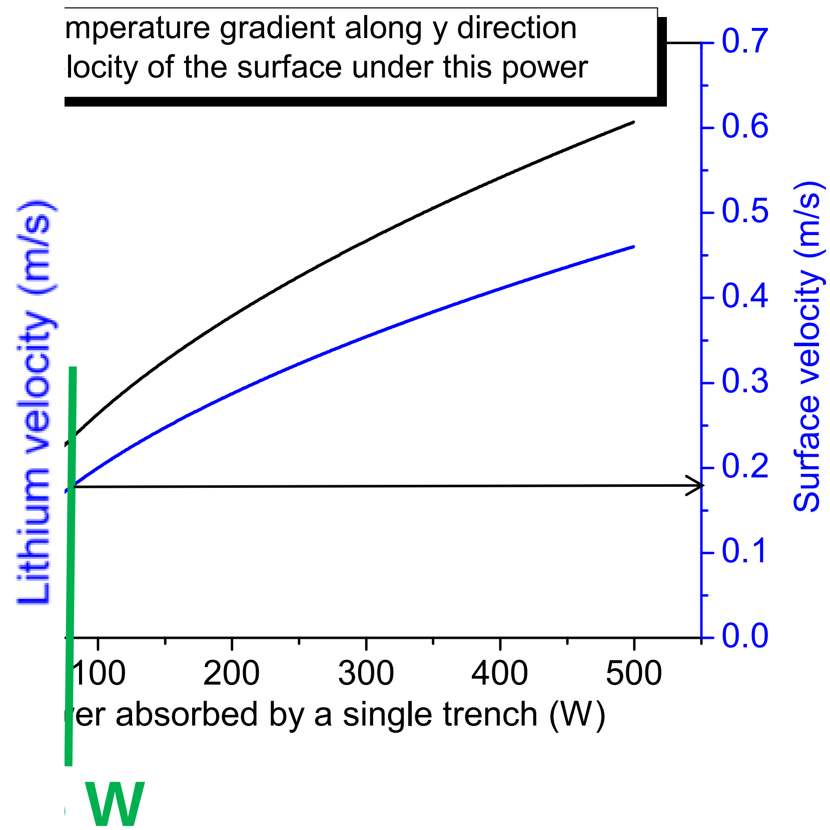
What is dT/dy for our experiment?



- In our experiment we used 1500W heating power and 0.059T magnetic field. The corresponding Ha is 9.86. h=0.01m and w=0.002m. L_1 is assumed to be half of the trench length so L_1 is 0.05m. Since we have 20 total trenches in the tray, the energy absorbed by each trench is 75W.
- ρ is the density of lithium, C_p is the heat capacity of lithium and k is the heat conductivity of lithium.
- Solving the above equation we get a dT/dy of 1940 C/m.

Comparison of Theory to Experiment





Predicted velocity by the analytic model is 0.18 m/s.

Measured velocity from movies is 0.22 +/- 0.03 m/s

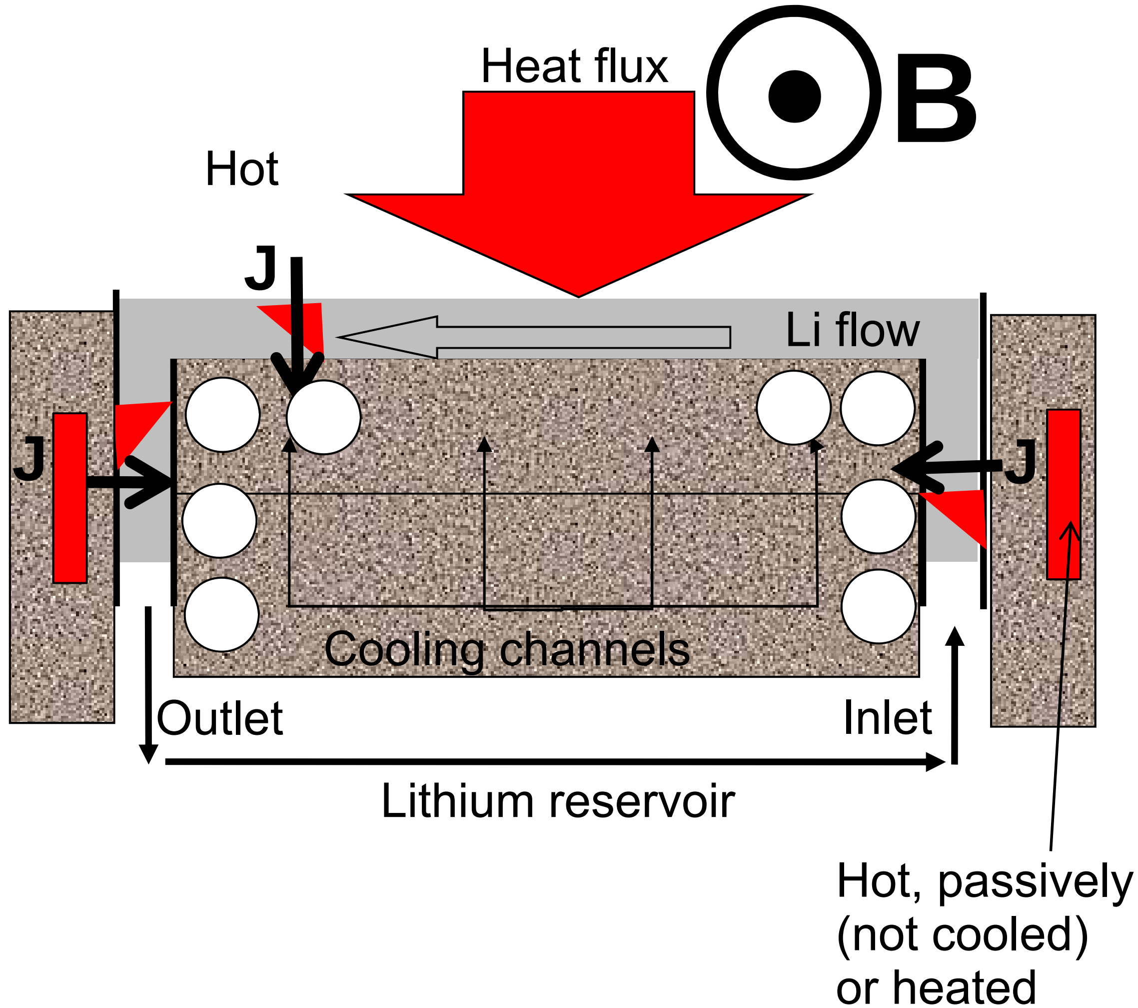
Velocity inferred from IR measurements is 0.15 +/- 0.07 m/s

Outline

- Introduction
- Thermo-Electric MHD seen in SLiDE (Solid/Liquid Divertor Experiment)
- Lithium/Metal Infused Trenches (LiMIT concept)
  - Concept
  - Proof-of-Principle experiments
  - Velocity Measurements
- Analytical Formulation
- Limits on LiMIT
- Conclusion

Limits on LiMIT: High Field

- Flow against a high field (from Leonid's talk -- next). Need to maintain temperature gradient even outside of the plasma heat flux zone.
- How: utilize TEMHD in the return flow legs too:
- In a limiter machine such as HT-7, this is easier



Limits on LiMIT: Ejection Force

- Temperature gradient in radial direction (poloidally along divertor) causes a thermoelectric current in the radial direction.
- This causes a force upward (or downward).
- The capillary force from the side walls balances this ejection force, which is why the channels have to be narrow (or flame sprayed to give more surface area)

$$j_{TEMHD\parallel} = \frac{1}{1+C}\sigma S \frac{dT}{dz}$$

For dT/dz = 2000 C/m, and C and S from earlier, the parrallel current is 9 $\times 10^4$ A/m^2 .

The total current along the Li trench is then 0.45A and the force from the TEMHD is 0.045N upward.

The capillary force is 0.3N/m at 300 ^{o}C. So the capillary force which constrains ejection is about 0.06N.

The capillary force is larger so Li won't be ejected into the plasma.

Limits on LiMIT: Heat Flux

- Heat can be removed in three ways. I will use Leonid Zahkarov’s back-of-the envelope numbers here:

  - By convection with the Li flow

    $$Q^{TE}_{\perp,MW/m^2} < \frac{6}{B_\phi}\frac{0.225}{L_m}\left(\frac{\Delta T}{200^0}\right)^2 .$$

    For NSTX ~ 24 MW/m^2

    For HT-7 ~ 6 MW/m^2

  - Conduction through the metal (SS)

    $$Q^{SS,\nabla T}_{\perp,MW/m^2} \simeq \frac{1.5}{h_{mm}}\frac{\Delta T^{SS}}{100^o}$$

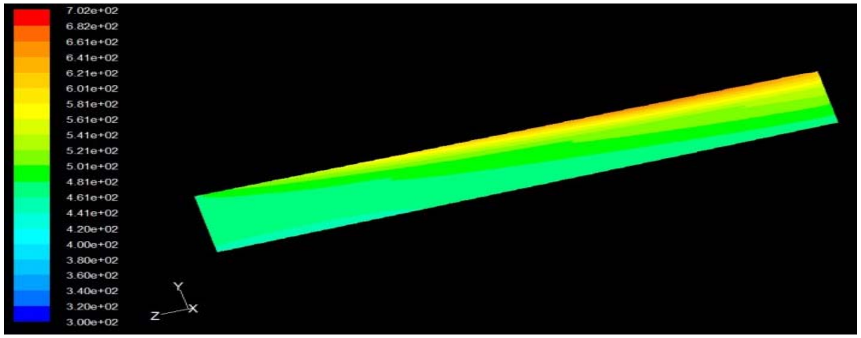
    For NSTX or HT-7 ~ 3 MW/m^2

  - Conduction through the lithium

    $$Q^{\nabla T}_{\perp,MW/m^2} = \frac{9.52}{h_{mm}}\frac{\Delta T}{200^o}$$

    For NSTX or HT-7 ~ 10 MW/m^2

The real way to do this is with a 3-D Fluent calculation:



Conclusions

- Experiments have shown that TEMHD can remove heat fluxes using flowing lithium. Lithium flows fast enough to present a clean surface to the plasma, ready to absorb D.
- The more heat that hits the lithium, the faster the LiMIT system will take the heat away. TEMHD may be able to be used to drive flow in return legs as well to overcome magnetic drag from high fields.
- Both LTX at PPPL and HT-7 in Hefei have expressed interest in testing this LiMIT concept soon. It would also be possible for the NSTX upgrade.
- Using TEMHD to remove high-heat-flux may allow a low-recycling, lithium PFC solution for the future of fusion which could lead to a smaller / cheaper / better reactor.