Demonstration of **High Heat Flux Removal** utilizing **Flowing Lithium** with the **LiMIT** (Lithium/Metal Infused Trenches) Concept

Feb. 16, 2011 VLT Conference Call

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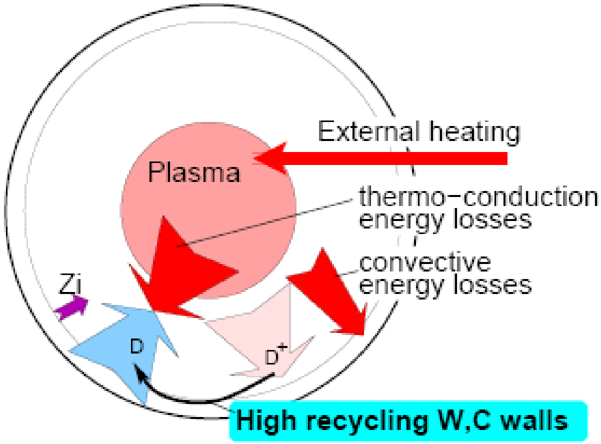
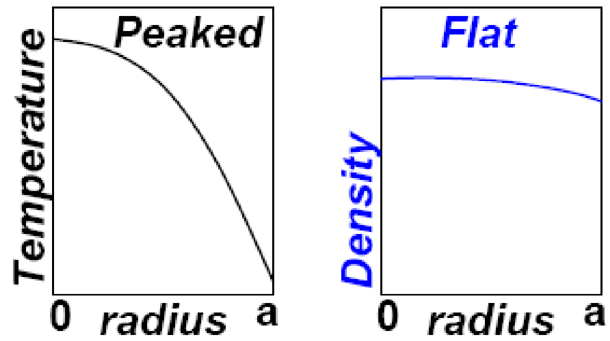
What Very-Low Recycling Does for Fusion

No cold hydrogen returns from wall: Plasma stays hot

Standard Case



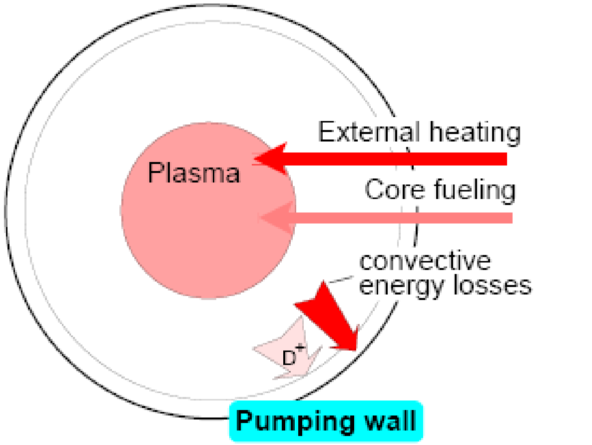
BBBL70 requires a low temperature plasma edge



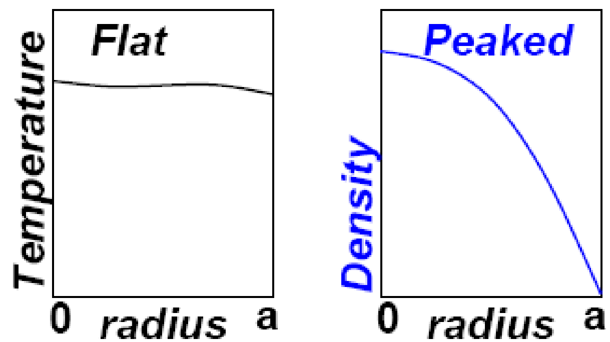
As a "gift" from plasma physics BBBL70 gets ITG/ETG turbulent transport.

Bad core and edge stability (saw-teeth, ballooning modes, ELMs)

Most of the plasma volume does not produce fusion



In LiWF the high edge T is OK



No "gifts" from plasma physics (ITG/ETG, sawteeth, ELMs) are expected or accepted.

Stability is excellent. LiWF re-lies only on external control.

The entire plasma volume produces fusion

Lithium Case – **Cost of Fusion Power is Reduced by a Factor of ~30**

Courtesy: PPPL

Consequences of Lithium

- Increased Confinement Time – seen across the world
- Higher Temperatures
- Suppression of ELMS (for tokamaks)
- Control of Density is possible, even with NBI
- Lower Z-effective
- Less Fuel Dilution (seen on NSTX)

Negative Consequences?

- Helium pumping?

M. Nieto, D.N. Ruzic, W. Olczak, R. Stubbers, "Measurement of Implanted Helium Particle Transport by a Flowing Liquid Lithium Film", J. Nucl. Mater., 350 (2006) 101-112.

- Power handling? See the rest of this talk!

How Could a Lithium Divertor Possibly Take the Heat?

- Lithium melts at 180 C and evaporates very quickly above 400 C

  So, it will have to be used ultimately as a flowing liquid

- It is a liquid conductive metal and therefore subject to MHD effects. After all, fusion devices have large circulating currents and high magnetic fields.

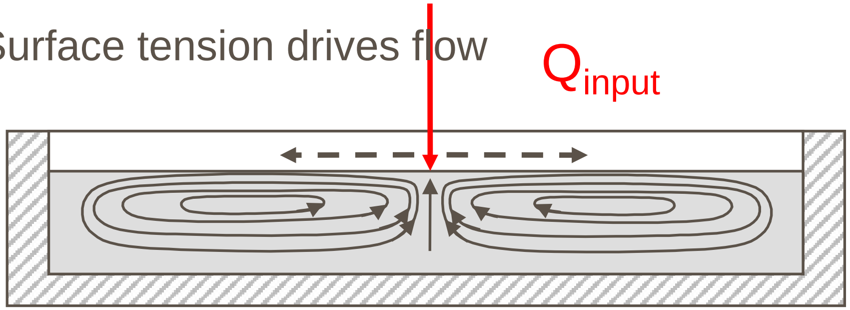
  So, careful planning is needed. Maybe it's MHD effects can be utilized?

- It has an extremely low density (half of water) and high surface tension (4 times water) and therefore difficult to deal with. It is also highly corrosive to some materials, such as copper.

  So, careful engineering is needed, but Molybdenum and Stainless Steel are compatible with Lithium.

CDX-U Results - The Unexpected Happened

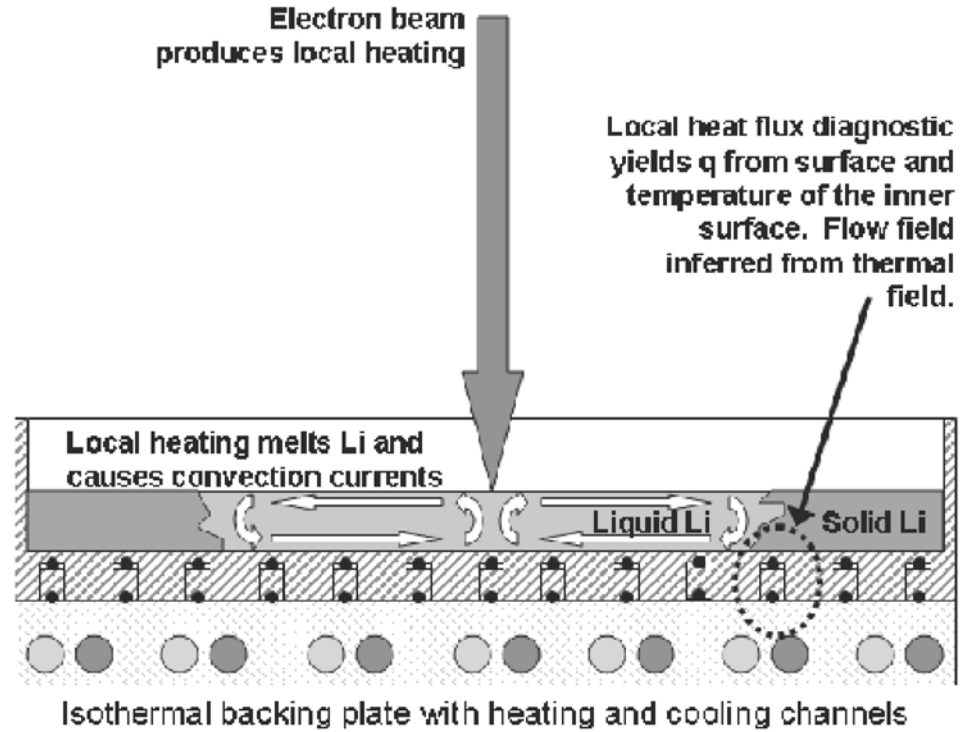
- Trying to melt lithium in CDX-U:
  - \- 50 MW/m^2 heat flux redistributed from spot heat
  - \- No evaporation despite lithium's tendency to do so (and purpose of e-beam run!)
- Why did the lithium melt the entire tray and not evaporate?
  - \- First explanation was thermocapillary phenomena
  - \- 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 ?

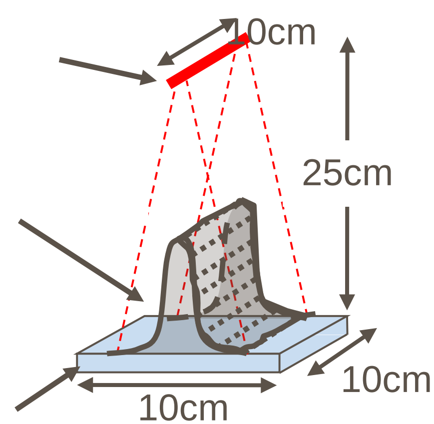


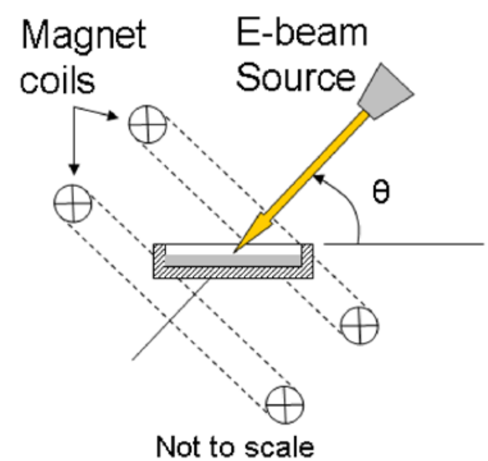
R. Majeski et al., "Final results from the CDX-U lithium program," *Presentation at 47th Annual Meeting of the Division of Plasma Physics (APS-DPP), Denver, Colorado, October, 2005.*

SLiDE at Illinois - Overview

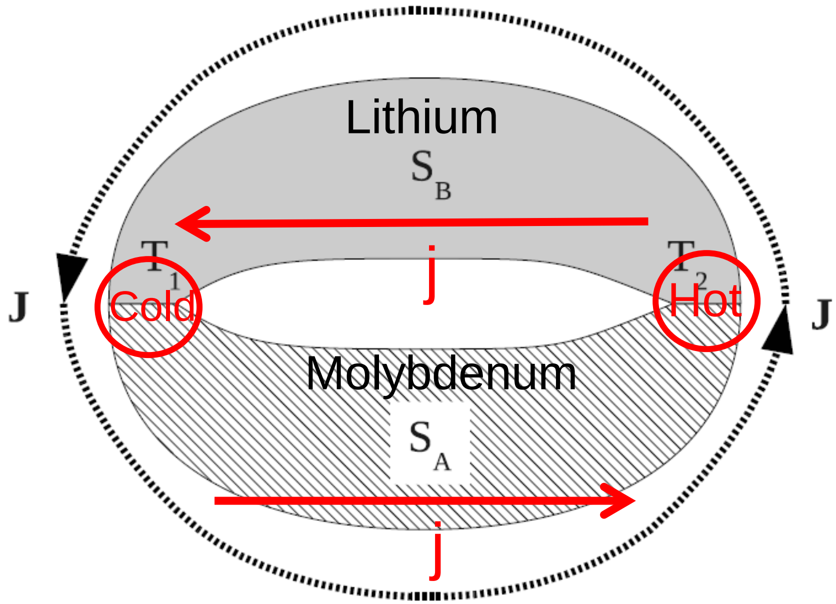
- Solid/Liquid Lithium Divertor Experiment (SLiDE). Built to see what happened on CDX-U
  - - Produces temperature gradients with an electron beam
  - - Creates magnetic field with external magnet system (these tests at normal incidence)
  - - Measures temperature distribution in tray containing lithium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

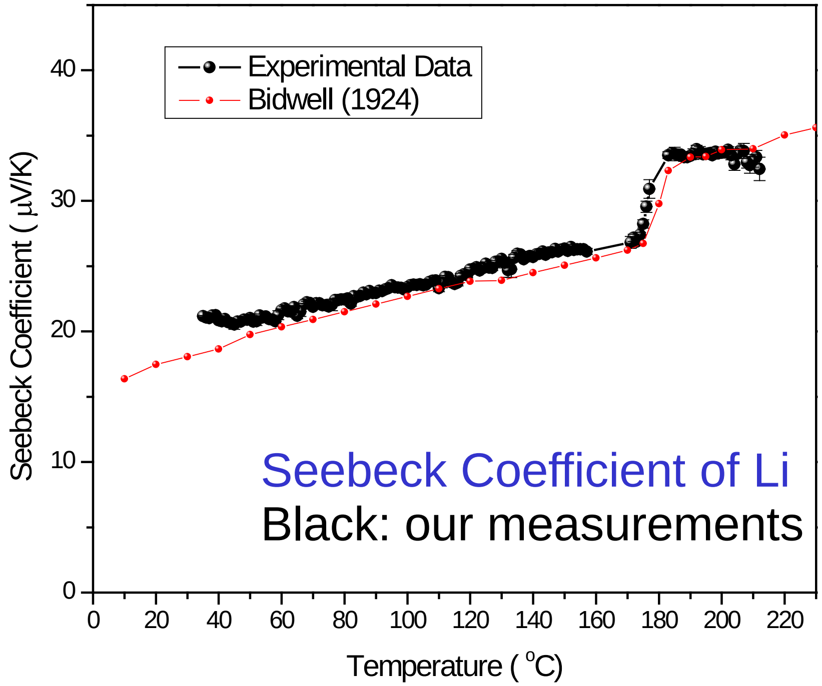






We found it was the Thermoelectric effect, not Thermocapillary





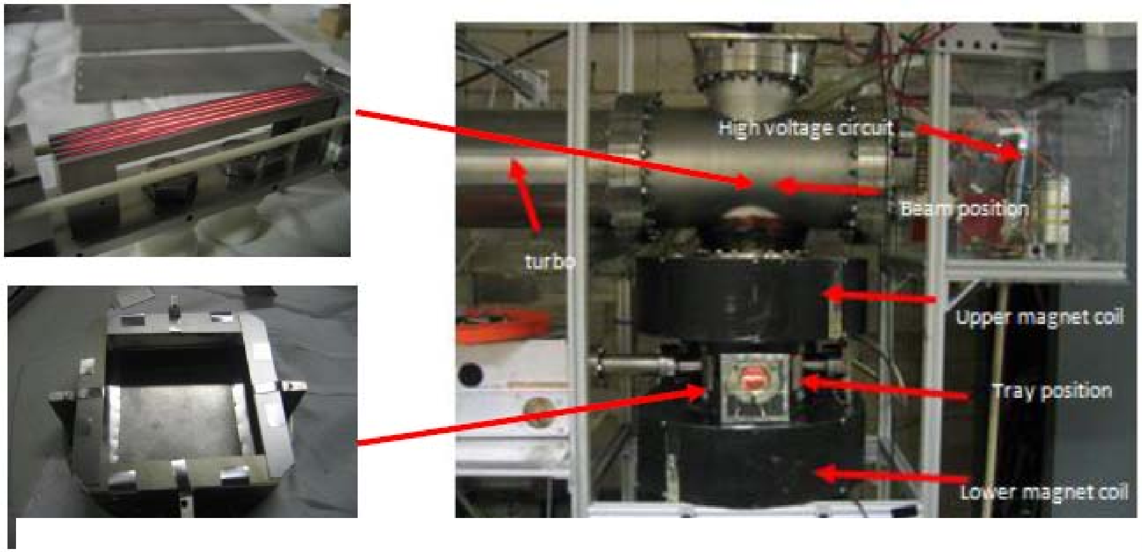
- Like a thermocouple, a voltage is created at a junction of two metals dependent on the temperature.
- A current will flow based on that voltage difference: $j = \sigma \Delta S \Delta T$

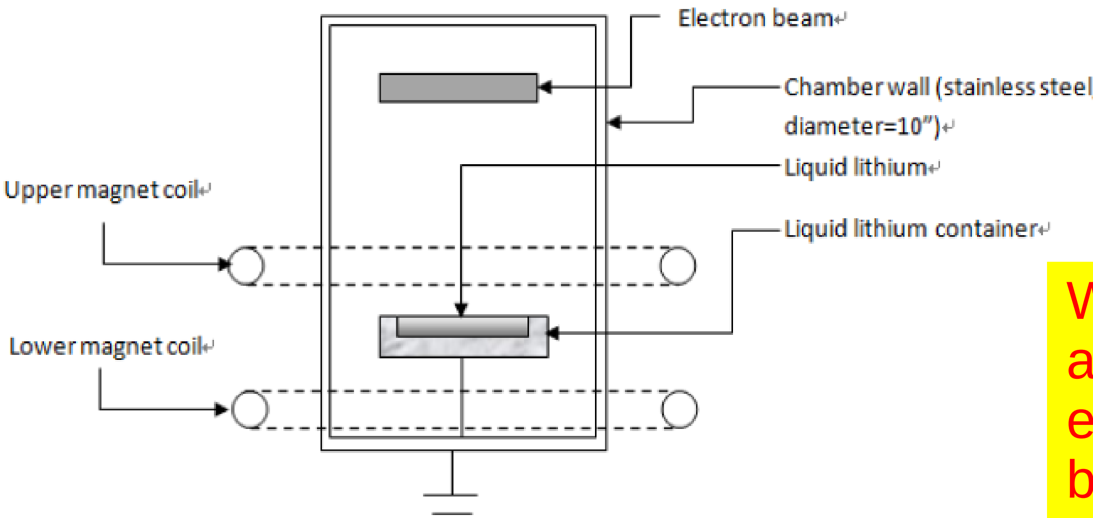
where σ is the conductivity, and ΔS is the difference in Seebeck coefficients. There is a large difference in S between Li and most other metals and it increases with T.

Does it work? Yes! SLiDE Results

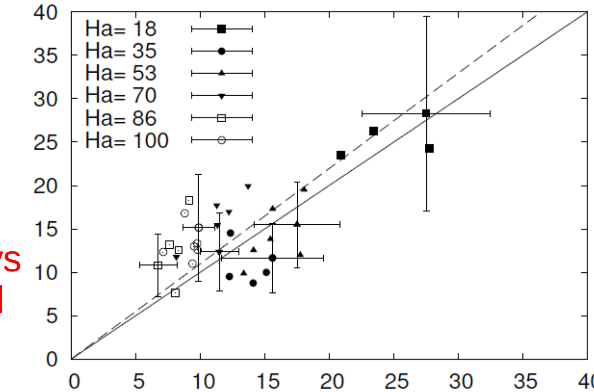
- As I showed previously, TEMHD is real and moves Lithium at significant velocities.

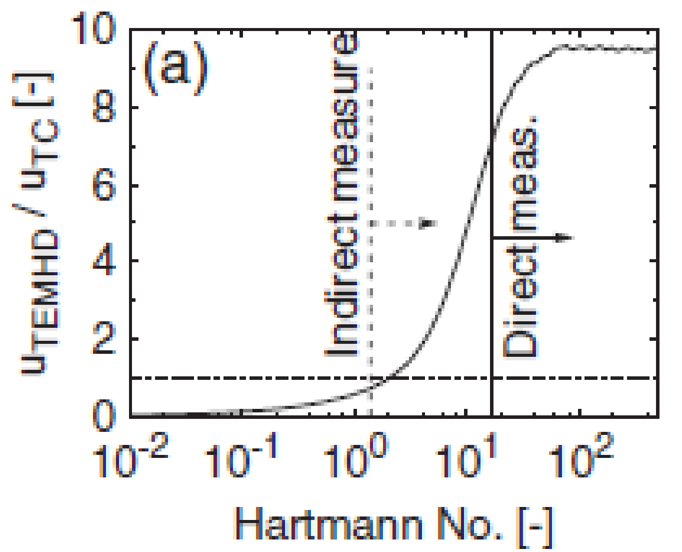
M.A. Jaworski, et al. Phys. Rev. Lett. 104, 094503 (2010)





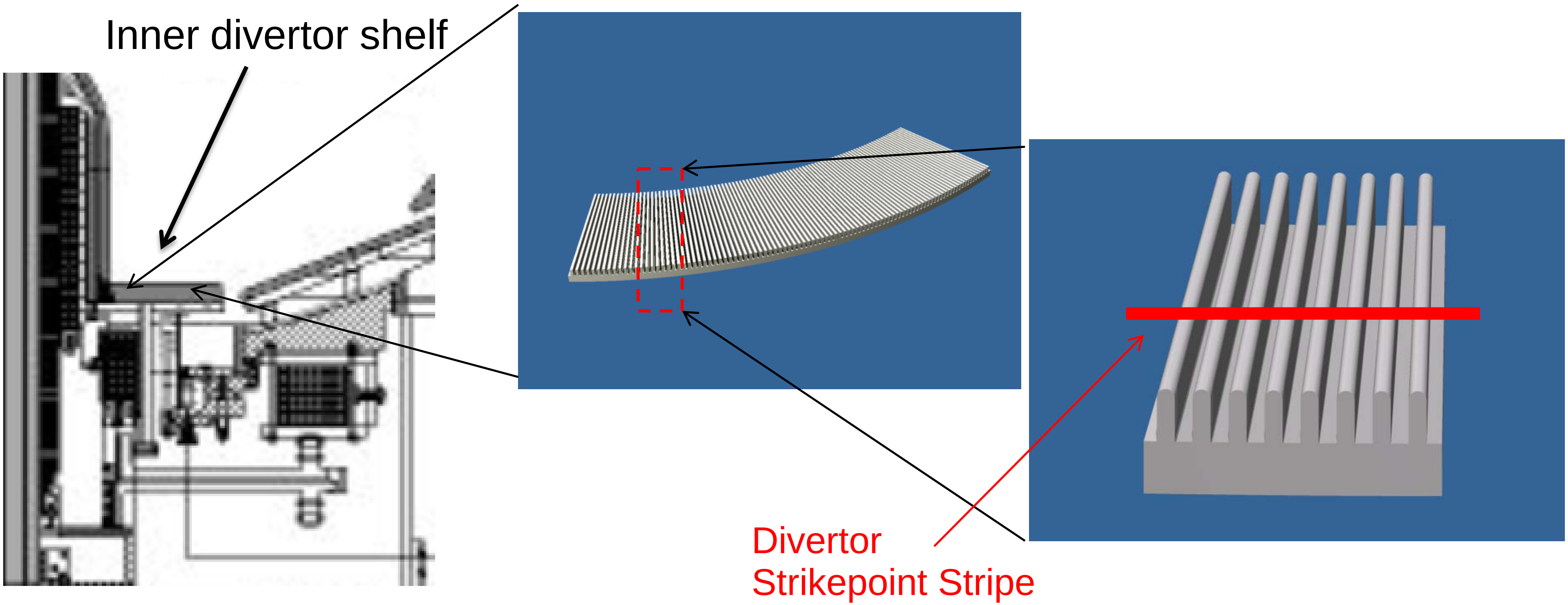
Theoretical vs experimental velocities :





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

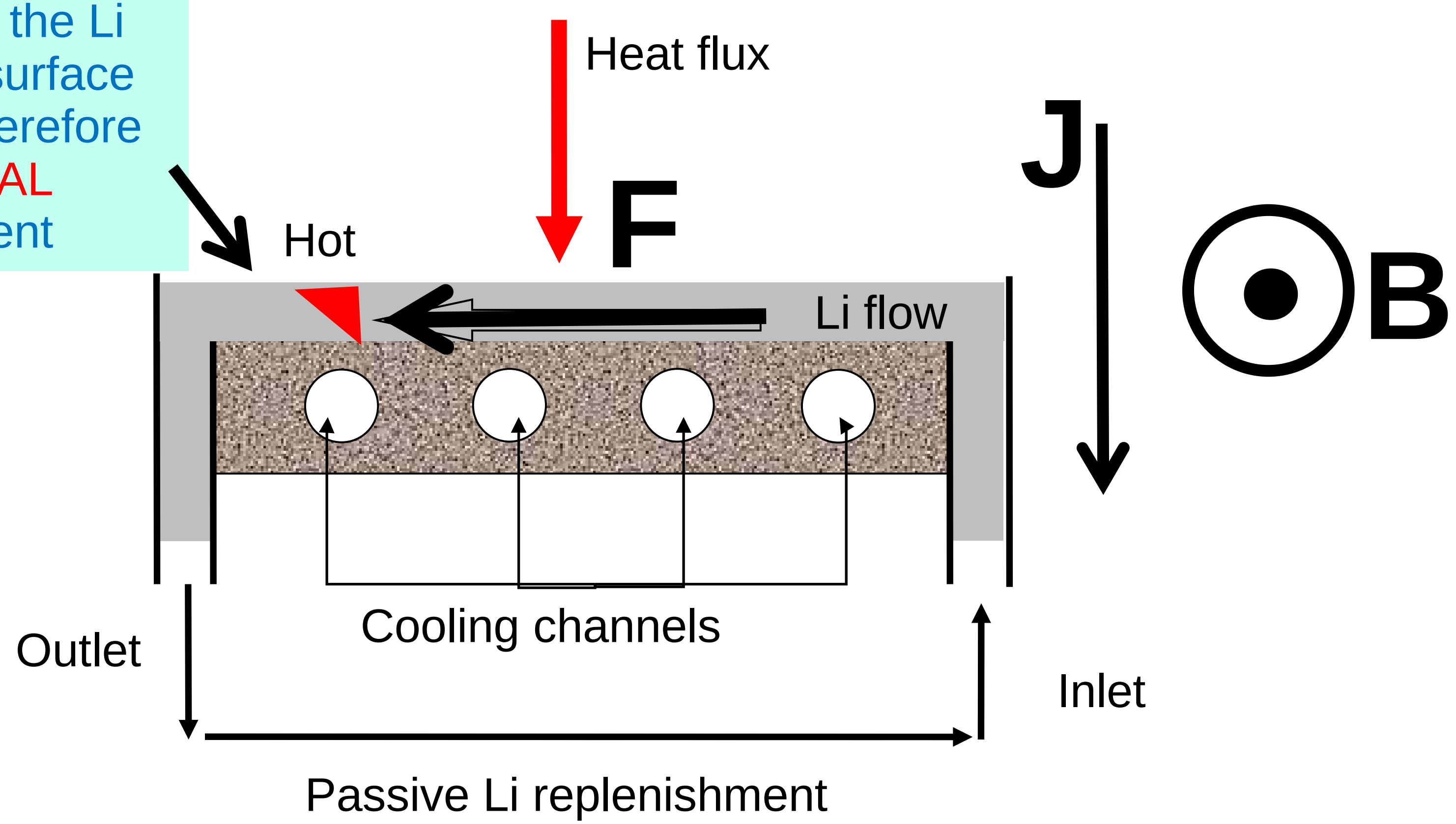
The Idea: "LiMIT" Design for NSTX



- 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.

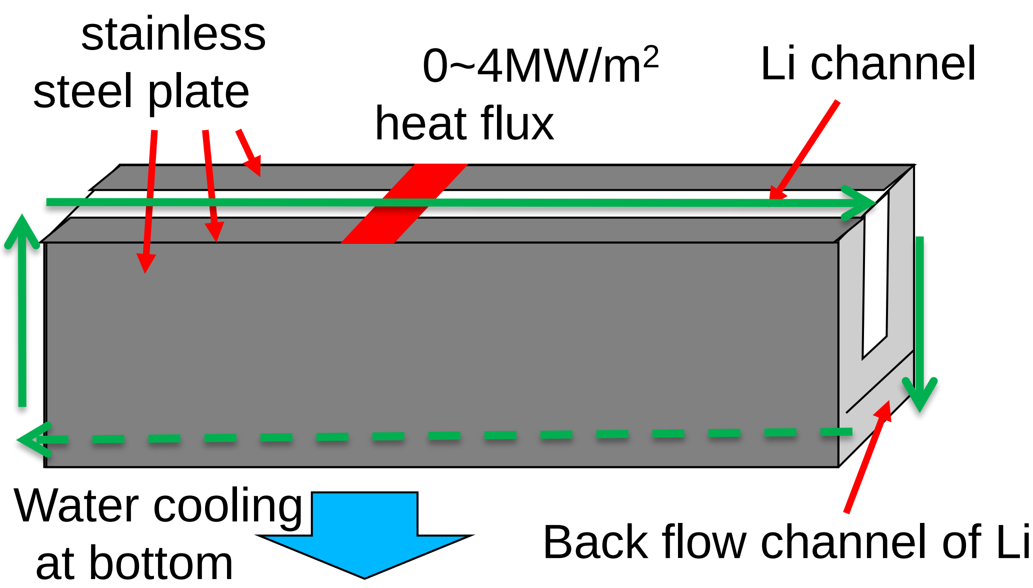
Lithium Flow in the Trenches is Self-Pumping

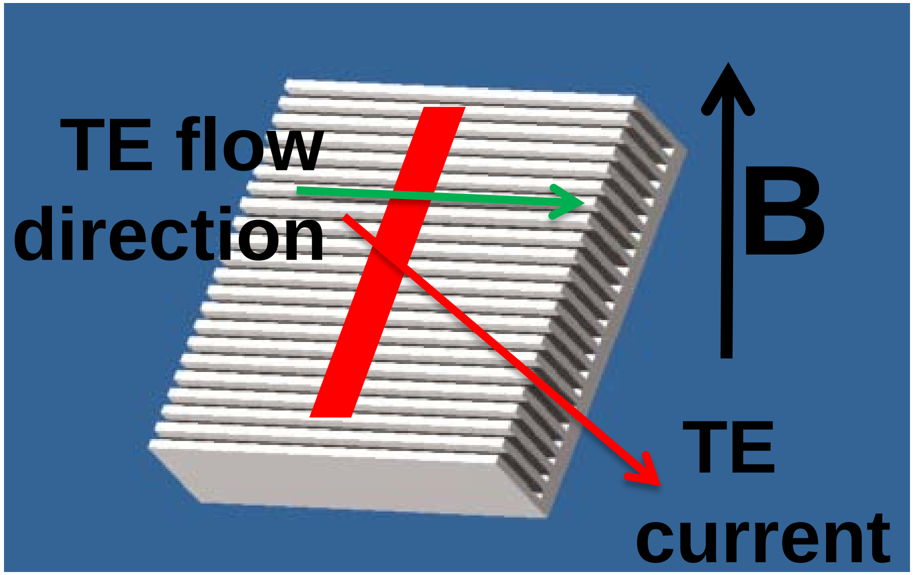
The top surface of the Li is hotter than the surface that is deeper. Therefore there is a VERTICAL temperature gradient



- 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.

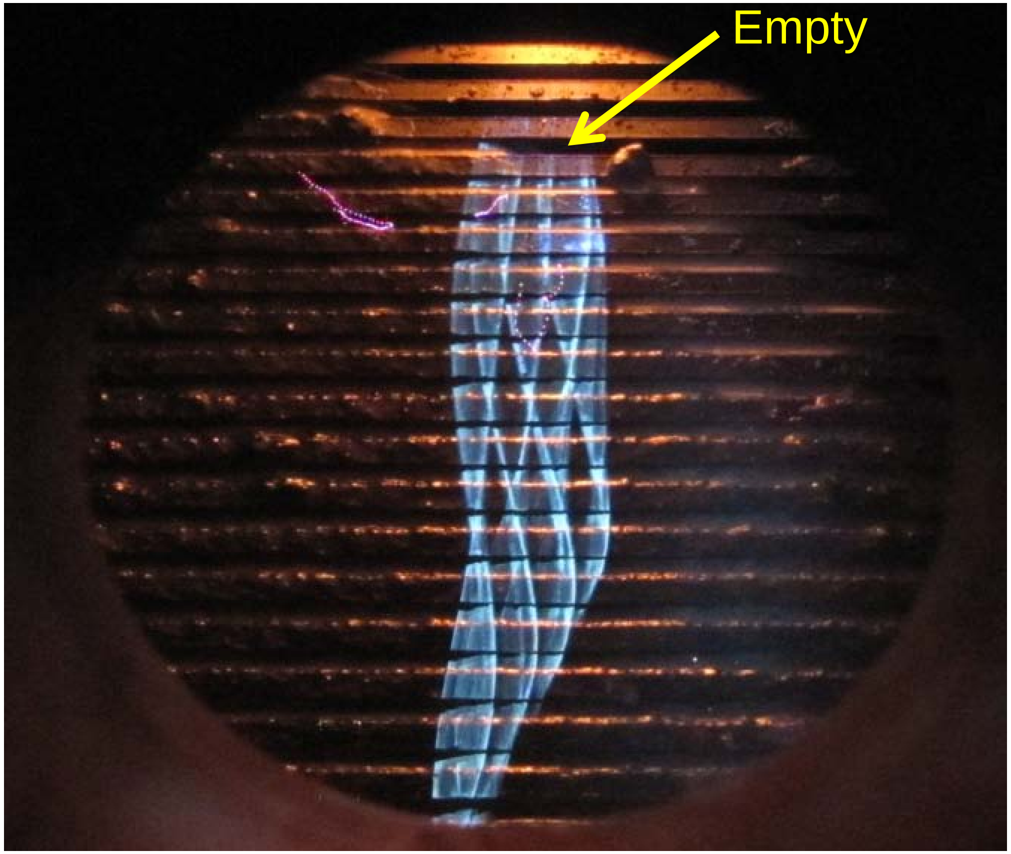
Tested in SLiDE at Illinois



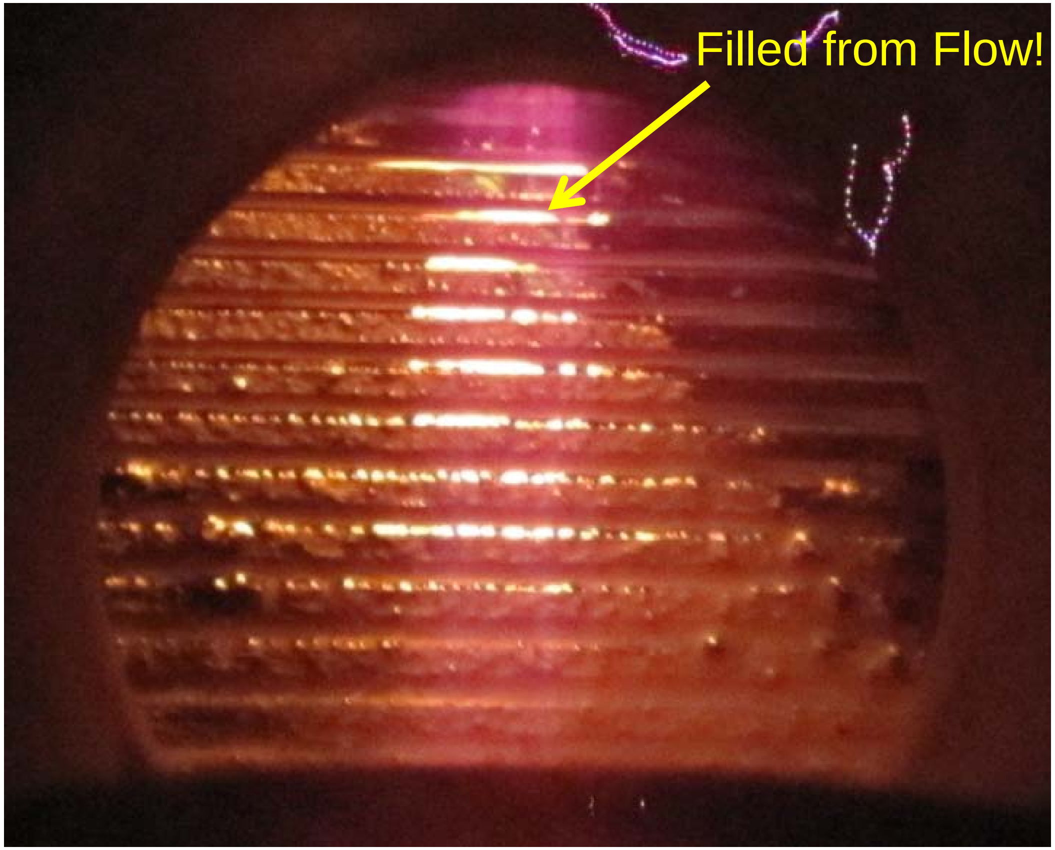


- The SLiDE experiment at Illinois has been reconfigured to test this concept. We expect to be able to show radial flows of Li along radial trenches in a stainless steel plate and measure the flow velocity compared to calculations.
- The lithium tray is tilted to a small angle with the magnetic field. 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 9cm long. The back flow channel is 4mm thick.

Observation of flow in the trenches



Initial melting of the lithium.
The lines seen are reflections of the filaments.

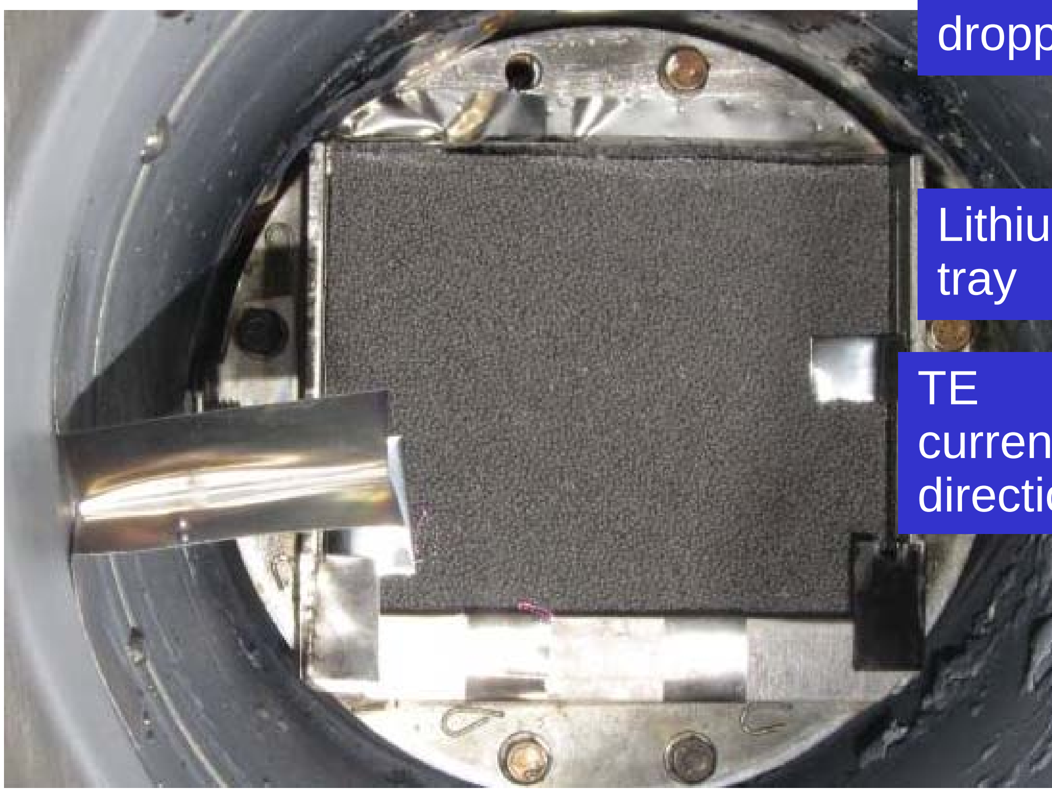


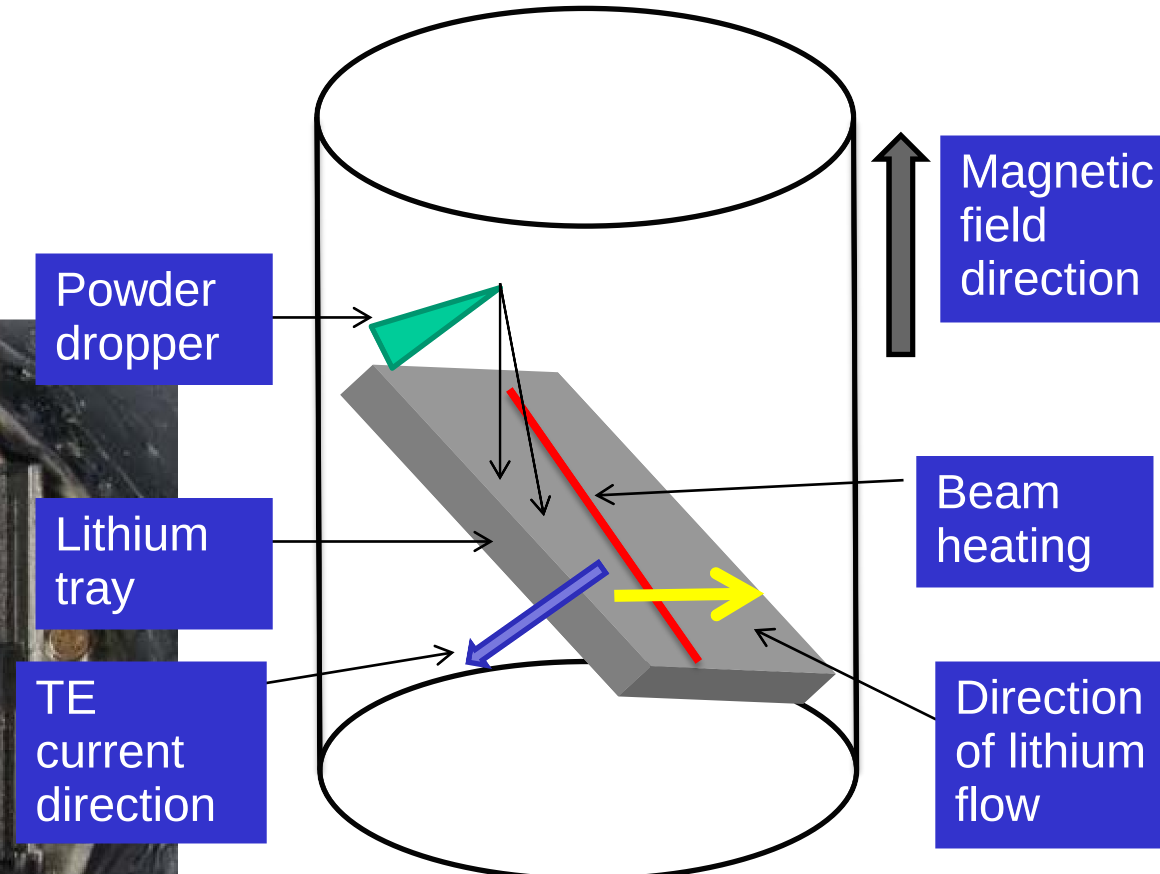
Lithium is totally melted.
Red glow indicative of lithium vapor

Li flow in the trenches goes across these images, left to right. Initial movies were not conclusive, but now we have movies that clearly show the predicted motion of the lithium.

We needed a marker: Sprinkle Dust on the Lithium !

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

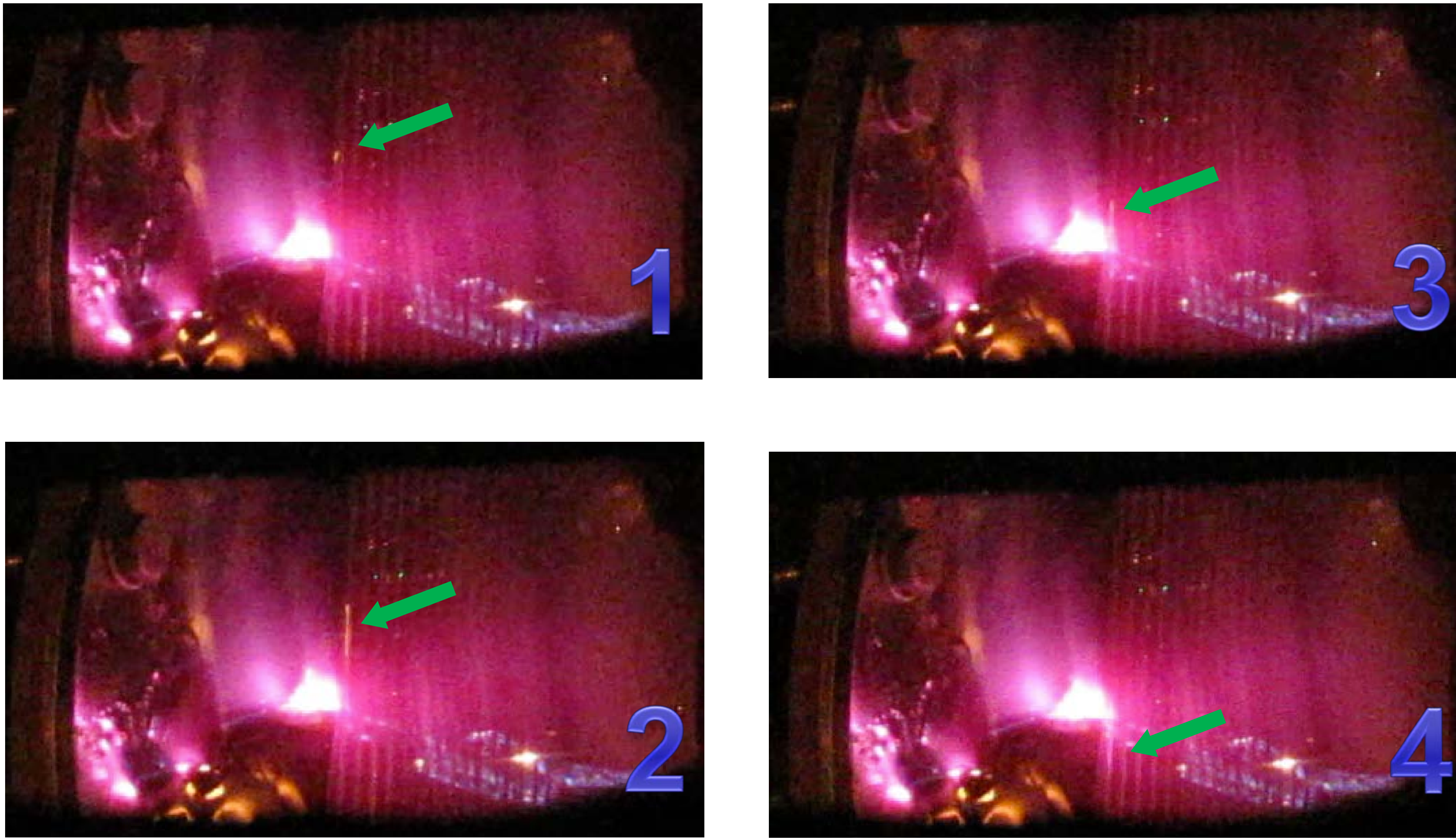




Four Frames that Show a Moving Dust Grain

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.



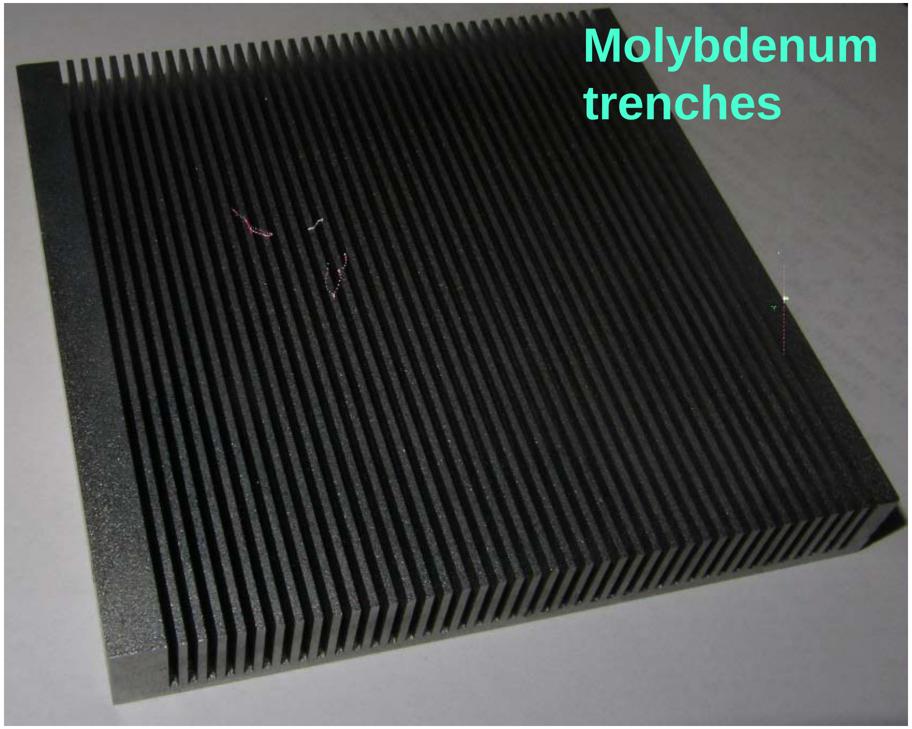
A Different Four-Frame Sequence

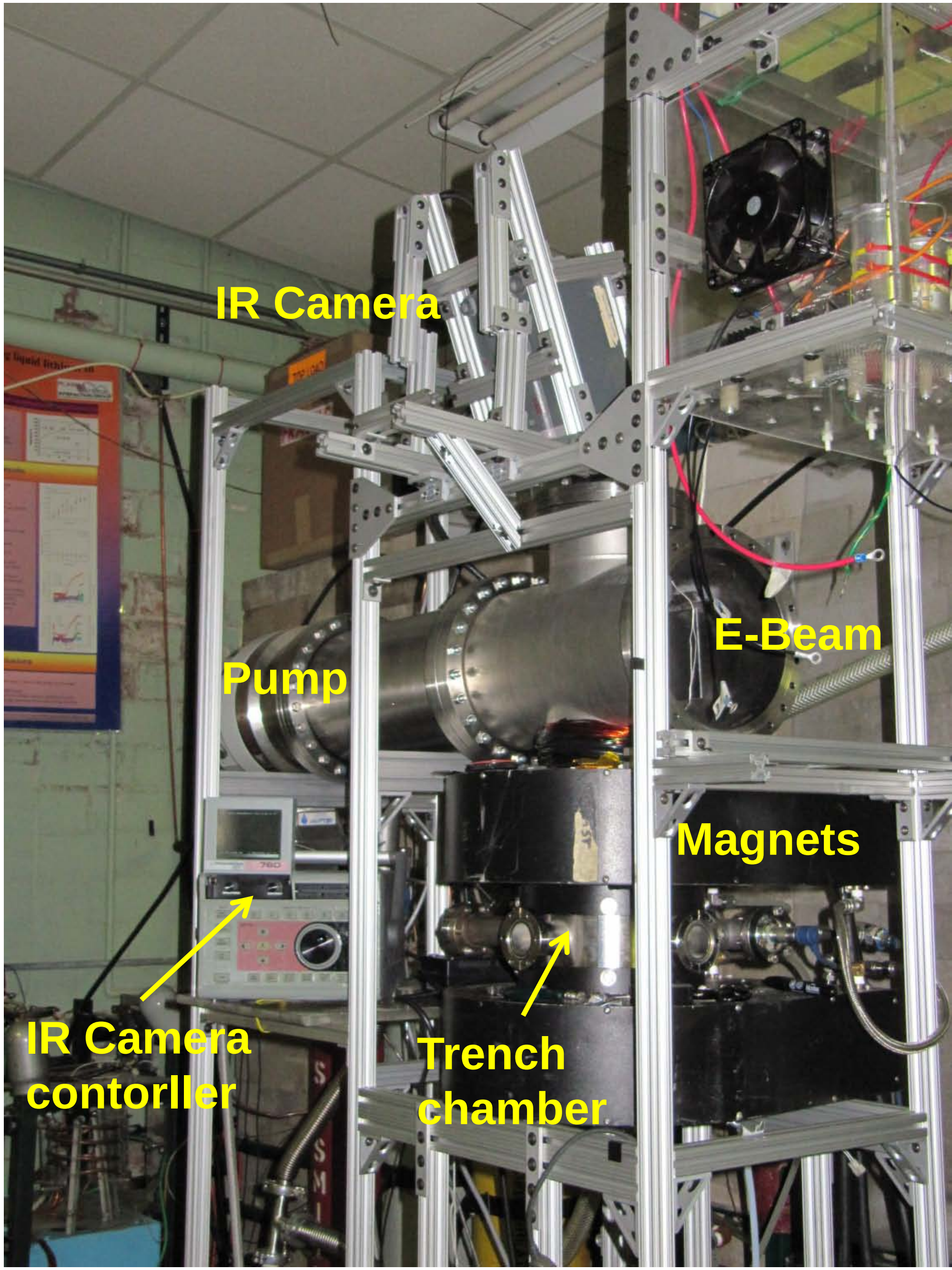
This one is first visible even more toward the edge of the tray.

We have movies from the side port as well.

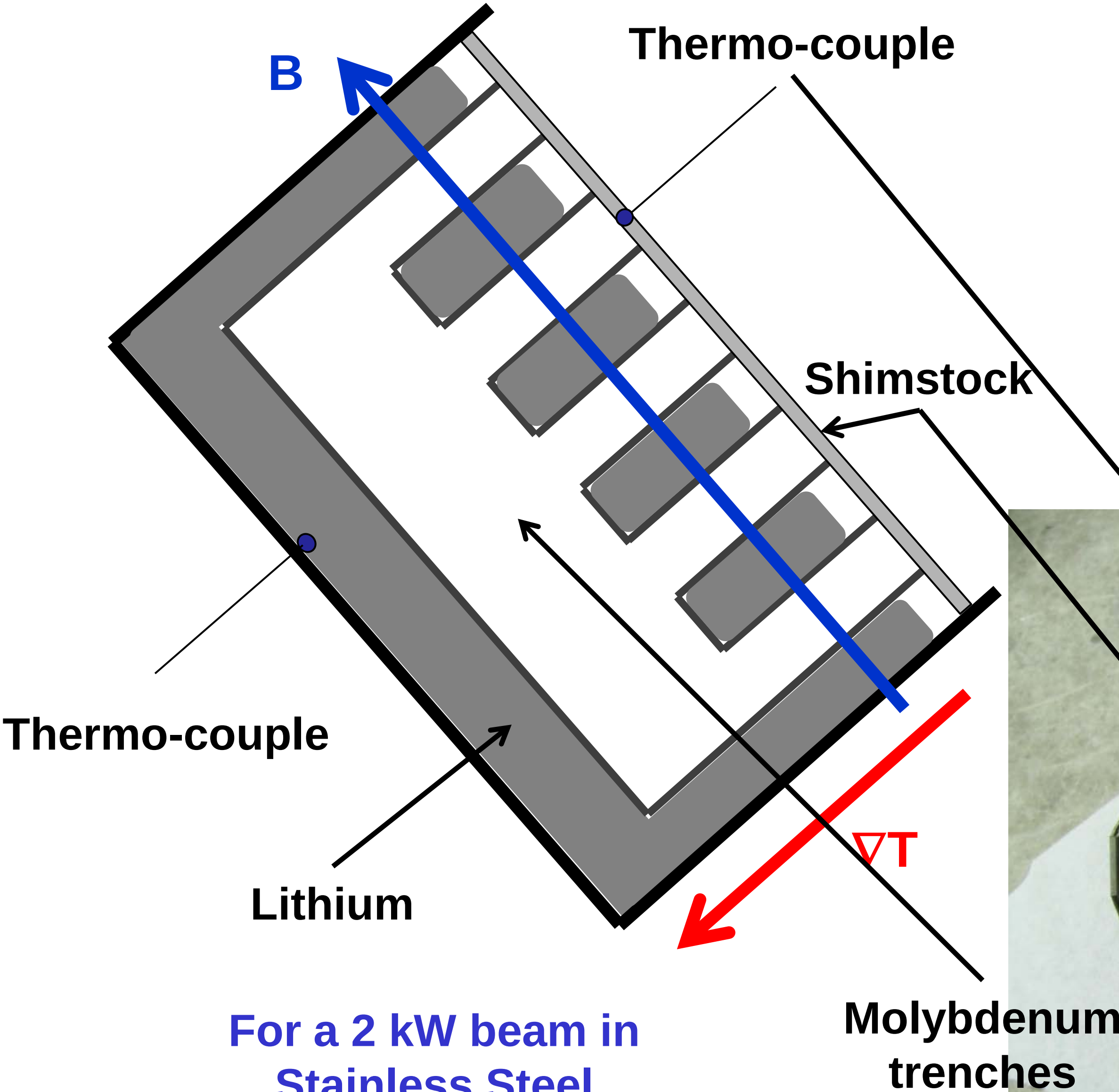
SLiDE Set-Up for Molybdenum Experiments

- Molybdenum is being considered as a tile material on NSTX
- Stainless steel trenches replaced with Molybdenum trenches 1mm wide instead of 2mm wide. Structure was made in China (for free!) by group in Hefei
- Same experiments repeated.

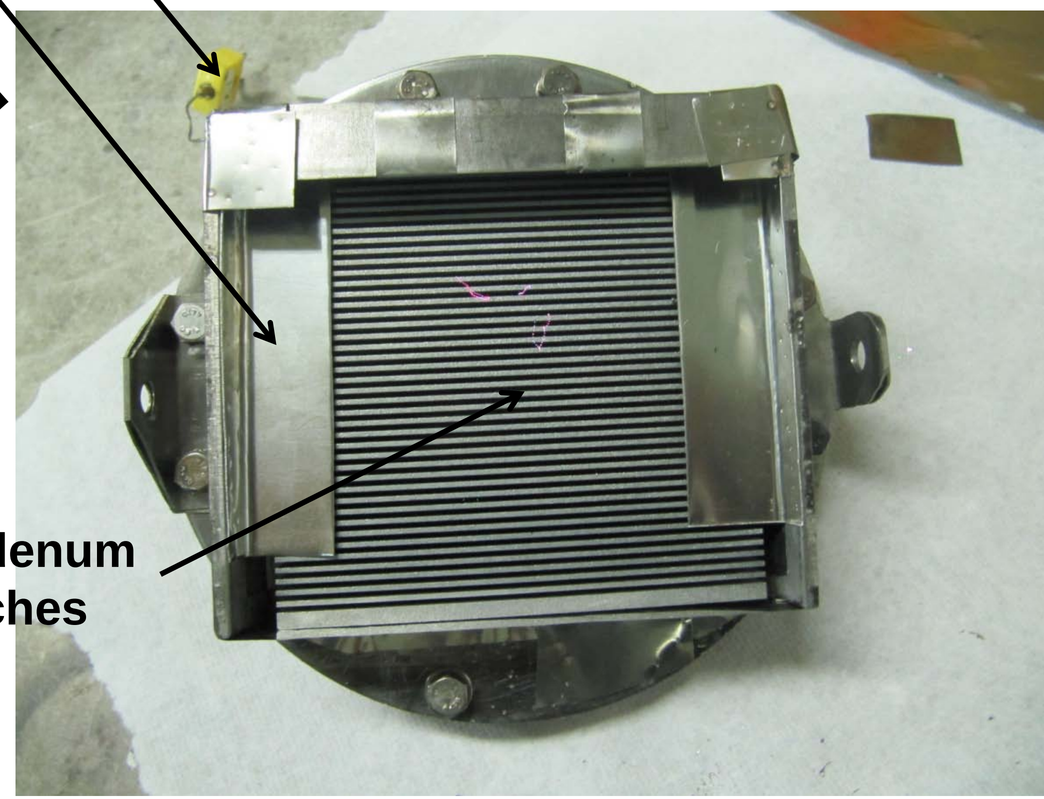




Molybdenum Trench Structure



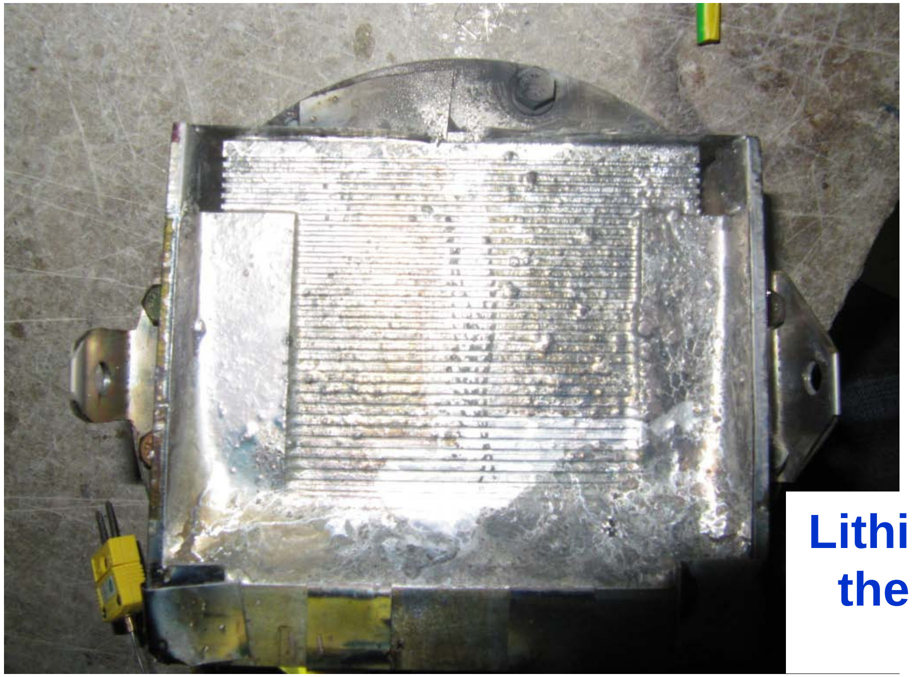
- Thermocouples are used to measure the temperature gradient
- Shimstock used to hold top thermocouple in place
- Lithium overfills the trenches

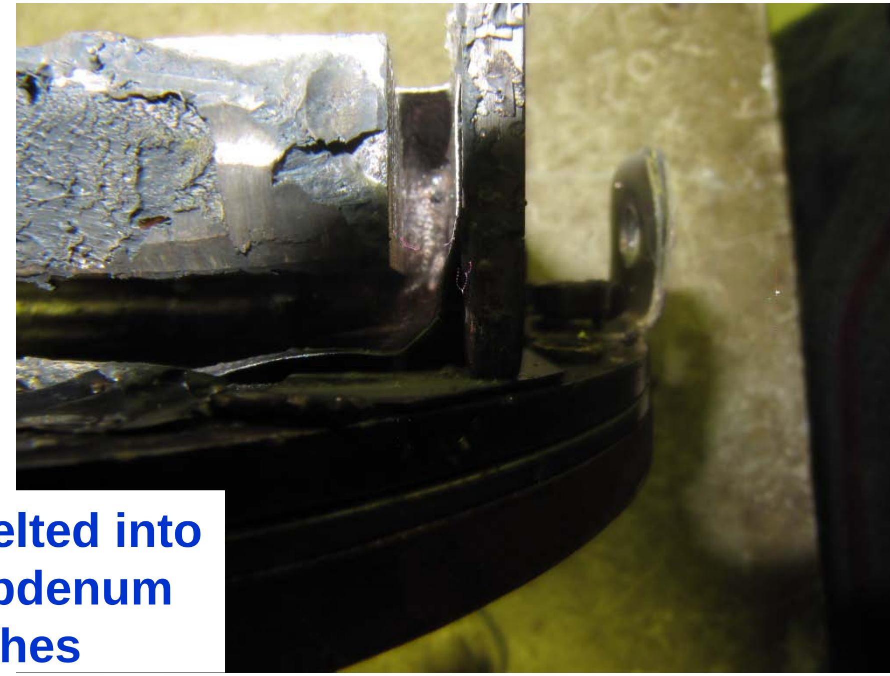


For a 2 kW beam in Stainless Steel

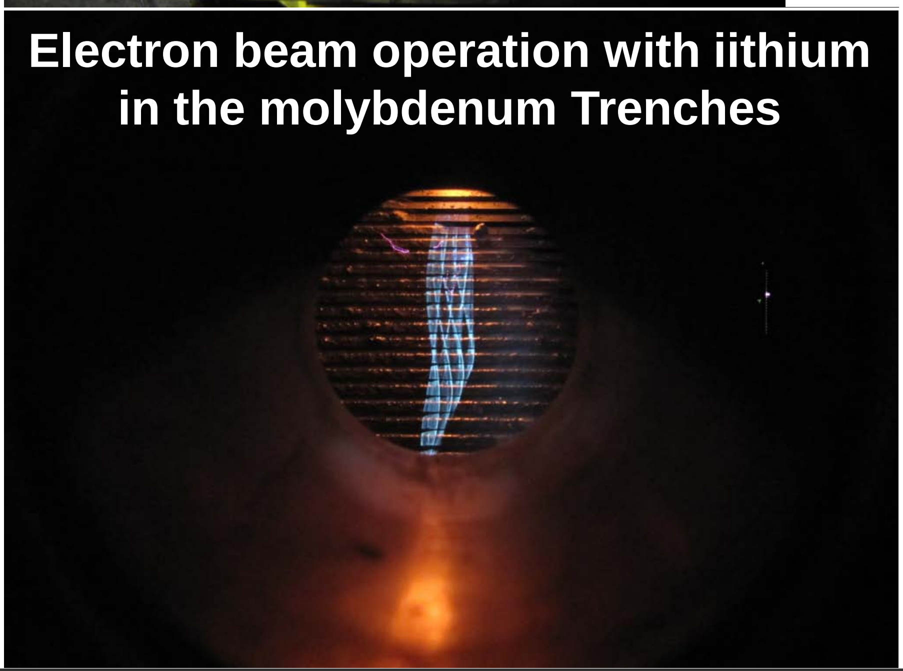
- **Bottom TC: range of 186º C to 215º C**
- **Top TC: range of 382º C to 452º C**

Molybdenum Experiments on SLiDE



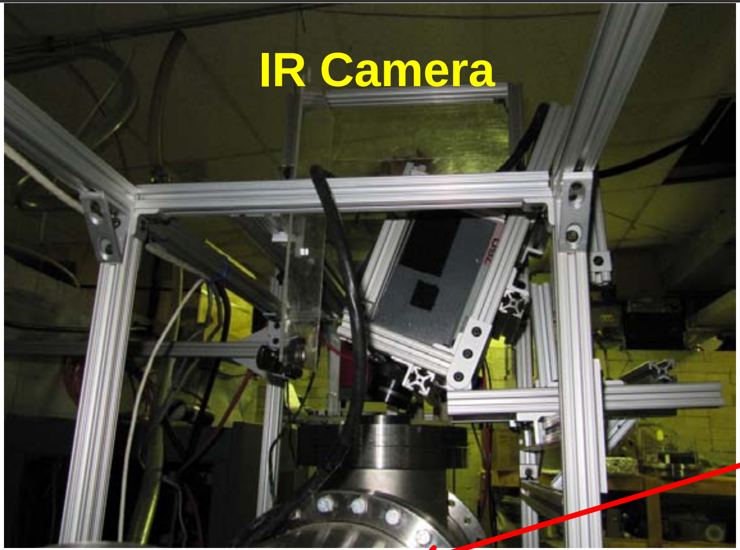


Lithium melted into the molybdenum trenches



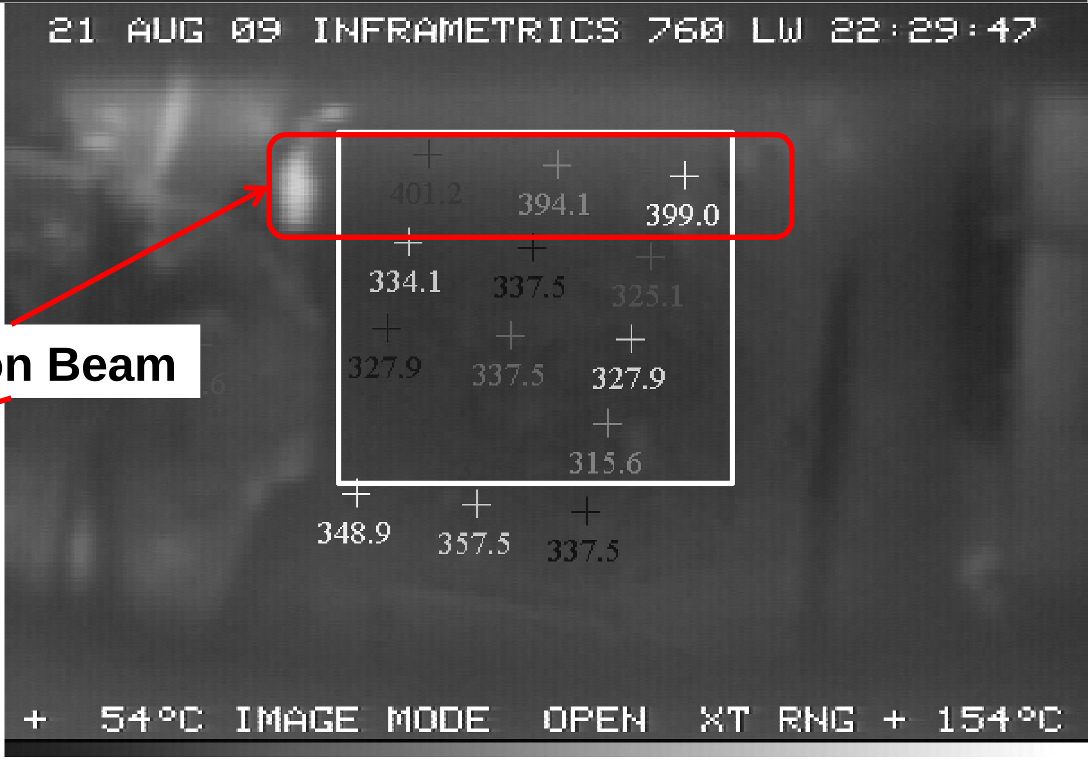
- **Top section of trench structure did not show return flow**
- **Middle and Bottom sections appeared to be flowing**
- **Velocity measurement (with same technique) impossible due to angle of view and smaller trench width!**

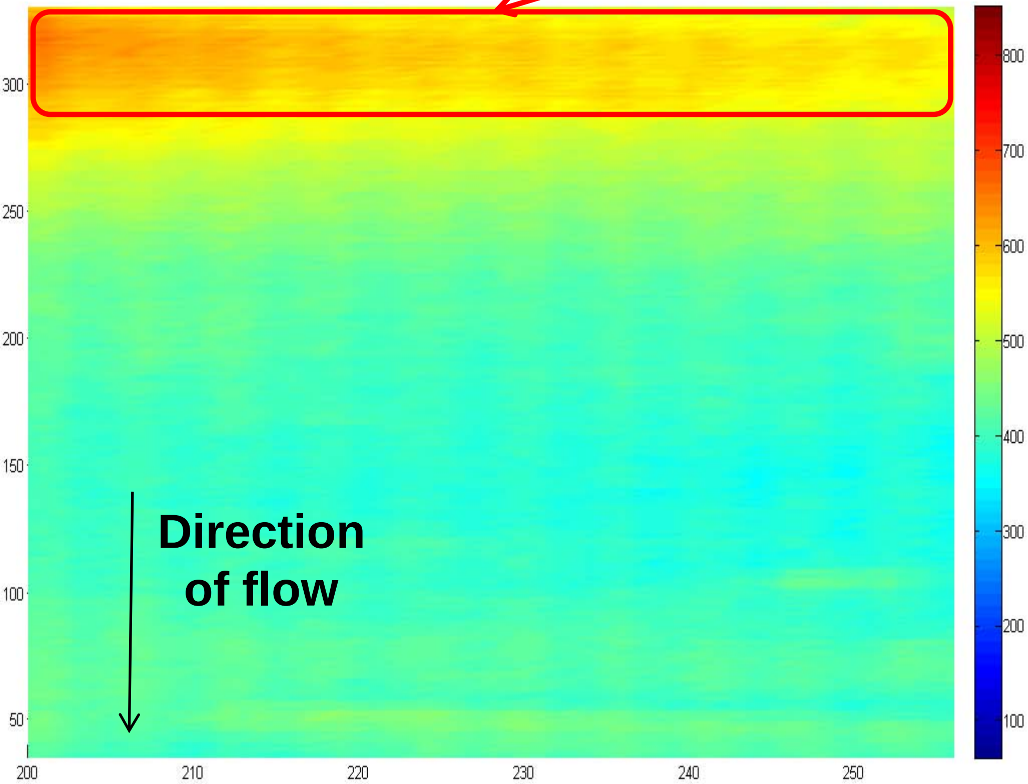
Temperature measurements using IR Camera



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)
- The electron beam is incident in the top of the images (red-boxed)

Modelling of the Temperature and Velocity

- The model has two part. The first is the Navier-Stokes equation:

$$\rho \frac{D\vec{u}}{Dt} = -\nabla p + \mu \nabla^2 \vec{u} + \vec{f}$$

- The velocity is assumed to be $u=(0,0,u_z)$
- The width of the trench is less than the length the body force f *is just the Lorenz Force* $f = jB$
- Pressure gradient assumed to be $\nabla p=0$
- Thus a steady state equation can be found:

$$0 = \mu\left(\frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2}\right) + jB$$

- From Ohm's law $j = \sigma B u_z + j_S$
  - where σ is the electrical conductivity, j_S is the Seebeck current
- From the continuous equation of the current $j = -(\tau/a) j_w$
  - where τ is the thickness of the wall, a is the thickness of the fluid lithium and j_w is the current density through the wall. Here $\tau = a = 2$ mm

- j_w and j_S can be eliminated through Kirchoff's law:

$$\frac{j_w}{\sigma_w} - \frac{j_S}{\sigma_{Li}} = S\frac{dT}{dy}$$

  - here σ_w is the electric conductivity of the wall and σ_{Li} of the lithium. S is the Seebeck coefficient.

- The Navier-Stokes equation can now be written as:

$$0 = \mu\left(\frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2}\right) + \frac{1}{1+C}\left(S\sigma_{Li}B\frac{dT}{dy} - \sigma_{Li}B^2 u_z\right) \quad \textbf{(1)}$$

viscocity **TE driven** **MHD damping**

  - here $C = a\sigma_{Li}/\tau\sigma_w$

- The Heat Transfer equation also is needed for the calculation:

$$\rho C_P \frac{DT}{Dt} = k\nabla^2 T$$

- Here k is assumed to be constant the heat transfer equation becomes:

$$\rho C_P\left(u_z \frac{\partial T}{\partial z}\right) = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \quad \textbf{(2)}$$

Only input is measured power and geometry

- With these two equations the velocity and temperature distribution can be solved.
- But – geometry does not yet have return flow
- The model has been solved using the Fluent program.
- Experimentally the velocity has been measured at 0.2 m/s, but the model shows much higher at this point as expected.
- Return flow being added.

Boundary condition	Value
Length (L)	100 mm
Width (W)	2 mm
Height (H)	10 mm
Peak Heat flux	3 MW/m2 1 cm long in z direction
	No heat flux on other parts of the surface
Side Wall	Insulating: meaning that there is no temperature gradient
Bottom	Constant Temperature of $T = 473\ K$
Inlet Flow	Zero inner pressure
Outlet Flow	Free out-flow boundary conditions

How can this be applied in real life?

- Even initial modeling shows that the trench does not have to be so deep. 3 mm deep is probably just fine. Whole gradient is near the top.
- In general, the more heat that hits the lithium, the faster the LiMIT system will take the heat away. Lithium and High Heat Fluxes are compatible. The TEMHD effect can be used to remove high heat fluxes!
- Both NSTX and HT-7 in Hefei have expressed interest in testing this concept once “proof-of-principle” was demonstrated at Illinois. The visiting Chinese scientist at our lab will recommend this system be used in the HT-7 upgrade.
- This system could be tried “easily” in LTX at PPPL.   We will work toward this next proof-of-principle step.