Lithium-Infused Trenches

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

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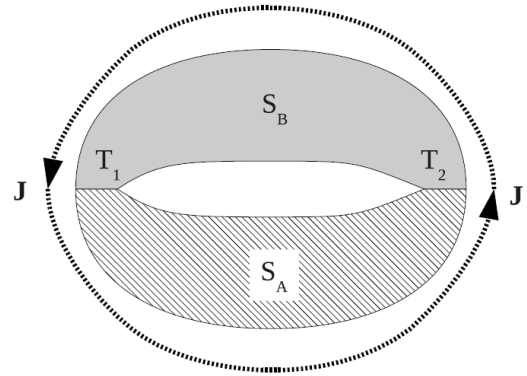
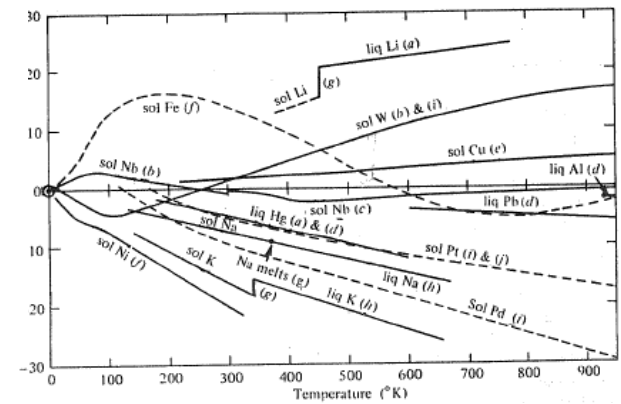
Outline

- Thermoelectric effect and thermoelectric MHD seen in SLiDE (Solid/Liquid Divertor Experiment)
- Lithium/Metal Infused Trenches (LiMIT) experiment
  - Experiment setup
  - Velocity measurement with particle tracking method
  - Uneven surface temperature distribution (IR camera)
  - Embedded thermocouples measurements
- Limits on LiMIT
- Conclusion

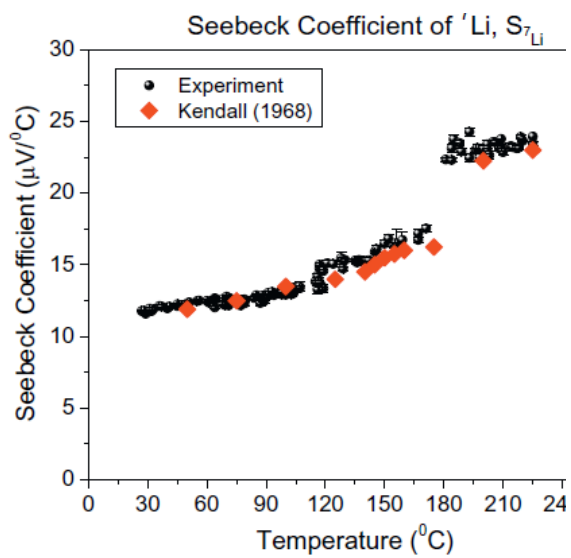
Thermoelectric effect

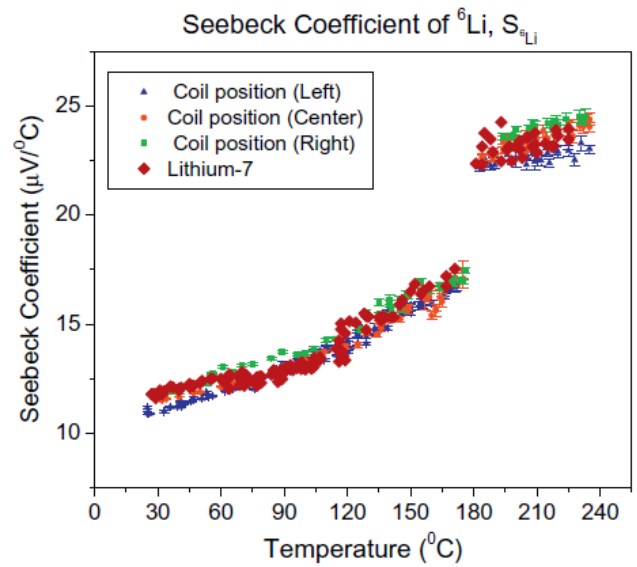
- Thermoelectric effect
  - Causes thermocouple junction voltage
  - Electric field generated by temperature gradient
  - Proportional to Seebeck coefficient ($E=S*\partial T/\partial x$)
  - Requires different material (or TE power) to provide current return path and to generate current
  - Lithium has a high Seebeck coefficient and is beneficial to fusion plasma. (low recycling, improved confinement, flat temperature profile and so on)





J.A. Shercliff, Thermoelectric MHD, J. Fluid Mech. **91**, 231 (1979)





V. Surla et. al. accepted in J. Nucl. Mater., to be published

Seebeck coefficient measurements of lithium isotopes ☆

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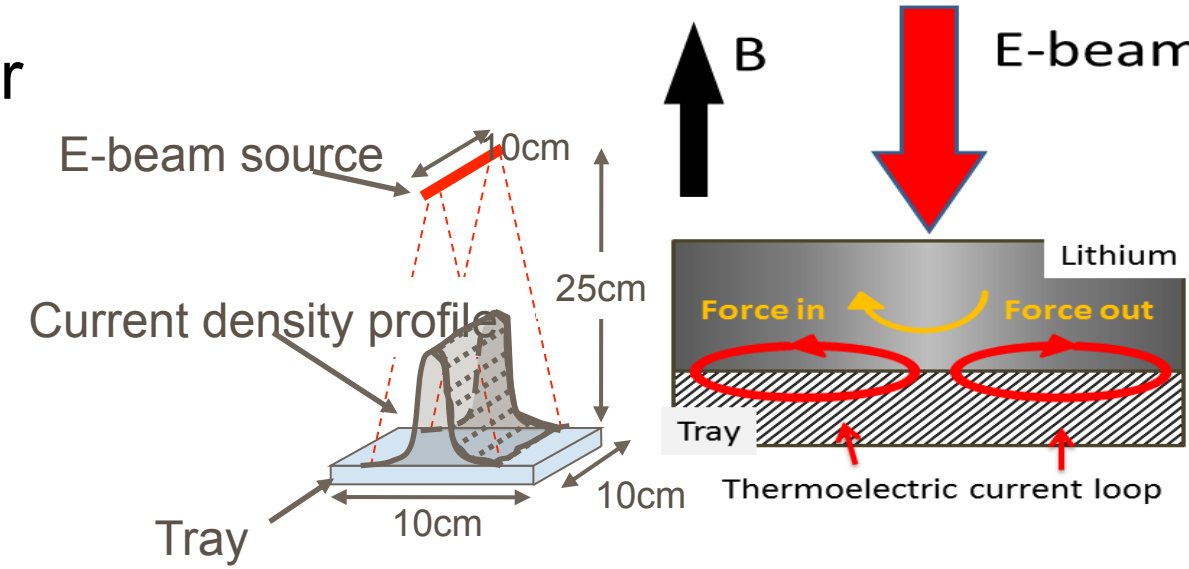
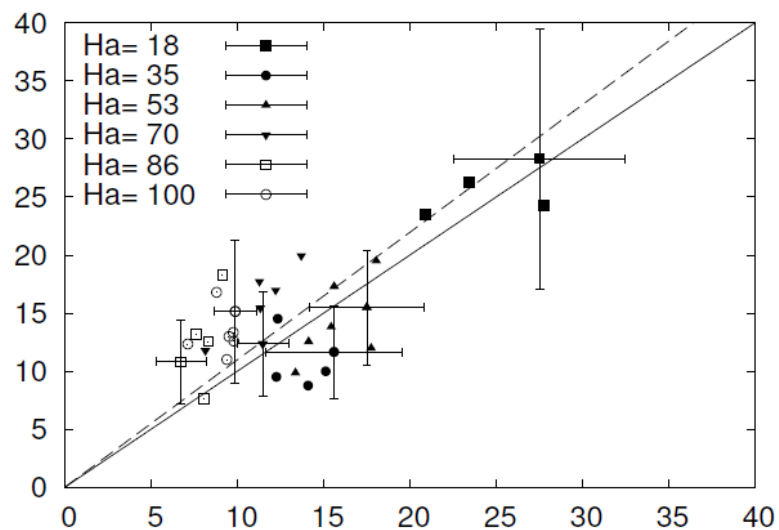
Thermoelectric driven swirling flow

- Solid/Liquid Lithium Divertor Experiment (SLiDE)
  - Linear Gaussian electron beam hits the center of lithium surface
  - Vertical magnetic field (0~700G)
  - Lithium melted in a stainless steel square tray
- Result found on SLiDE
  - Swirling flow of liquid lithium
  - Flow speed changes with magnetic field, depth of lithium and heating power.
  - Heat is redistributed from interface by convection



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

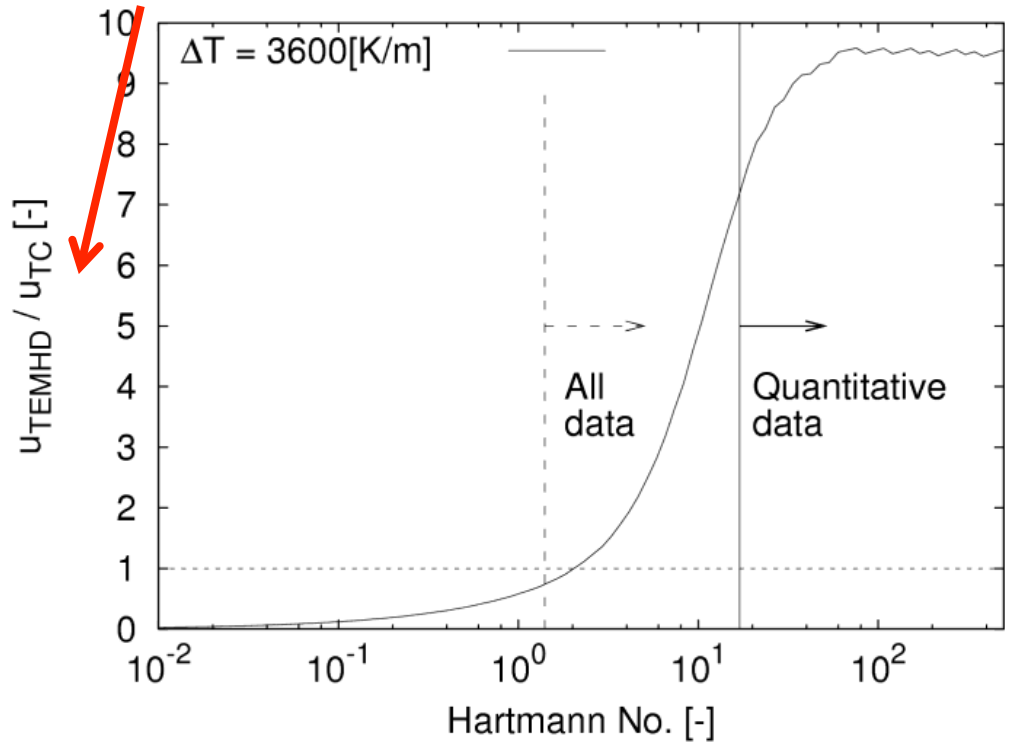
When the Jaworski number is near 1 and TEMHD and TCMHD (Maragoni effect) are balanced, so flow oscillates between swirling and splitting.

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

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

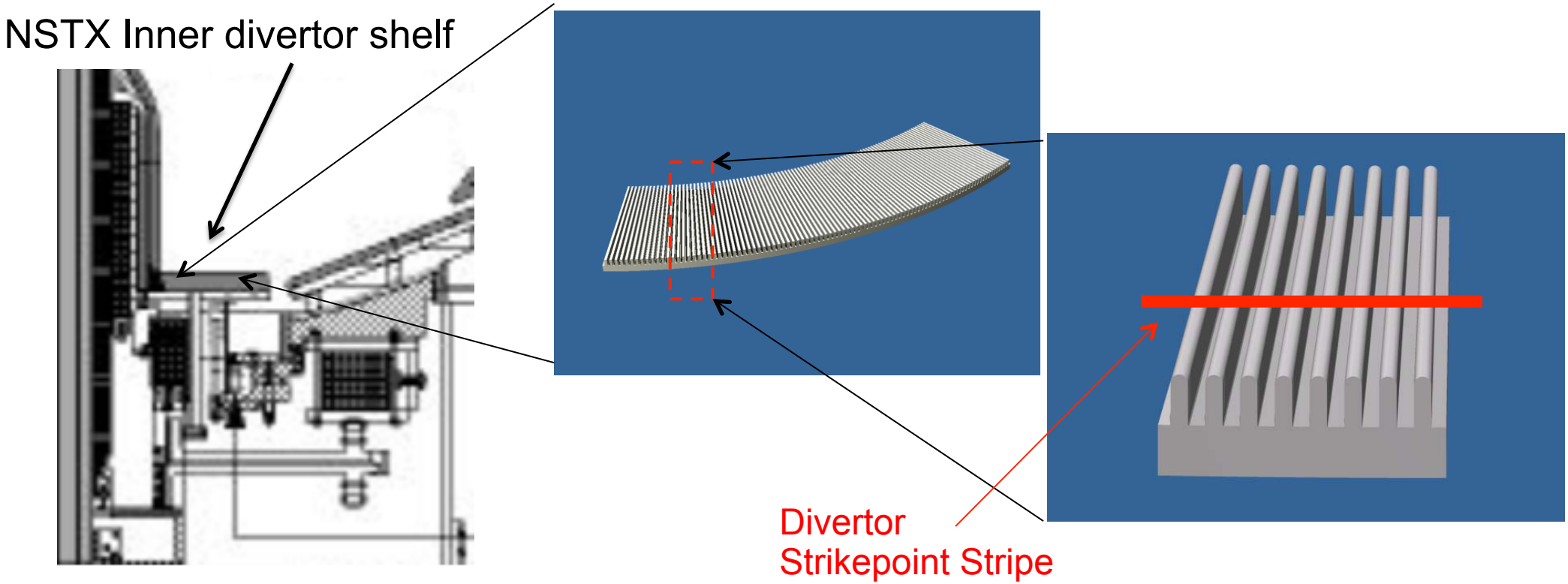
M.A. Jaworski, et al. Phys. Rev. Lett. 104, 094503 (2010)

Jaworski Number was always greater than 1 !



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

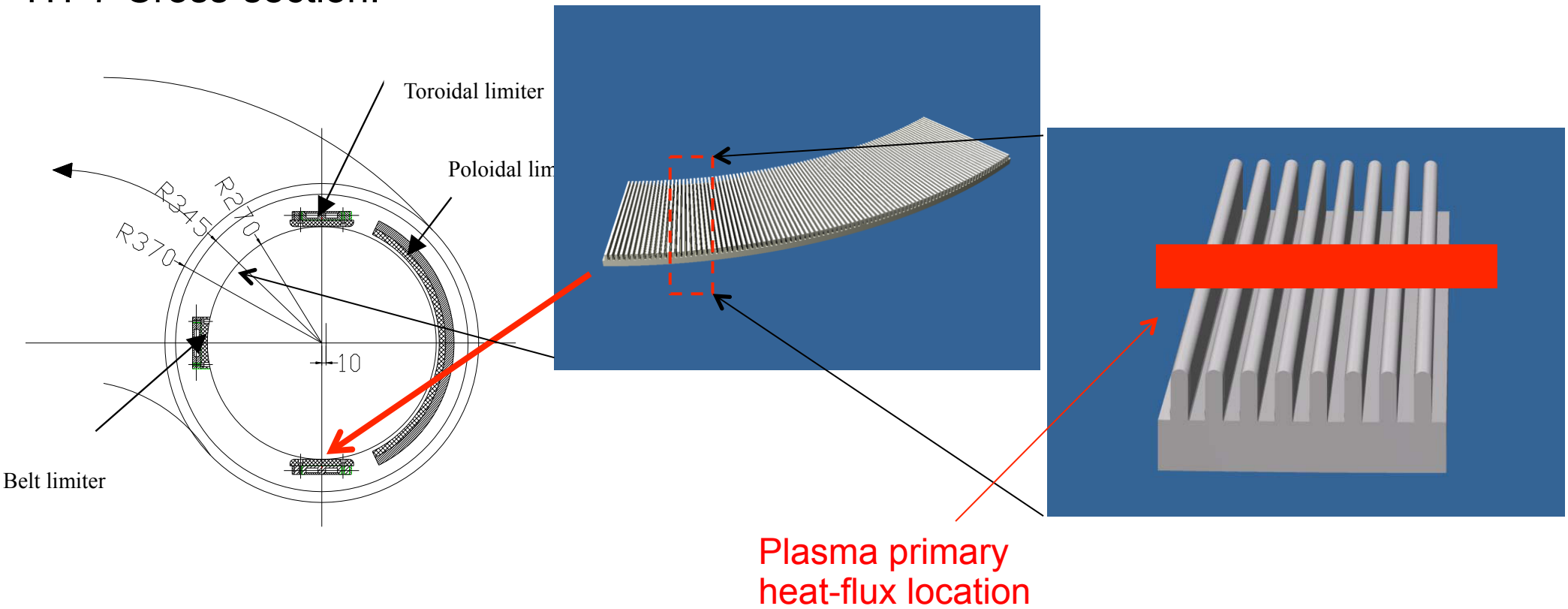
The Idea: "LiMIT" Design in NSTX



- Left is a cross-section of NSTX showing the "shelf-like" inner divertor plates.
- Right is the LiMIT concept: metal 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: metal 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-Driven

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

D.N. Ruzic, et al. Nucl. Fusion Lett. (accepted, to be published)

Lithium - Metal Infused Trenches (LiMIT) for Heat Removal in Fusion Devices

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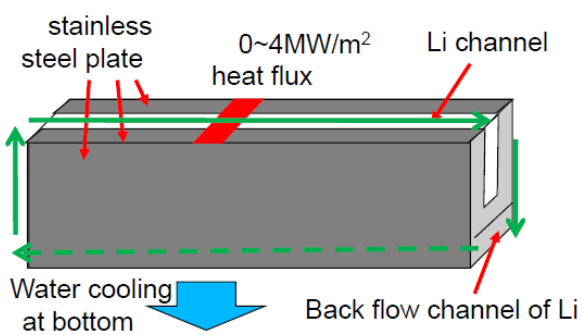
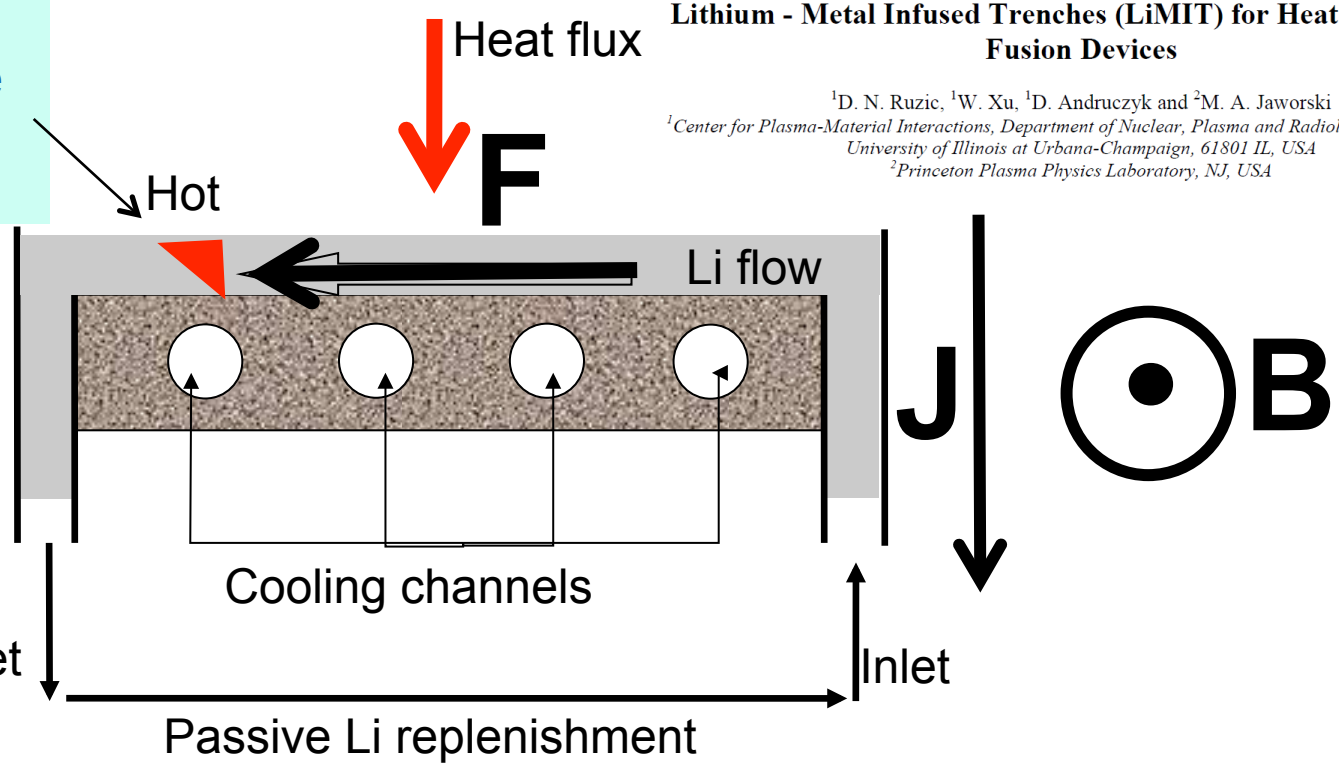
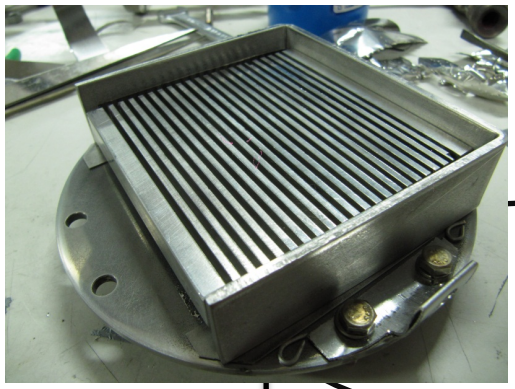


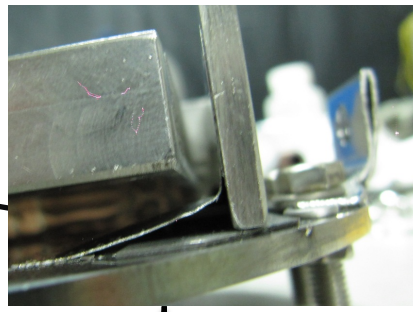


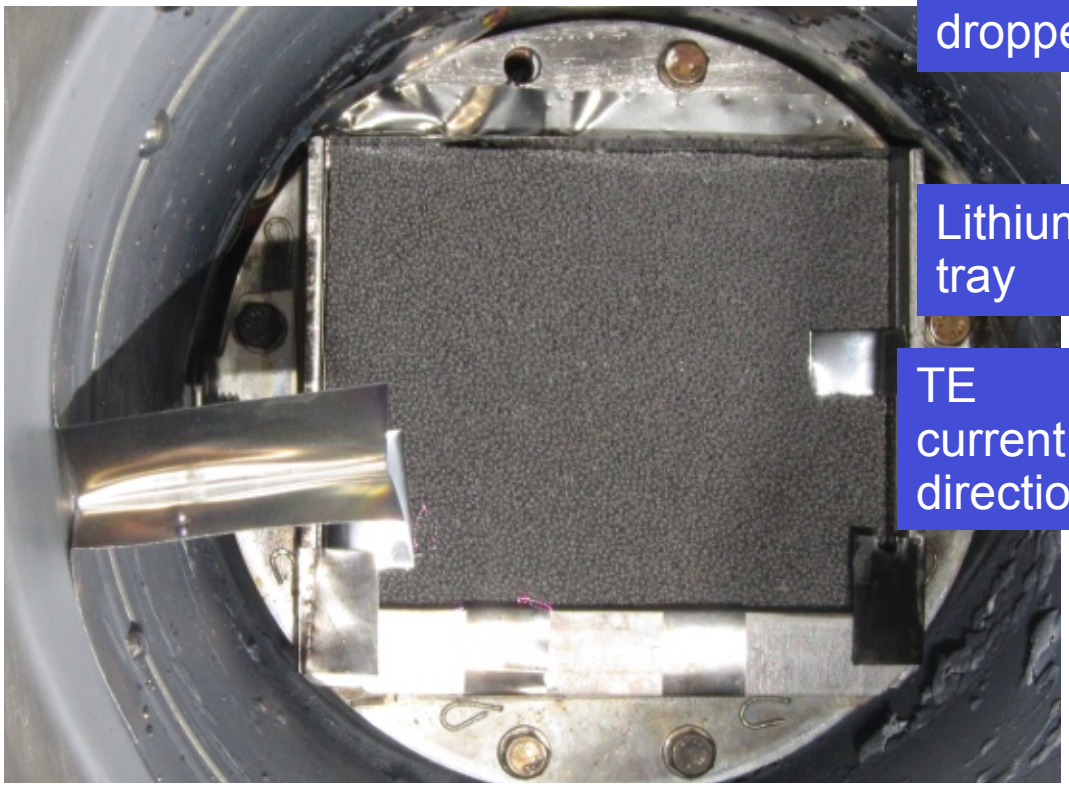
- Concept for heat removal using TEMHD. The Li flows in the slots of the metal plate powered by the vertical temperature gradient. This vertical temperature gradient generates vertical current, which when "crossed" by the torroidal magnetic field, will create a radial force on the Li driving it along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

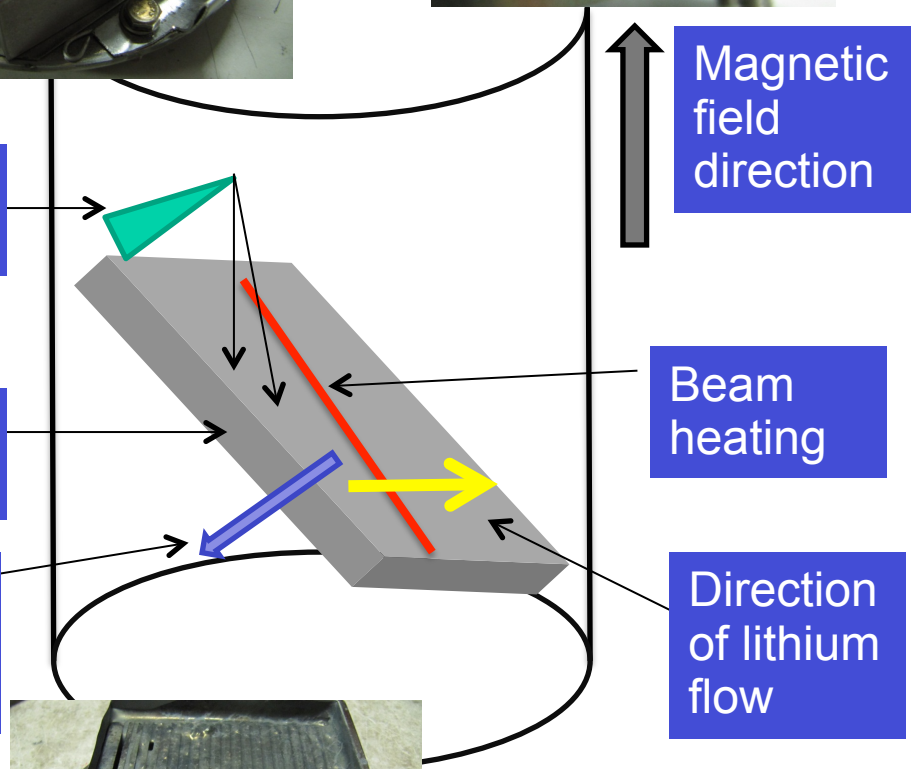
To really observe flow: sprinkle dust on the lithium !

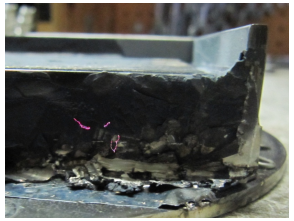
We added a tray to hold some lithiumoxide dust and hit the device with a hammer to knock the dust onto the tray. It worked !











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.

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.

Calculation of the speed of the flow

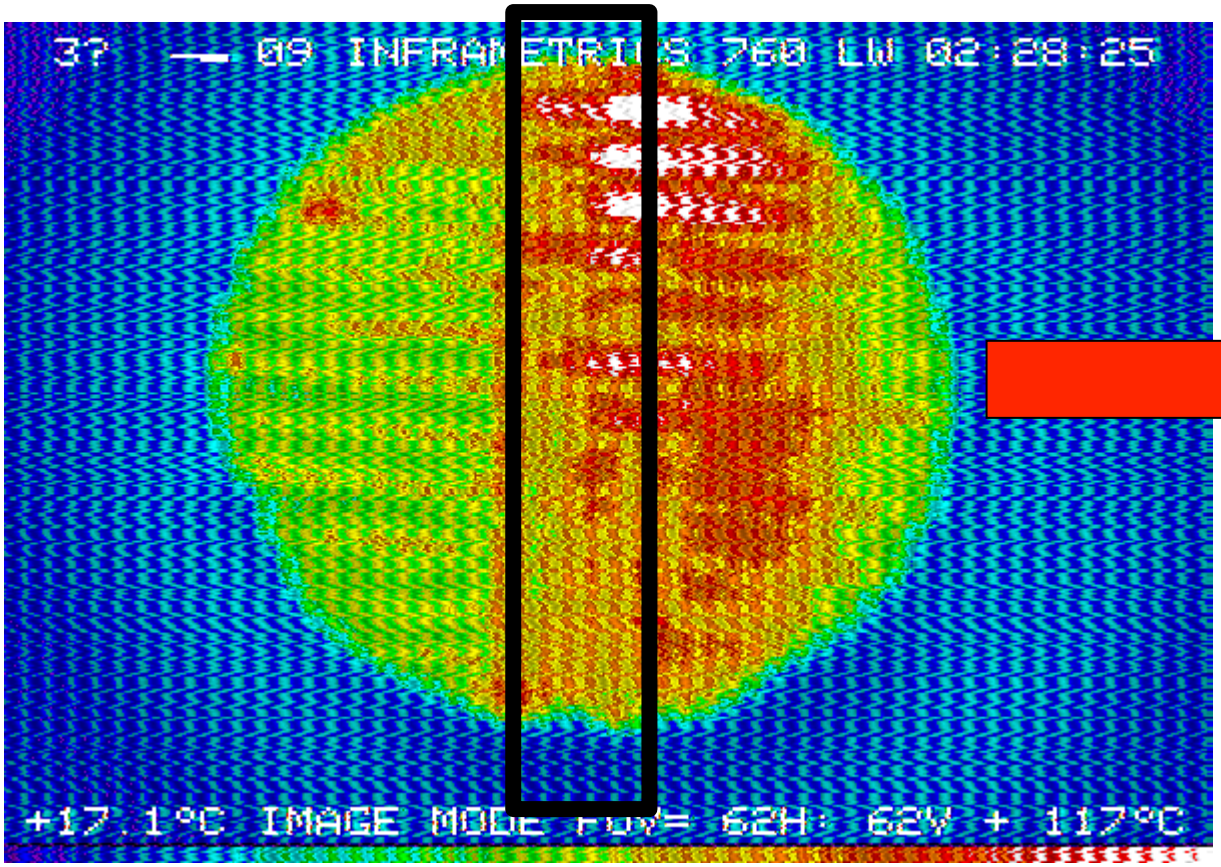
- The time between each frame is 1/25 s. The total length of the moving trace is measured and divided by the time interval.

- 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

IR pictures of Stainless Steel (400 W)

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

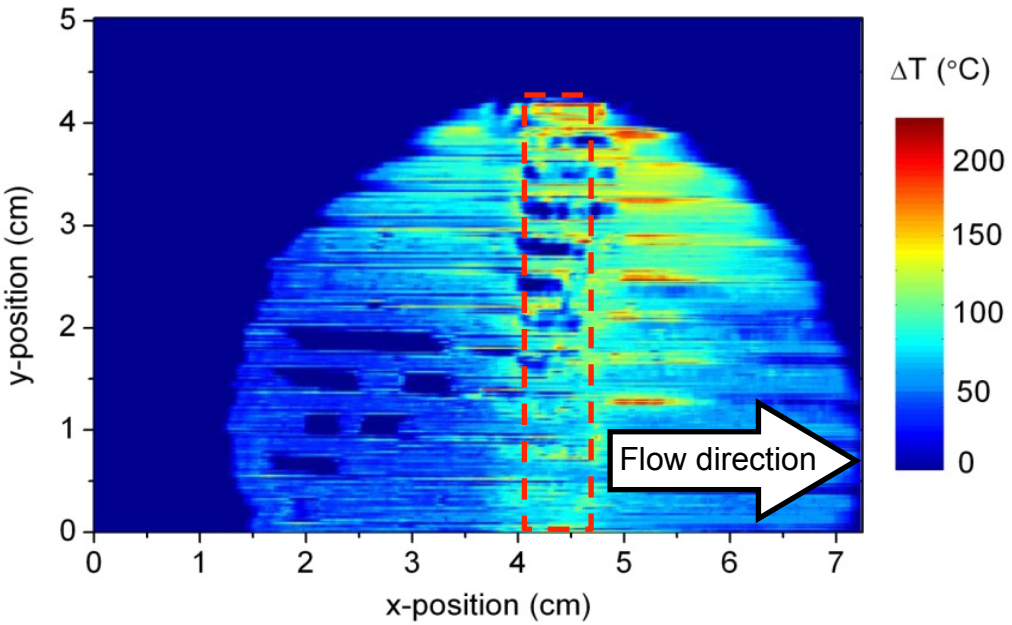
Electron Beam Heat Stipe

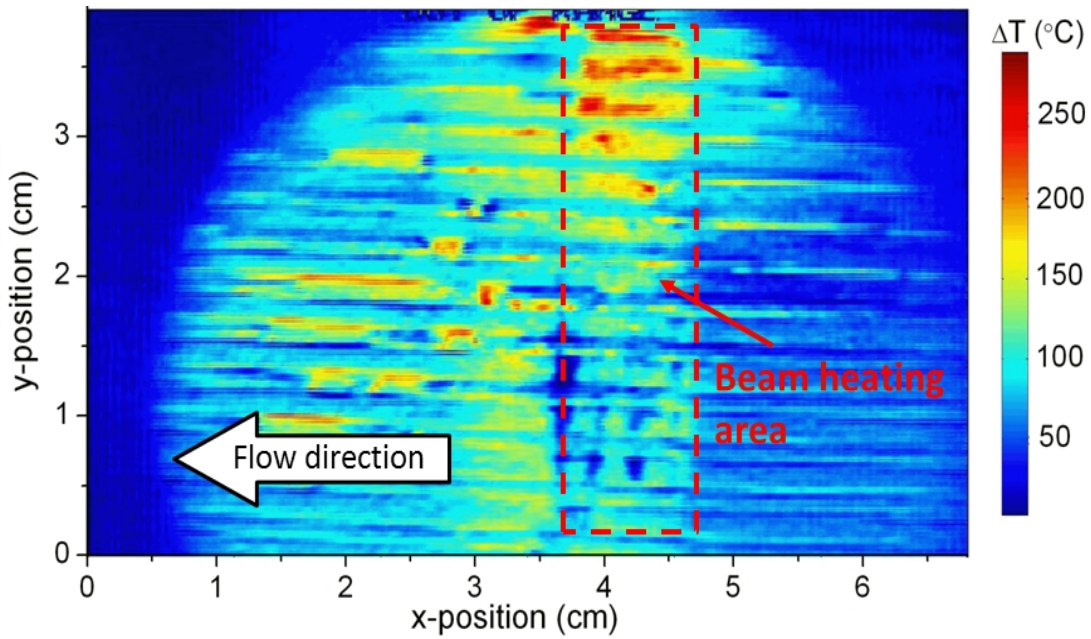


Lithium Flow Direction

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

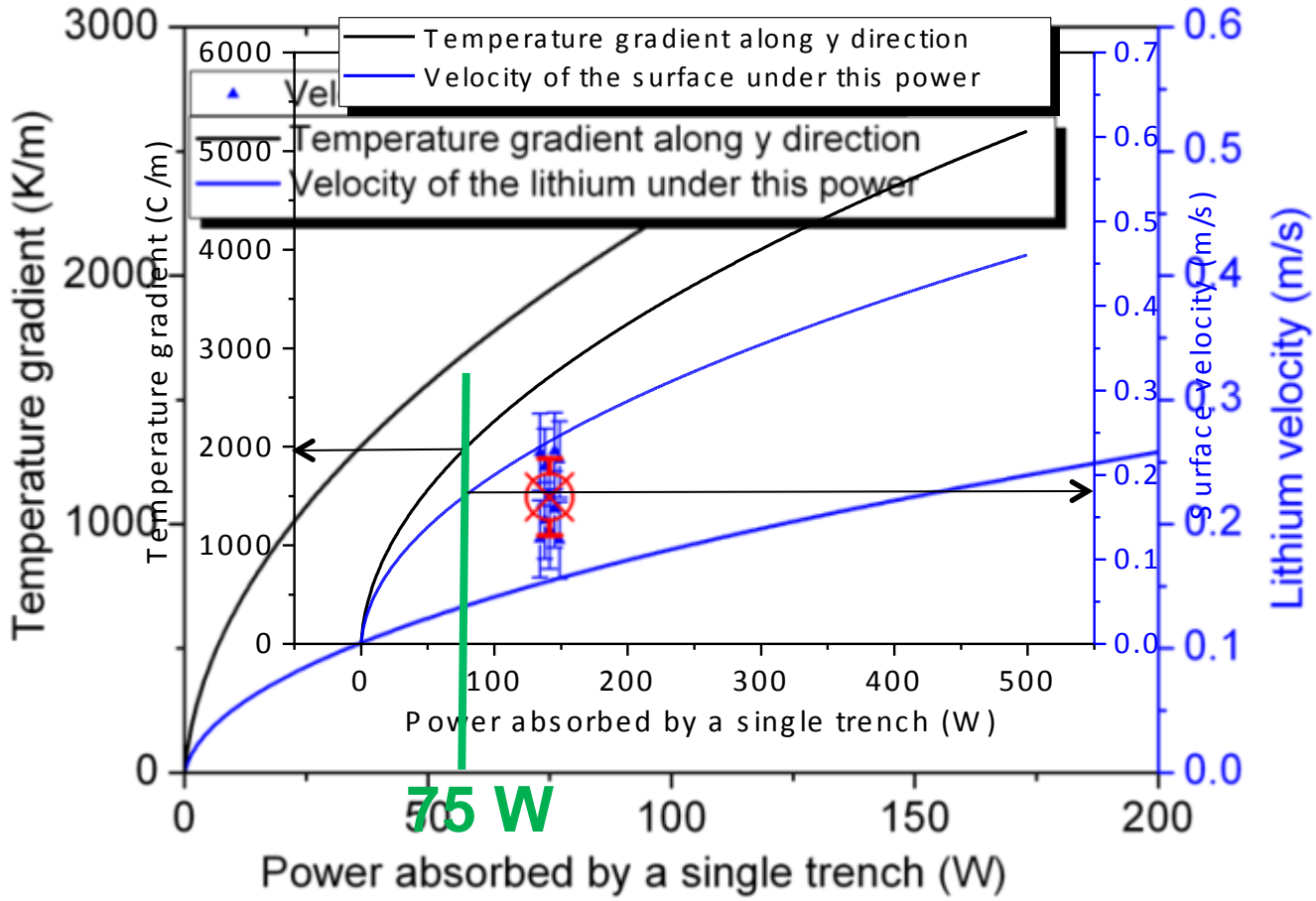
IR images when reversing the magnetic field





- IR camera measurement of the top surface shows an uneven temperature distribution.
- When the direction the magnetic field is changed, the direction of the flow is changed. So is the temperature distribution.
- Although the heat flux at the heating area is about 4MW/m^2 the temperature increase at the heating area is not very high. A lot of heat is brought away by the flowing lithium to the outlet area.
- From IR camera movies we can also get an estimate of the flow velocity. A value of 0.15 +/- 0.07 cm/s was measured.

Comparison of Theory to Experiment



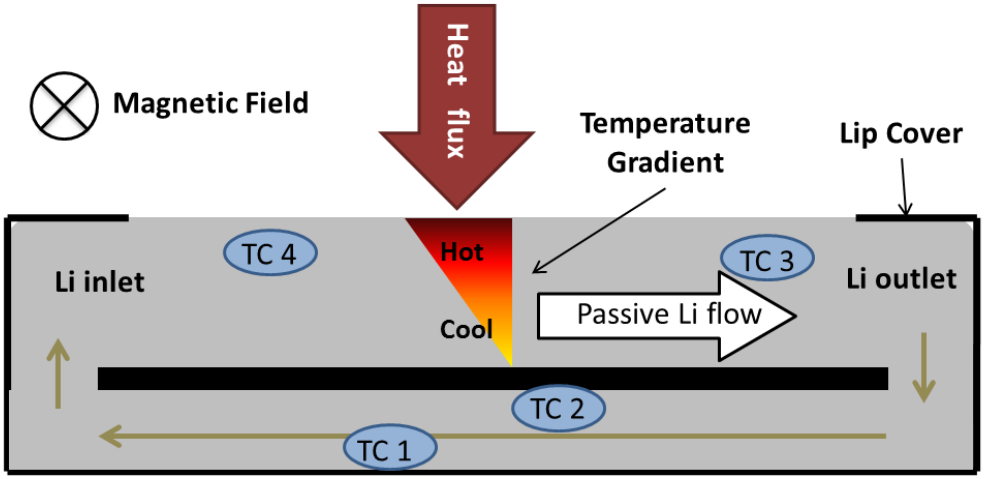
Predicted velocity by the analytic model is 0.18 m/s.

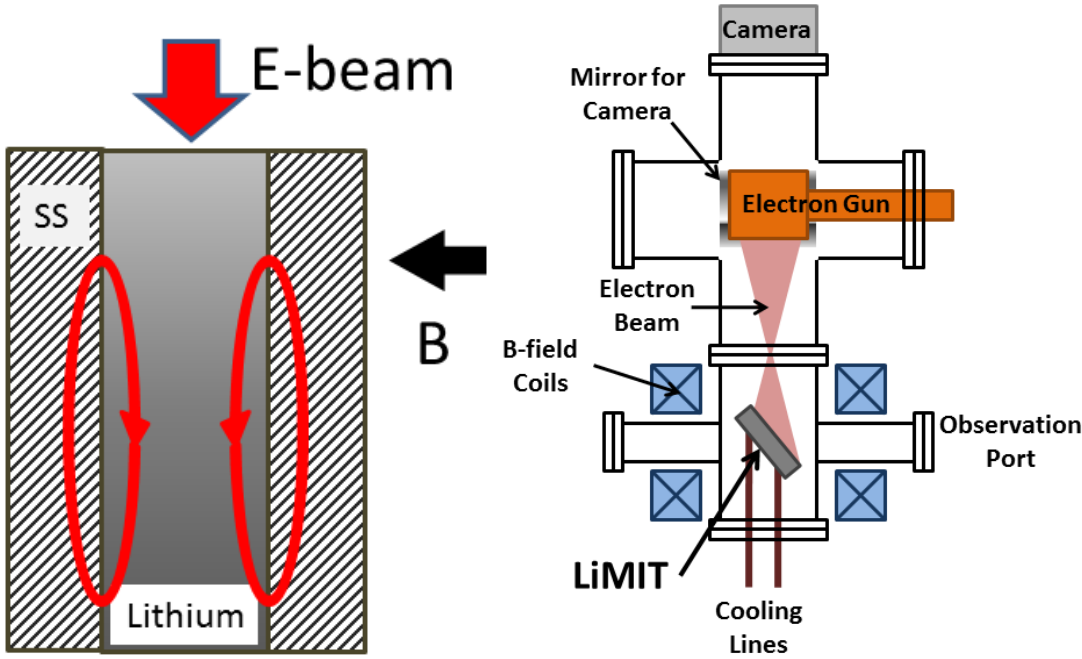
Measured velocity from movies is 0.22 +/- 0.03 m/s

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

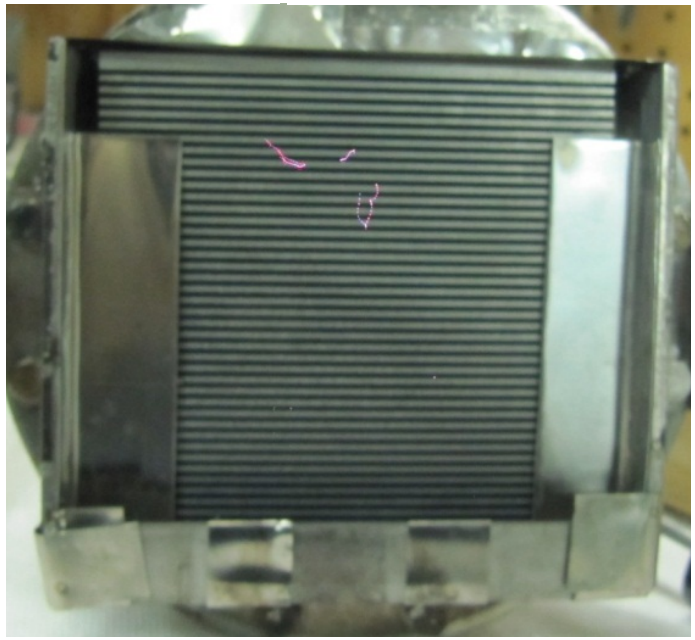
Experiment setup for thermocouples

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



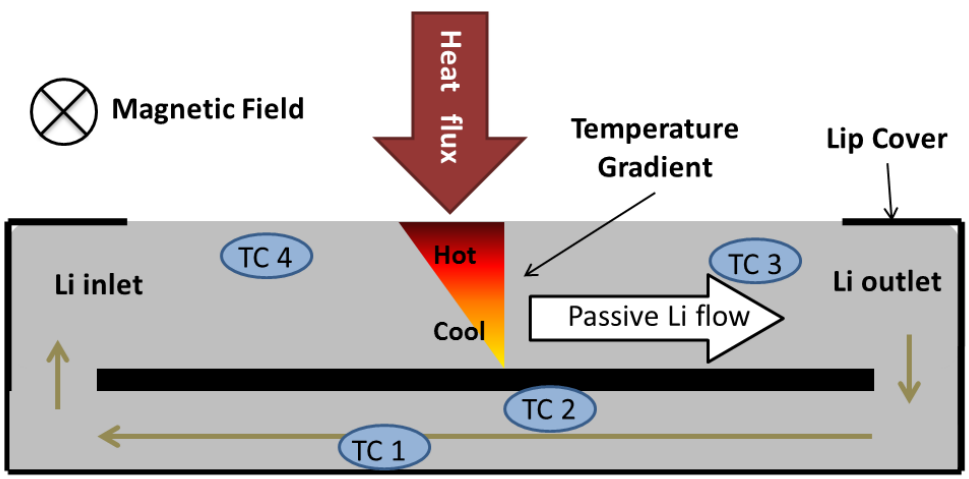


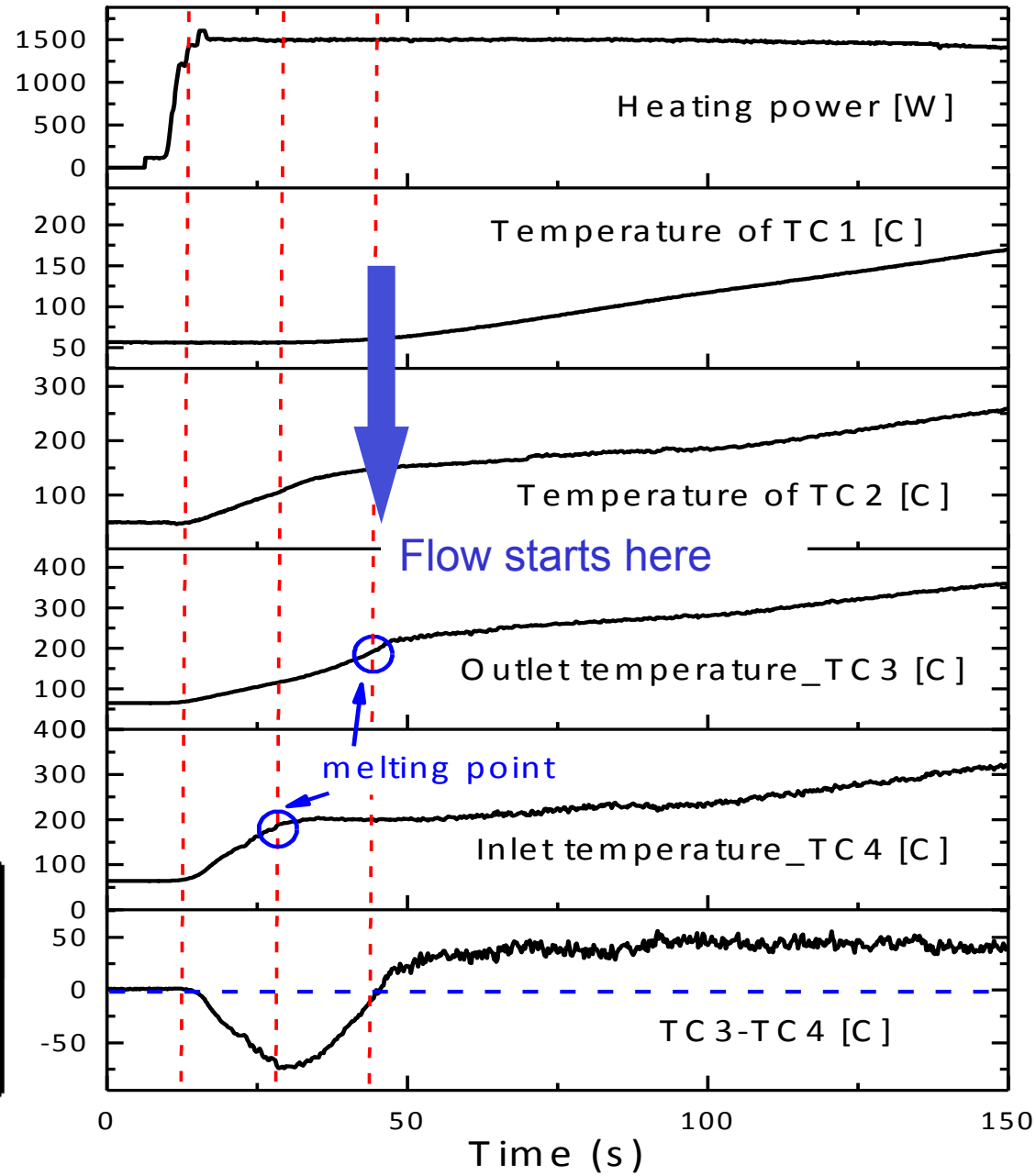
- The lithium tray is tilted to a small angle with the magnetic field. The electron beam is used to provide the heating while the magnet can generate about 600 Gauss magnetic field parallel to the tray surface.
- The stainless steel trench is 2mm wide, 1cm high and 10 cm long. The back flow channel is 5mm thick.



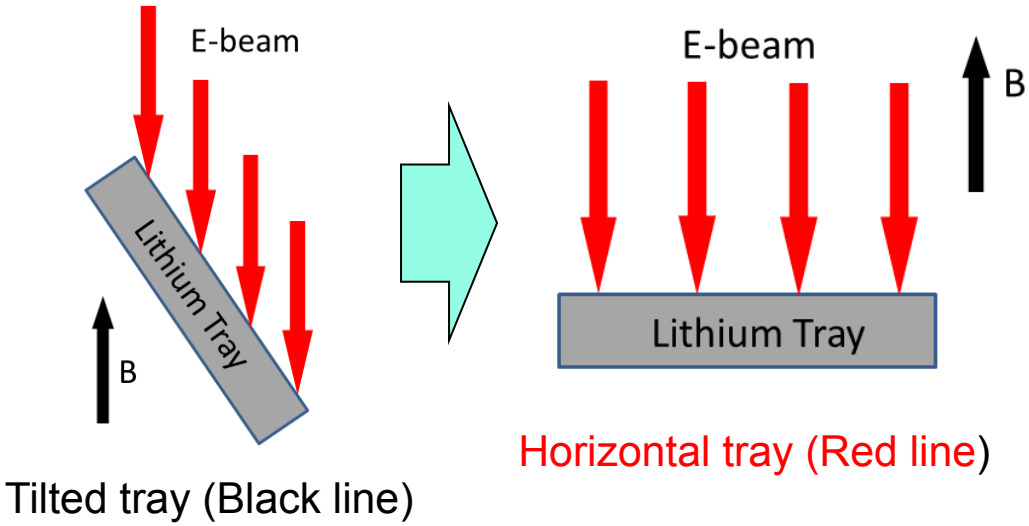
Crossing the melting point

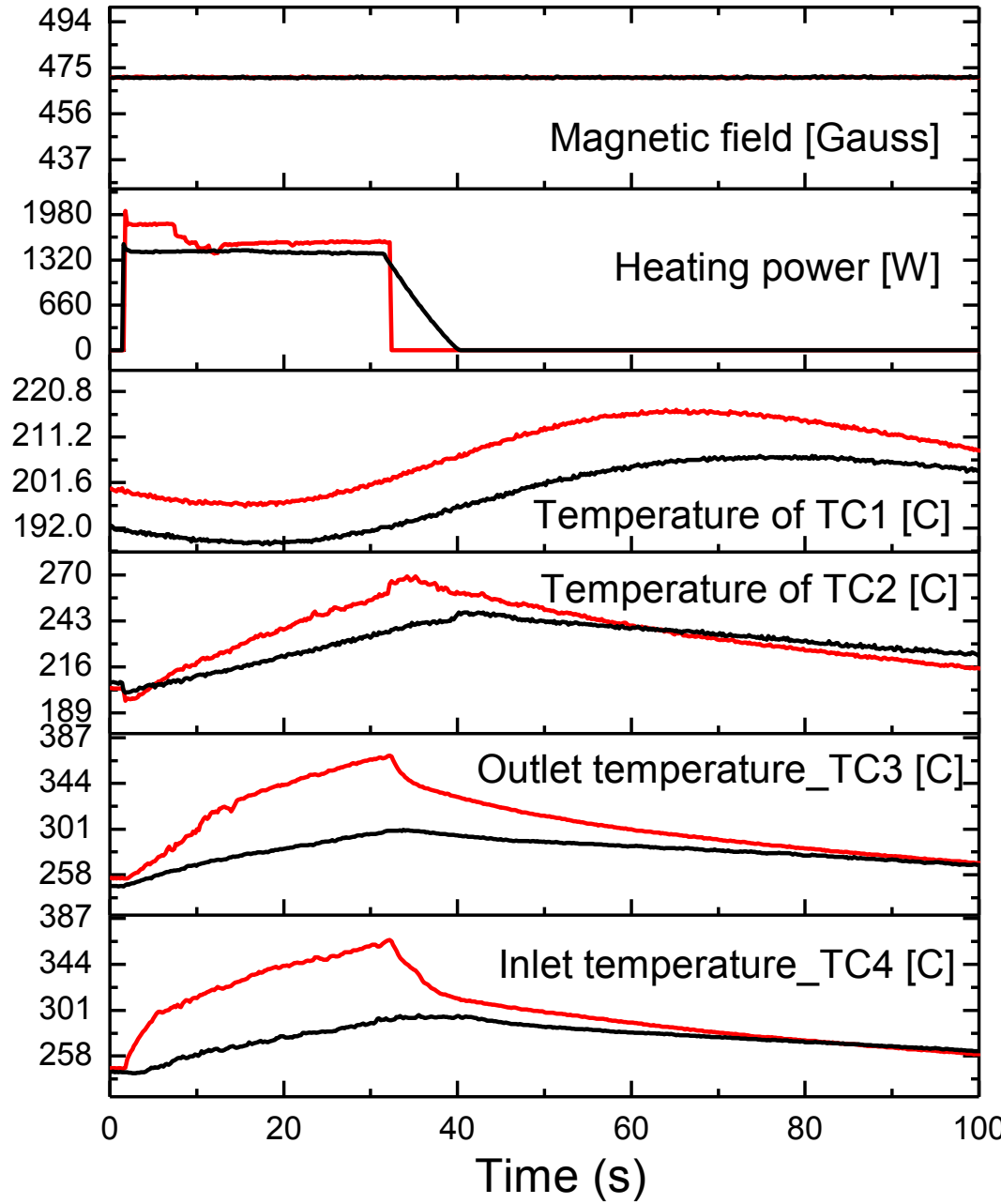
- Magnetic field is 350G.
- TC3 and TC4 are in the same channel and TC4 is closer to the heating area than TC3.
- Temperature difference is negative when lithium is solid and positive when lithium is totally melted and starts to flow.





With and without tangential magnetic field

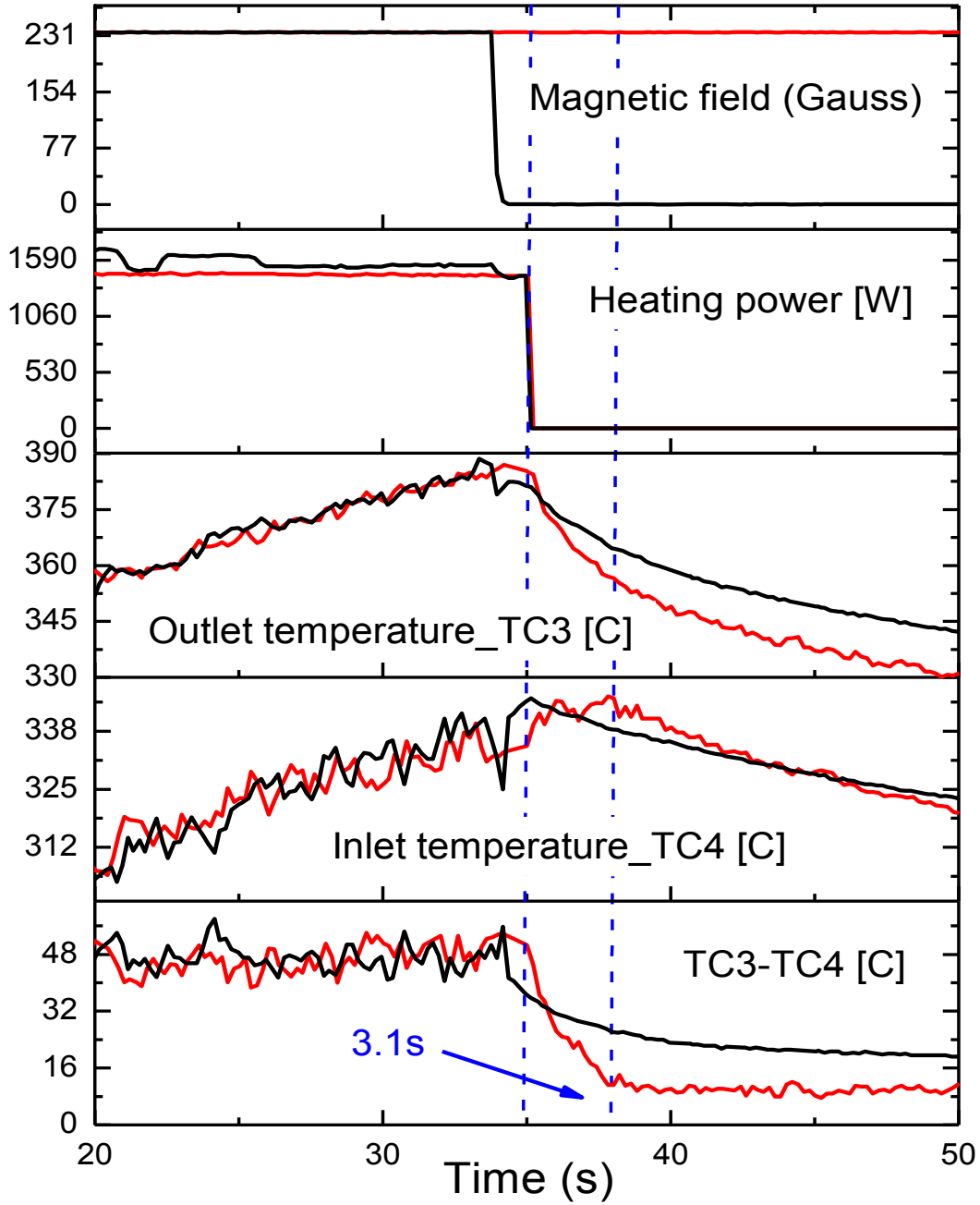




- When the tray is placed horizontally (red) the magnetic field is parallel to the thermoelectric current and therefore provides no force. The magnetic field and power are unchanged.
- No driven force, no flow.
- Without the flow, the temperature is significantly higher during and after the heating(30s).

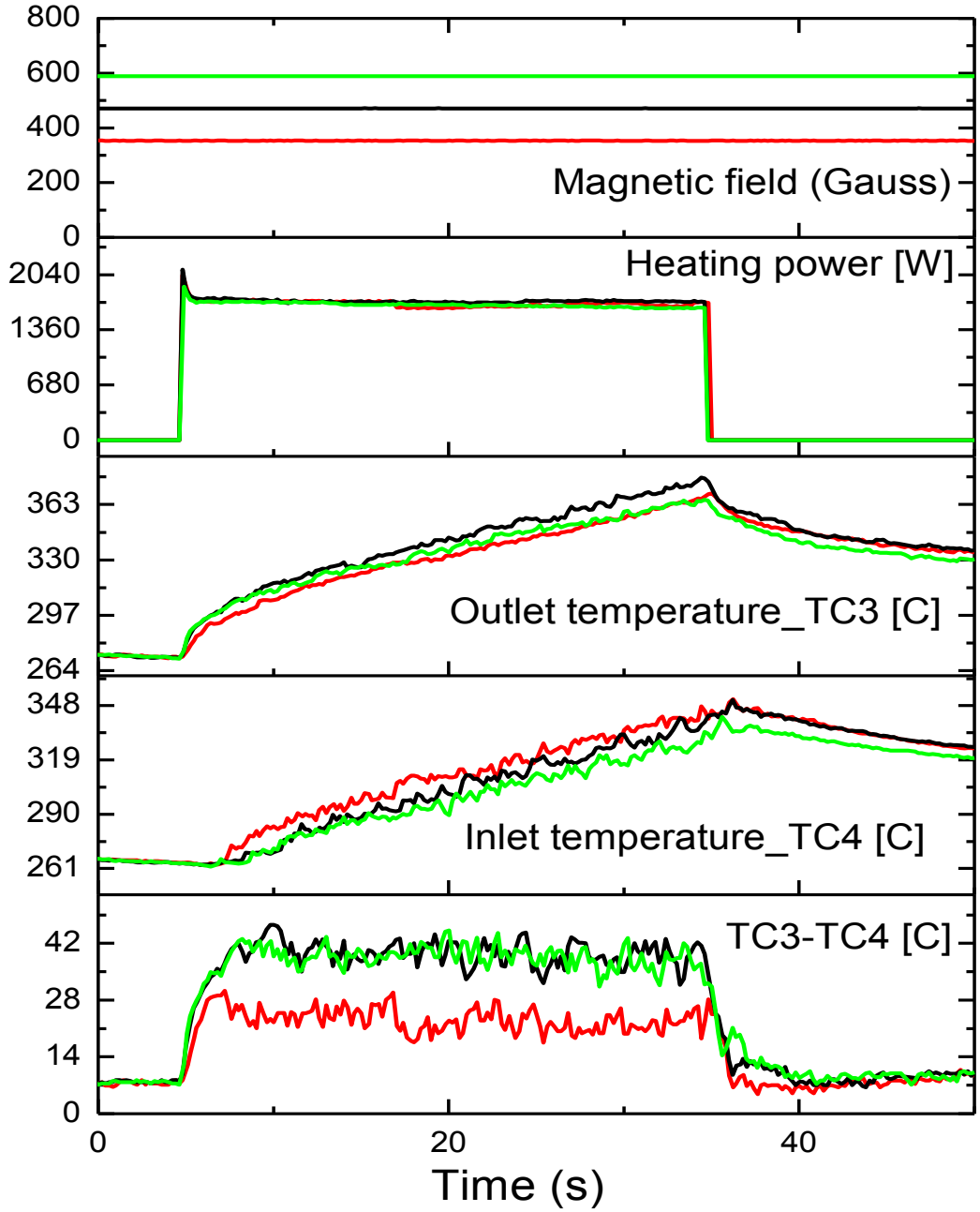
With and without magnetic field

- From previous swirling flow experiment we found that when the magnetic field is on the flow can exist for a long time. Red line: B stays on.
- After the heating, if the magnetic field is on, the inlet temperature keeps increasing for about 3.1 seconds and then starts to decrease.
- If the magnetic field is immediately turned off, the temperature decrease will be slowed down since the flow stops.



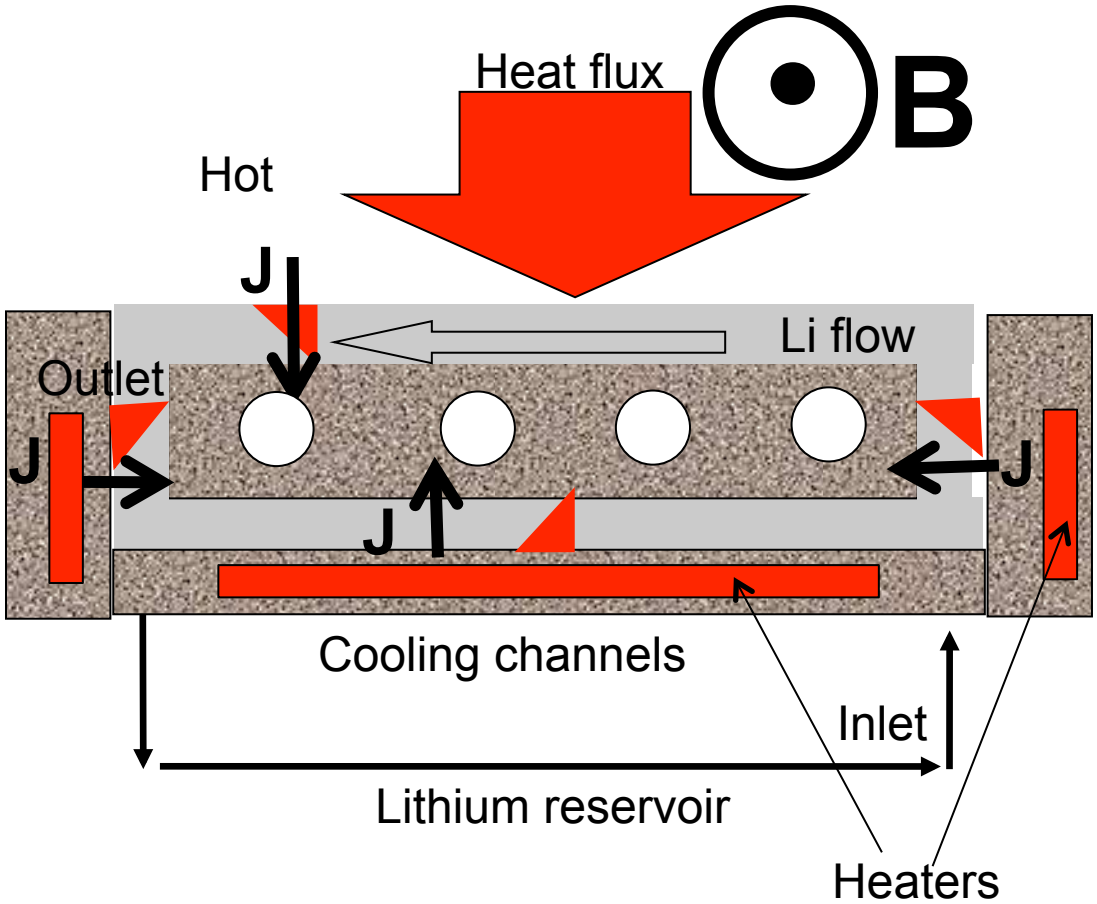
With different magnetic field strength

- The swirling flow experiment reveals that the flow speed is dependent on the magnetic field strength.
- When the magnetic field is higher, there will be a higher temperature difference between inlet and outlet.



How to use this in High Fields ?

- To ensure a return flow in a high field we need to maintain temperature gradient even outside of the plasma heat flux zone.
- This will be built by the Chinese and tested in HT-7 in April/May 2012
- It will go on their retractable limiter and be diagnosed with TCs and visible fast-framing camera



Retractible Liquid Li Limiter Tray on HT-7

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 x10^4 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 ^oC. 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

    For NSTX ~ 24 MW/m^2

    For HT-7 ~ 6 MW/m^2

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

  - Conduction through the metal (SS)

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

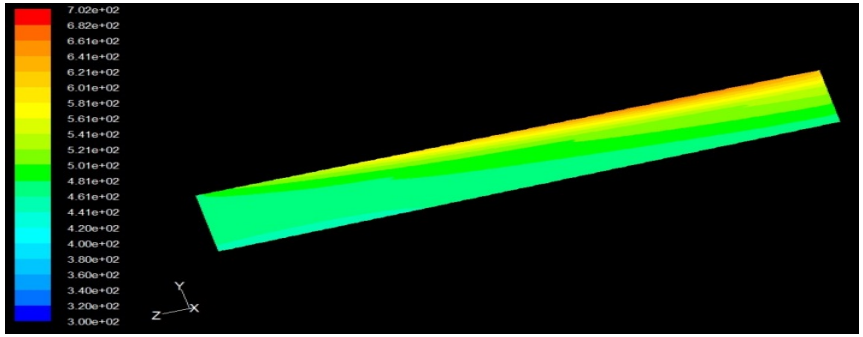
$$Q^{SS,\nabla T}_{\perp,MW/m^2} \simeq \frac{1.5}{h_{mm}}\frac{\Delta T^{SS}}{100^o}$$

  - Conduction through the lithium

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

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

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 can 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.