Update on SLiDE
(Solid/Liquid Divertor Experiment)

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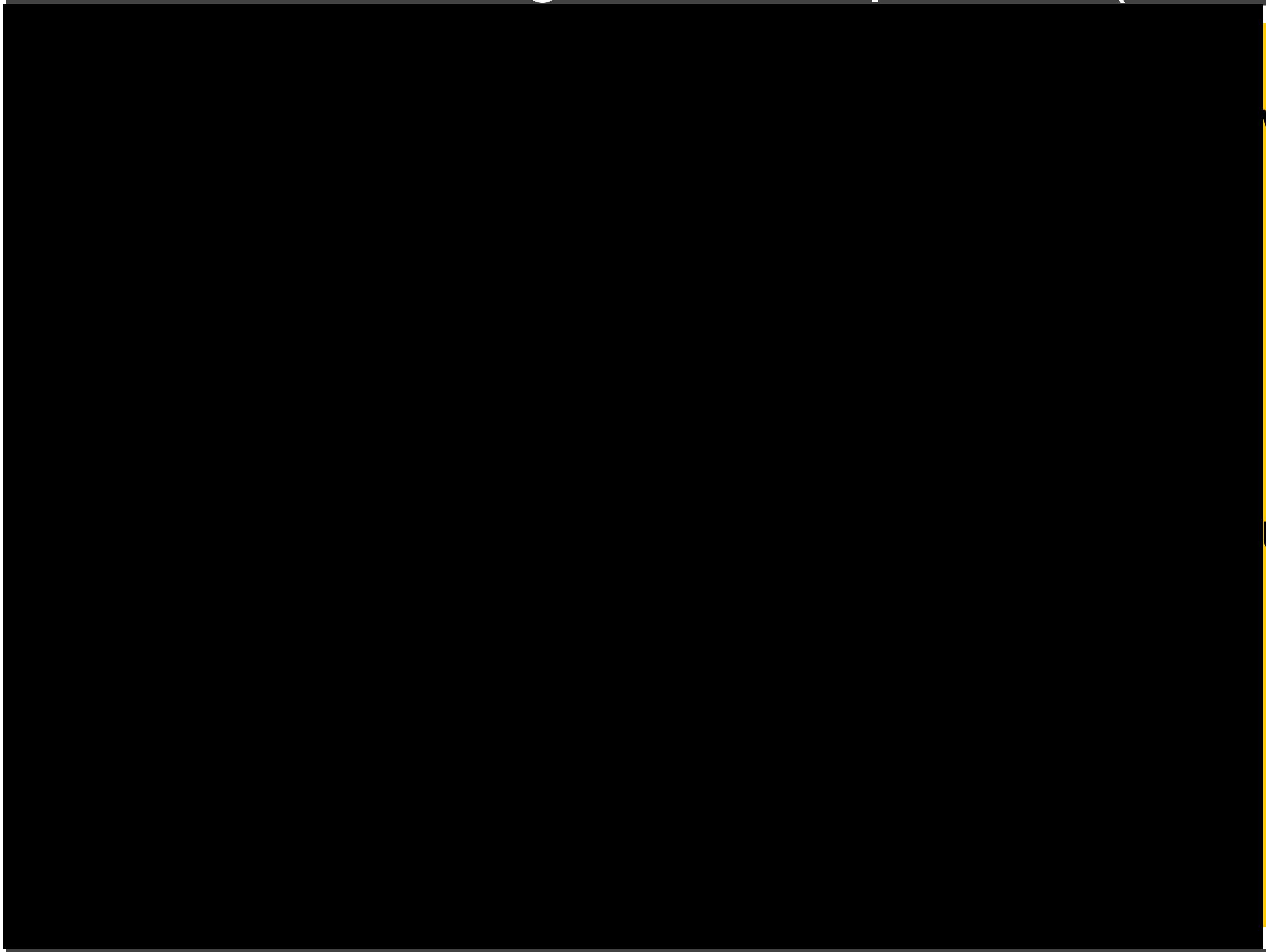
Outline

- The Lithium/Metal Infused Trenches (LiMIT) Concept
- Eliminating Gravity
- Comparison to Modeling
- Operation at Higher Magnetic Field
- Preparations for use in HT-7
- Conclusion

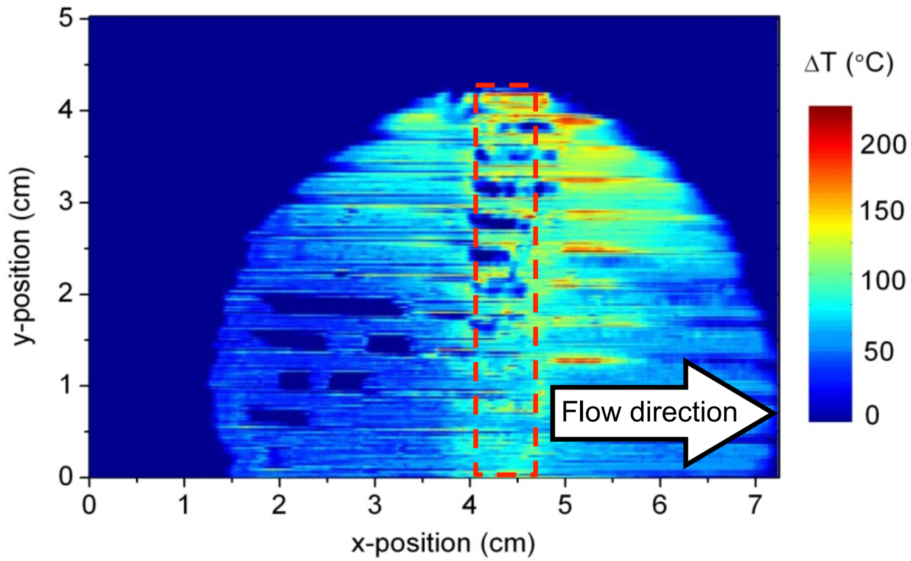
Movie of flowing lithium impurities (side view)

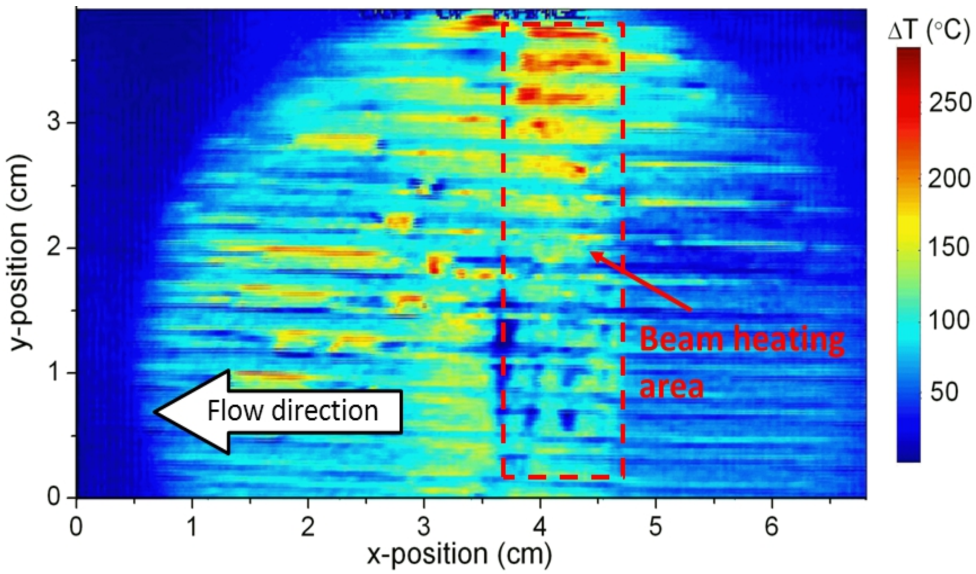


Motion will be left to right.

Look at "large" piece of scale in upper left. It will suddenly detach and flow across

IR images when reversing the magnetic field





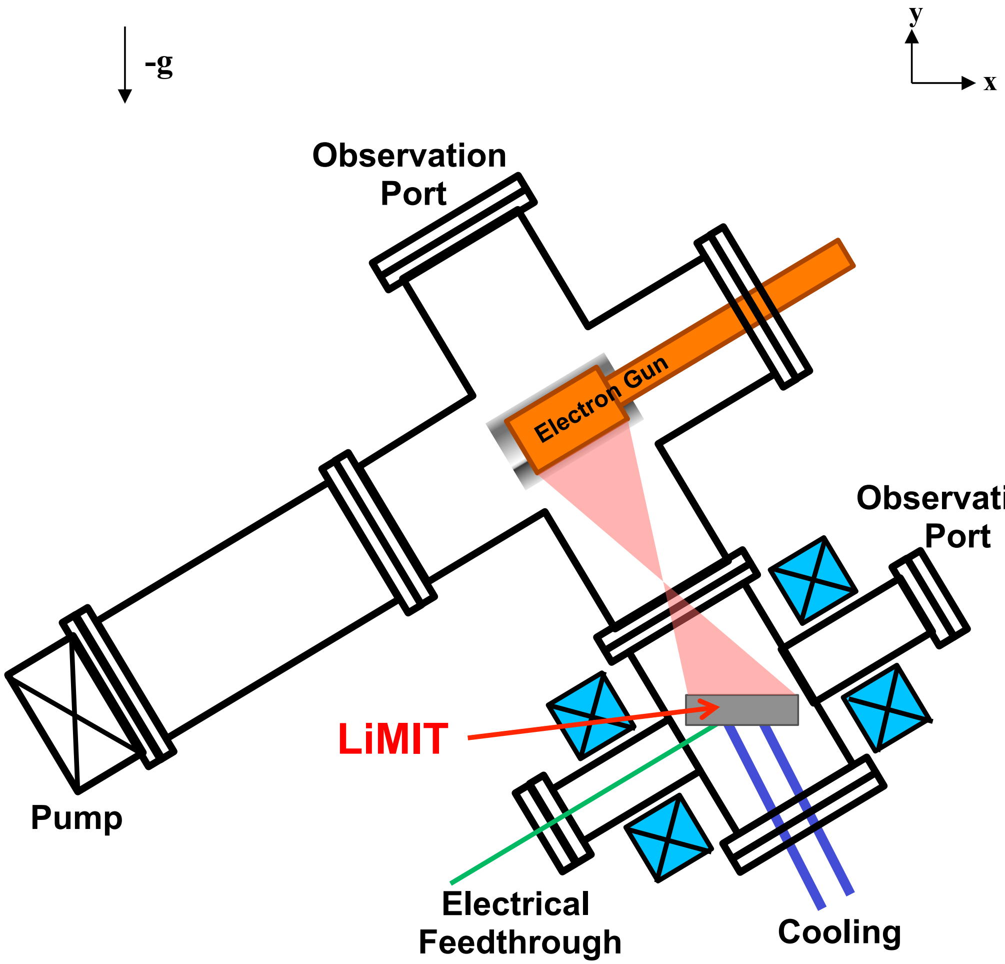
- IR camera measurement of the top surface shows an uneven temperature distribution.
- When the direction the magnetic field is changed, the direction of the flow is changed. So is the temperature distribution.
- From IR camera movies we can also get an estimate of the flow velocity. From the IR a value of 0.15 +/- 0.07 cm/s was measured.

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

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

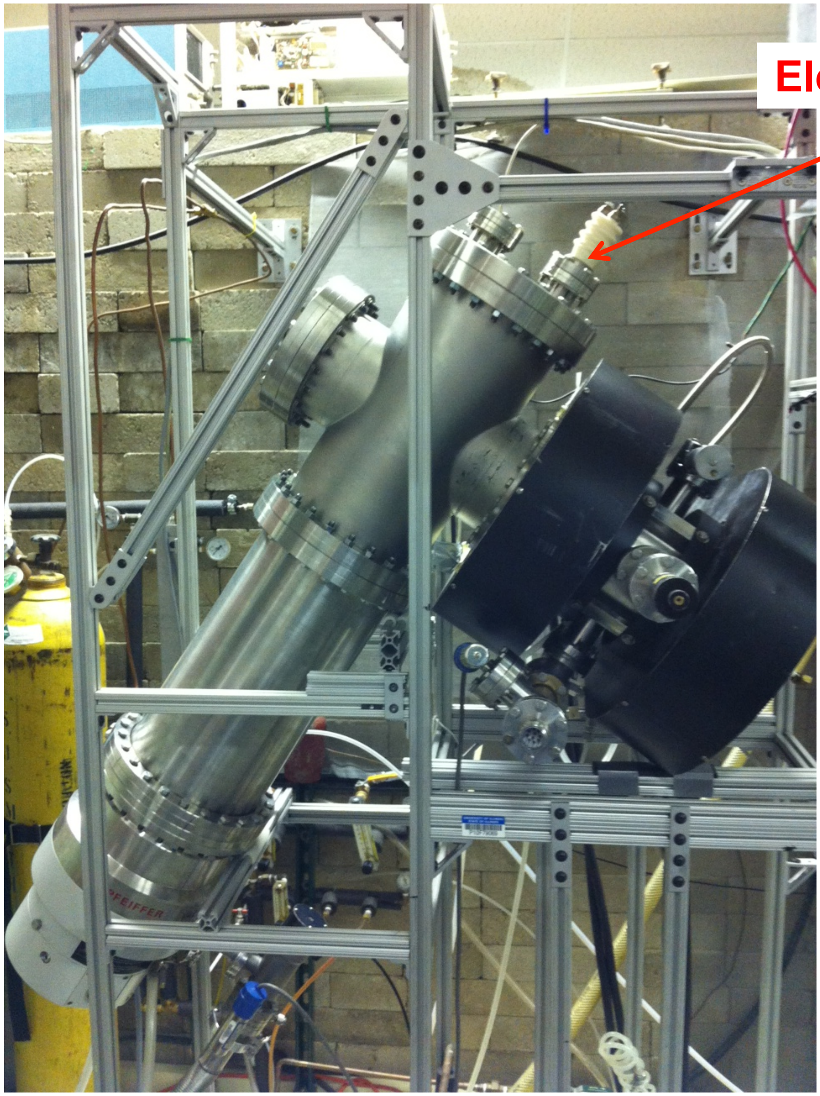
Eliminate Gravity effects on LiMIT

- Previous measurements on LiMIT
  - Inclined at 60º
  - There are some gravitational effects with LiMIT being inclined?
  - Lithium also flows down the trenches
- Important to show that LiMIT will still work without being inclined
- SLiDE tilted 60º so that LiMIT can stay level
  - No effect of gravity
- High Speed videos made of the flowing surface.
  - Clear movement of the liquid lithium
  - Surface waves



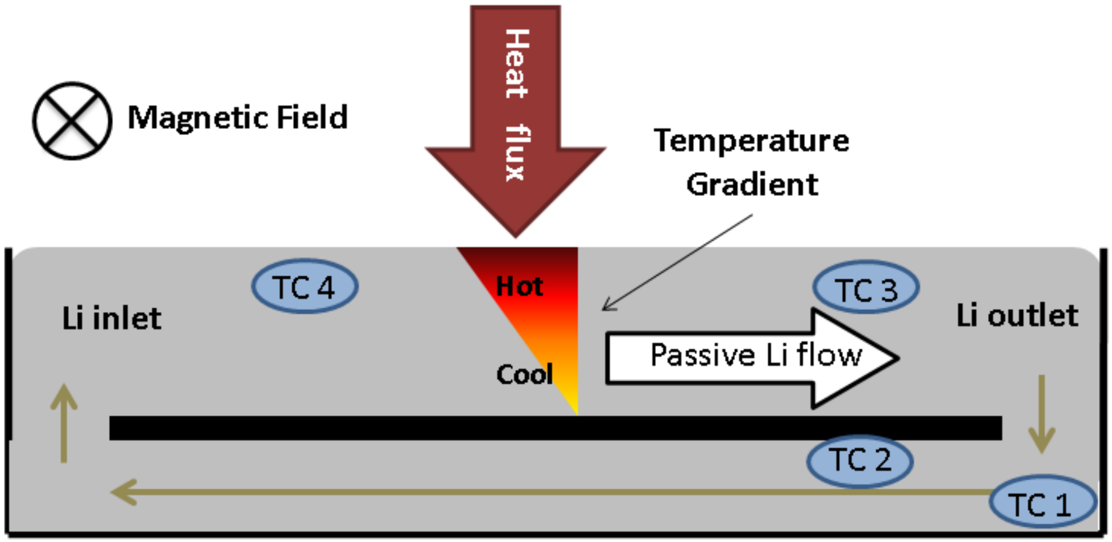
New SLiDE Configuration

Electron Beam



Clean at high temperature – flow downward

Thermocouple positions

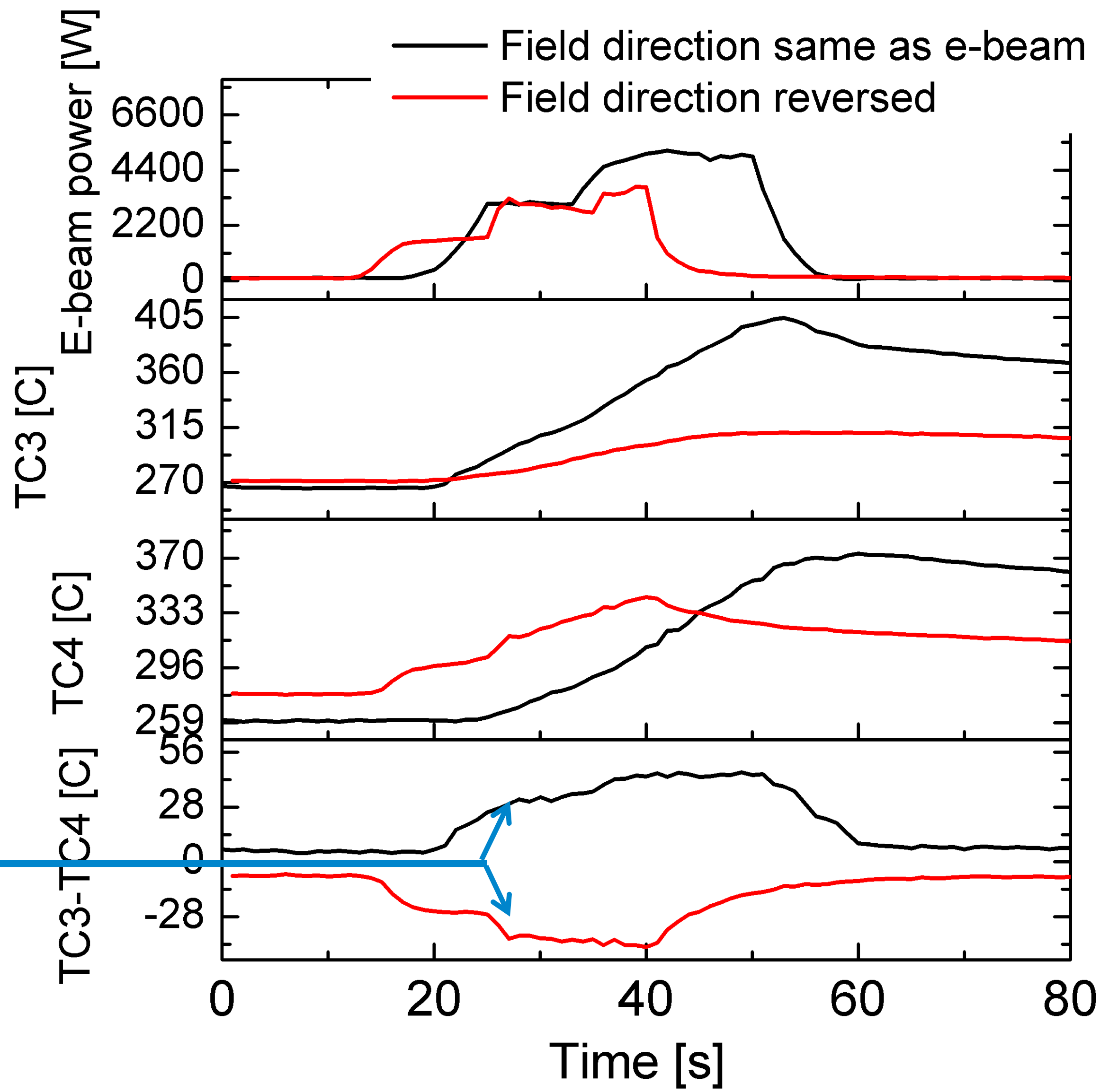


- Four thermocouples are attached inside lithium.
- Thermocouple 1 (TC1) is placed at the edge of the tray. TC2 is attached to the back side of the trench.
- TC3 and TC4 are placed inside the same trench to measure the temperature change of the trench flow.

Temperature change along the trench shows that flow exists

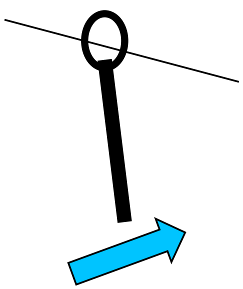
- When the e-beam heating power is increased, a temperature gradient creates a thermoelectric force. If the lithium is flowing, there should be a temperature difference (TC3-TC4) within the trench.

- If the direction of the magnetic field is reversed the left/right temperature difference should also reverse.

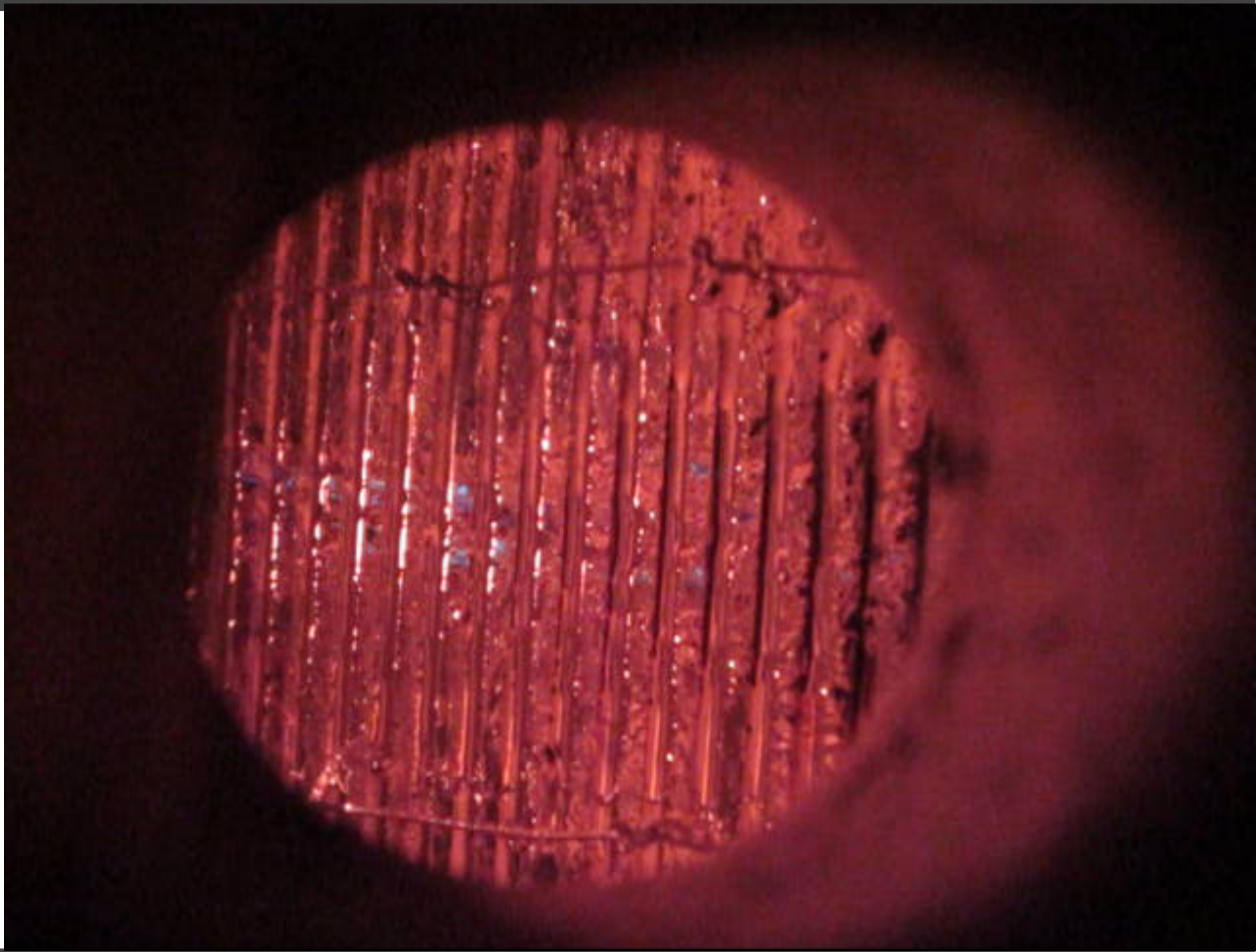


Movement of Flow Indicator

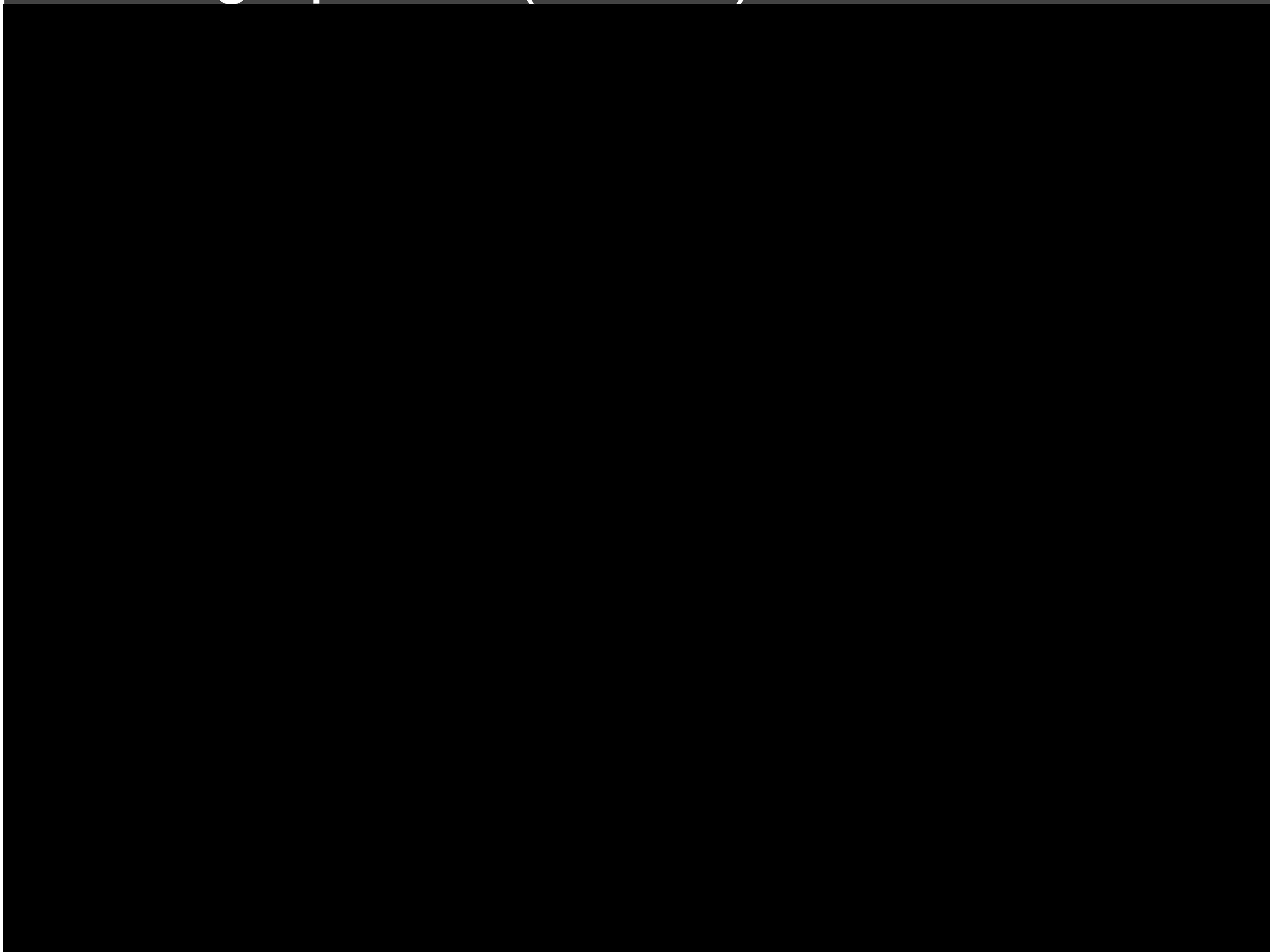
Installed a "flow indicator" to attempt to measure velocity.

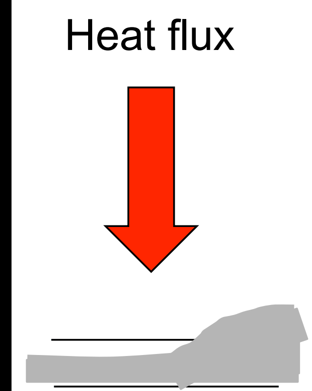


It is a swiveling piece of SS shim stock hanging in a trench.



At high power (6+ kW) downstream Li bulges

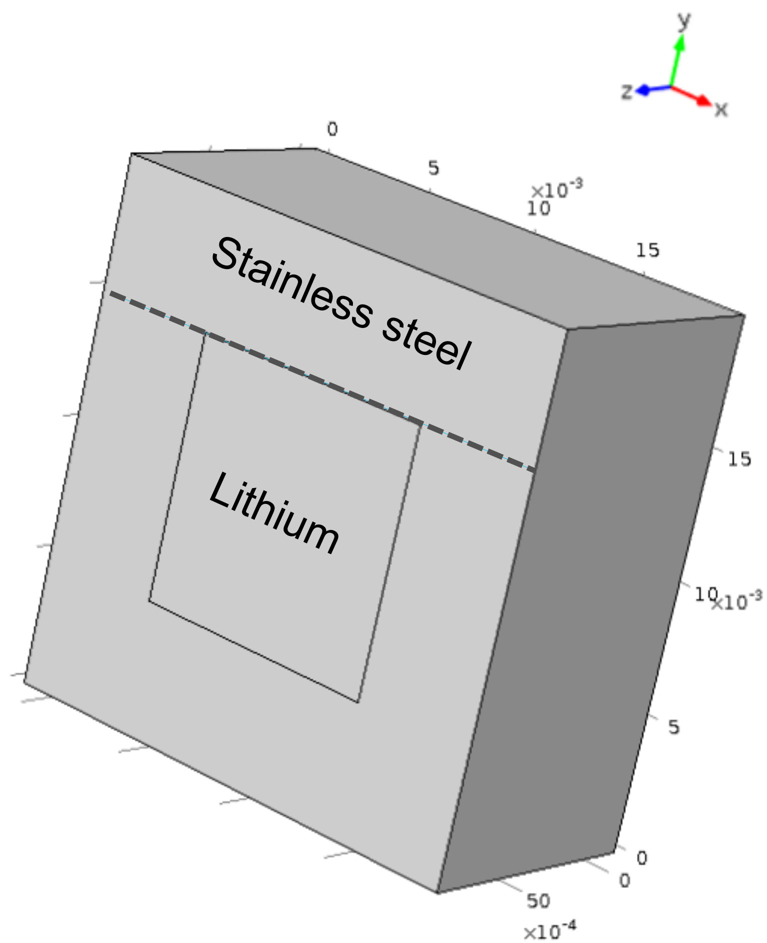




Modeling from Davide Curreli (yesterday) shows origin of this effect

3D Simulation of TEMHD driven flow

- This geometry is used to simulate an infinite long lithium flow in a stainless steel duct.
- The lithium part is a cube with 0.01m side length. The stainless steel part is a 0.02m by 0.02m by 0.01m shell structure with 0.01m wall thickness.
- Modeling done using FEM (COMSOL® MultiPhysics)
- The numerical convergence of the problem strongly depends on the physical parameters such as Reynolds number and Hartmann number



Governing equations

- Continuity

$$\nabla \cdot \vec{u} = 0$$

- Navier-Stokes

$$\rho \vec{u} \cdot \nabla \vec{u} = -\nabla P + \mu \nabla^2 \vec{u} + \vec{J} \times \vec{B}$$

$$Periodic\ boundary\ condition\ for\ inlet\ and\ outlet$$

- Heat transfer

$$\rho C_P \vec{u} \cdot \nabla T = \nabla \cdot (k \nabla T)$$

$$Boundary\ condition:\ T|_{y=0} = 473K\ ,T|_{y=0.02m} = 573K$$

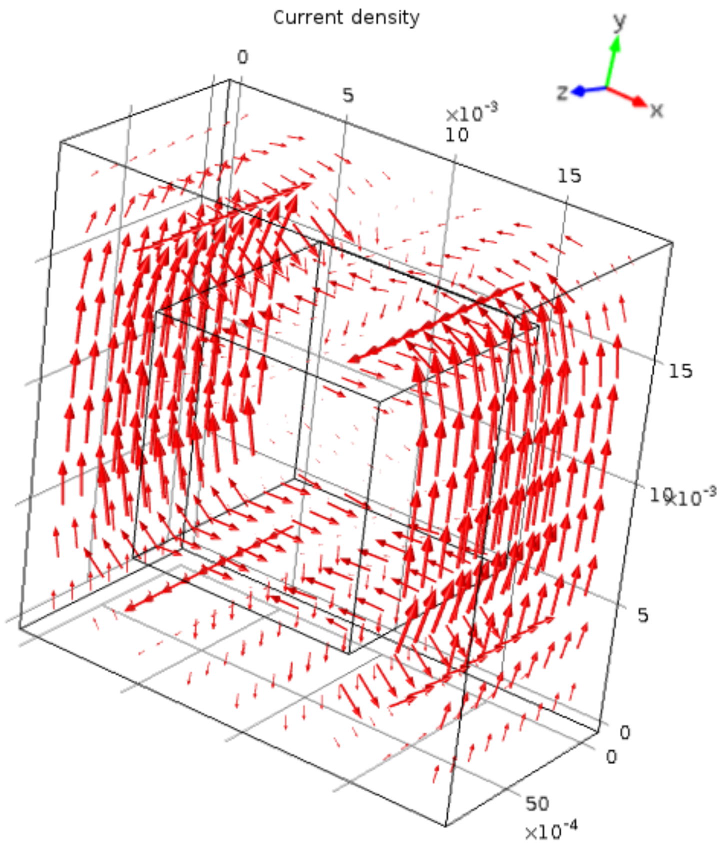
- Current conservation

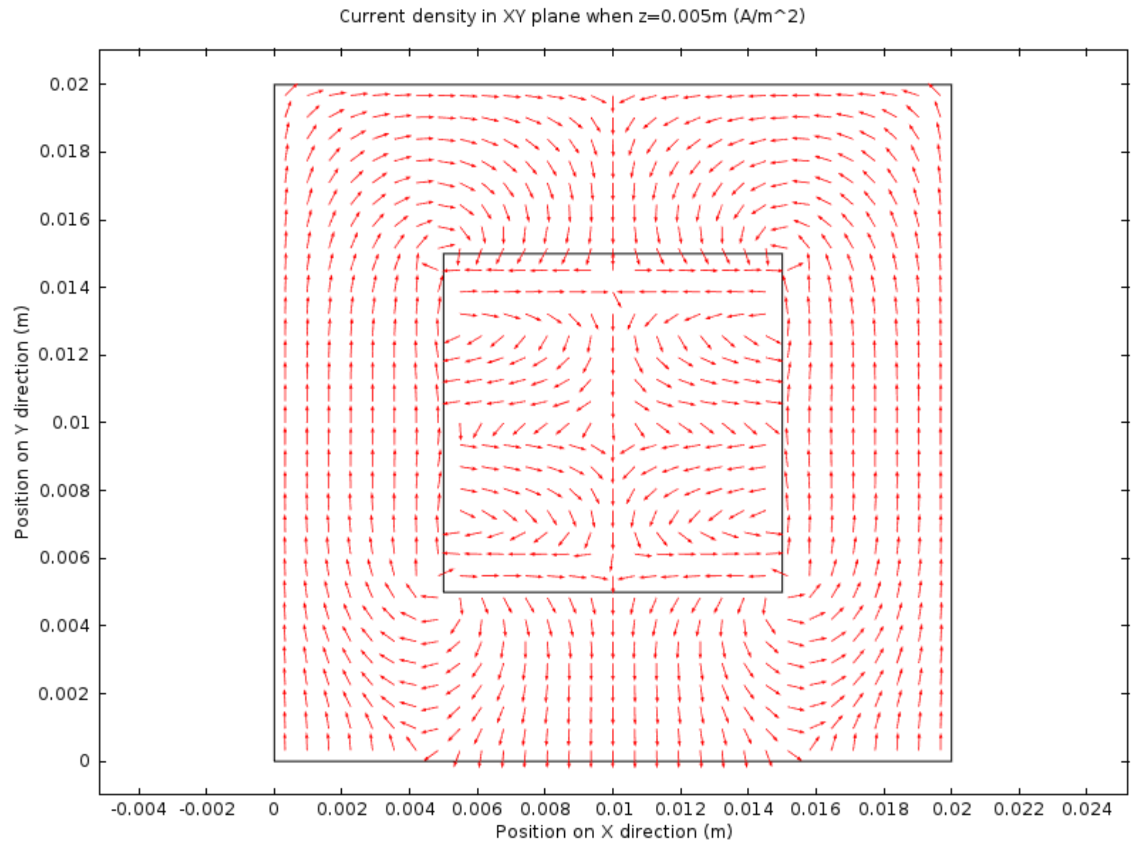
$$\nabla \cdot \vec{J} = 0\ and\ \vec{J} = \sigma\left(-\nabla \varphi + \vec{u} \times \vec{B} - S \nabla T\right)$$

$$Boudary\ condition: y = 0\ surface\ grounded, other\ surfaces\ insulated$$

- In above equations B is assumed to be constant. S is the Seebeck coefficient of lithium.

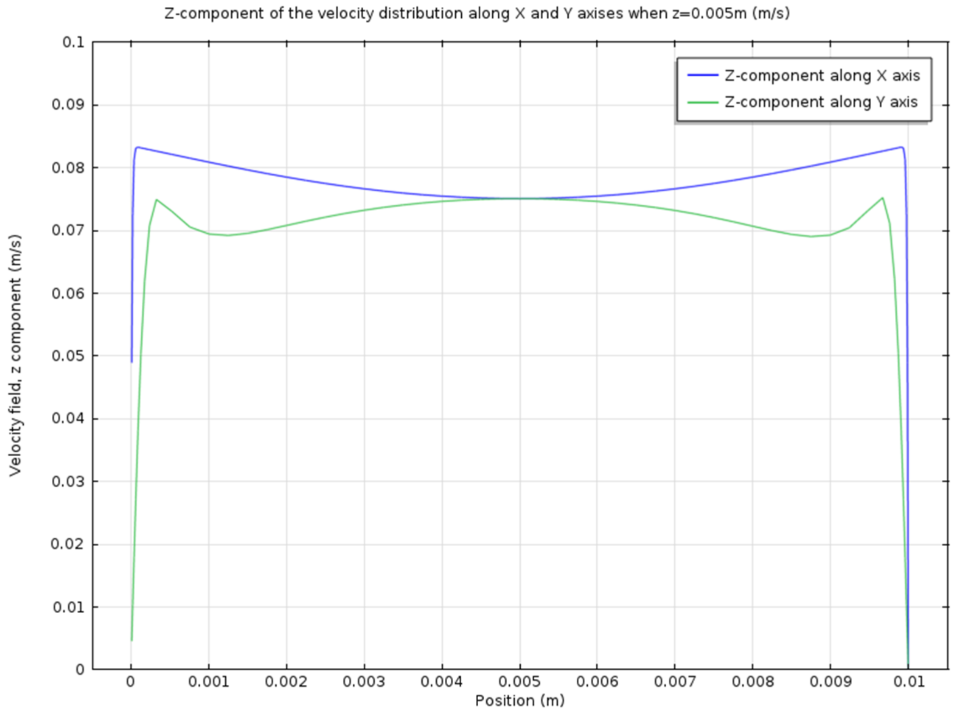
Current density

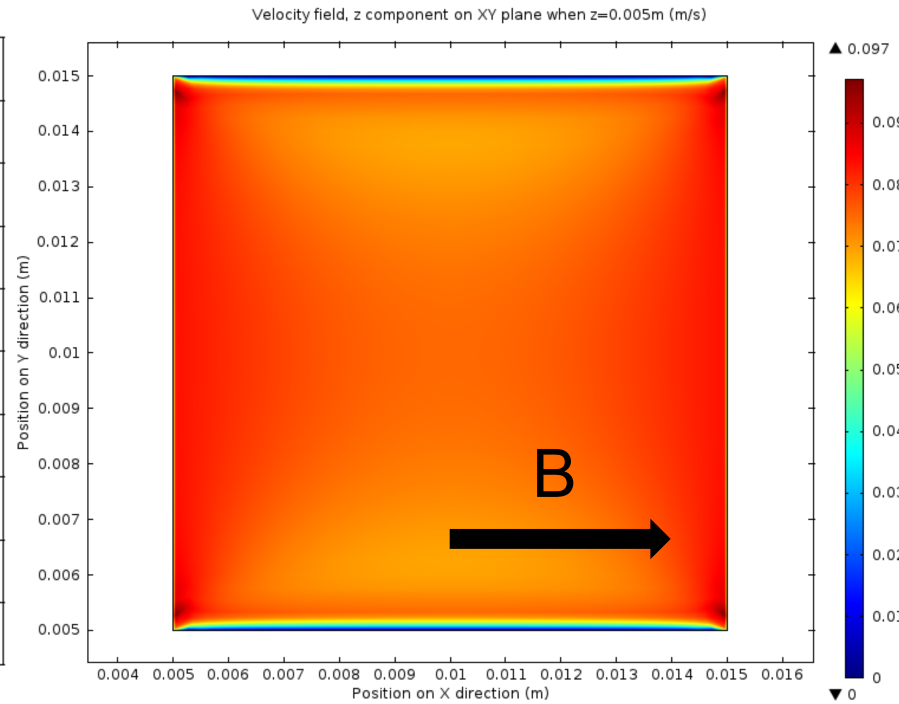


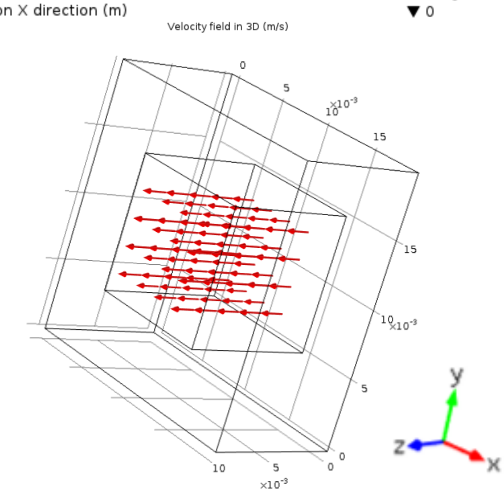


- The current pattern is smaller inside the lithium part because the thermoelectric current is cancelled by MHD current.
- Most of the current flow in XY plane accordingly to the temperature gradient.

Velocity field







- The velocity along B exhibits the classical profile from Hartmann layer
- The $S\nabla T$ term modifies the classical “Hartmann” solution allowing a flow without pressure gradients forces

3D Modeling of TE-MHD

- The basic physics of the TE-MHD problem can be modeled with the following system of equations

$$\nabla \cdot \vec{u} = 0 \qquad \nabla \cdot \vec{J} = 0$$

$$\vec{J} = \sigma(-\nabla\phi + \vec{u} \times \vec{B} - S\nabla T)$$

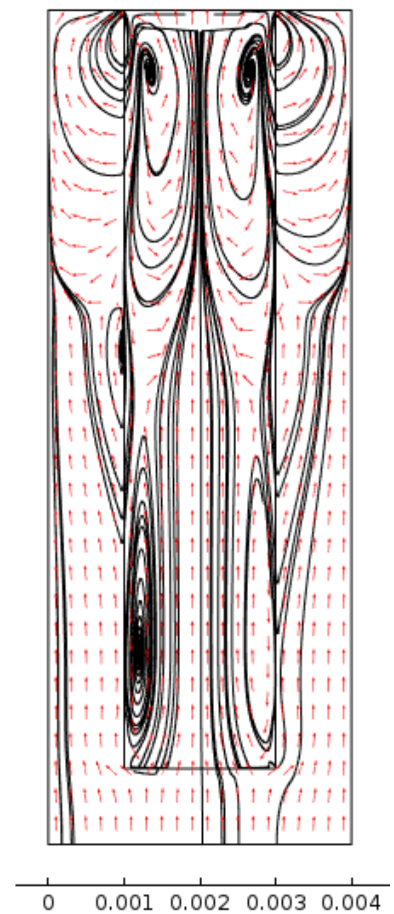
$$\rho \left[\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla)\, \vec{u} \right] = \nabla p - \mu \nabla^2 \vec{u} + \vec{J} \times \vec{B}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) = \nabla \cdot (k \nabla T)$$

- A source term that represents the Seebeck effect is added into the Ohm equation

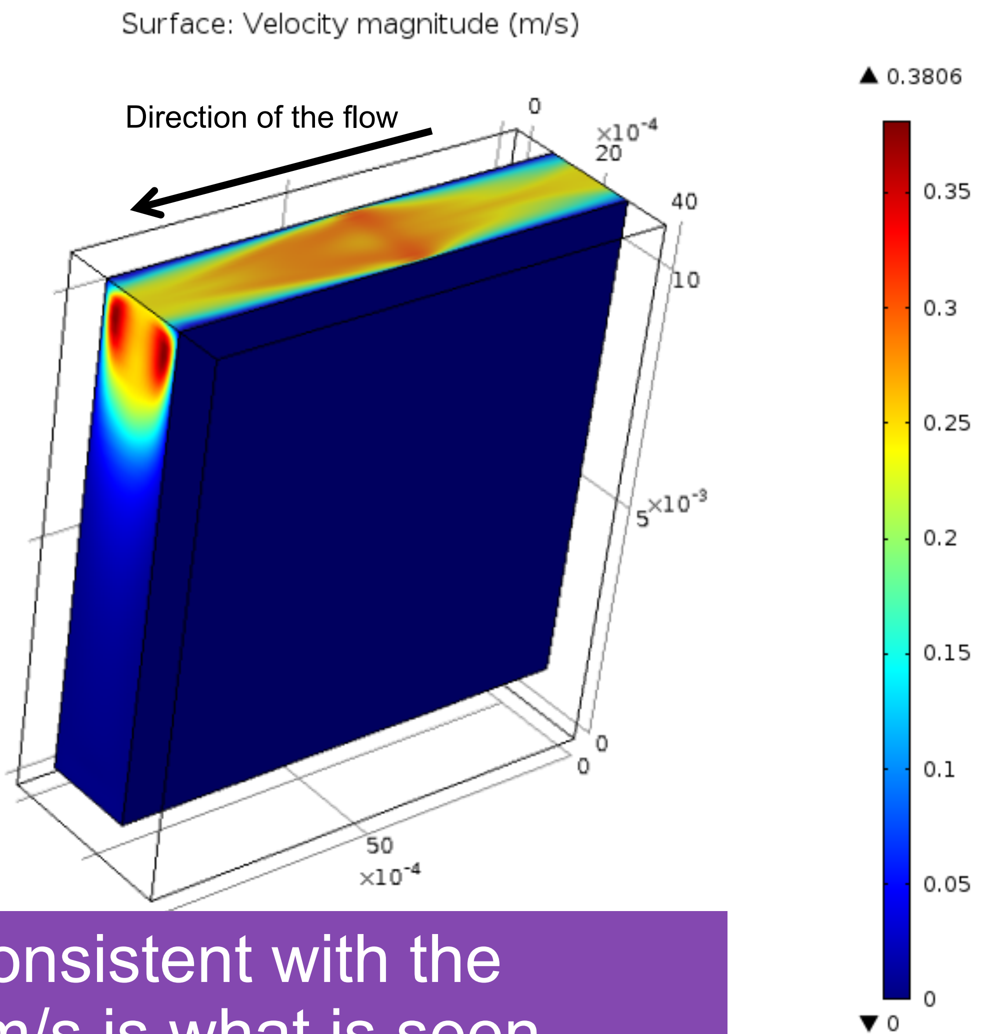
- COMSOL® has been used to simulate the TEMHD problem in 3D

Streamlines of current density



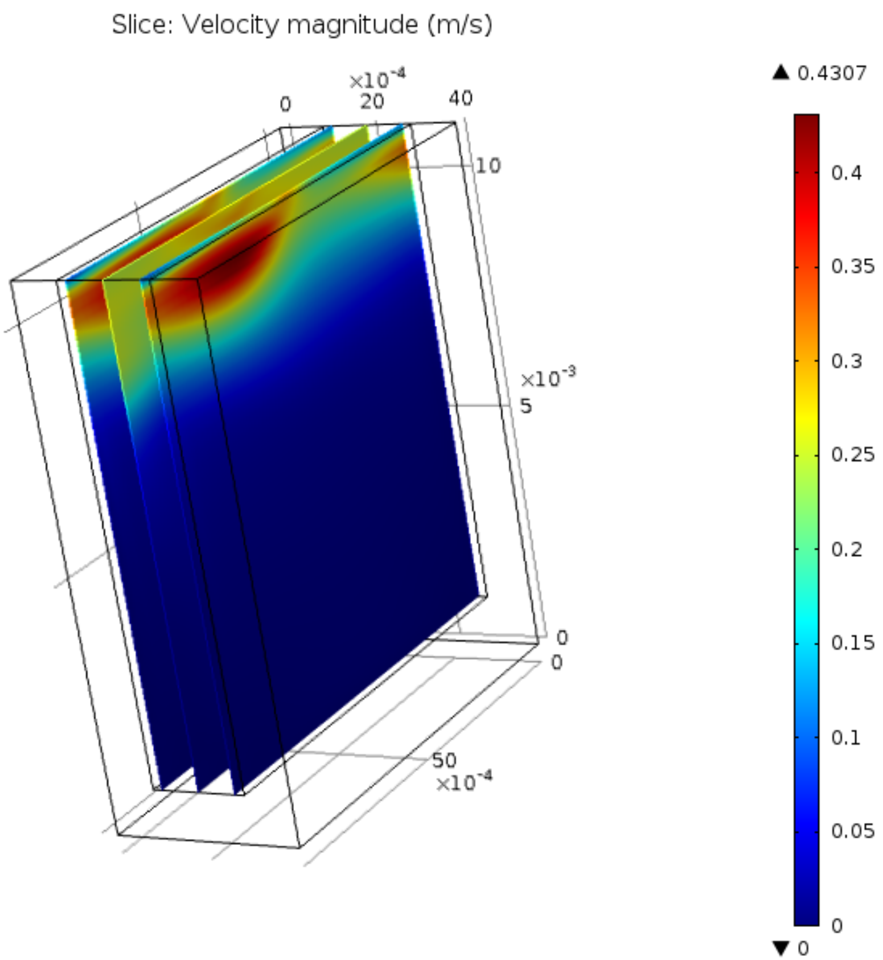
Establishment of Li flow inside a trench

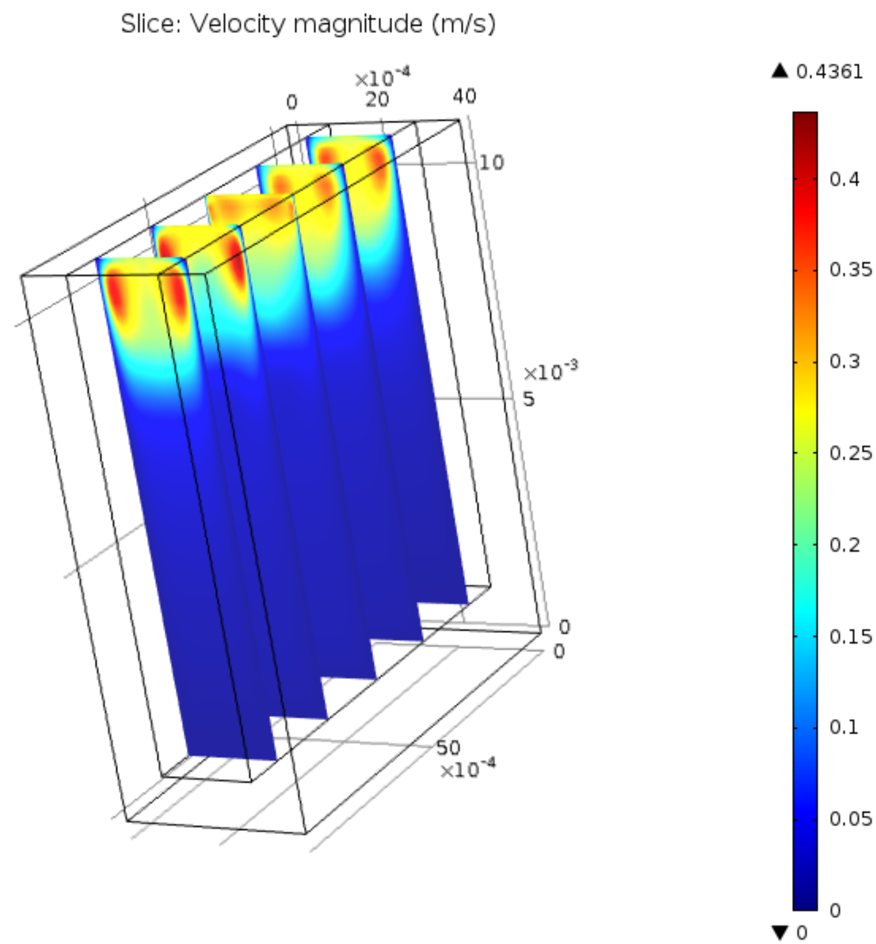
- In stationary conditions a Lithium flow is developed along the trench, driven by the thermoelectric JxB force
- The flow exhibits a pattern with double velocity peaks near to the walls after the heated region
- Most of the high-velocity flow is developed close to the free surface at the top
- The peak flow velocity is of the order of tens of cm/s, thus allowing a practical removal of heat from the heated region



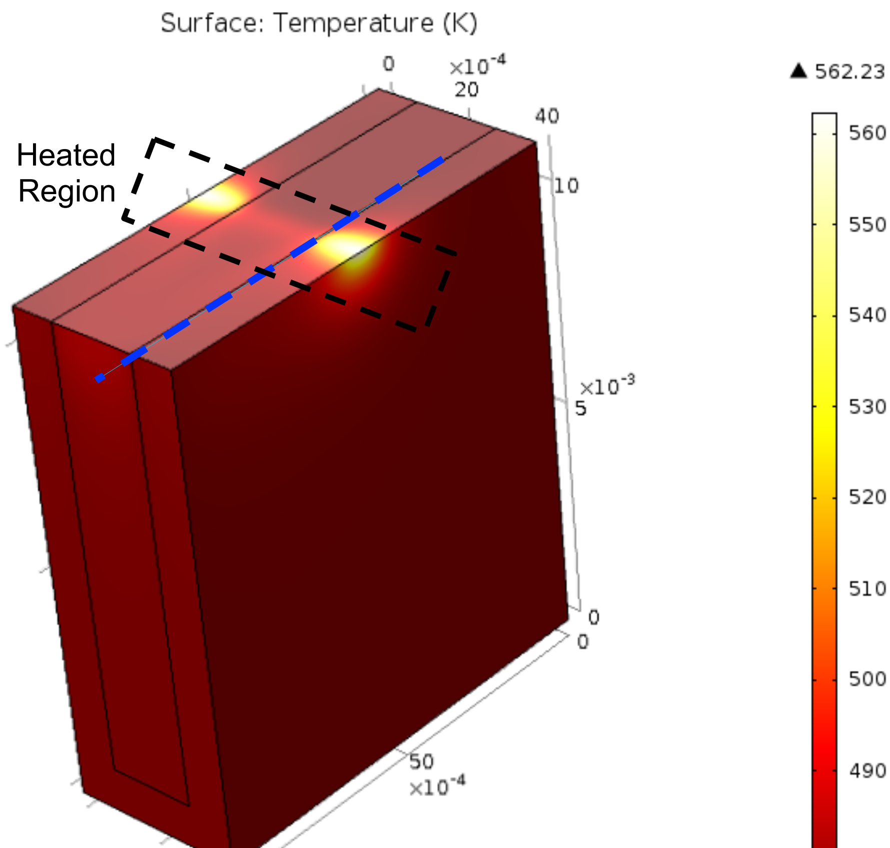
Note that these are consistent with the experiment – ~0.22 m/s is what is seen

Features of the velocity field

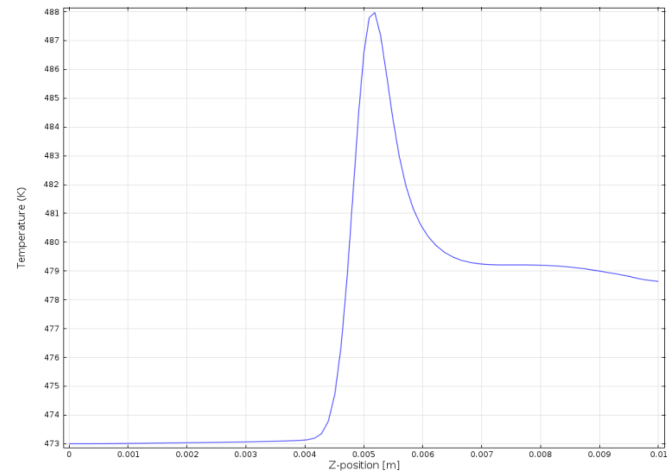


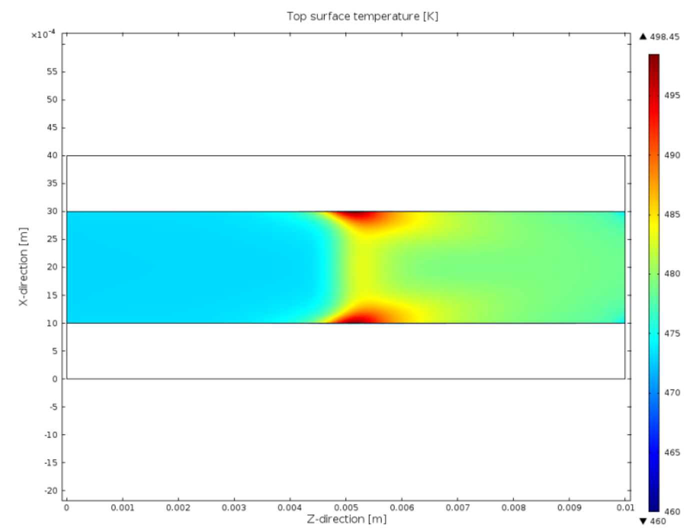


Temperature field and heat removal



Temperature along the center line
(along the blue line in the 3D picture)

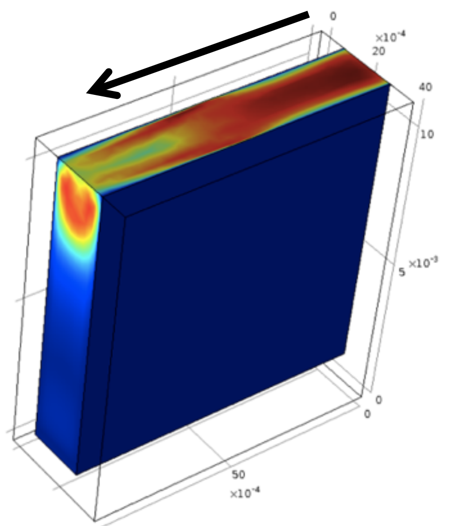


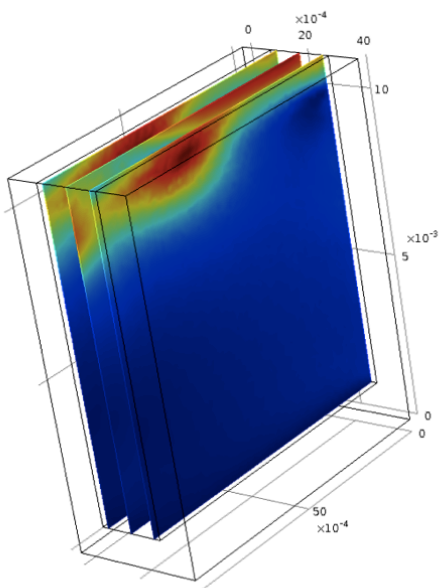


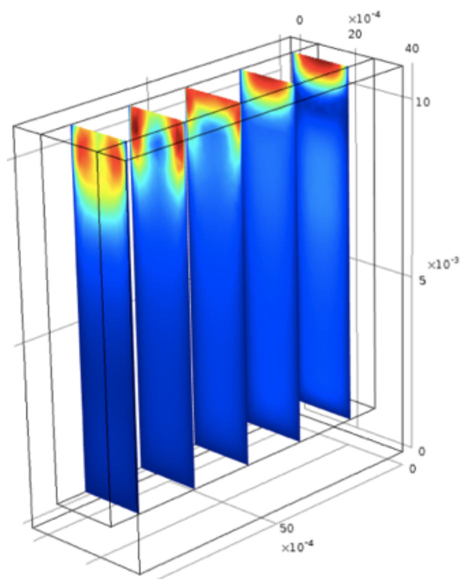
Note that these are consistent with the experiment – for this power delta T of 10C is what is seen

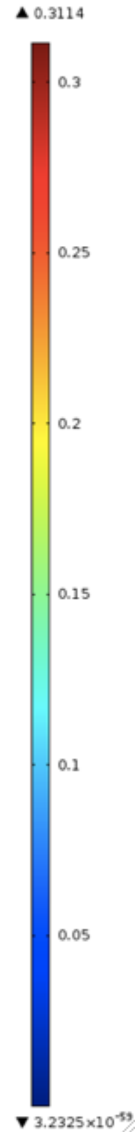
k-epsilon treatment of Li turbulence

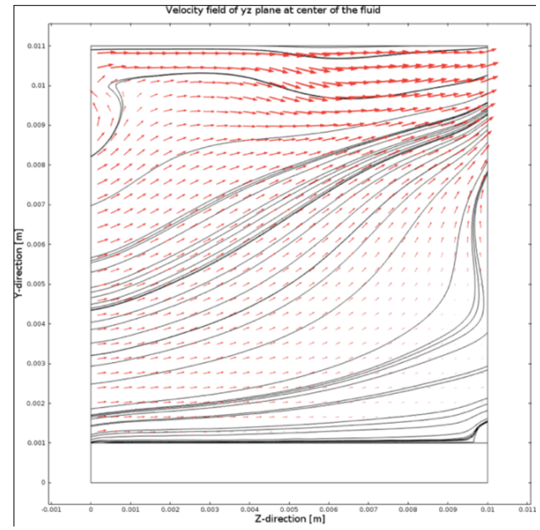
3D COMSOL® simulations using the standard k-ε turbulence model reveal features similar to the laminar case

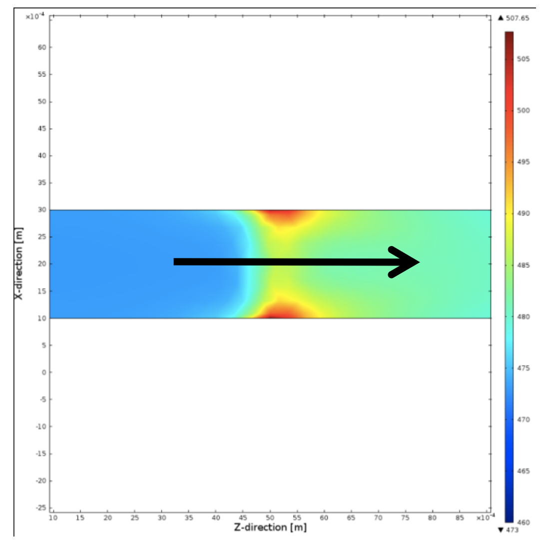












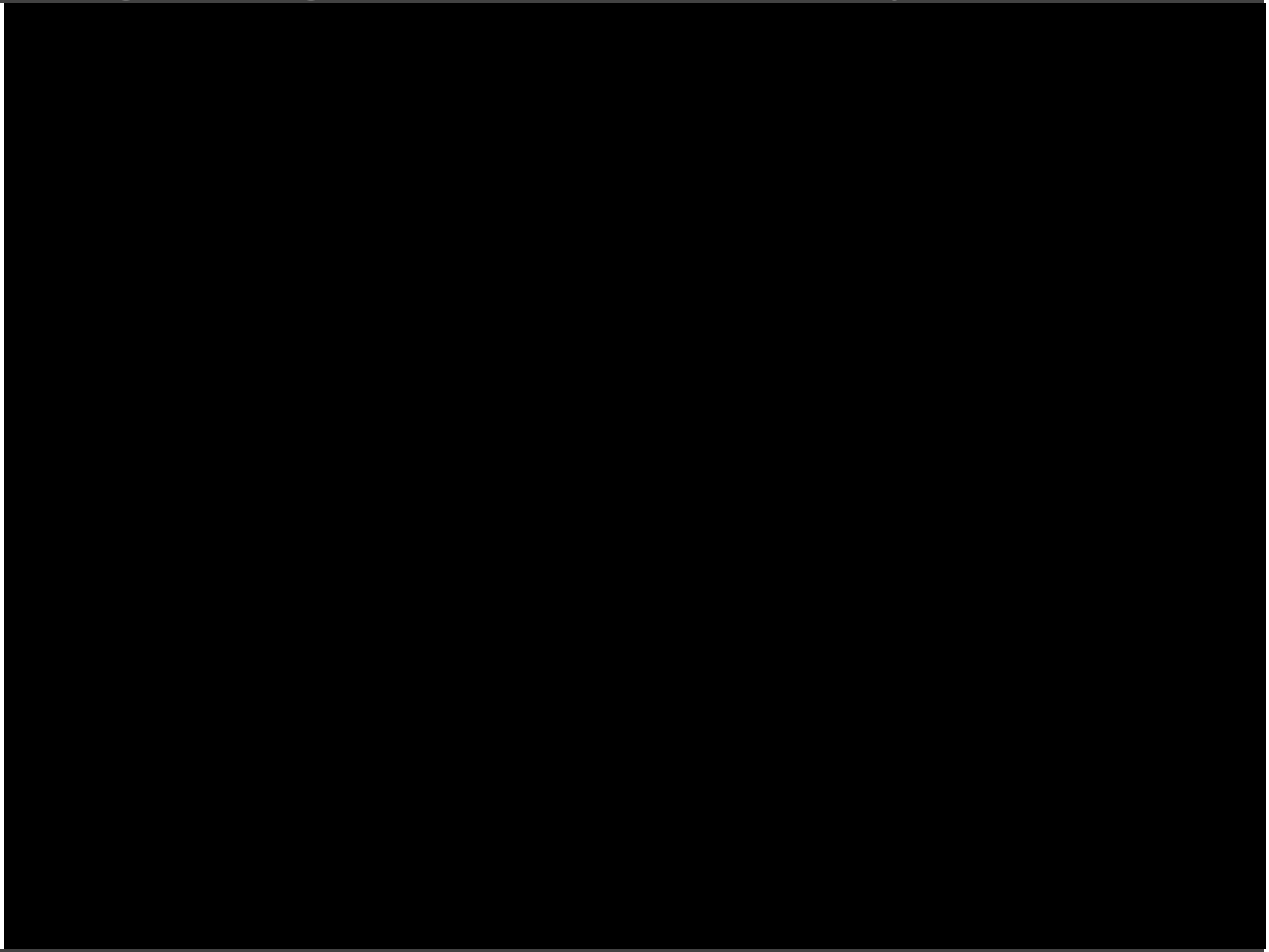
Going to higher field: test safety first!

Four car batteries in parallel for each coil.

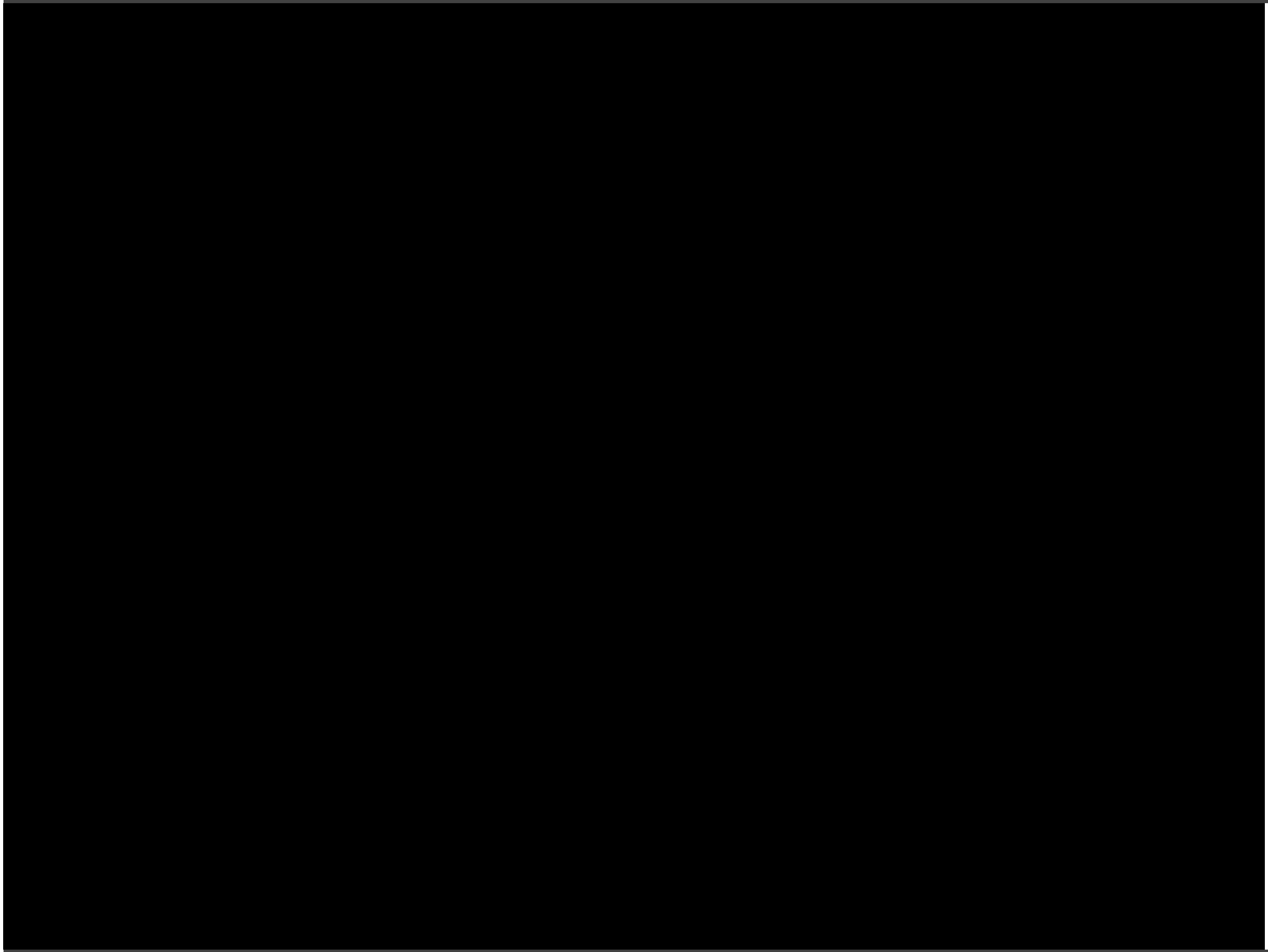
Diode installed to prevent induced reverse current on disconnection.

Limit is on heating up the coils. We need to measure that better so we can go higher.

Went from 800 Gauss to 2200 Gauss.



2 seconds of 0.22 Tesla field



Sequence:

Low field

No field

High field

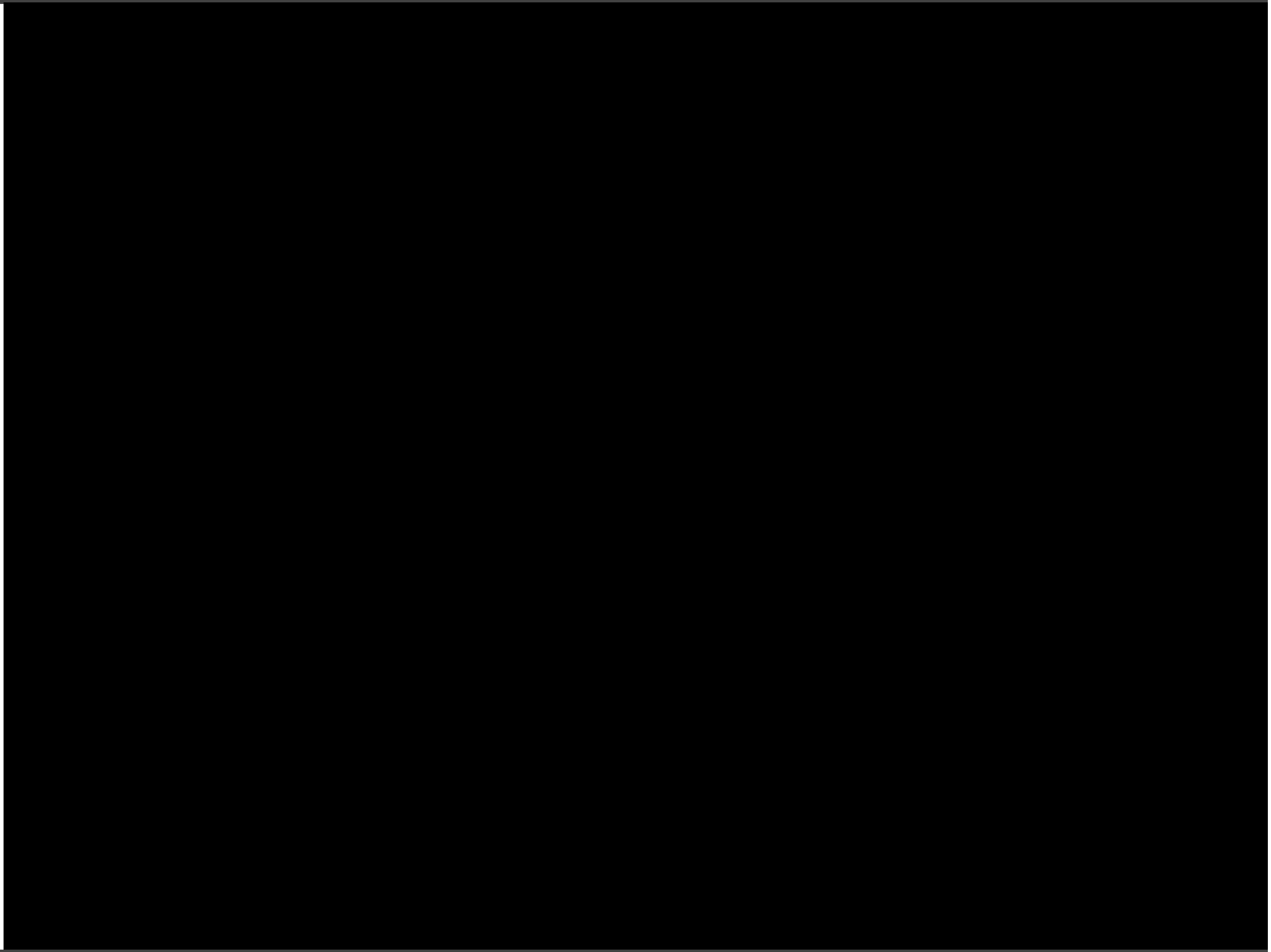
No field

Low field

5 seconds of 0.22 Tesla field

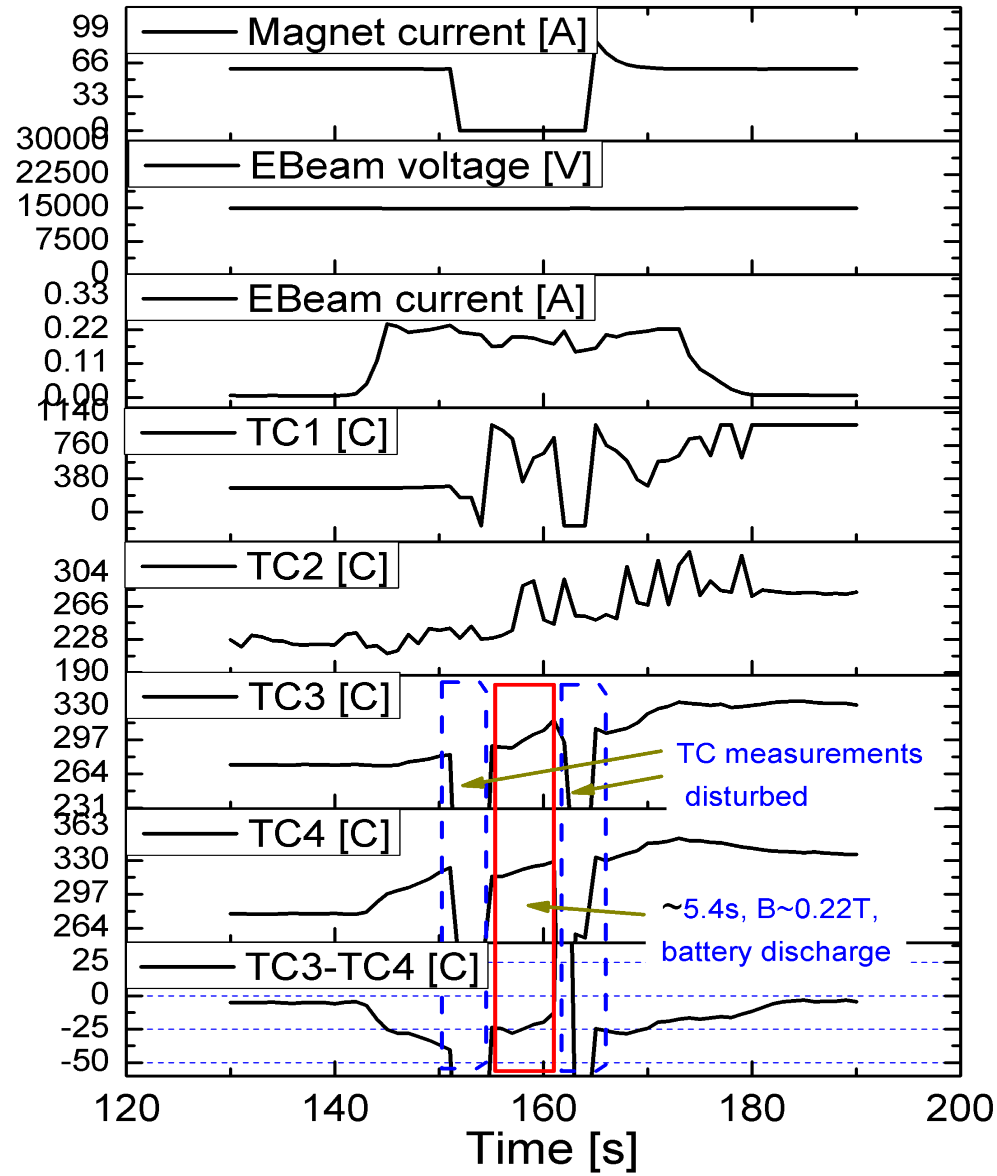
During high field portion of the pulse, the flow velocity increases dramatically overflowing downstream trenches.

Upstream / downstream temperature difference is reduced as expected due to faster flow (next slide)

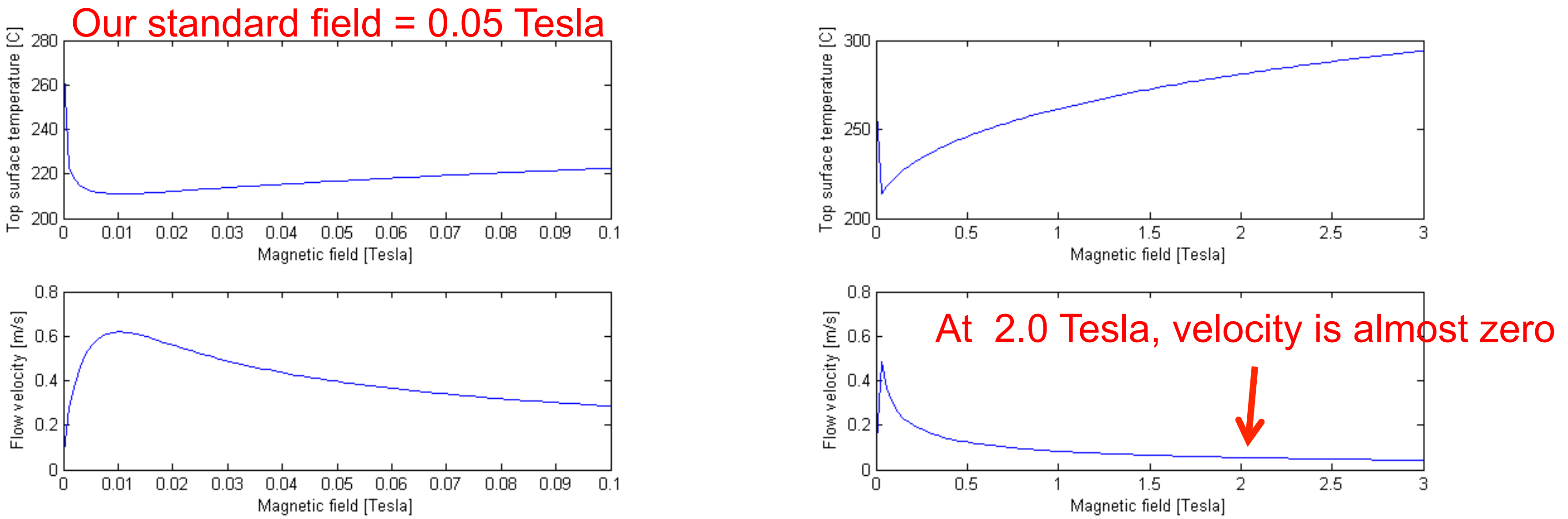


Thermocouple measurements in strong magnetic field

- With car batteries discharge the magnetic field is kept at 0.22T for about 5.4s.
- The temperature of upstream side (TC3) does not jump when the field is changed. The temperature of downstream side (TC4) has a clear drop when the strong field is on.
- Temperature difference across the heating area (TC3-TC4) dropped from 41C (when B=0.04T) to 24C (when B=0.22T).
- During the short period with B=0 TC3 and TC4 are disturbed because the ebeam is not focused and hits the thermocouples directly.



What about even higher fields?



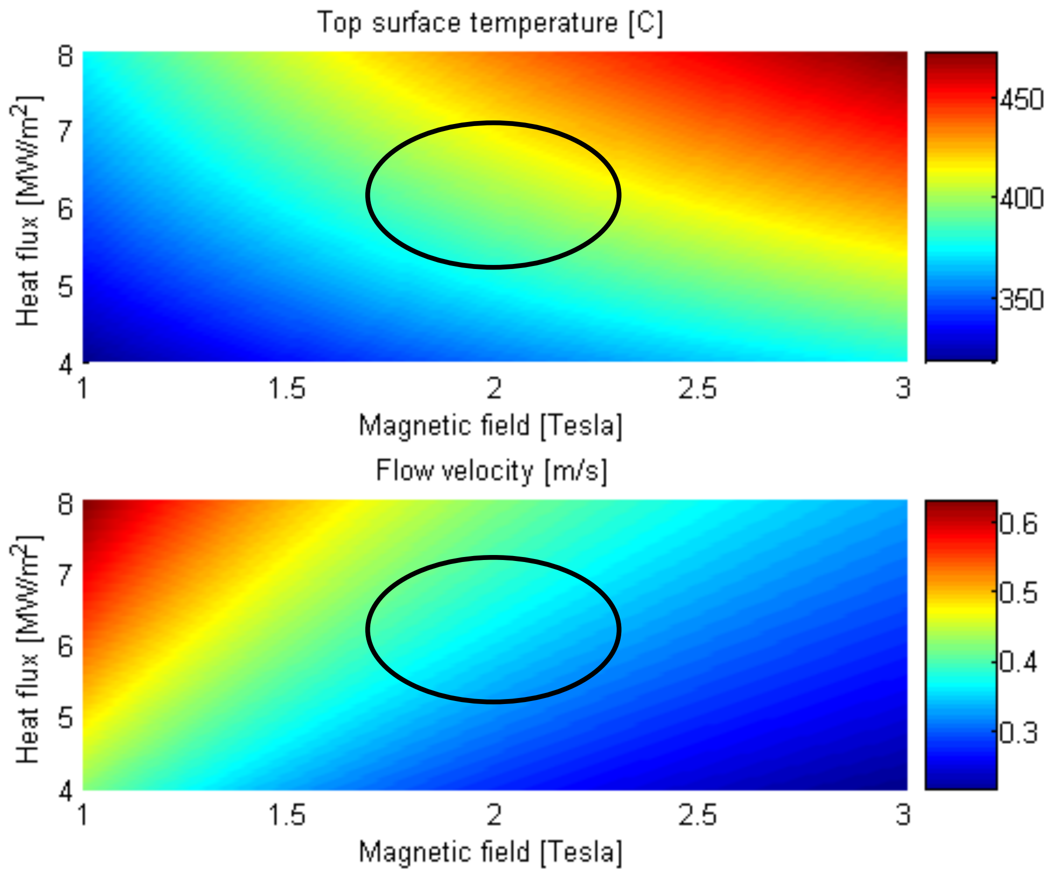
- SLiDE's geometric parameters are used here. Heat flux is $4 MW/m^2$ (typical value for our experiment, corresponding to 1500W e-beam power) This model fits our experimental results
- We can change the geometry though – trench size and depth to handle higher fields and heat fluxes

Altered Geometry: Temperature and Flow Velocity

Width = 1 mm
Depth = 3 mm

For 2 Tesla
and 6 MW/m^2

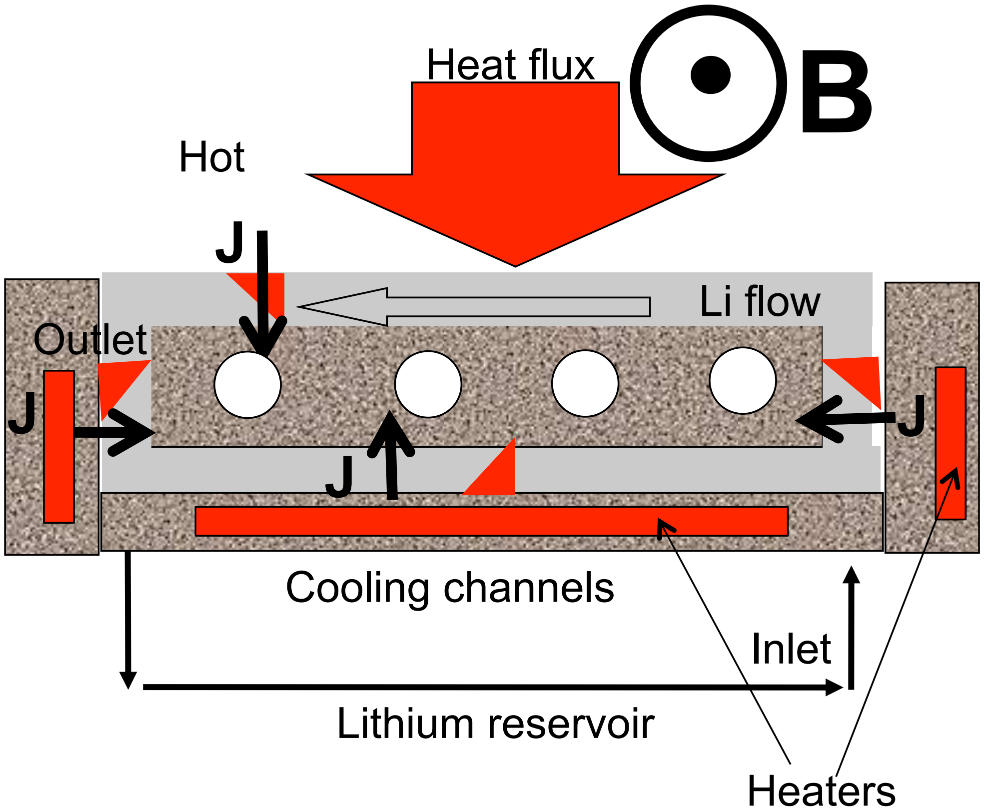
(HT-7
parameters)



- Max top surface temperature is ~ 400 C and flow velocity is 0.36m/s.
- Bottom of trench is assumed to be kept at 200C. How?

How to Implement this at 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 August 2012
- It will go on their retractable limiter and be diagnosed with TCs and visible fast-framing camera



HT-7 in Hefei, China

A medium-size Tokamak

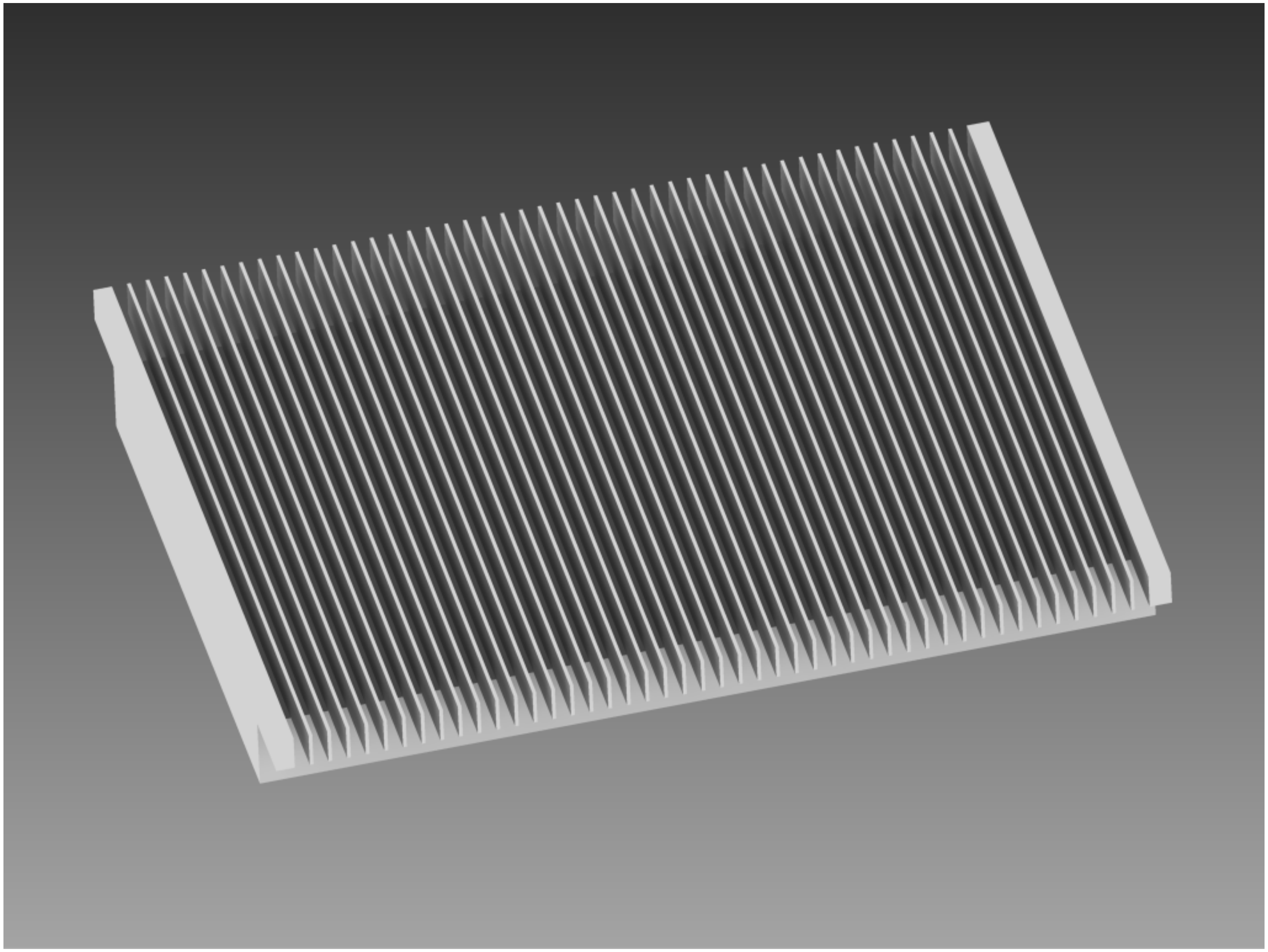
T_e = 1 keV
n_e = 0.8 x 10 19 m-3

B_T = 2 Tesla
Superconducting Coils

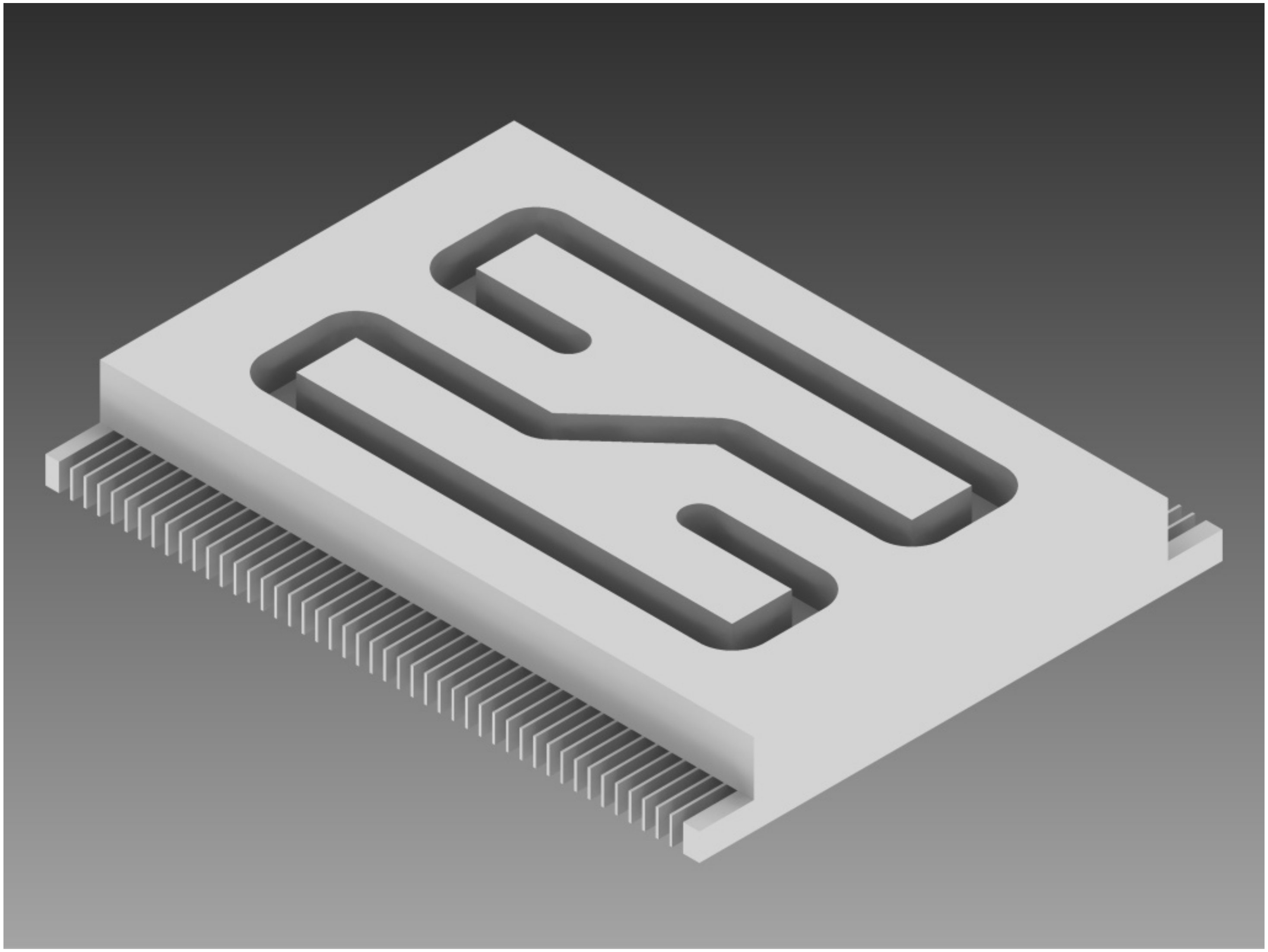
Heat Flux = 6 MW/m^2

They are building a 10cm by 12 cm "LiMIT" module and will test it in August of this year on moveable limiter

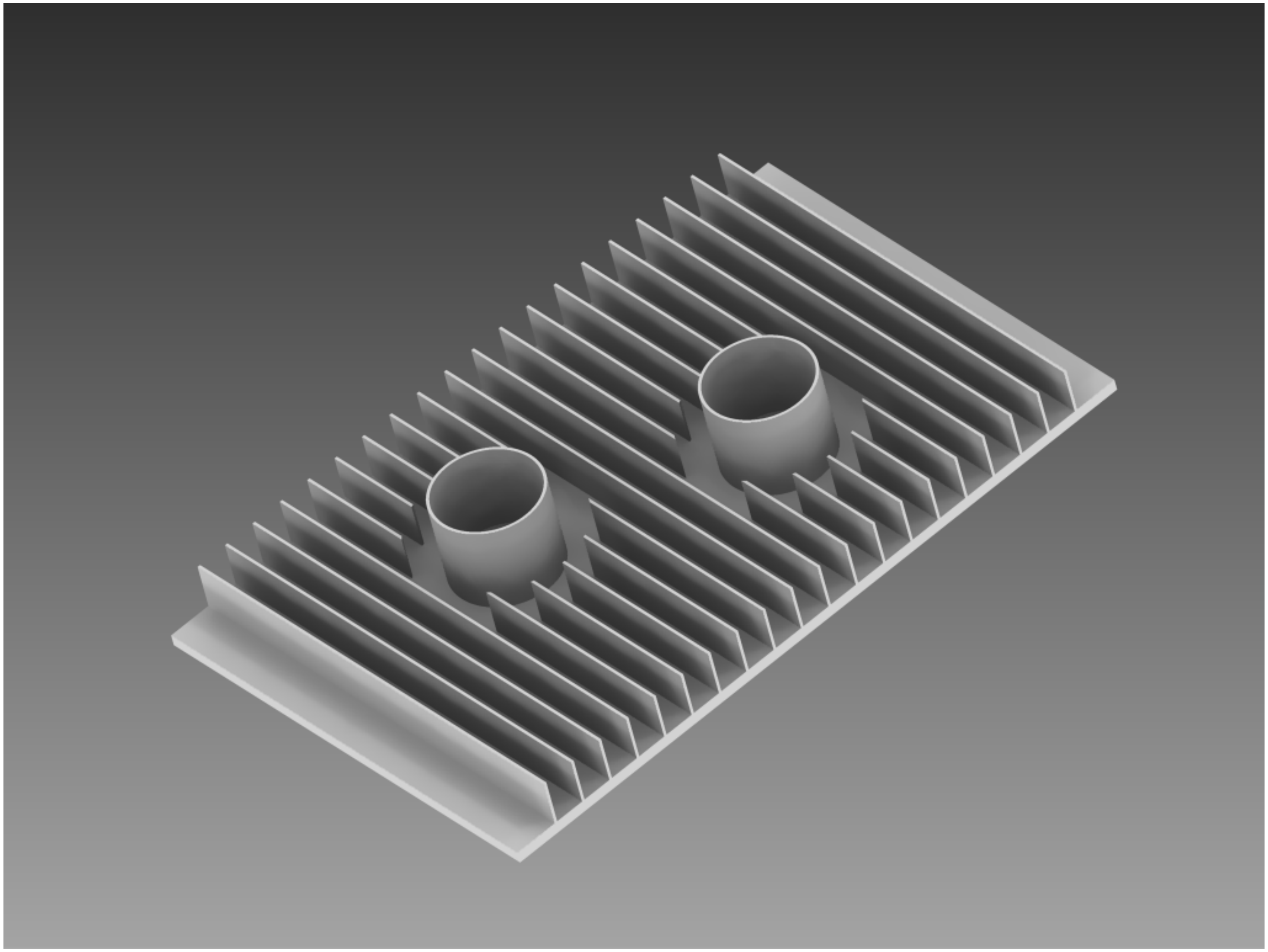
Top view of the lithium trench plate



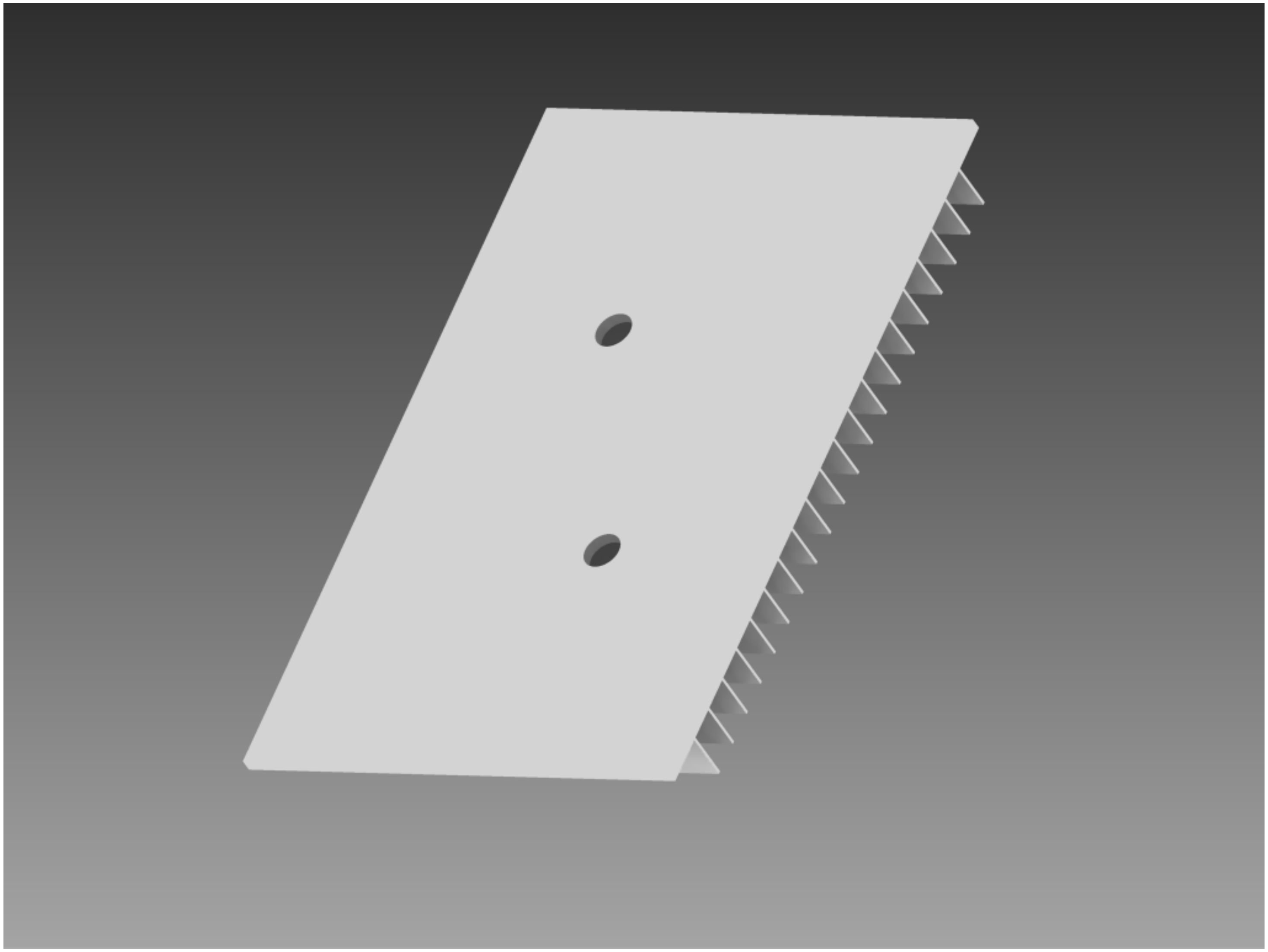
Bottom of the lithium trench plate



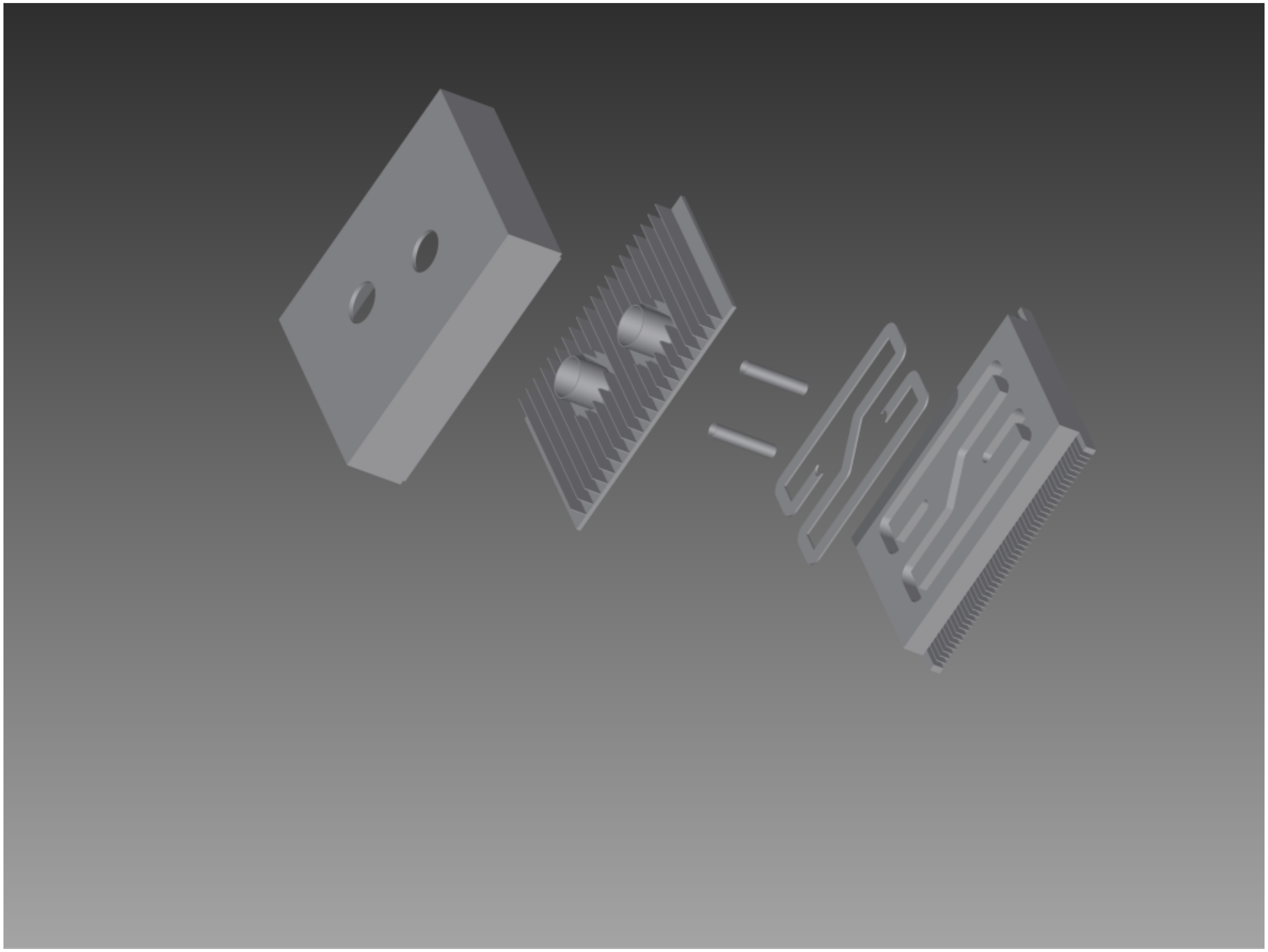
Bottom side of the return flow channel



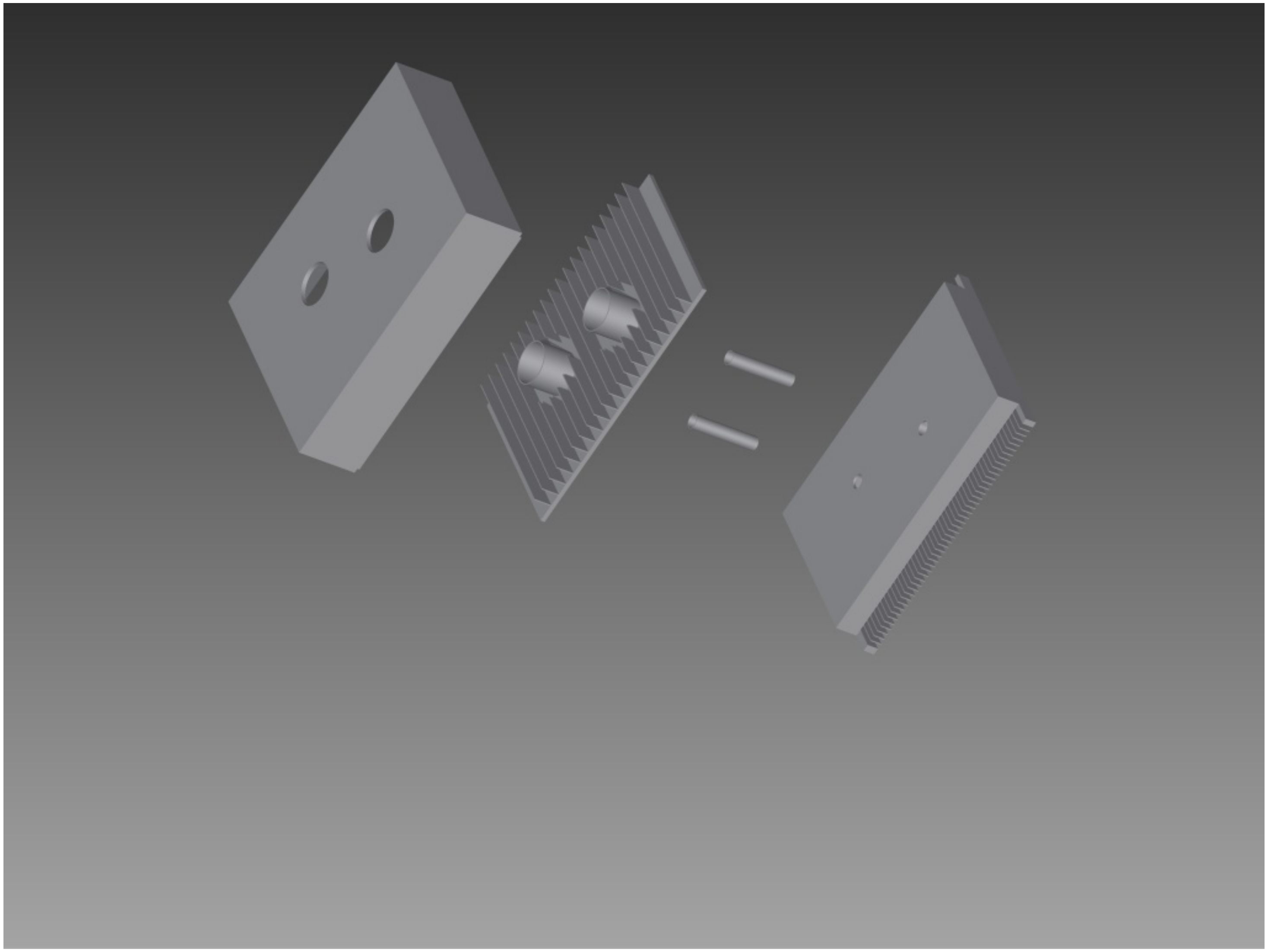
Top view of the return flow channel



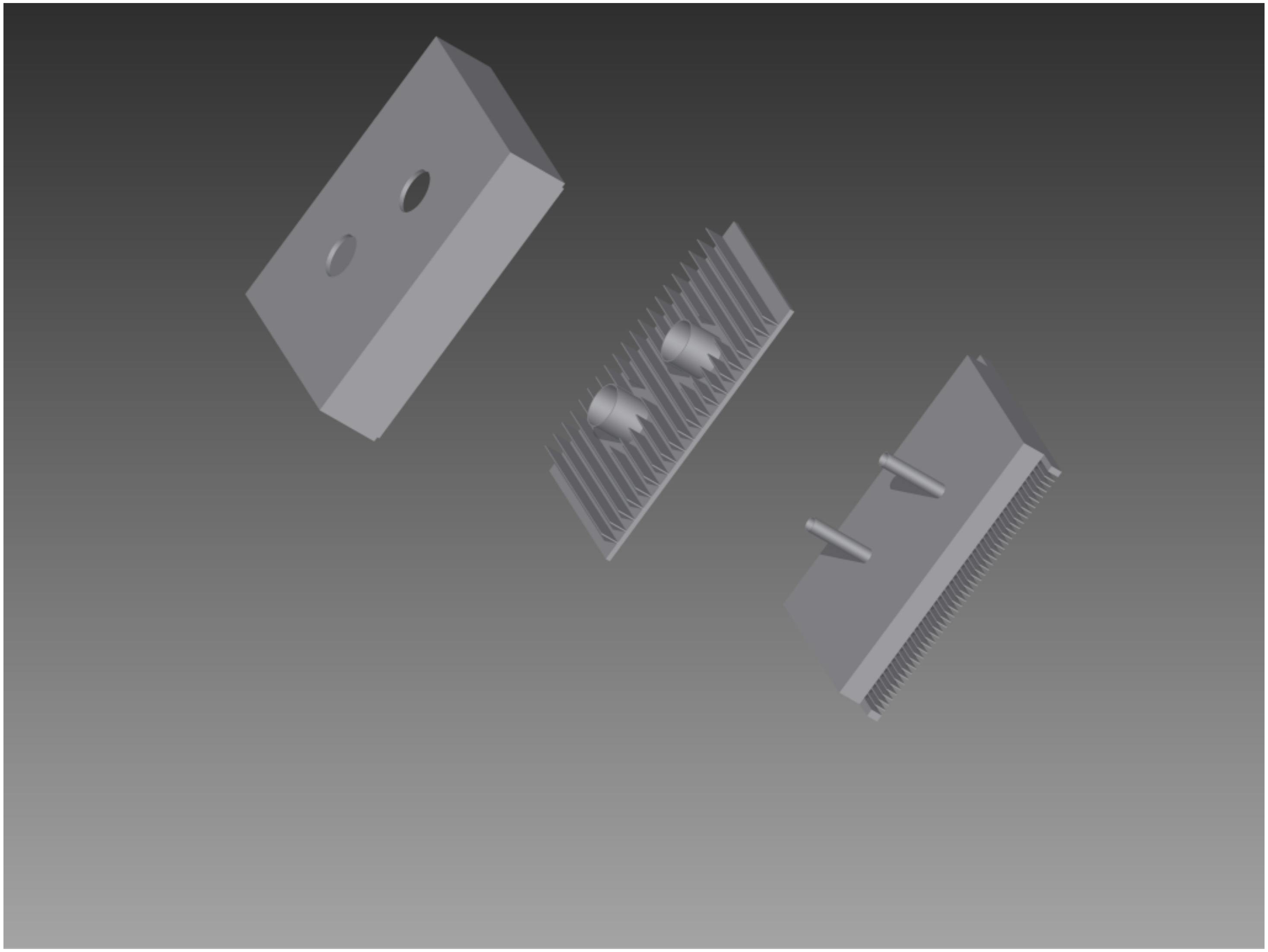
Assembly 1



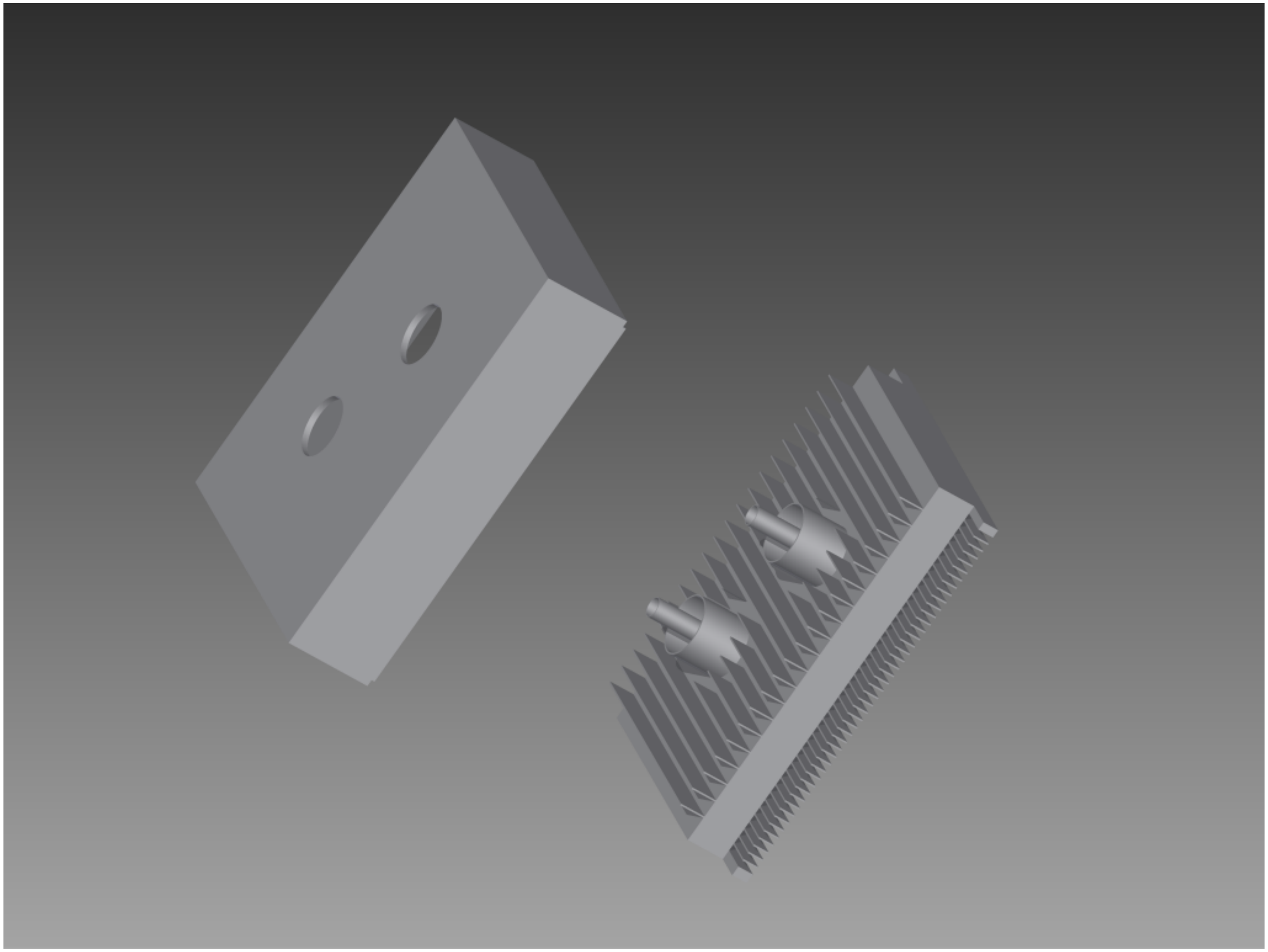
Assembly 2



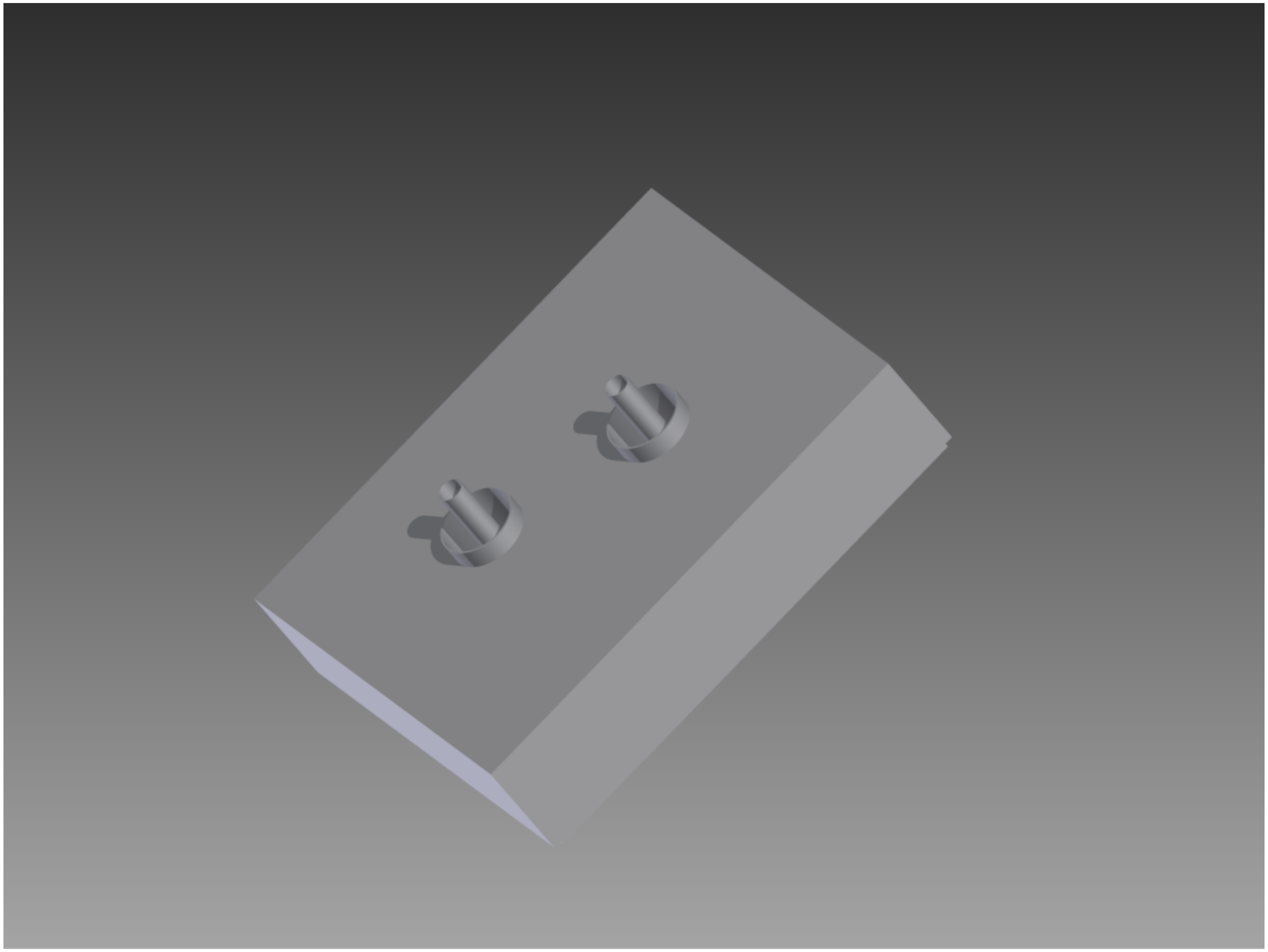
Assembly 3



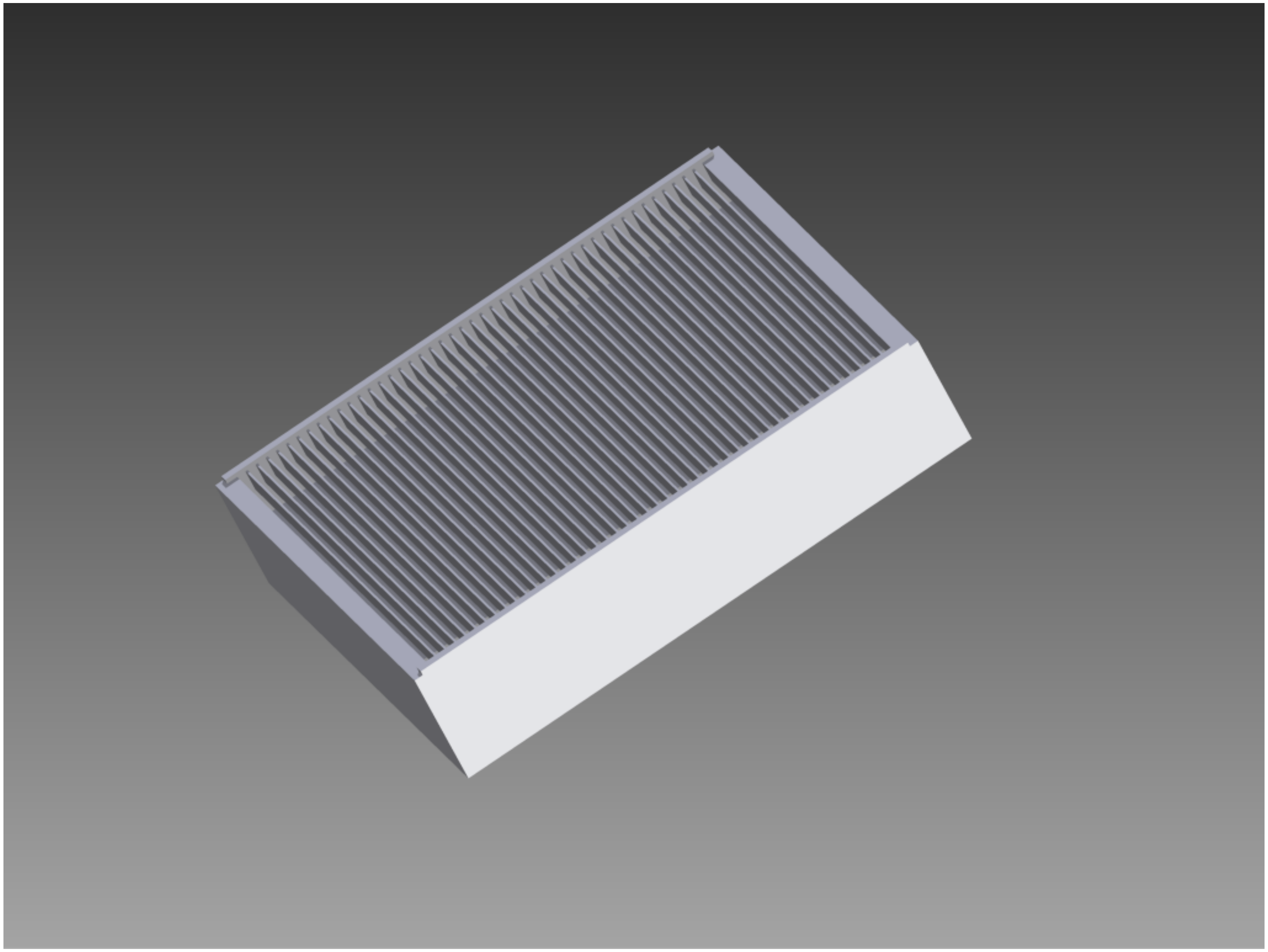
Assembly 4



Assembly 5



Top view of the liquid lithium limiter



Conclusions / Next Steps

- SLiDE continues to test flowing lithium. We will make a similar test structure to the one to be used in HT-7 next. This will test a system where we have a thermal gradient all the way around and should prevent “pile-up”.
- Modeling has stepped up and we are working toward a complete time-dependent 3-D model of the system.
- We are measuring the thermoelectric properties of Sn and Sn-Li eutectics. Depending on funding we want to test these other liquid metals in SLiDE.