MHD pumping of Liquid Lithium in plasma facing components

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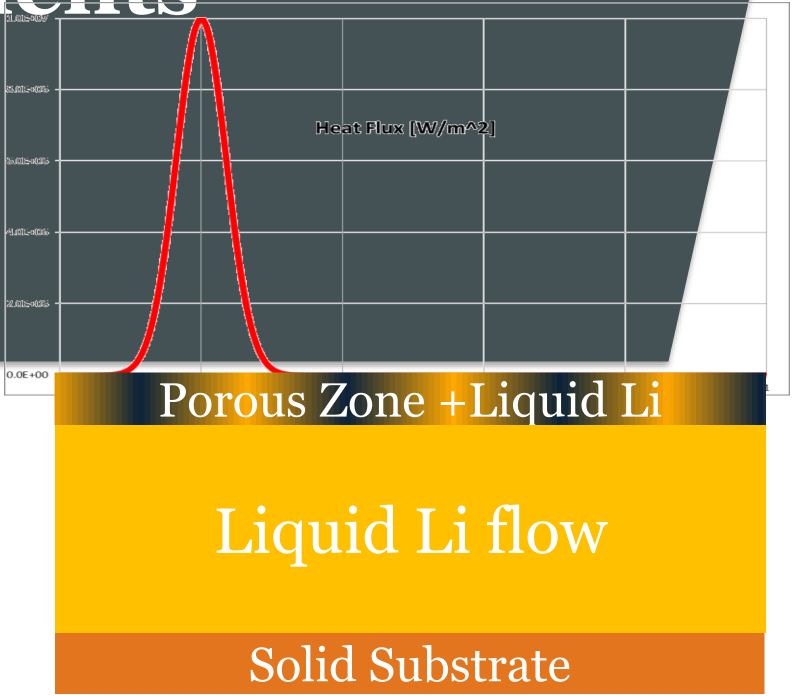


A domestic liquid metal PFC design study was initiated in FY 2020

- Goal: design LM PFC concepts for a nuclear device
- Options: cooling with Li, with Li and He, & a porous layer concept
- Potential issues: MHD flow instabilities, Li pumping through a strong magnetic field, corrosion/erosion, plasma/material interactions….

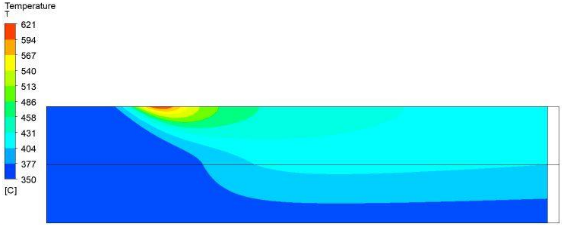
- We look for a design window - high heat removal capability while meeting all the limitations with scoping calculations and 3D analysis

- Experiments for model validation and to test material and flow properties conducted in test stands and linear flow experiments with applied B

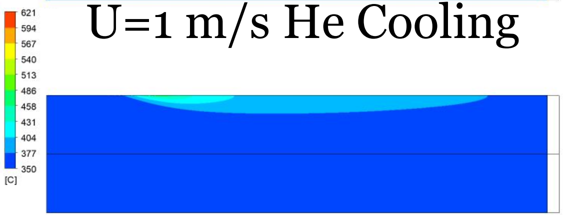
From Rajesh Maingi Presentation

Liquid Lithium Flowing Wall

- Surface temperatures below 450 °C can be achieved at 10 MW/m^2 heat flux ~10 m/s Lithium Velocity
- Effect of He Cooling is Negligible
- Stability of the free surface is an issue



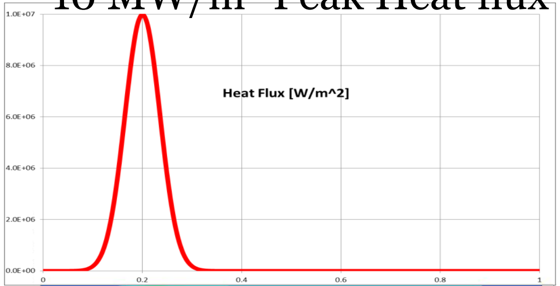
U=1 m/s He Cooling



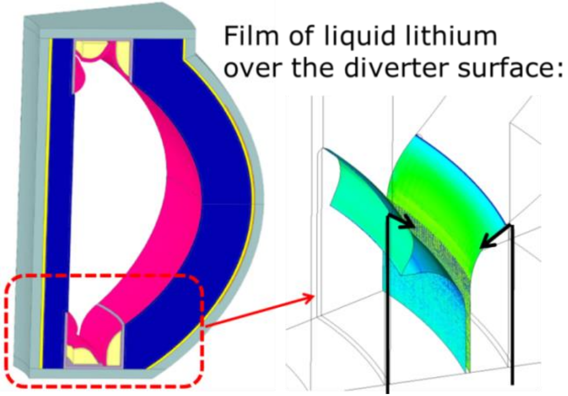
U=5 m/s He Cooling

U=10 m/s He Cooling

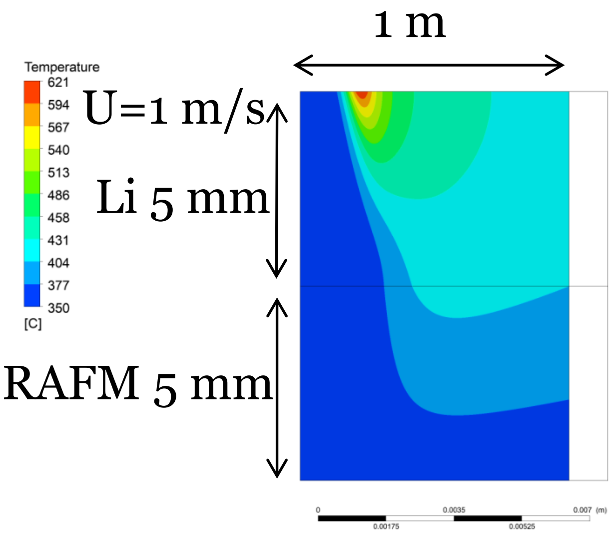
10 MW/m^2 Peak Heat flux



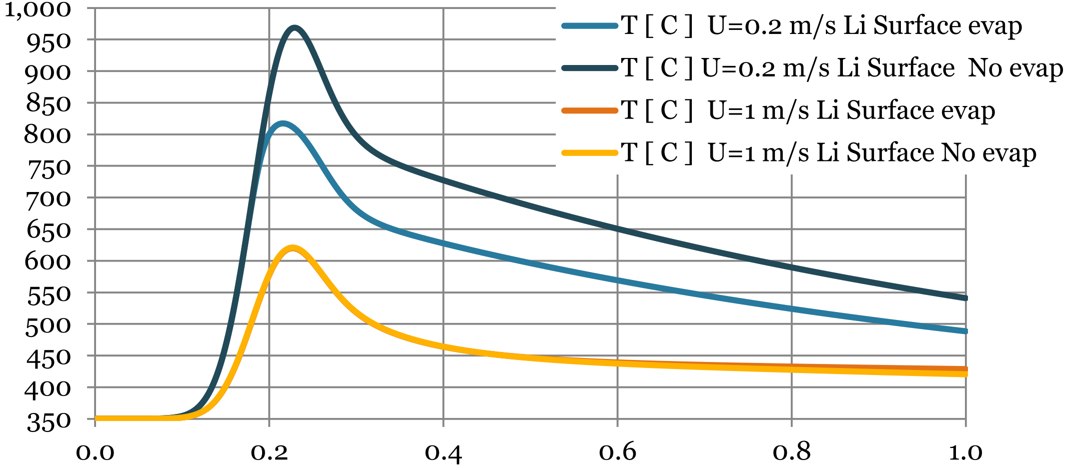
U=5 m/s adiabatic wall

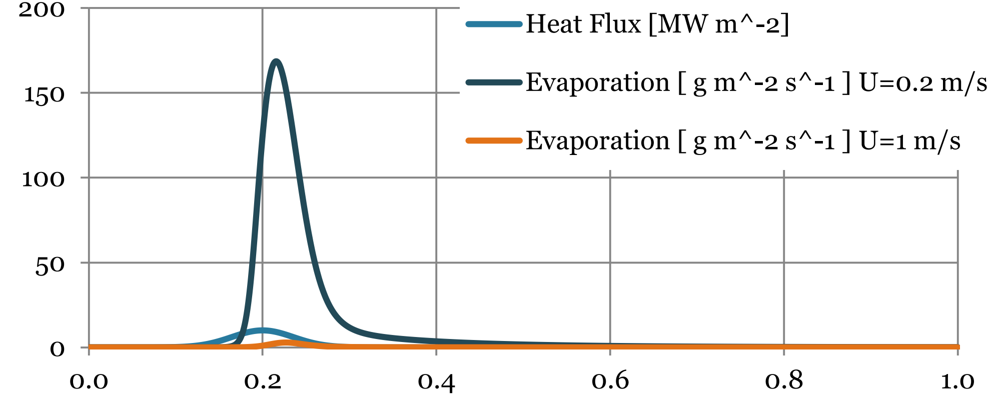


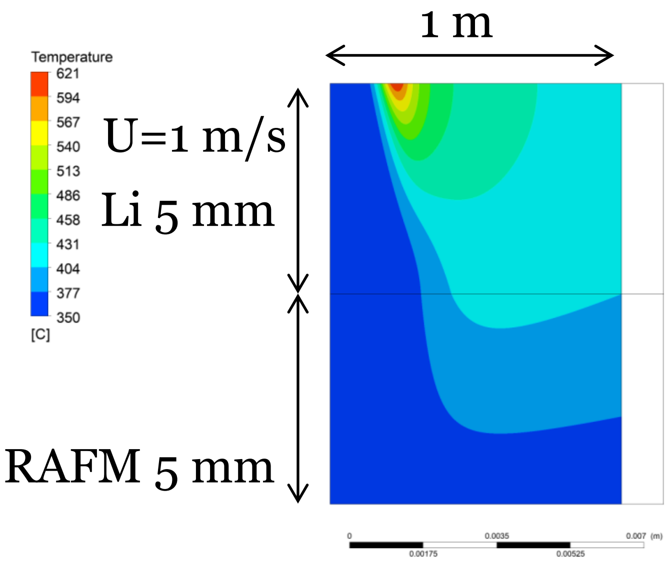
Film of liquid lithium over the diverter surface:



Liquid Lithium Flowing Wall Evaporation Effect







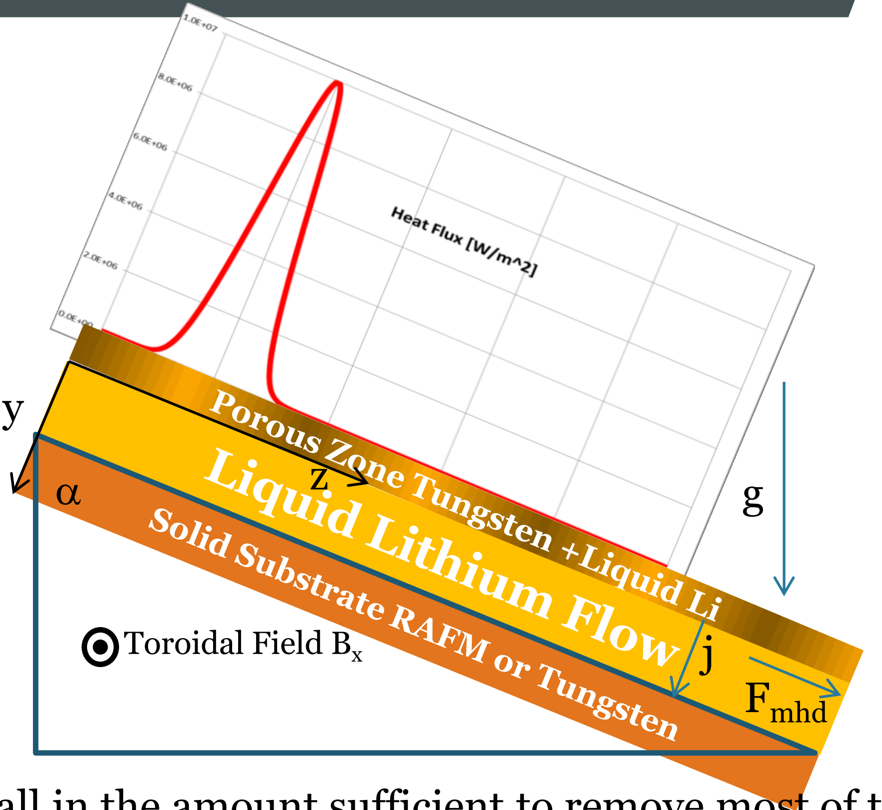
- Evaporation Effect on Temperature Distribution is Negligible Below 600°C

$$q_{Li}^{evap} = -\frac{145920[J/mole]\cdot 8.5\cdot 10^{-15}[1/(m^2 s)]\left(T|_{y=-h}-50[°C]\right)^{13.6}}{N_{Avogadro}}$$

Items outlined for the study:

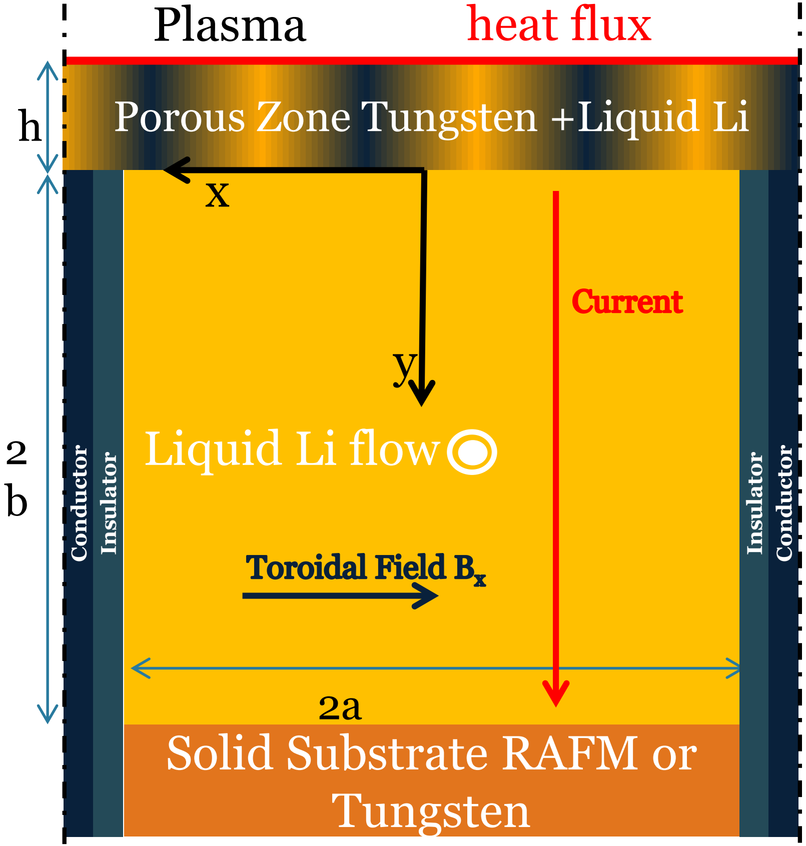
- **Can such high-velocity Li flow be established?**
  - Li injection and extraction
  - Li flow over the divertor plates
  - Li pumping
- **How to intensify heat transfer in the Li flow?**
  - Active and passive flow control
  - HT promoters
  - Surface waves
- **What could be practical design solutions?**
  - Curved substrate vs. flat substrate
  - Axisymmetric flow vs. segmented flow
  - Insulating walls vs. conducting walls
  - Inserting He pipes directly into Li as a heat sink/HT promoter

Liquid Lithium System with Porous Wall

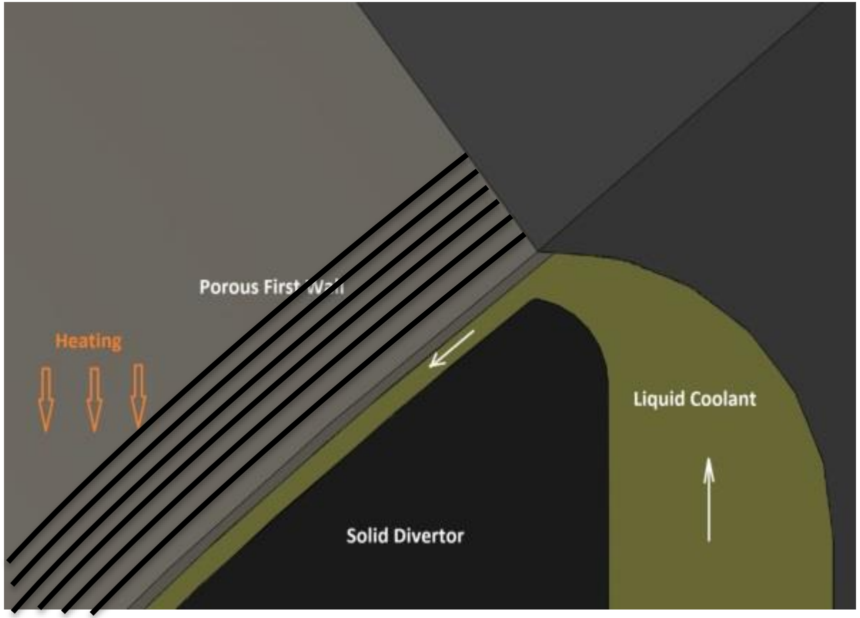


- Liquid lithium is flowing along the heated wall in the amount sufficient to remove most of the incoming heat. The porous wall is placed on top of the liquid coolant.
- This porous wall allows stabilizing the surface of the flowing coolant due to porous system drag.

LL MHD Pumping system

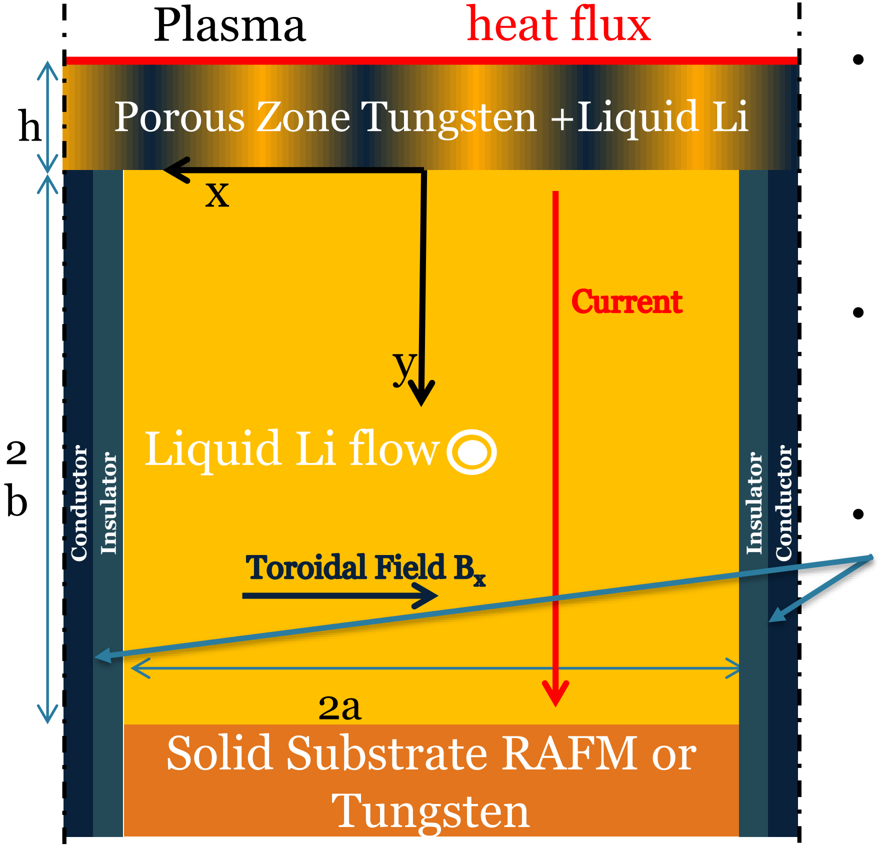


Cross-section of liquid lithium channel with porous wall



- Liquid lithium flow under the porous wall is organized into a series of rectangular channels directed perpendicular to the toroidal magnetic field.

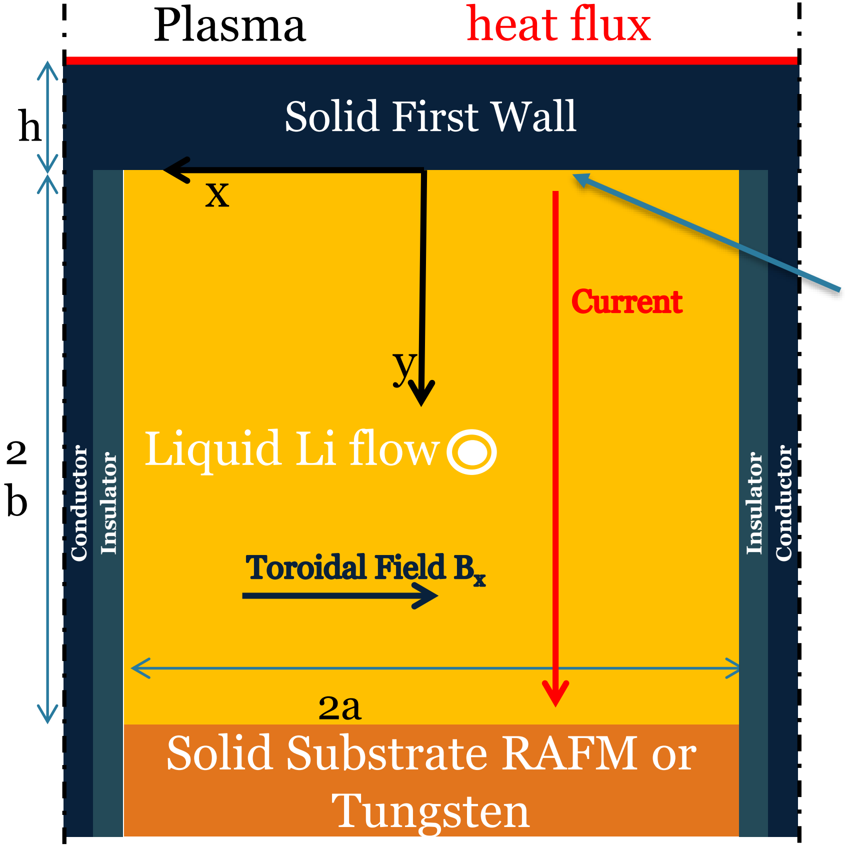
MHD Pumping system in rectangular channel



Cross-section of liquid lithium channel with porous wall

- Liquid lithium flow under the porous wall is organized into a series of rectangular channels directed perpendicular to the toroidal magnetic field.
- Negligible Pressure difference between lithium and plasma can be maintained due to MHD pumping
- The walls of the channel perpendicular to the magnetic field provide structural support for the porous wall, and simultaneously serve as a conduit for the current for MHD pumping

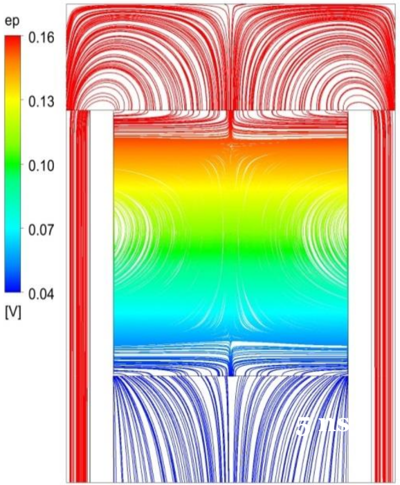
Solid Blanket with LL as a Coolant



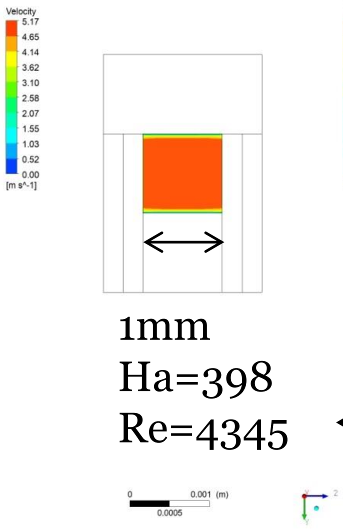
Cross-section of liquid lithium channel with porous wall

- MHD pumping system can be realized with solid first wall.
- Evaporation of Li can be used in this case to enhance heat transfer
- Pressure difference can still be very low

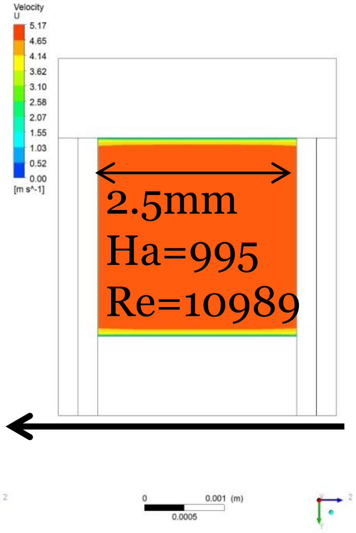
MHD Flow very Favorable for Efficient Heat Transfer



Electric Current
Colored with Electric Potential



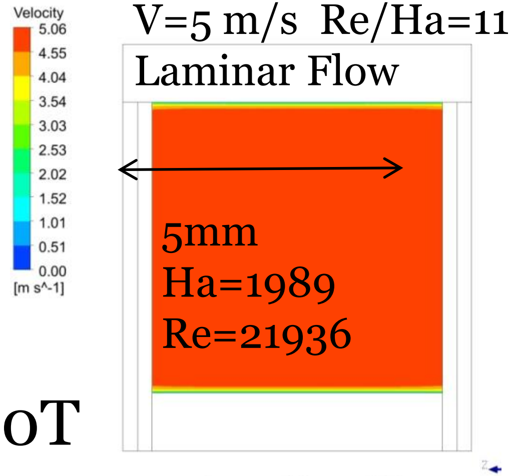
1mm
Ha=398
Re=4345



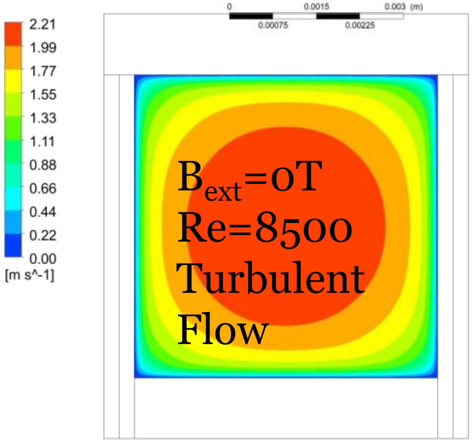
2.5mm
Ha=995
Re=10989

B_{ext}=10T

V=5 m/s Re/Ha=11
Laminar Flow



5mm
Ha=1989
Re=21936

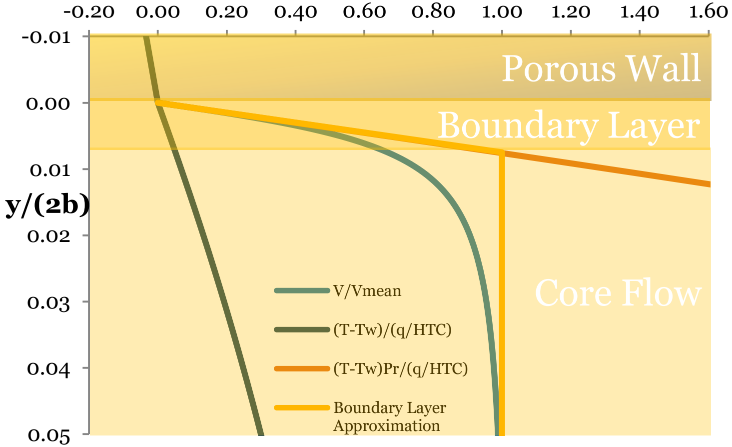


B_{ext}=0T
Re=8500
Turbulent
Flow

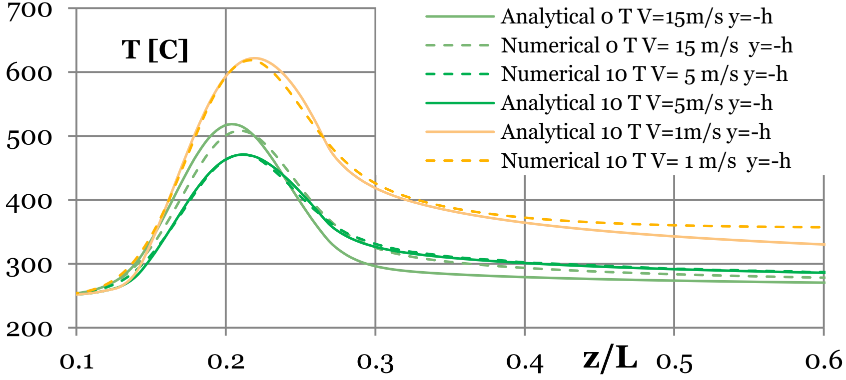
- For the parameters we considered MHD flow is laminar
- MHD velocity structure is favorable for heat transfer: flat core and thin boundary layer
- With magnetic field flow in 5 mm vertical channel is turbulent

Analytical Model Reynolds Analogy

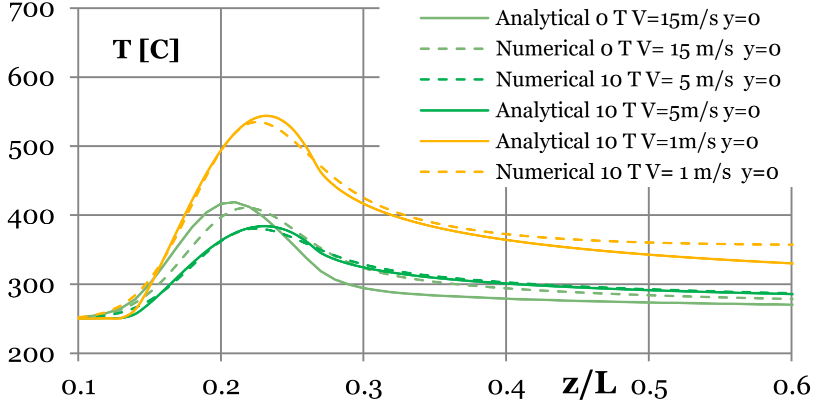
- Boundary layer zone the thermal profile is linear and follows Reynolds analogy.
- Heat transfer coefficient is proportional to the friction coefficient.
- Analytical model developed for the free surface MHD flow is successfully applied to channel flow



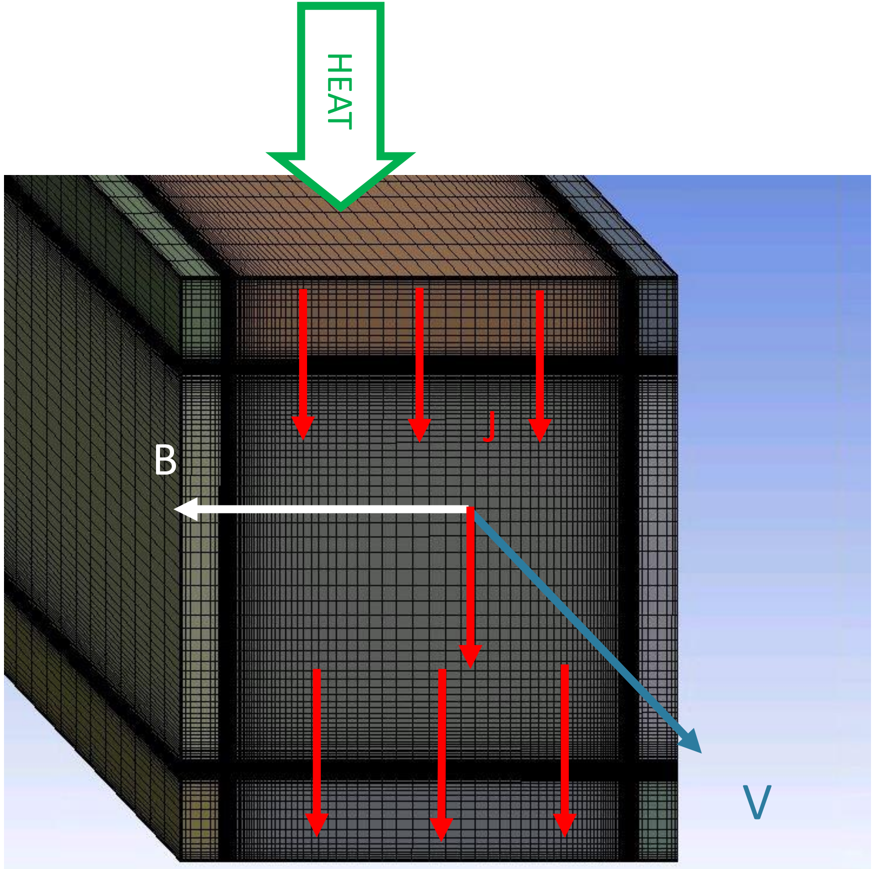
Temperature on plasma facing Wall



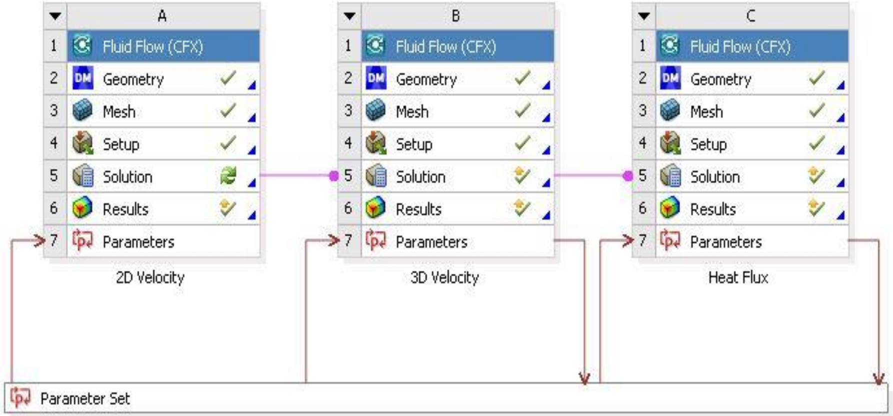
Temperature on porous liquid interface Wall



Numerical Modeling and Assumptions



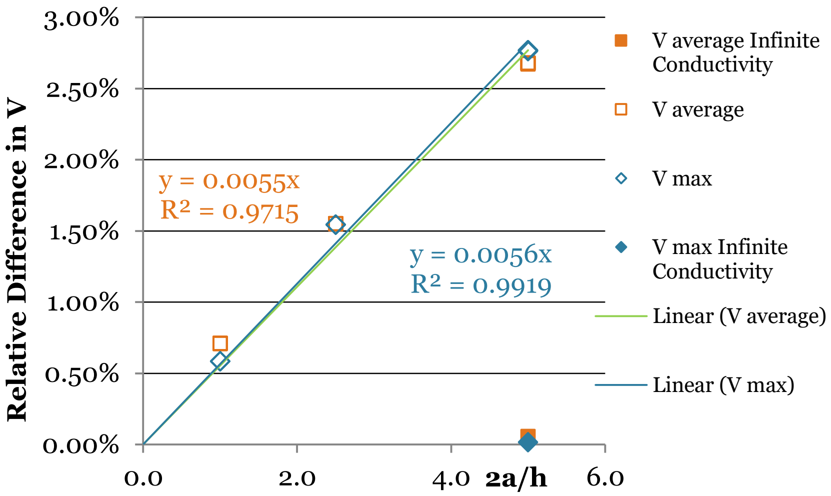
1. Solve MHD equations over a 2d slice of the channel
2. Interpolate over the 3d channel
3. Solve heat transport equations on frozen velocity field



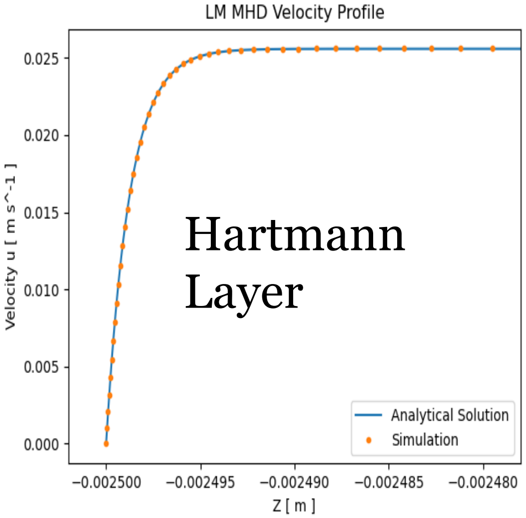
Validation of the MHD pumping model

Validation of the numerical model was performed using analytical solution.

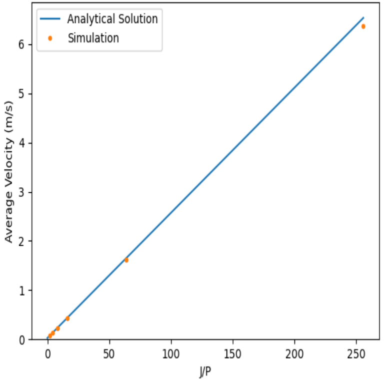
Relative difference between present CFD results and analytical solution linearly decreases with increase of relative wall conductance



Inverse proportional to relative wall conductance



Hartmann Layer

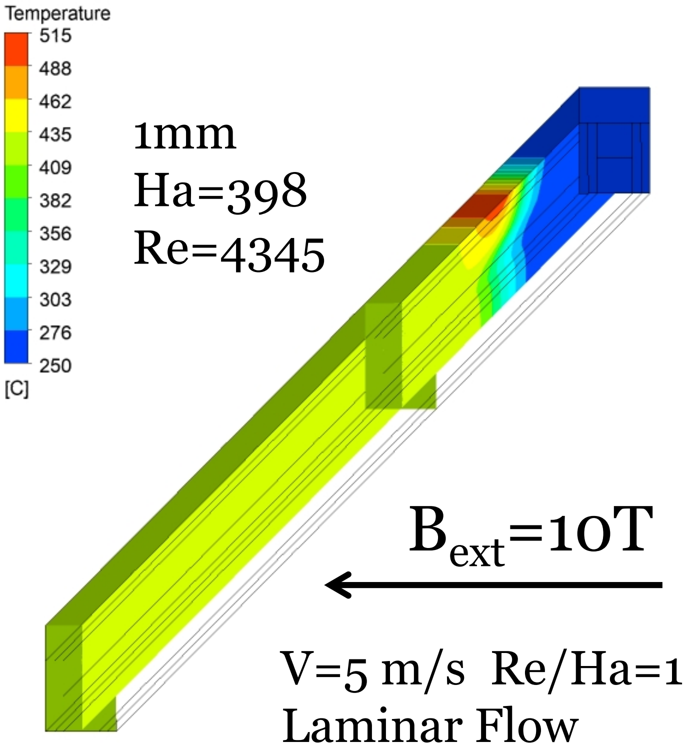


Analytical solution for MHD flow in rectangular channel with infinitely conductive walls parallel to external field:

$$v_{max} = \left(\frac{I_y B_{ext\,x}}{2a} + \rho g \cos\alpha\right)\frac{a^2}{\mu Ha} \qquad v_{average} = v_{max}\left(1 - \frac{0.956a}{b\sqrt{Ha}} - \frac{1}{Ha}\right)$$

G. A. Grinberg, Appl. Math. and Mech. (PMM) 2 5 (1961) 1536
J. C. R. Hunt and K. Stewartson, Journal of Fluid Mechanics 23, 563-581 (1965).

Temperature Distributions



1mm
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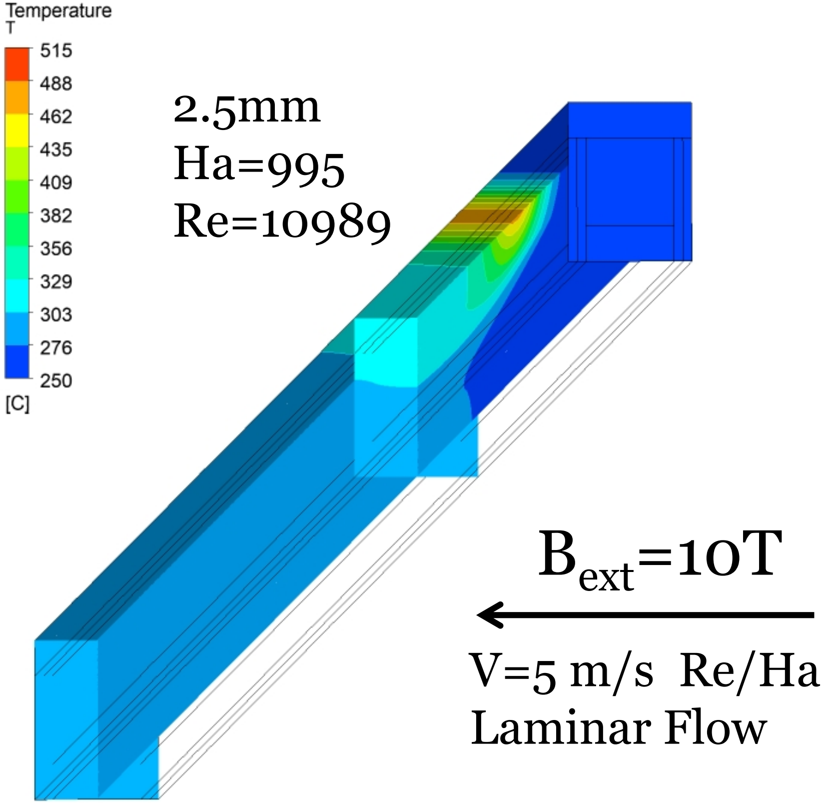
Laminar Flow



2.5mm
Ha=995
Re=10989

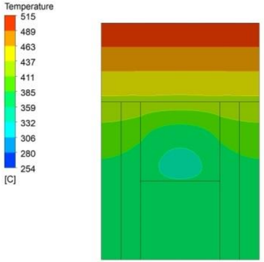
B_{ext}=10T

V=5 m/s Re/Ha=11
Laminar Flow

Incoming plasma heat flux is absorbed by the flowing liquid lithium

Temperature Distributions in Peak Temperature Cross-section

V=5 m/s Re/Ha=11
Laminar Flow



1mm
Ha=398
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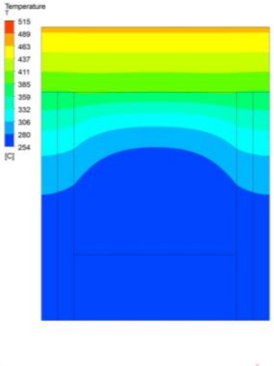
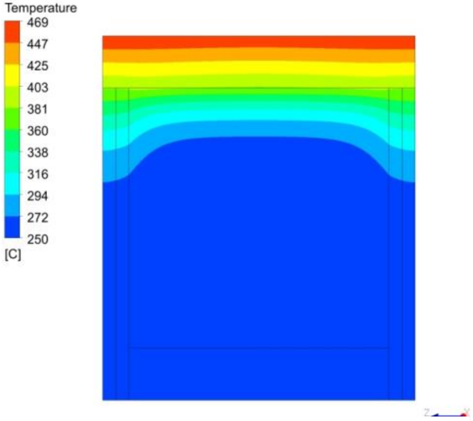
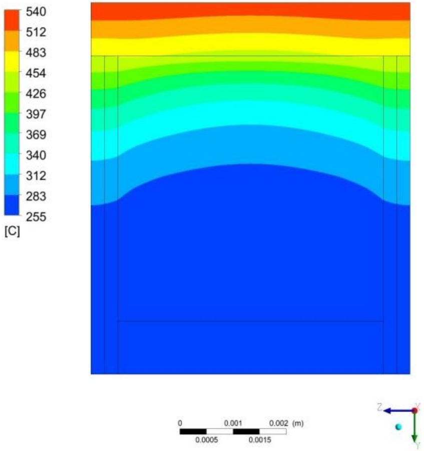


2.5mm
Ha=995
Re=10989

Temperatures below 500 C can be achieved



5mm
Ha=1989
Re=21936

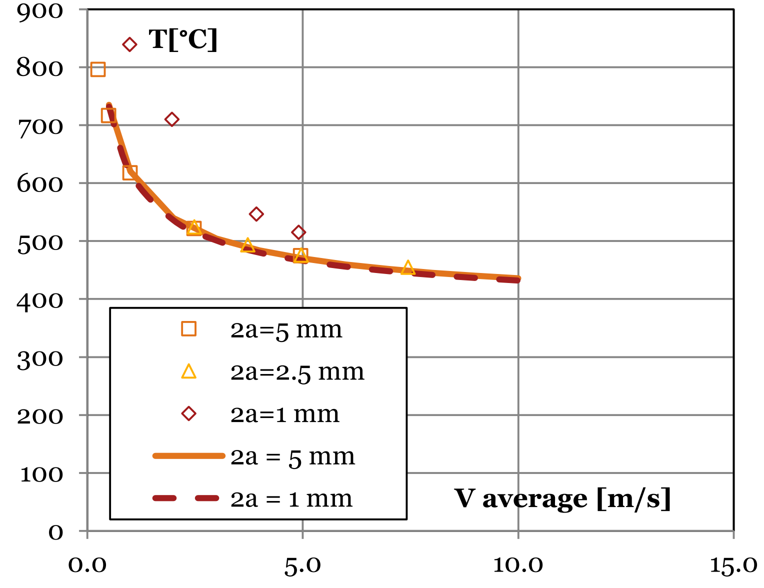


B_{ext}=0T
Re=8500
Turbulent
Flow

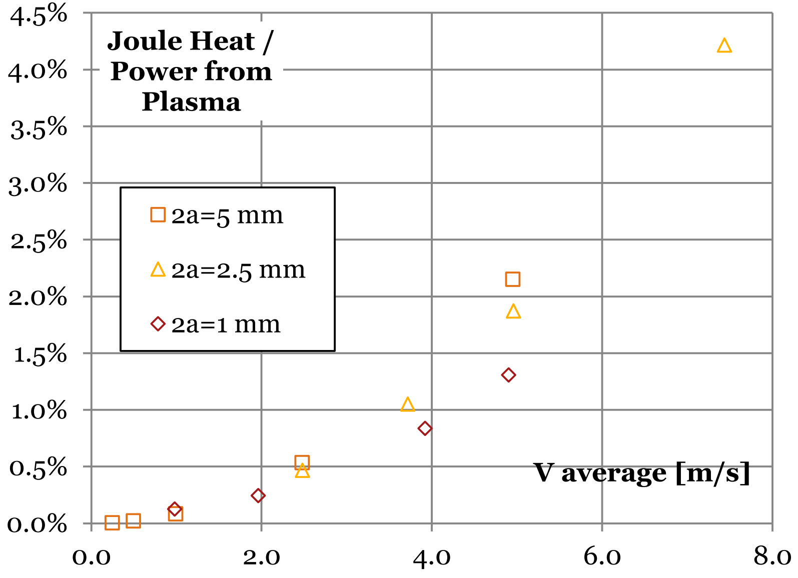
Porous System Peak Temperature and Efficiency

- **High-Velocity Li flow can be established.**
- Li injection and extraction
- Li flow over the divertor plates
- Li pumping

Peak Temperature on the Plasma Facing Wall

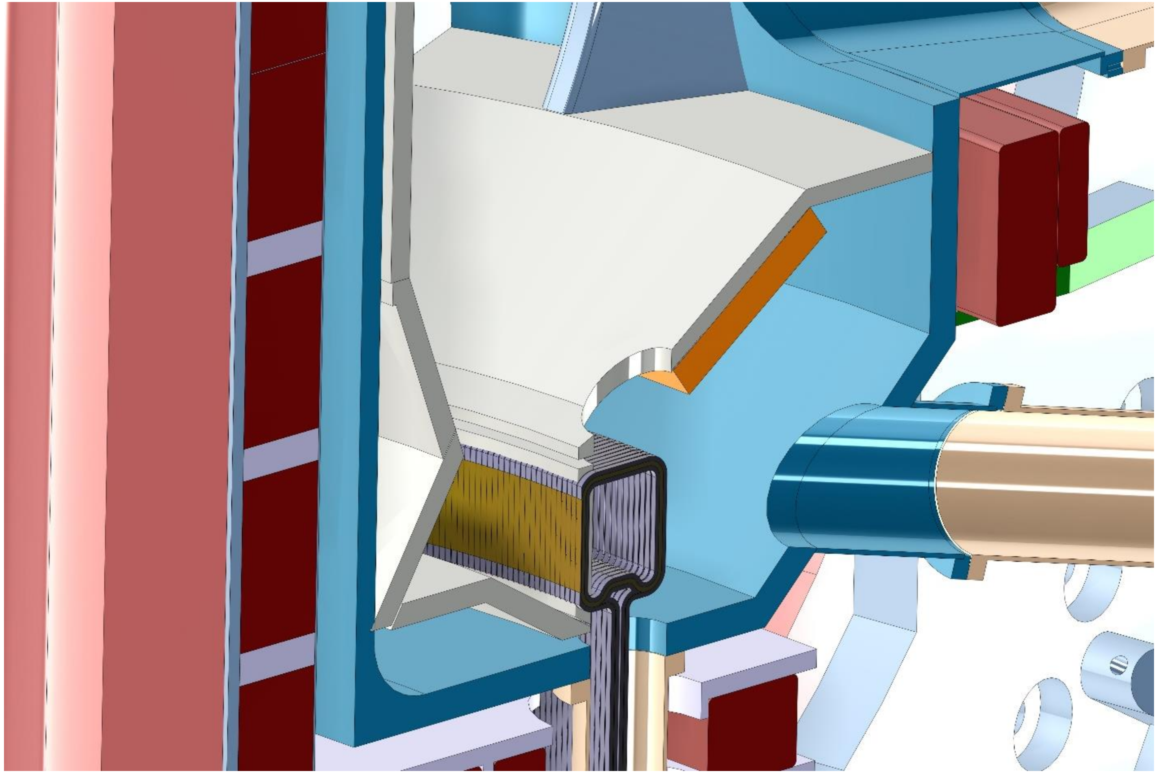


MHD pumping loss 1m long Channel as a percentage of incoming heat

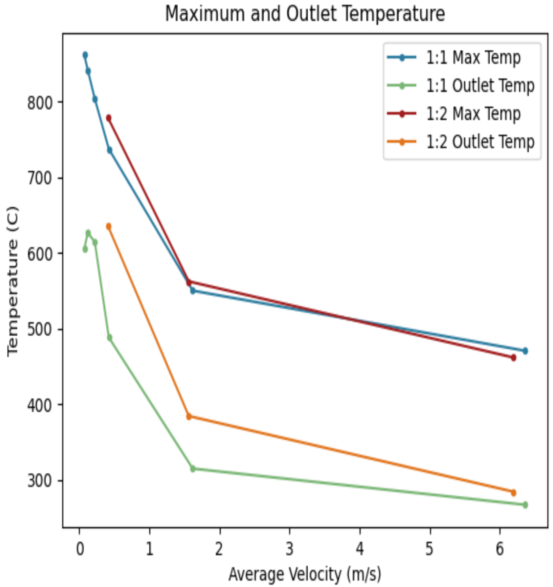


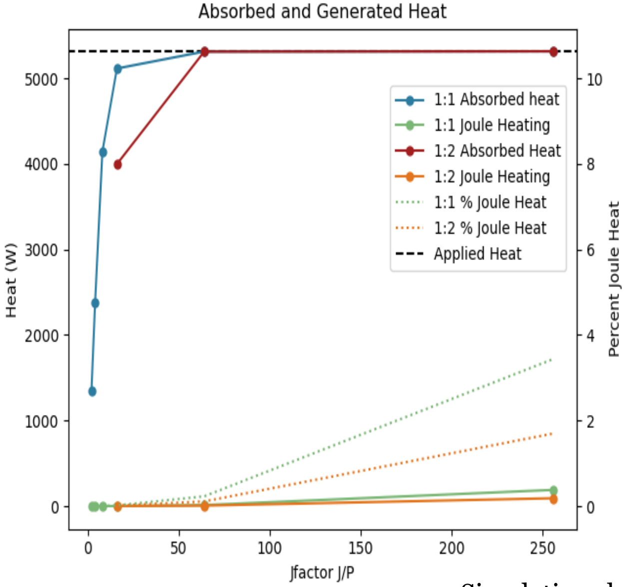
Implementation

- Porous Liquid Lithium System is under development
- Model of the liquid lithium cooling system was created
- Parametric studies are performed for the novel divertor liquid lithium system which includes porous front wall.



Optimization





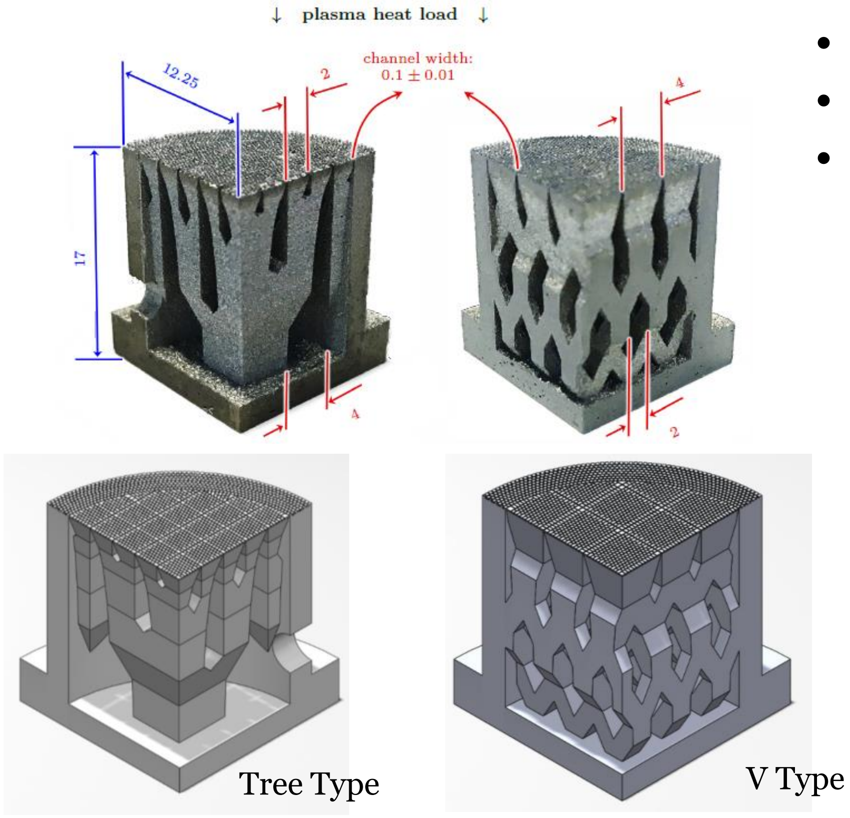
Simulations by B. Arnold SULI 2020

- Temperature is decreased by increasing current and velocity
- Smaller Channel can’t remove as much heat at low currents

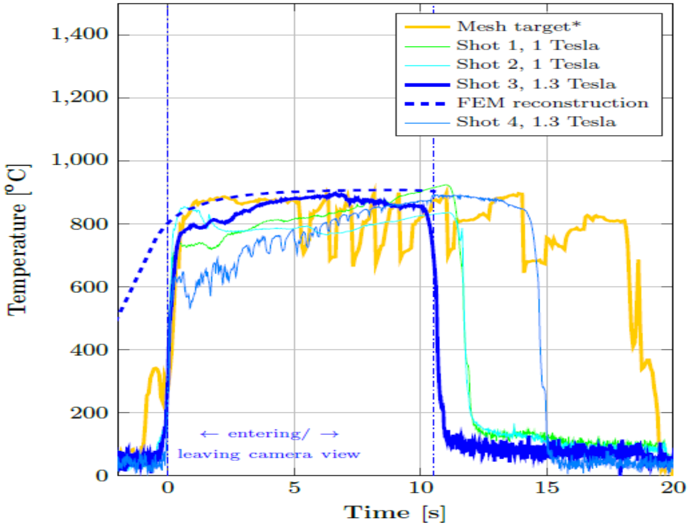
- Heat is only lost to evaporation at very low velocities
- Smaller channel is more efficient — generates less Joule heat

Porous 3D Printed Tungsten

- Organized porous structures
- Conductive material
- Porous structures with liquid metal can limit temperature on the divertor surface

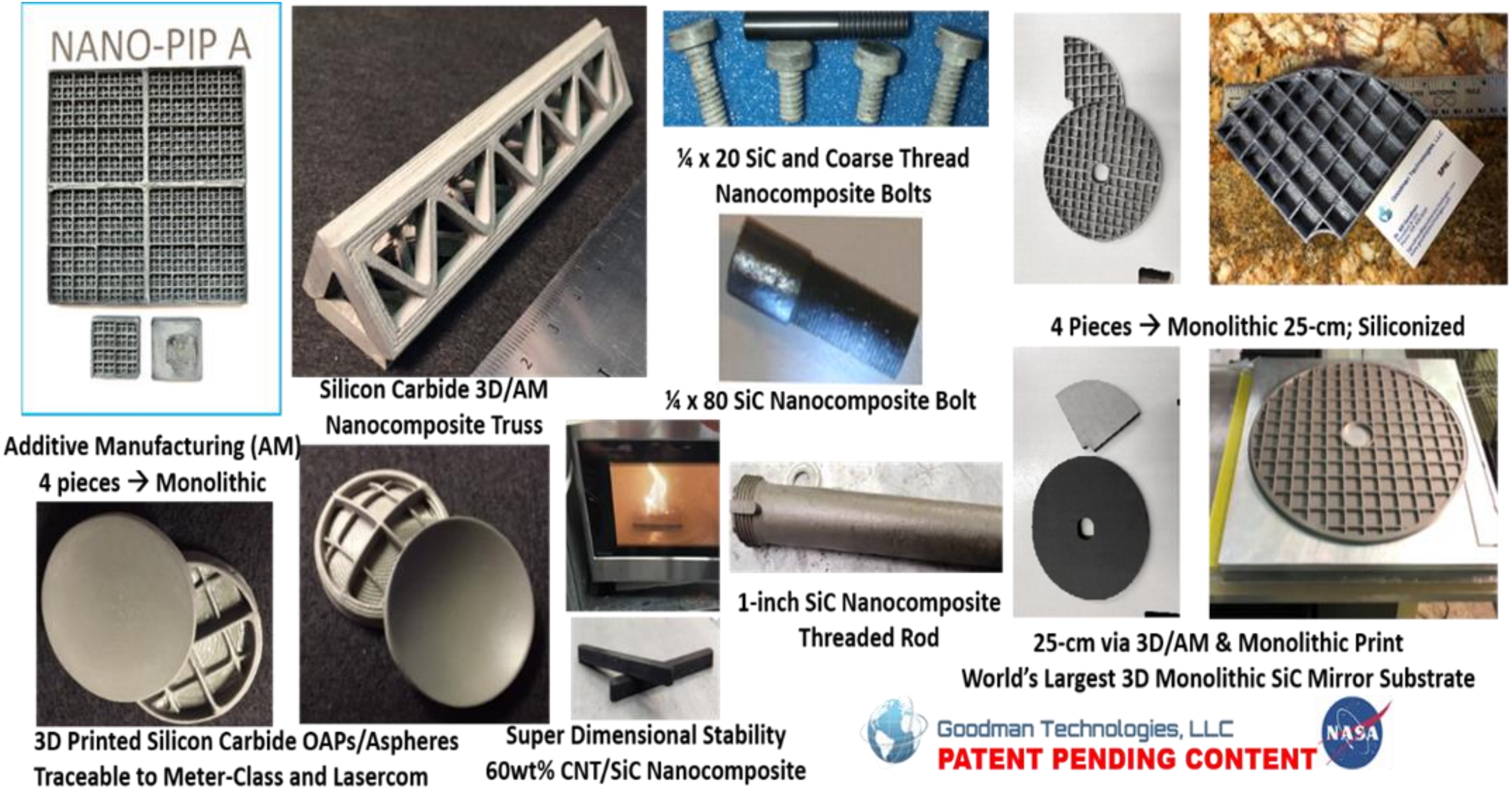


3D printed tungsten porous model imported from CAD Imported from P Rindt



Magnum PSI results. P. Rindt 2019

3D printed SiC can provide insulation material



Additive Manufacturing (AM)
4 pieces → Monolithic

Silicon Carbide 3D/AM
Nanocomposite Truss

¼ x 20 SiC and Coarse Thread
Nanocomposite Bolts

¼ x 80 SiC Nanocomposite Bolt

4 Pieces → Monolithic 25-cm; Siliconized

3D Printed Silicon Carbide OAPs/Aspheres
Traceable to Meter-Class and Lasercom

Super Dimensional Stability
60wt% CNT/SiC Nanocomposite

1-inch SiC Nanocomposite
Threaded Rod

25-cm via 3D/AM & Monolithic Print
World's Largest 3D Monolithic SiC Mirror Substrate

Goodman Technologies, LLC
PATENT PENDING CONTENT

From www.goodmantechnologies.com

Conclusions

- **MHD Pumping of Liquid Lithium near the first wall has the following advantages:**
  - Efficient Removal of plasma heat flux at relatively low temperature
  - Maintaining constant low pressure along the channel
  - Favorable profile for efficient heat transfer
- **Porous first wall allows**
  - Liquid lithium delivery on plasma facing surface
  - Stabilization of liquid lithium free surface due to surface tension and MHD drag
- **Solid first wall can be considered creating efficient blanket design**
- **Numerical and analytical models show feasibility of the concept**
- **Experimental proof of concept can be achieved at PPPL using Galinstan**