Summary of Current R&D Efforts for Liquid Metal Based Blankets and ITER TBM (with thermofluid MHD emphasis)

Presented by

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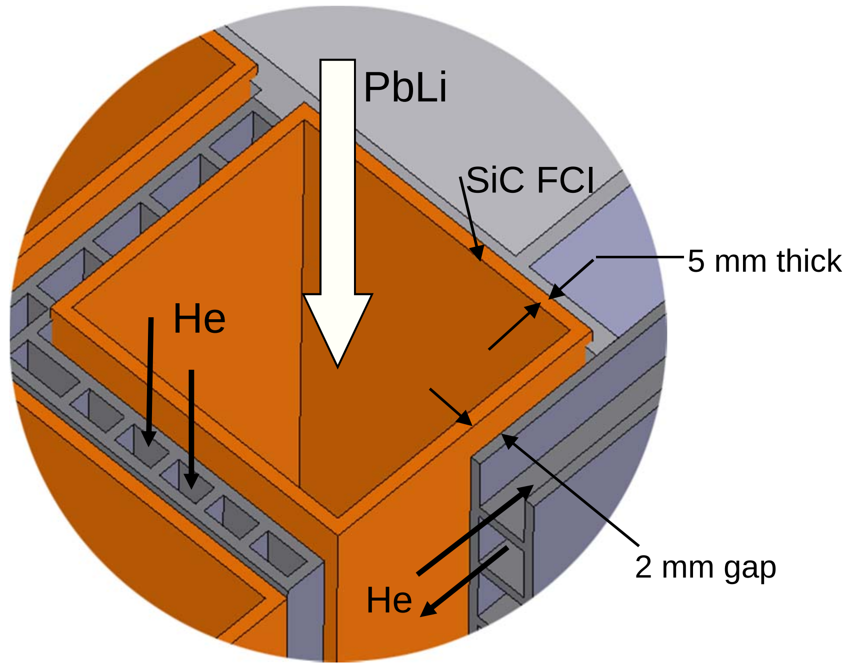
Primary Focus for Liquid Metal Based Blankets

Pathway toward higher temperature and higher efficiency through innovative designs with current structural material (Ferritic Steel):

Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept

How can high outlet temperature be reached while maintaining steel structure < 550C?

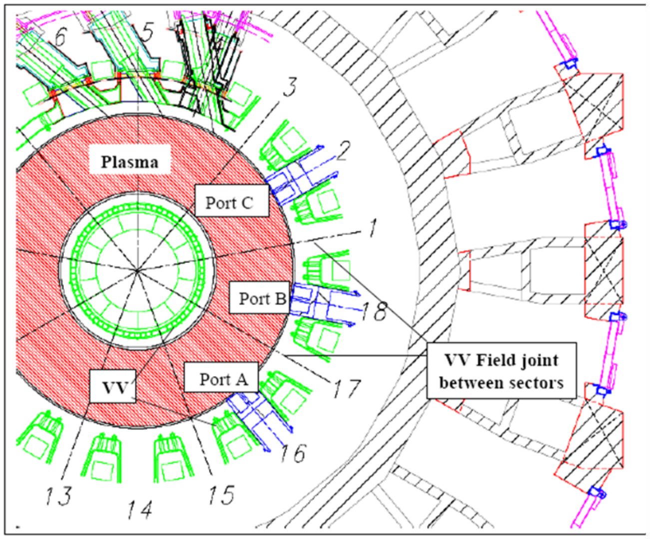
- Cool all steel structures with He (Tin/Tout ~ 350/450C, carries 50% of the total energy).
- Have a PbLi breeding zone that is flowing and self-cooled. Operate Pb-17Li exit temperature at significantly higher than the operating temperature of the steel structure (Tin/Tout ~ 450/700C, carries other 50% of the total energy)
- Isolate the hot PbLi from the cooler structure by use of a non-structural liner called a Flow Channel Insert (FCI) that:

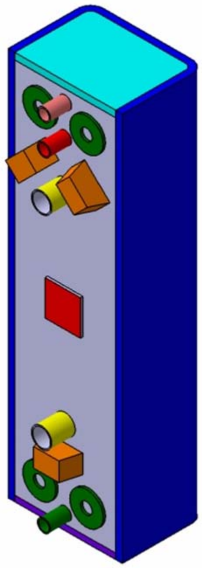


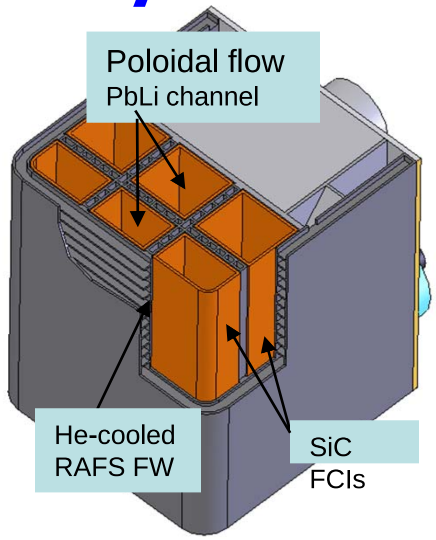
DCLL design concept evolved with focus on accommodating thermofluid MHD effects

- ❖ Prevents leakage of volumetric nuclear heat deposited in the PbLi from entering the (lower efficiency) He coolant stream
- ❖ Provides nominal electrical insulation to keep MHD pressure drop manageable
- ❖ Is compatible with PbLi at elevated temperatures ~800C (peak).

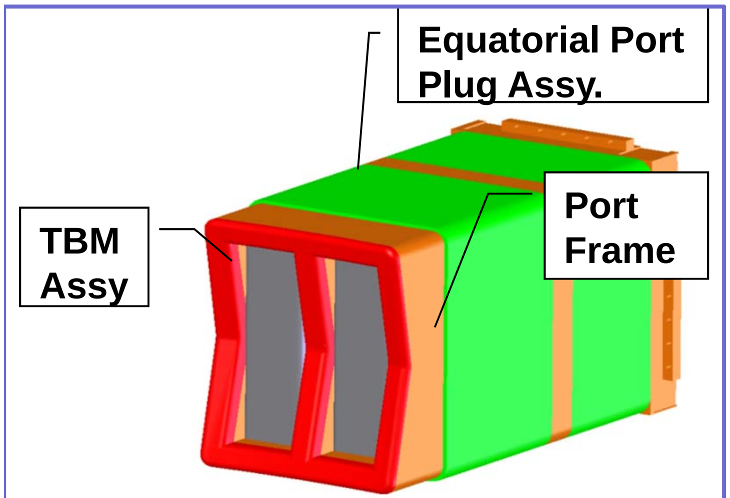
ITER Provides Substantial Capabilities for Testing of Blanket System



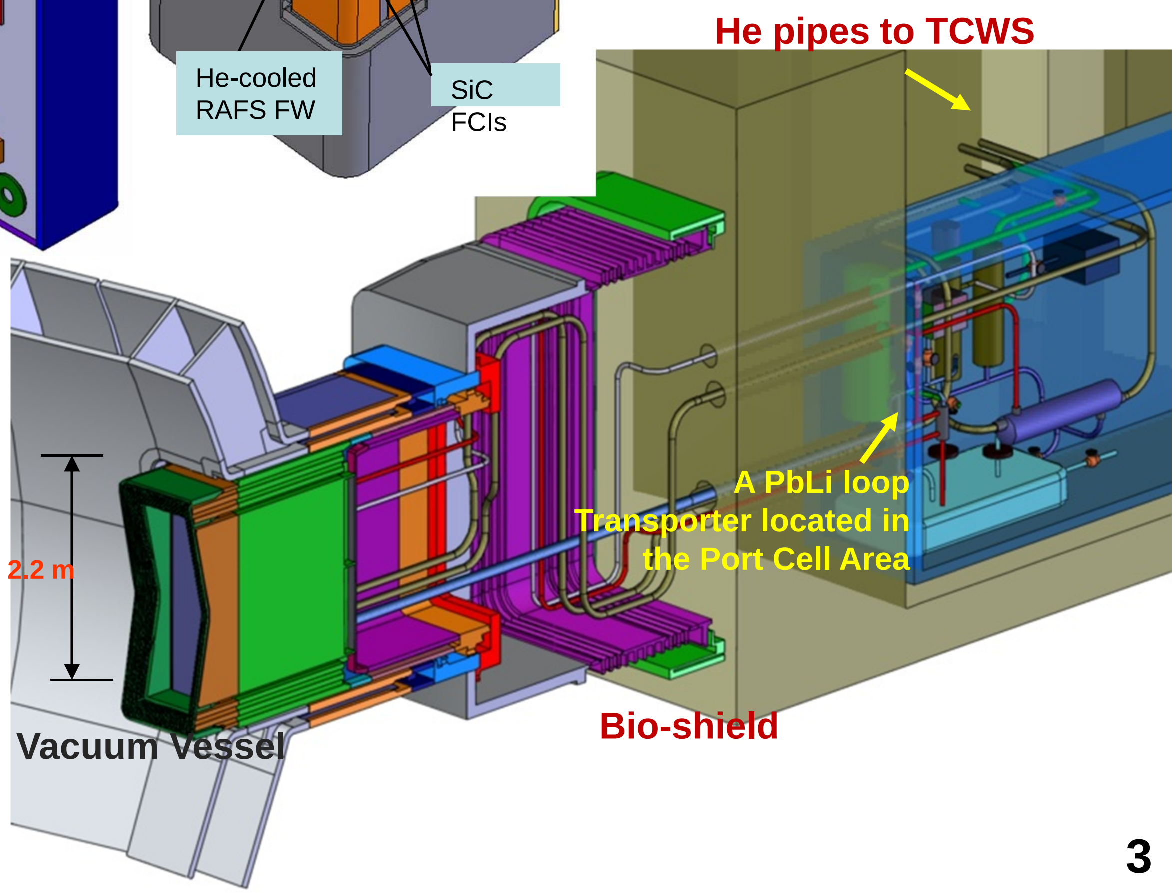




However, DOE has not yet decided on the US' participation in the ITER TBM program



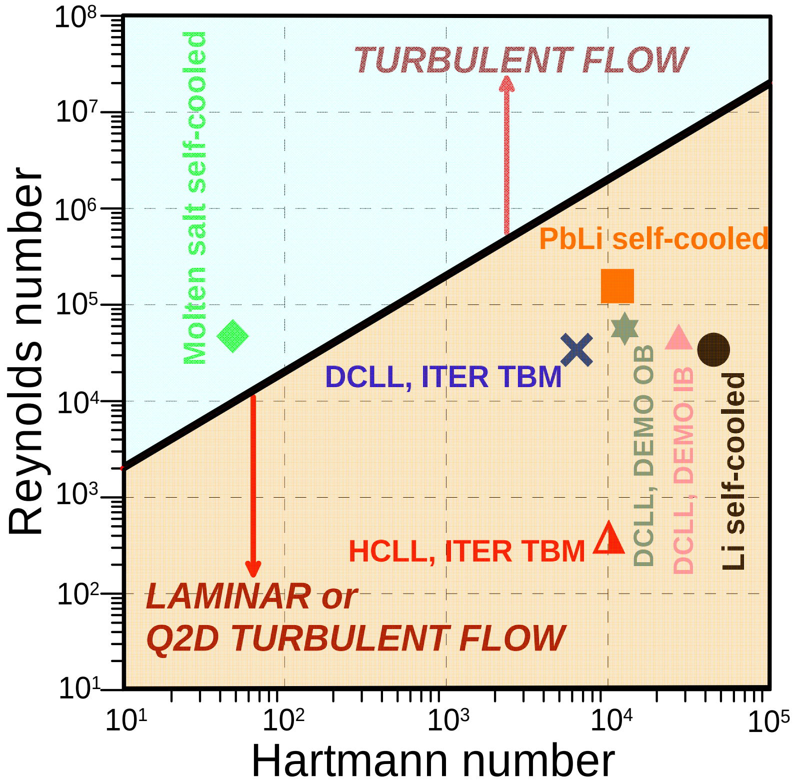
- **Each port can accommodate 2 Modules (i.e. 6 TBMs)**



Key Research Areas in the PbLi based DCLL Blankets (applicable to both DEMO and ITER TBM)

- MHD flow Dynamics for liquid metal blankets (experiments and modeling)
- Interfacial phenomena, MHD Heat and Mass Transfer (Corrosion, Tritium Transport)
- Tritium transport properties and permeation in PbLi (experiments and modeling)
- FCI material/component development & properties
- Compatibility, Corrosion experiments
- Safety analysis and modeling
- Irradiation effects in RAFM steels and SiC
- Integrated modeling/Virtual TBM
- Neutronics

Where we were on Thermofluid MHD Research for Fusion



$$Ha = B(a/2)\left(\sigma/\rho\nu\right)^{1/2}$$

- **For decades, blankets were designed using very simple models**
  - slug flow assumptions, core flow approximation, 2D, complete laminarization in modeling efforts
  - limited experimental data, mostly with surrogate LMs and materials at low temperature
  - Assuming ideal or self healing insulator coatings
- **These blankets were never built or tested.**

Results:

- **No success in Li insulator coating development. Blankets based on this assumption are not currently credible options**
- **Significantly more mixing, turbulence, and instabilities are present than previously accounted**

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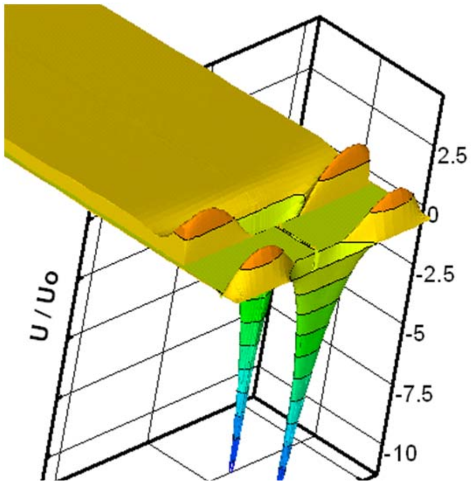
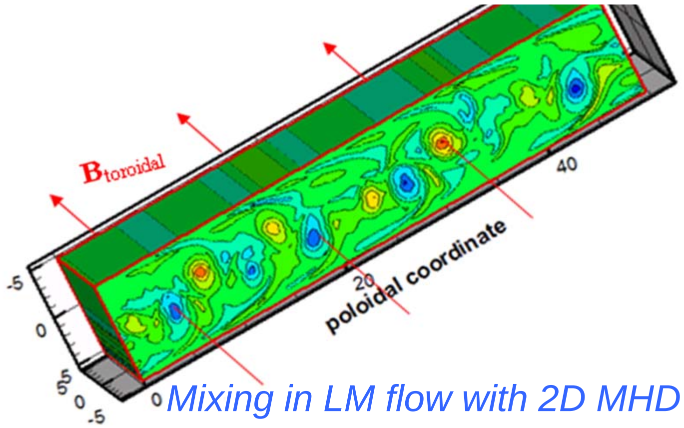
In addition to MHD pressure drop, MHD dominates LM flow behavior -- Velocity profiles impact on heat/mass transfer

- The velocity itself is dramatically modified by the MHD forces it creates via JxB force
  - -- MHD forces generally exceed viscous and inertial forces by 4-5 orders of magnitude (Ha, N)
- Typical MHD velocity profiles in ducts with conducting walls include the **potential for very large velocity jets** near in shear layers that form on walls parallel to the magnetic field.
  - -- In channels with insulators **reversed flow regions** can also spring up near local cracks and gaps.
- Non-uniform heating leads to strong buoyancy forces that also drive secondary flow

The impact on the temperature distribution, thermal stress, tritium transport, and corrosion can be very strong. --Interfaces between materials are key and have to be studied together



Reversed flow jets in region near cracks or gaps in insulator – Local reversed velocity 10x the average forward flow



Mixing in LM flow with 2D MHD Turbulence – Smolentsev

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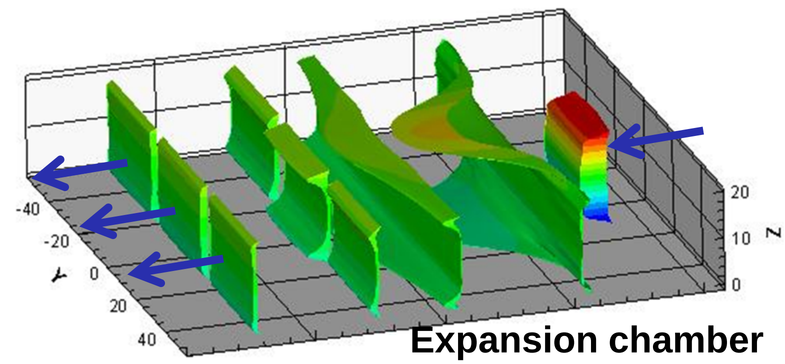
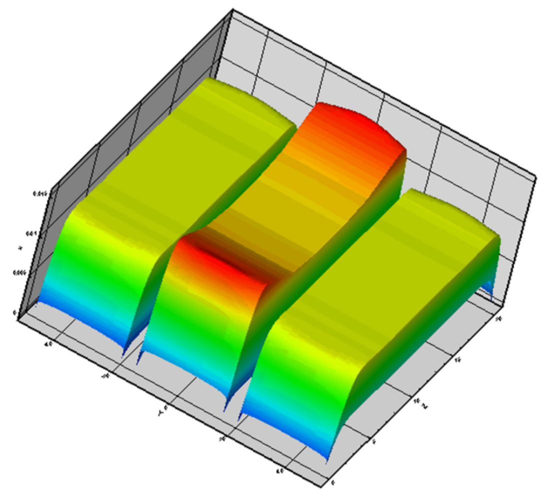
Recent Trends in Thermofluid MHD Numerical Modeling Development

- Focus modeling on key physical mechanisms not always included during design studies of liquid metal blankets
  - Realistic geometrical models
  - Flows with multiple materials, coolants and complex structures
  - Realistic magnetic field distributions
  - Instabilities, mixed convection, turbulence
  - Strong magnetic fields (Ha~10^4), prototypic flow velocities (Re~10^5) and volumetric heating (Gr~10^{12});
  - Coupling flow, current to transport and interfacial phenomena , such as impact on tritium transport and corrosion

HIMAG 3d Manifold simulation



Velocity profiles from inlet to outlet



The center channel has flow rate 11.8% above the uniform flow, and the side channels have -5.% below the uniform flow.

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Development of 3-D MHD Codes (full solution) is very challenging
HIMAG: Joint development UCLA- HyPerCom

- Current offerings in commercial CFD have serious limitations in being able to model liquid metal MHD(LMMHD) relevant to fusion.
- Multiphysical modeling including LMMHD is crucial to fusion reactor liquid breeder blanket analysis
- HIMAG has been created to bridge this gap in technology
- Extensive validation and benchmarking has been performed for canonical problems. <u>Cases involving Ha > 1000 have never been demonstrated on non-rectangular meshes prior to HIMAG</u>
- Present research seeks to improve the **speed of MHD calculations (start-to-finish)**

Reasons why MHD solutions are slow to compute:

1. The need to resolve and minimize numerical errors in Hartmann layers(Thickness about 1/Ha)
2. The pace of convergence of Poisson equation solvers (for Pressure, Electric potential, divergence of B)
3. Computationally intensive corrections for non-orthogonal meshes
4. Long periods of integration needed to account for flow development, unsteady effects

Wall Function Methods for MHD Simulation Speed-up

- **Boundary layers are very thin, and too costly to resolve properly.**
- Adopting an analytical wall function for interpolation between the first computational node and the wall (similar to the logarithmic law of the wall applied to the turbulent flow simulation)
- Applied to laminar MHD flows for both conducting and insulating walls
- Analytical integration of the momentum and potential equations give near-wall model expressions of velocity and electrical potential
- Wall factions for velocity and electric potential (as an example)

$$U_P^i(n) = \tau^i \frac{\delta_H \sinh(n/\delta_H)}{\mu} + \left(C_i + J_{wall} D_B^i + E_0^i\right)\frac{\delta_H^2}{\mu}\left(\cosh\left(\frac{n}{\delta_H}\right) - 1\right) + \left(d_J D_B^i + E_1^i\right)\frac{\delta_H^3}{\mu}\left(\sinh\left(\frac{n}{\delta_H}\right) - \frac{n}{\delta_H}\right)$$

$$\phi(n) = \phi_{wall} - \frac{nJ_{wall}l}{\sigma} - \frac{n2d_J}{2\sigma} + (B\mathbf{xn})\overline{U}_P(n)$$

Average parallel velocity in the near wall region

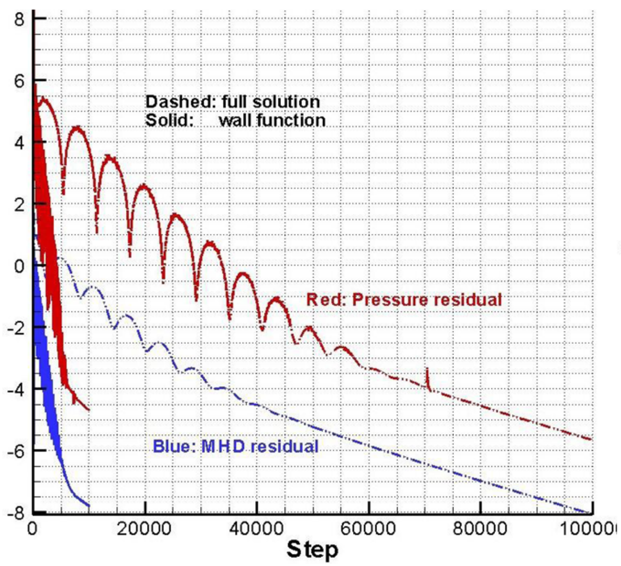
$$0 \le n \le n_P$$

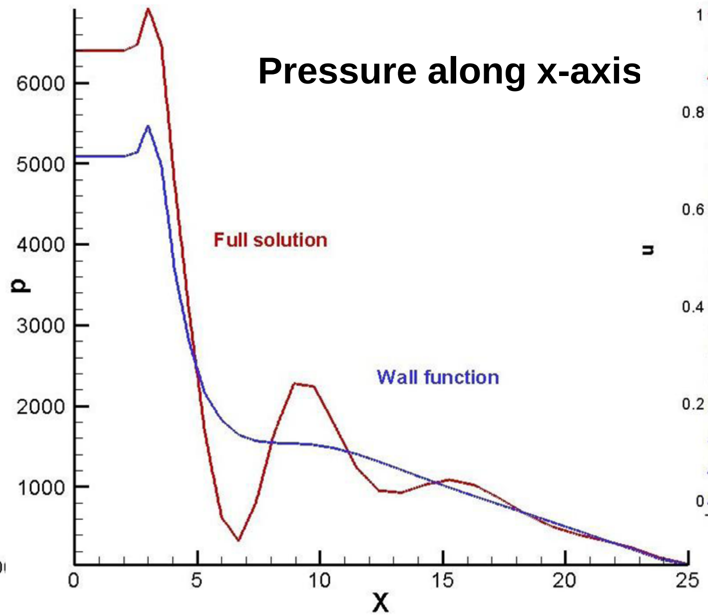
n_P = the first computational node

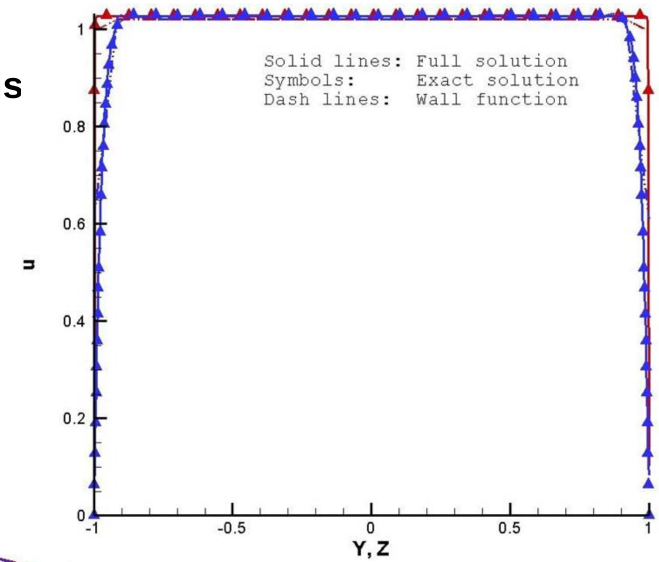
Reference: Ola Widlund, Wall functions for numerical modeling of laminar MHD flows, European Journal of Mechanics B/Fluids 22 (2003) 221-237

Example Test Case 5:
Shercliff's 3-D flow with Ha=1000, B=0 when x≤3, B=1 when x>3

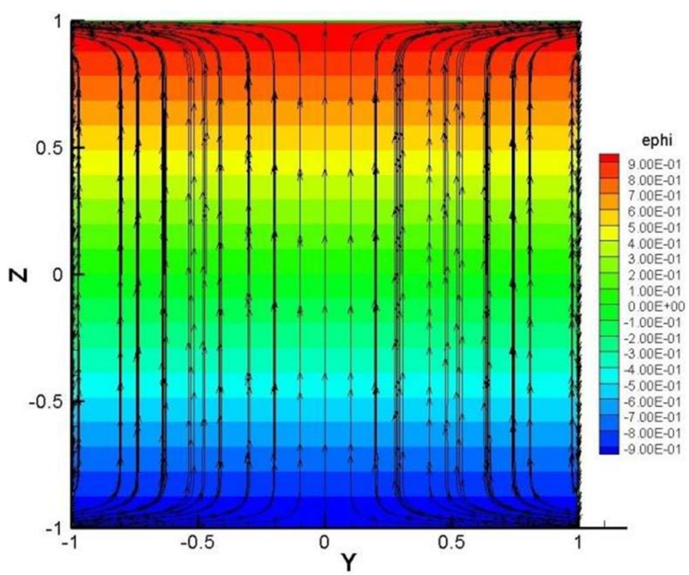
Computation speed



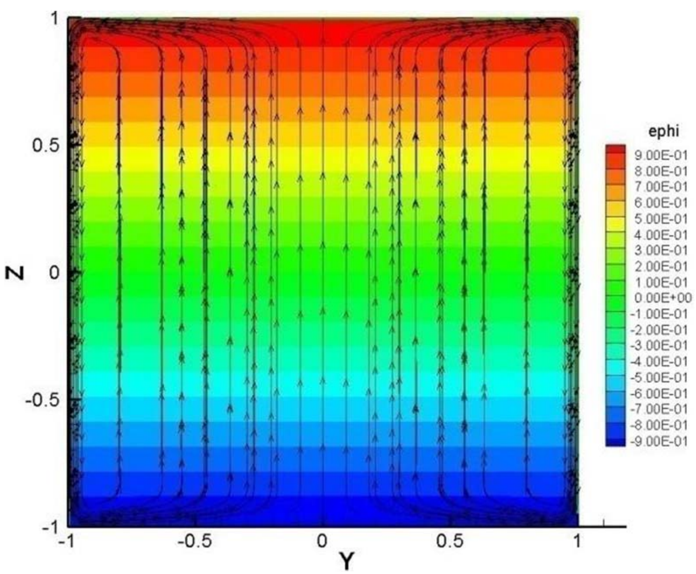




Velocity profile at mid-plane

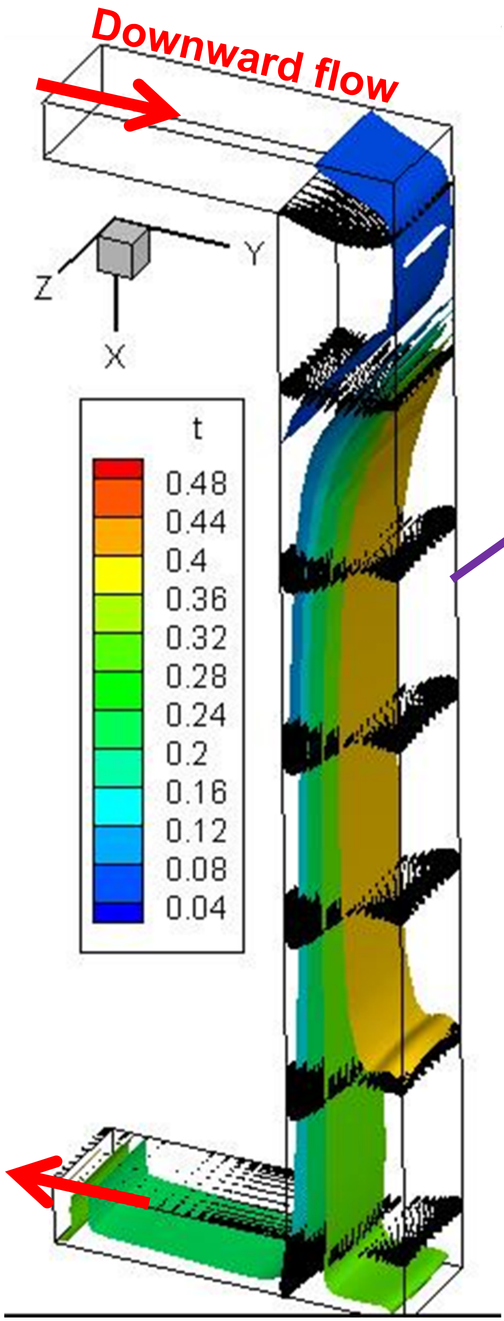


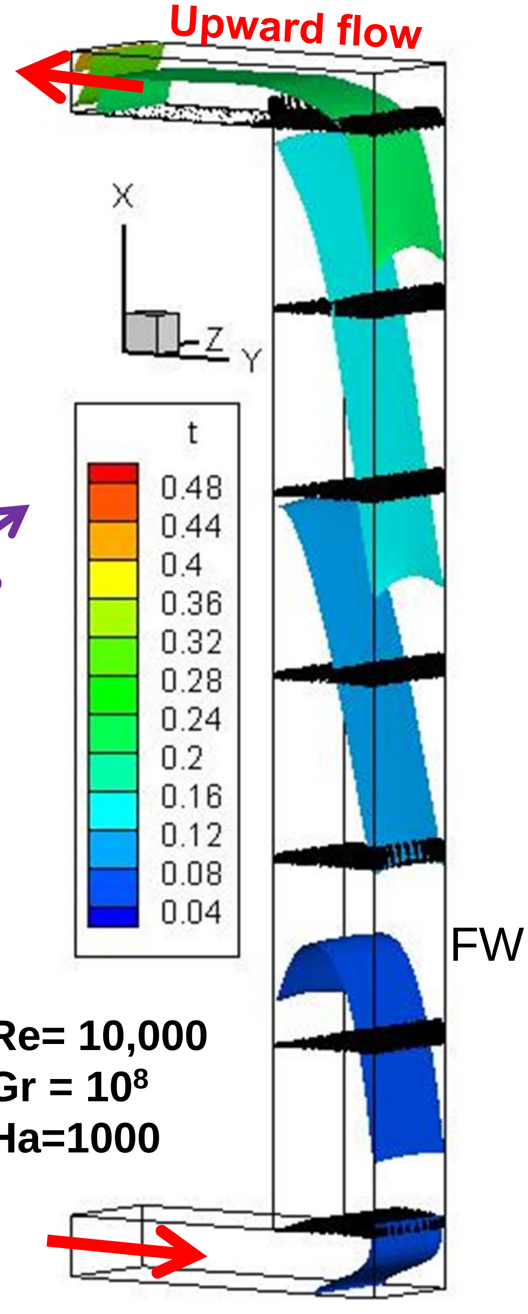
Full solution current



Wall function current

Buoyancy Effects in DCLL Blankets





Re= 10,000
Gr = 10^8
Ha=1000

The steep gradient in nuclear heating creates a skewed and large temperature gradient across the duct perpendicular to the flow direction

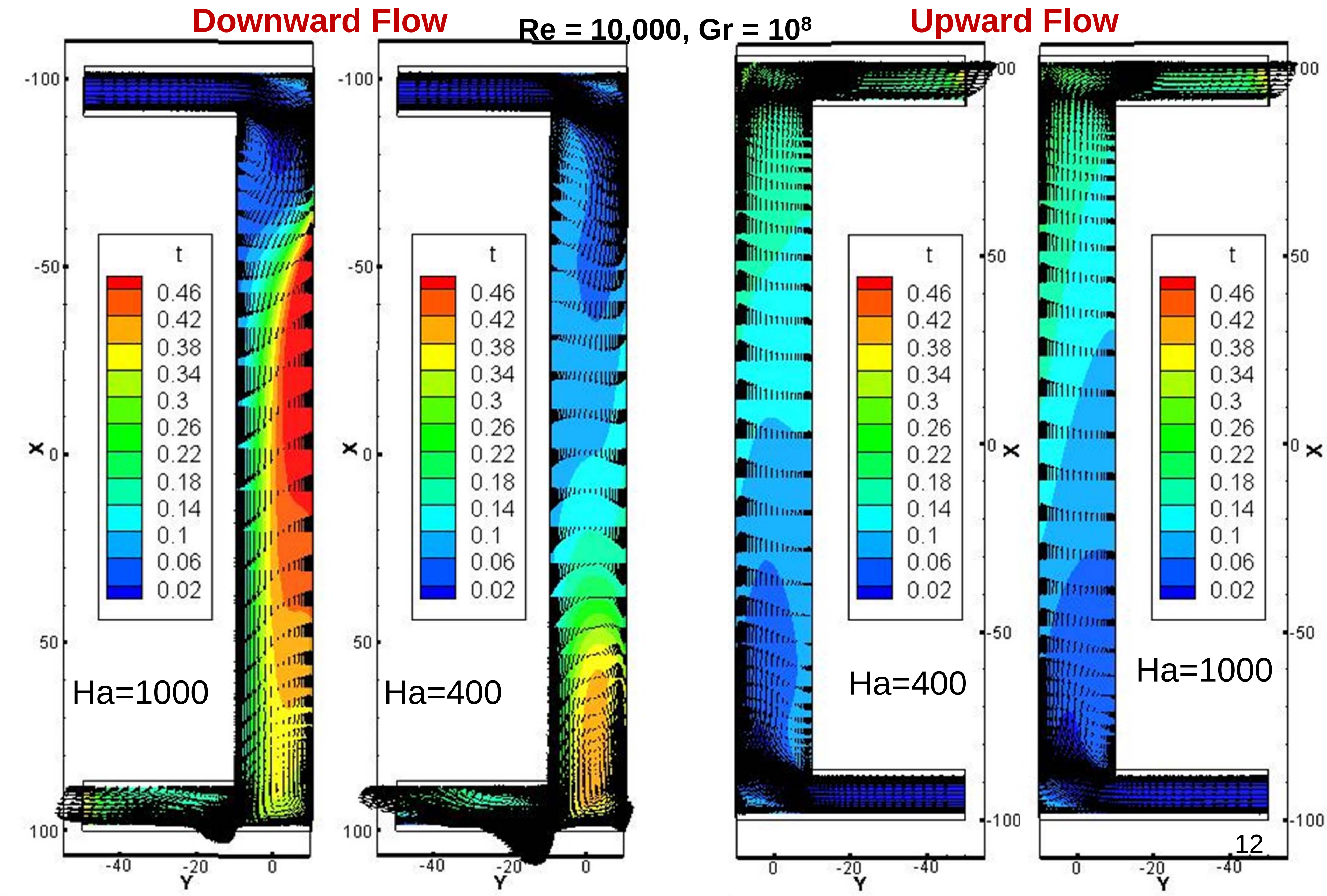
$$q'''(y) = q'''_{\max} Exp(-\alpha y)$$

Parameter	ITER	DEMO OB
Ha	6500	12,000
Re	30,000	60,000
Gr	7.0×10^{9}	3.5×10^{12}

Grashof Number $Gr = g\beta\Delta TL^3 / \nu^2$

- **In buoyancy-assisted (upward) flows, buoyancy effects may play a positive role due to the velocity jet near the "hot" wall, reducing the FCI ΔT.**
- **In buoyancy-opposed (downward) flows, the effect may be negative due to recirculation flows.**

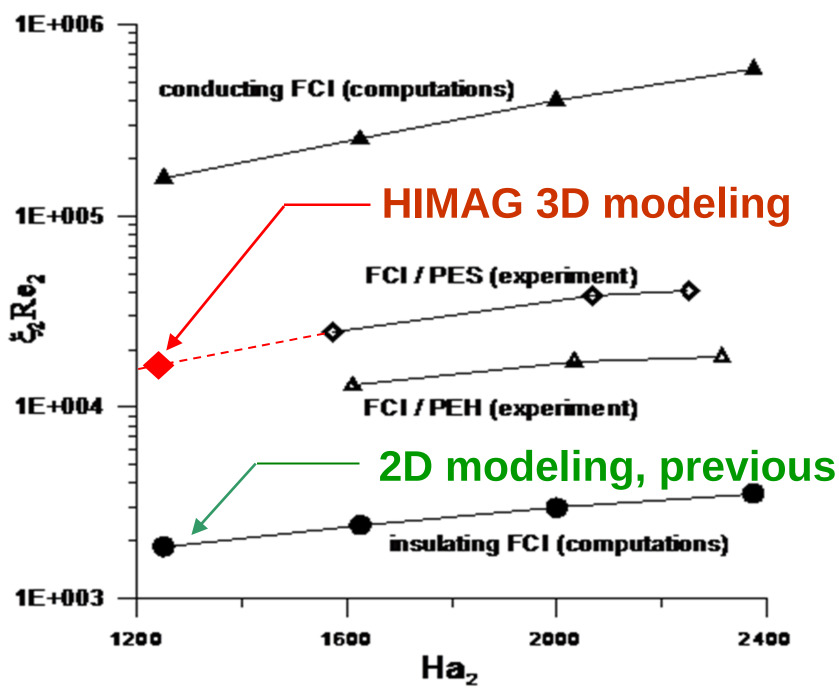
Buoyancy Effects on MHD Flow (Cont'd)

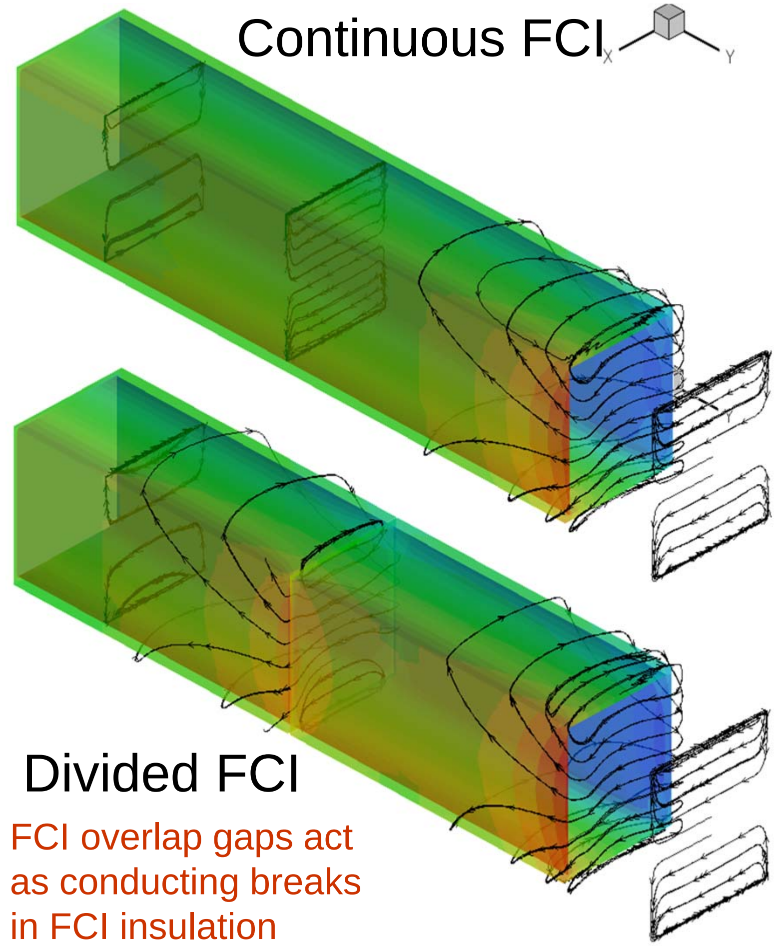


Even perfect insulation doesn't eliminate "3D pressure drop" effects

3D geometrical elements, or breaks in insulation will lead to locally strong pressure drop effects

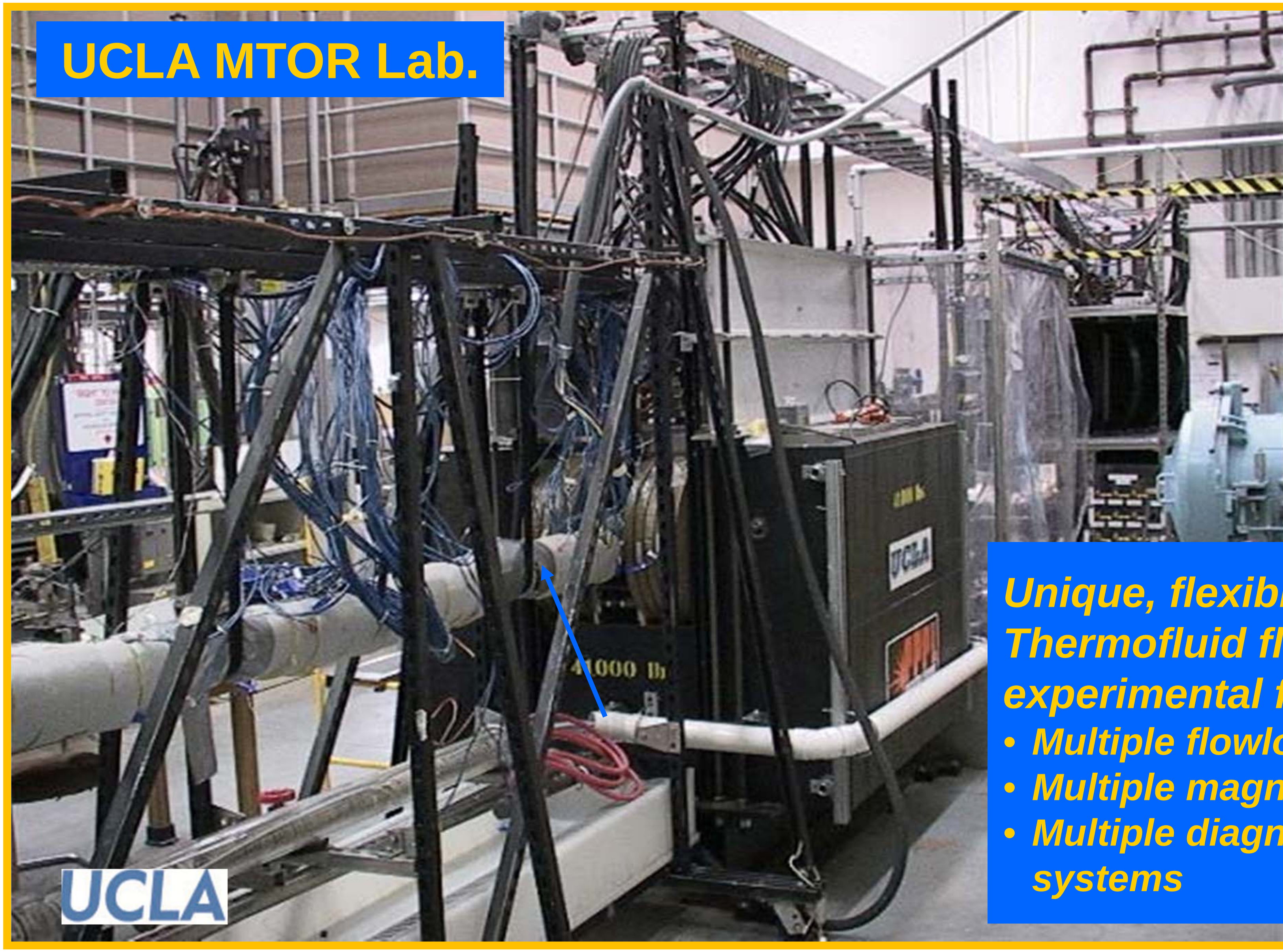
- FCI overlap regions
- Flows in non-uniform, 3-component B-field
- Bends, manifolds, expansions, etc.
- Property variation or imperfections





HIMAG simulations of FCI overlap gaps, impact on the current closure, and hence velocity and pressure drop (Ha=1000; Re=1000; σ=5 S/m, cross-sectional dimension expanded 10x)

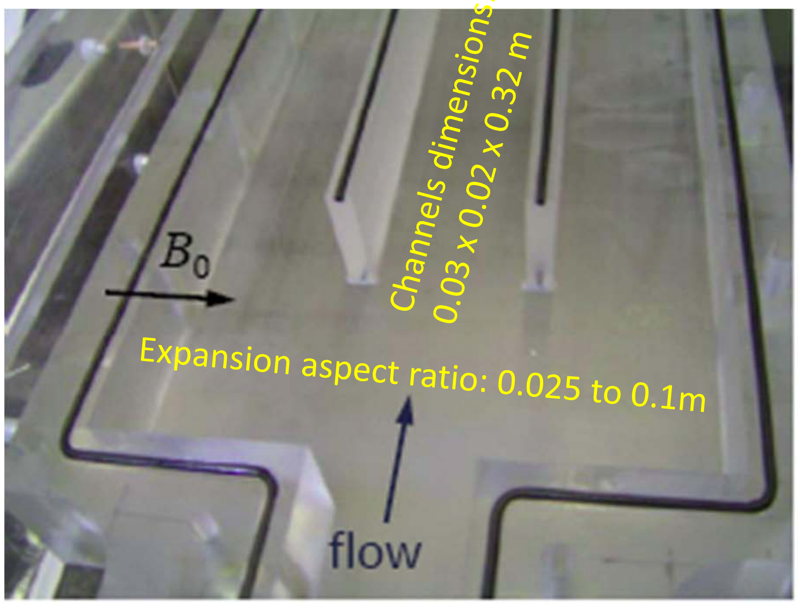
MTOR Lab, BOB magnet, and experimental systems for MHD Thermofluid flow Experiments

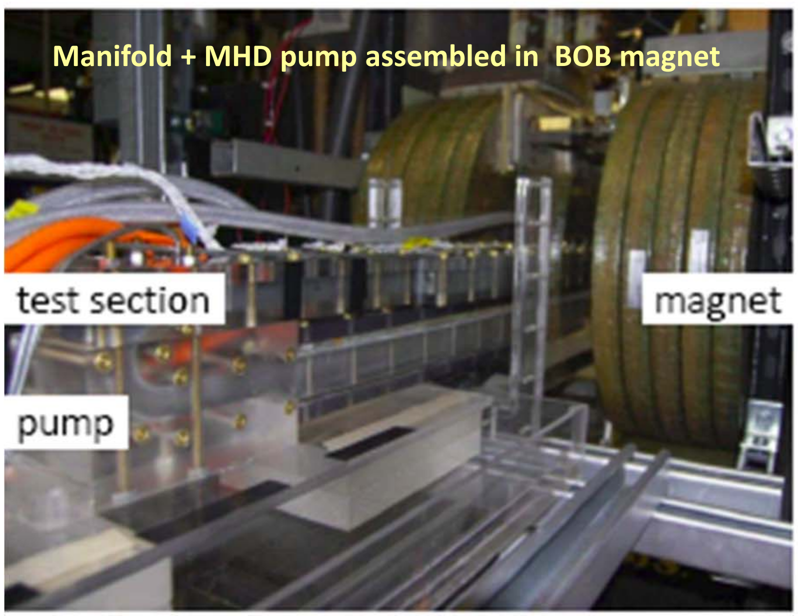


Unique, flexible MHD Thermofluid flow experimental facility

- ***Multiple flowloops***
- ***Multiple magnetic***
- ***Multiple diagnostic systems***

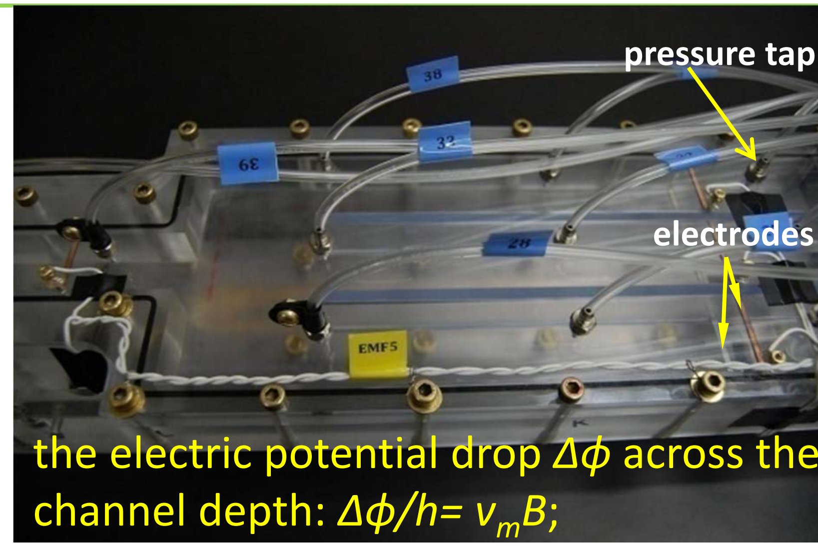
Impact of magnetic field on liquid metal flow division between parallel channels in a blanket





FLOW PARAMETERS

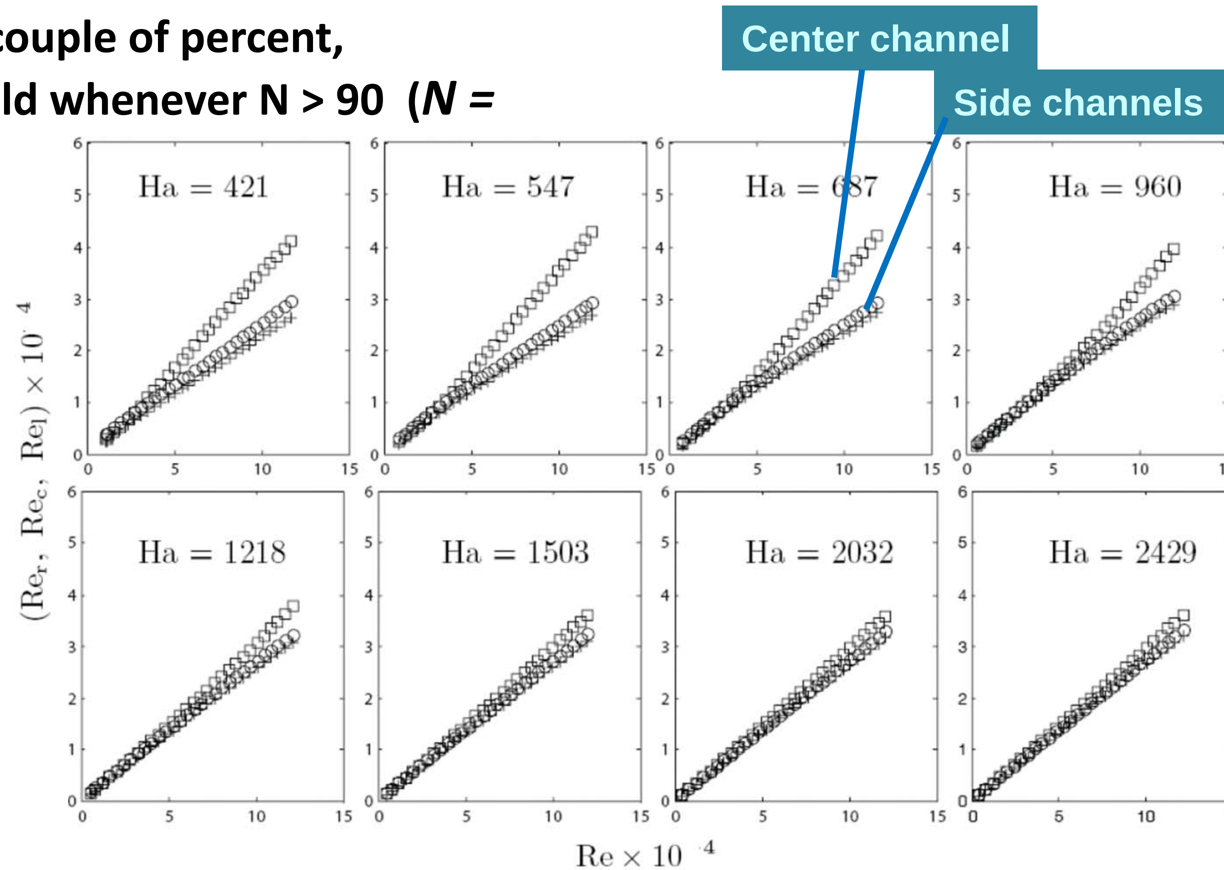
- Working fluid: Hg at about 20 °C
- B=1.8T (Ha_{max} = $3 \cdot 10^3$, based on a=0.05m)
- U_{inlet}=0.5m/s (Re_{max} = 10^5, based on h=0.02)

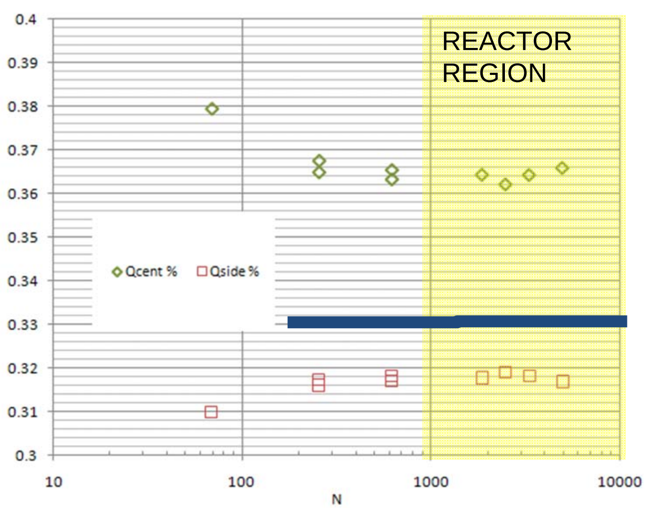


	ITER TBM	Experiment
B-field [Tesla]	4	1.8
Typical inlet velocity [m/s]	0.3	0.02–0.6
$Ha=B(b/2)(\sigma/\rho\nu)^{1/2}$	7500	2430
$Re=vh/\nu$	$2 \cdot 10^5$	$4 \cdot 10^3 - 1.2 \cdot 10^5$
$N=Ha^2/Re$	280	34–100

Typical Results for flow rates in the 3 channels as a function of overall flow rate and increasing Ha

- **Very uniform flow, within a couple of percent, enforced by the magnetic field whenever N > 90 (*N = Ha²/Re*)**
- **Some asymmetry between right and left channel observed for lower Ha**
- **3d Modeling results also indicate strong tendency towards uniform flow w/ increasing N**

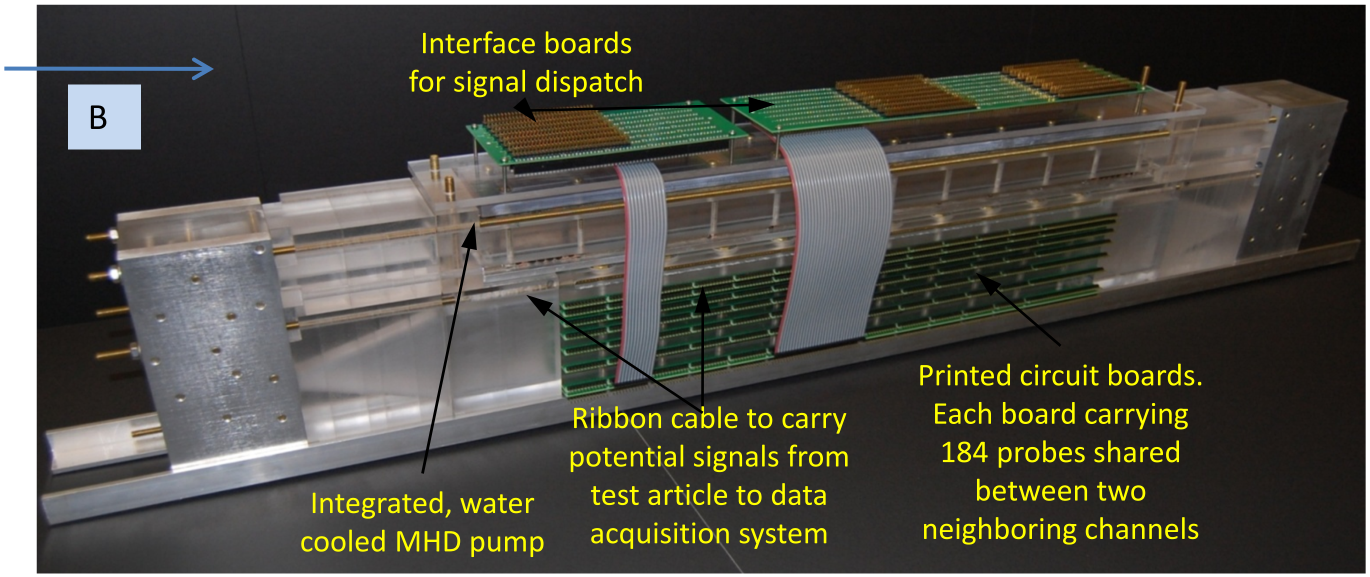


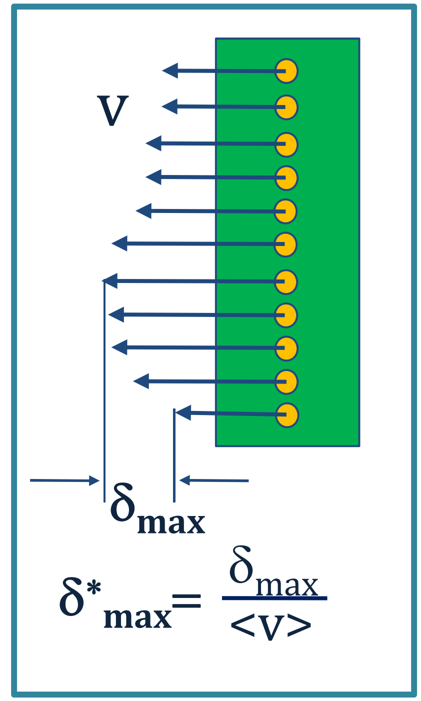


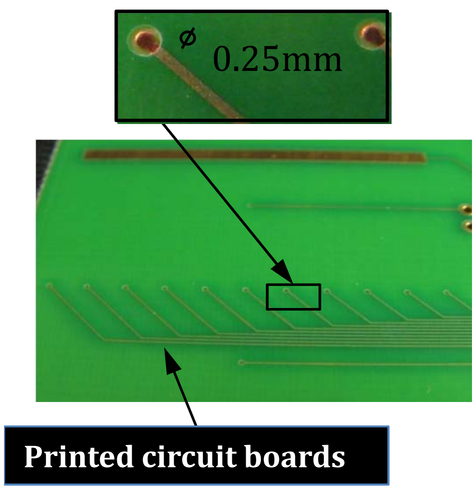
- **Experiment is consistently more uniform than model in high Ha regime**
- **Importance of both expansion and contraction regions on flow distribution seen**

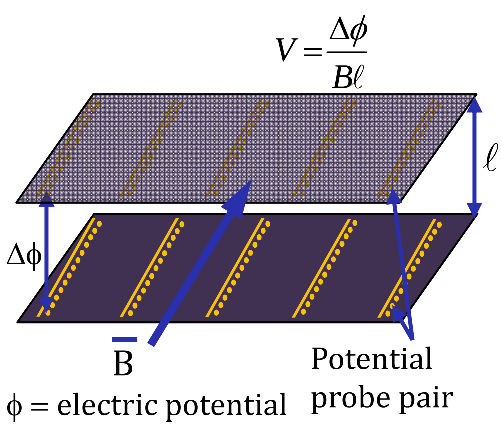
Mixed convection "Qualification" experiment performed to validate the novel wall potential measurement technique using printed circuit boards

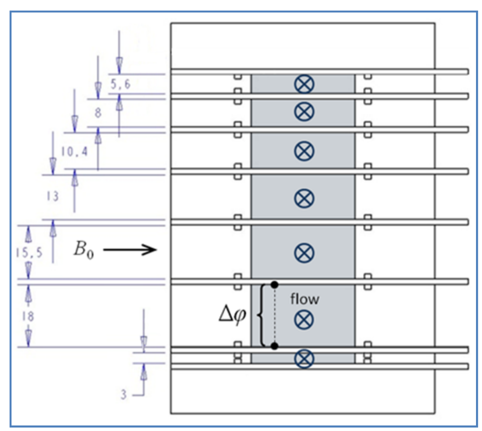
And, to test where a 3D structures of flow becomes a 2D flow





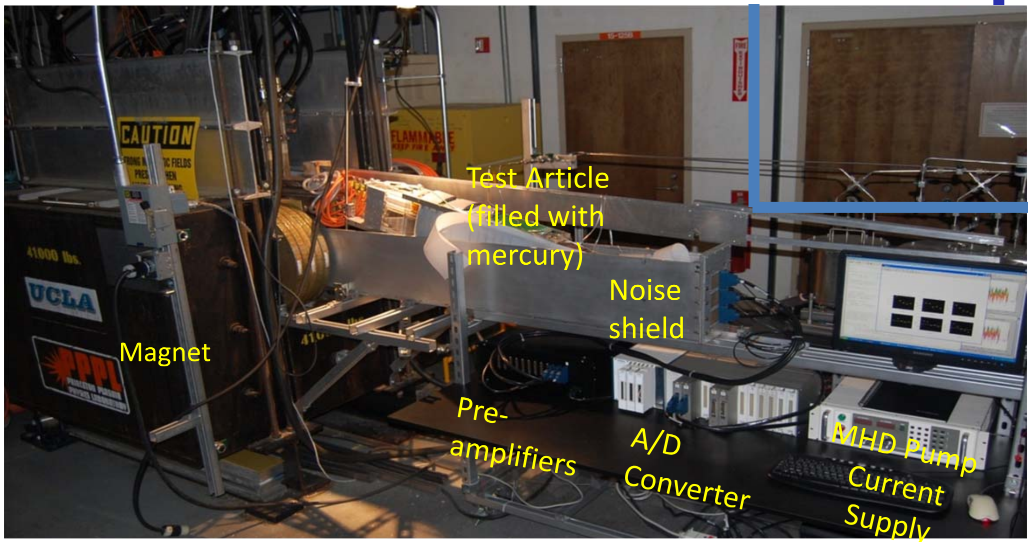




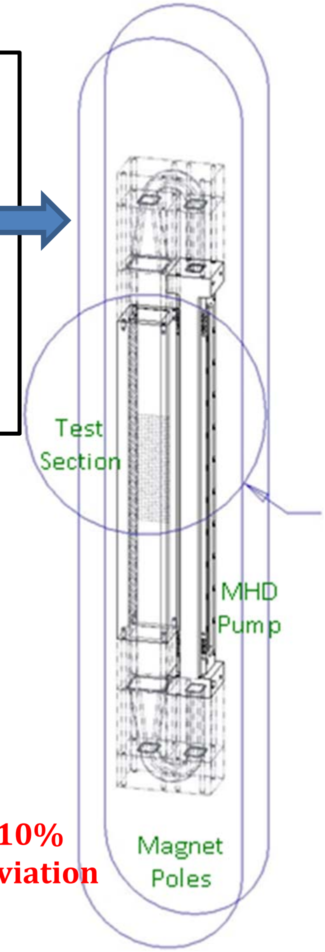


The test section for the Pre-Qualification Experiment consists of a stack of 7 insulated channels with heights ranging from 3mm to 18mm. All channels have the same width and length [W = 30.5mm, L = 600mm].

Pre-Qualification experiment in transition to Mixed Convection experiment

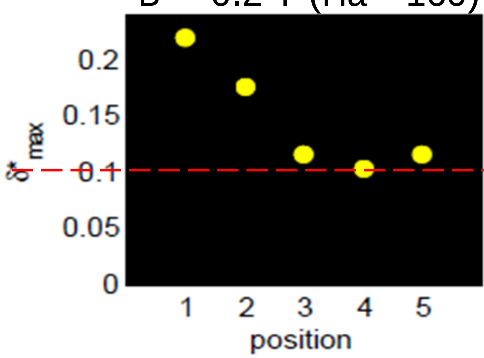


Mixed convection Experiment planned:
the magnet will be turned vertically to study buoyant MHD flows in poloidal-likechannels



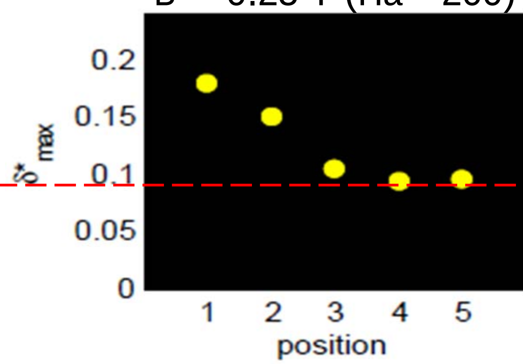
Channel height = 18mm, <v> = 0.4m/s (<Re> = 3 x 10^4)

B = 0.2 T (Ha= 160)



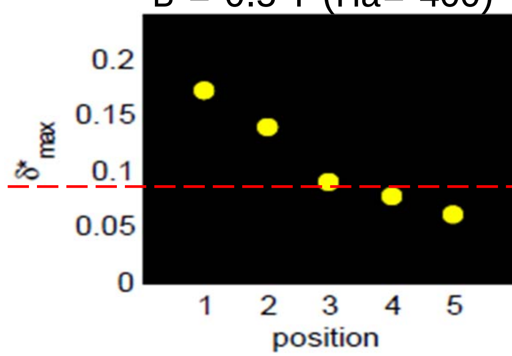
Relatively strong 3D flow at inlet.

B = 0.25 T (Ha= 200)



3D flow at inlet. Tends to be 2D.

B = 0.5 T (Ha= 400)

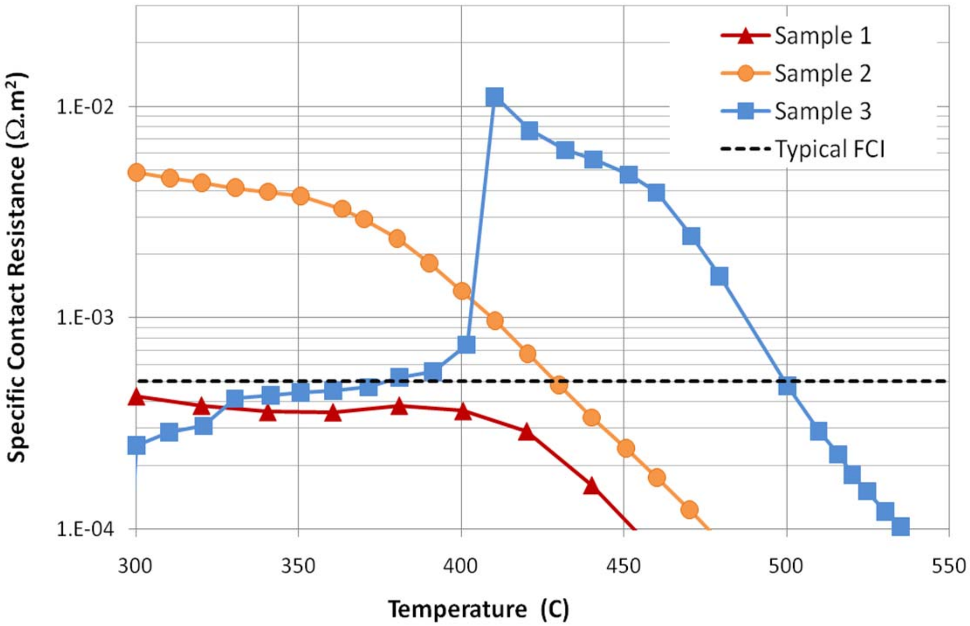


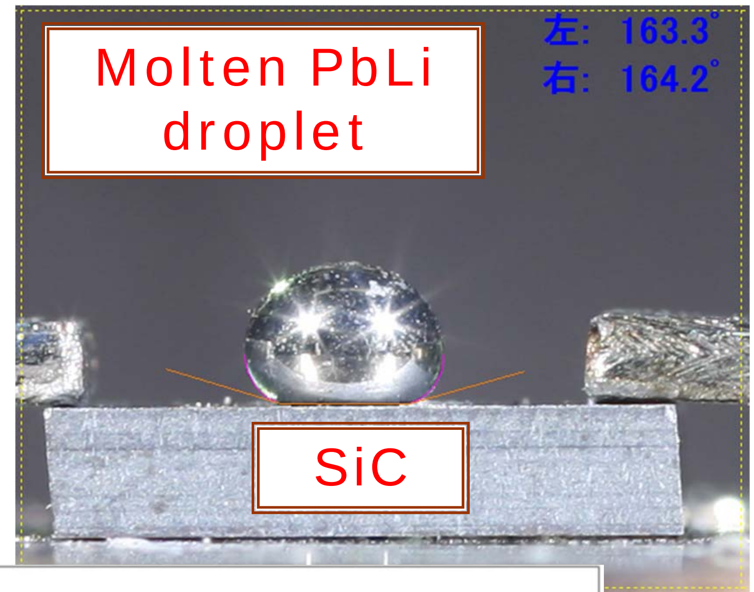
3D flow at inlet. Clear trend towards a 2D flow.

10% deviation

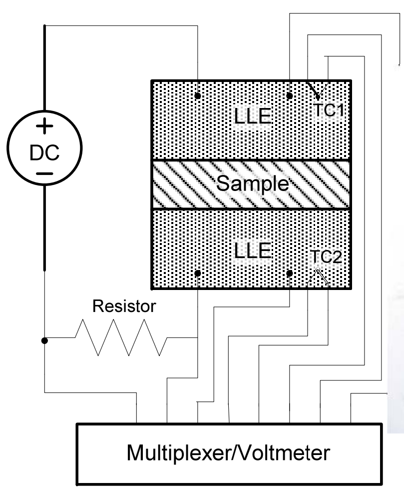
3D and 2D flow states can coexist in the same channel. There is a constant competition between Joule dissipation, which tends to elongate the structures in the direction of the magnetic field [tendency towards 2D behavior], and inertia which tends to restore some isotropy [3D behavior].

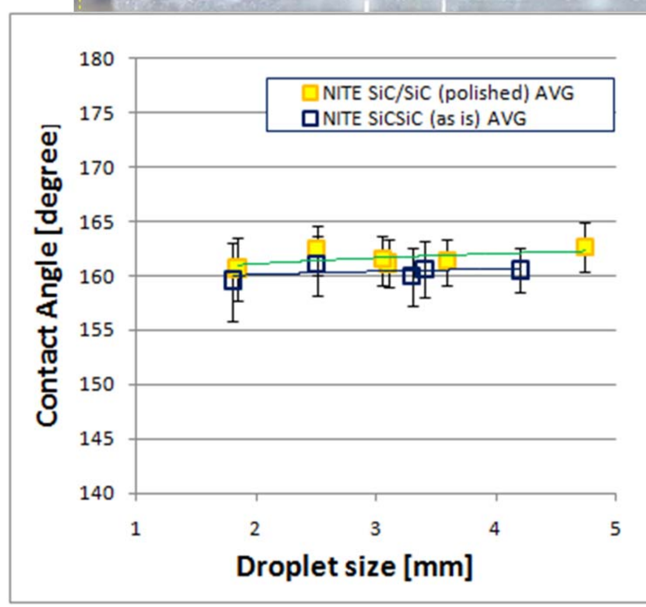
Many small scale tests of PbLi interface effects and diagnostics systems to prepare for high temperature PbLi experiments



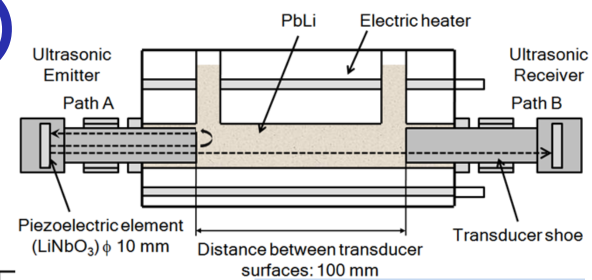


PbLi/SiC Contact Resistance





Example of Lab-scaled Studies (cont'd) Development of molten PbLi acoustic database for UDV diagnostic

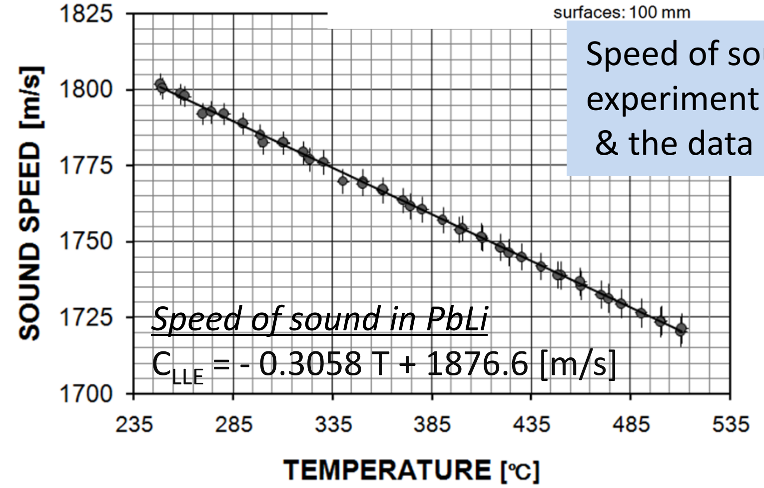


PbLi acoustic database

- Wetting influence on Ultrasonic transmittance at the material interface
- Speed of sound in PbLi

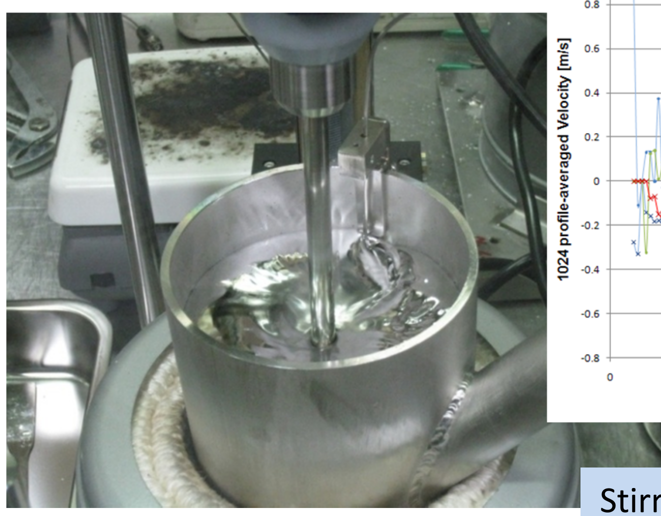
  (necessary for evaluating the velocity and the location)
- Acoustic Impedance

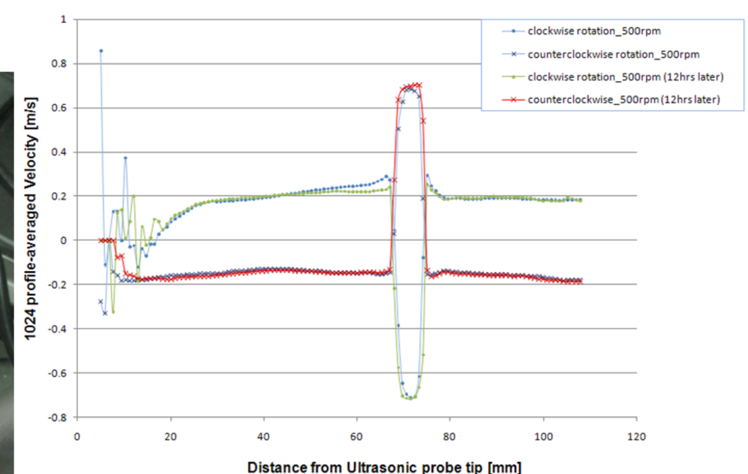
  (acoustic parameter determining the Ultrasonic behaviors at the material interface)
- UDV tracer (fine oxide particle in PbLi) scattering the emitted Ultrasonic in the PbLi flows



Speed of sound experiment & the data

Tests on stirred pots in both Japan and US

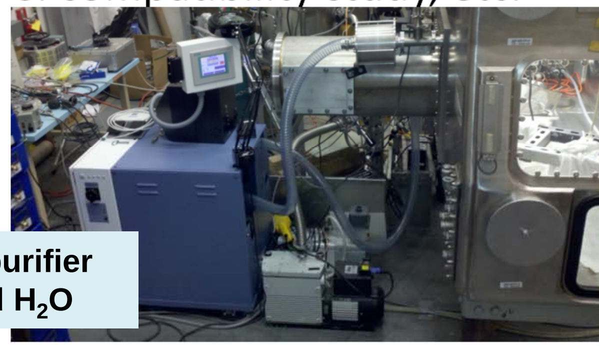


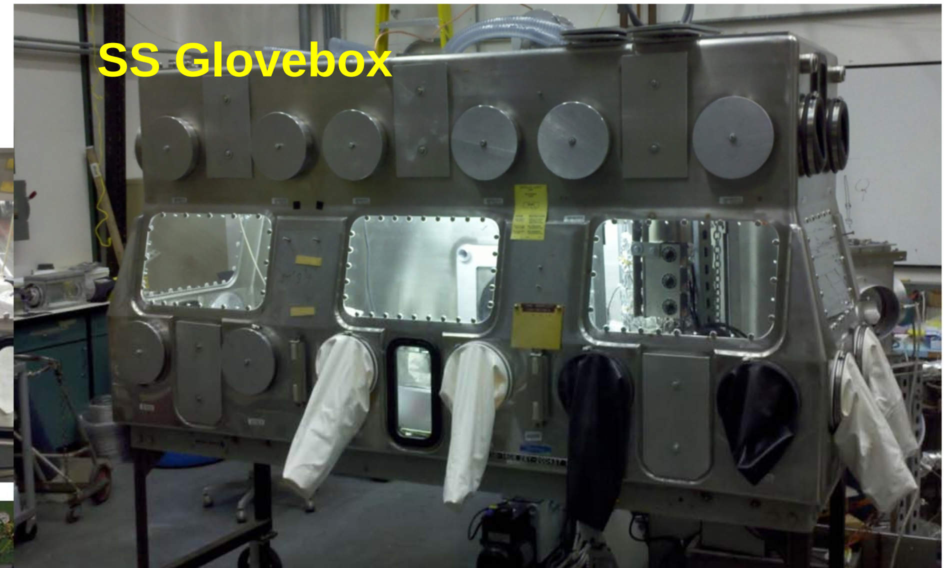


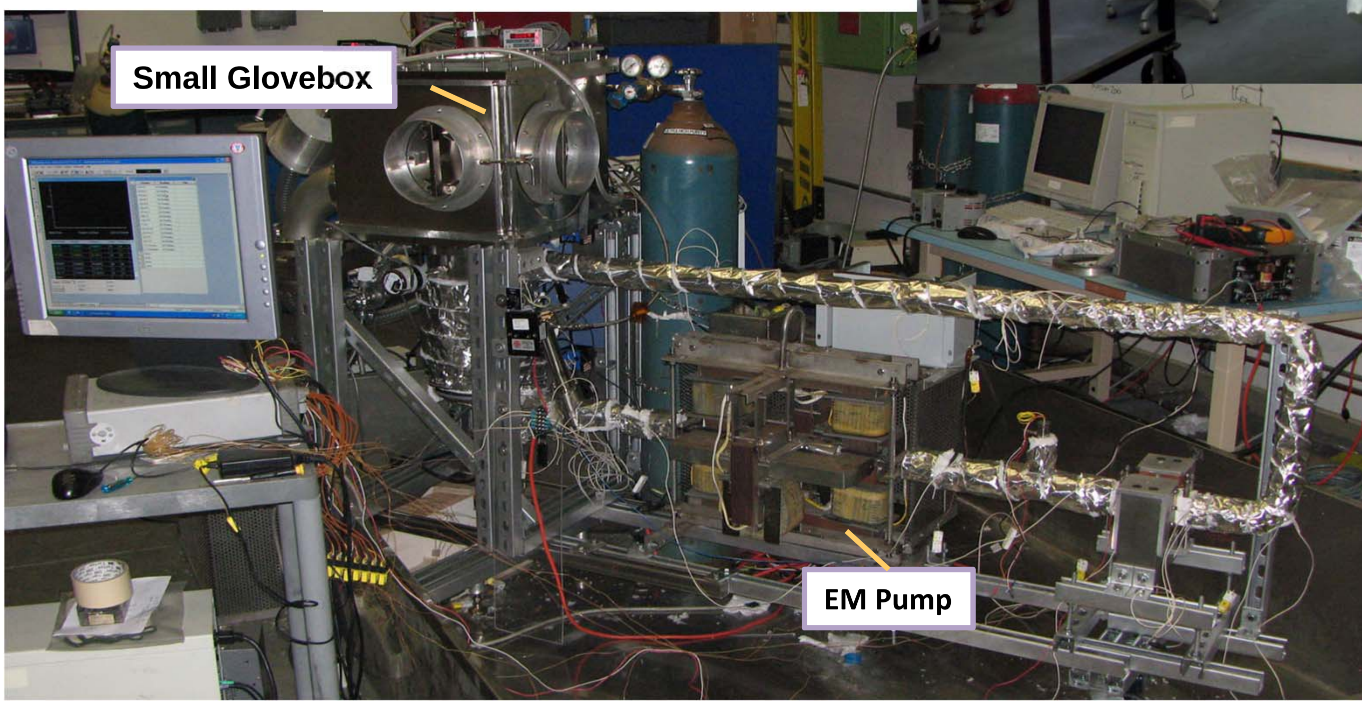
Stirred pot

Experimental MHD flow study using prototypical material PbLi loop at UCLA

Experimental goals :PbLi technology experience, develop and test diagnostics, foam-based SiC FCI compatibility study, etc.







Parameters

Flow rate: up to 0.5 l/s

Magnetic field:
up to 1.7 T

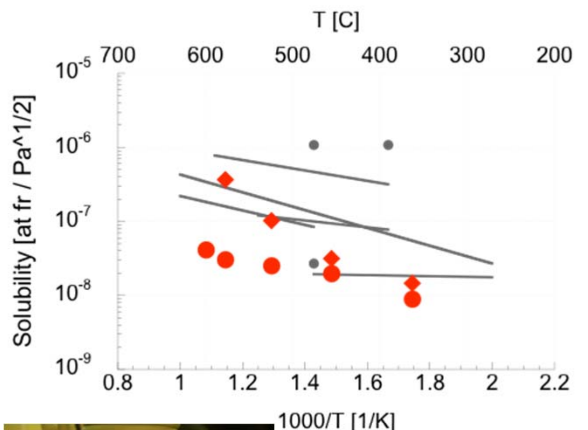
Re: up to 50,000

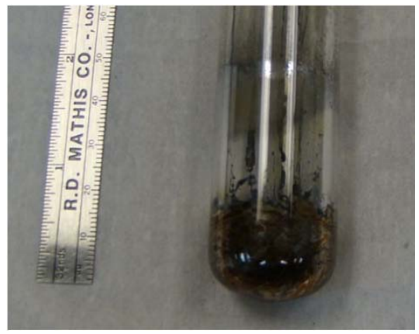
Ha: up to 1000

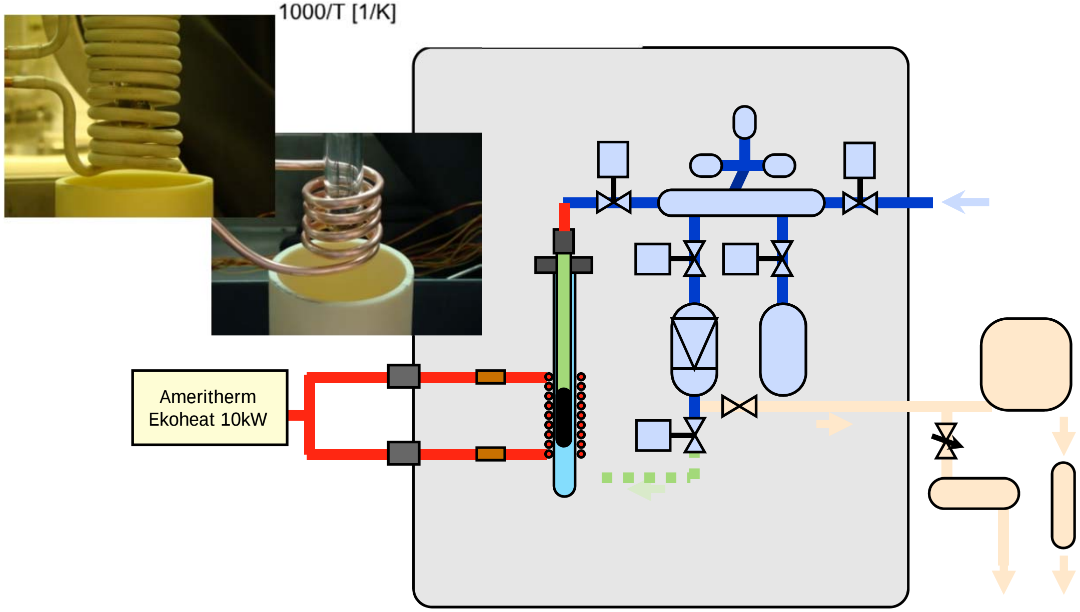
UCLA

Ongoing H_2 and T_2 solubility experiments (Adsorption/desorption system for solubility measurements)

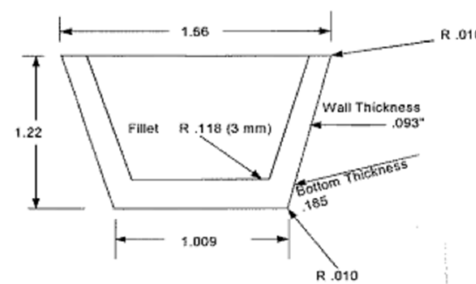
LLE showed evidence of strong interaction in resistive and induction heating configurations with both alumina and quartz crucibles during hydrogen solubility tests







Tritium test configuration:
W crucibles (99.97%, smooth forged)
induction heating



Compatibility of refractory metals and beryllium with molten Pb–17Li

H. Feuerstein *, H. Gräbner, J. Oschinski, S. Horn

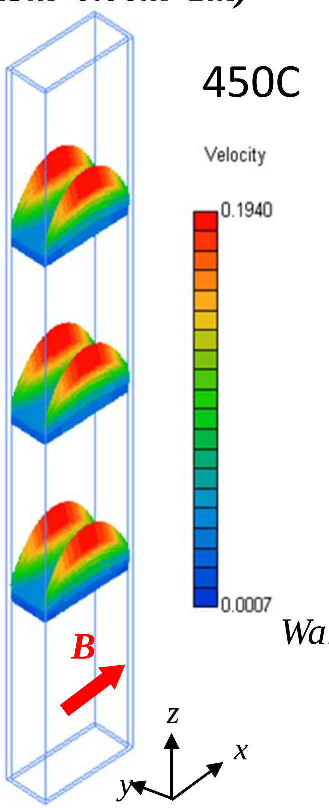
Tritium transport modeling development for LLB

Tritium Convection-Diffusion in PbLi

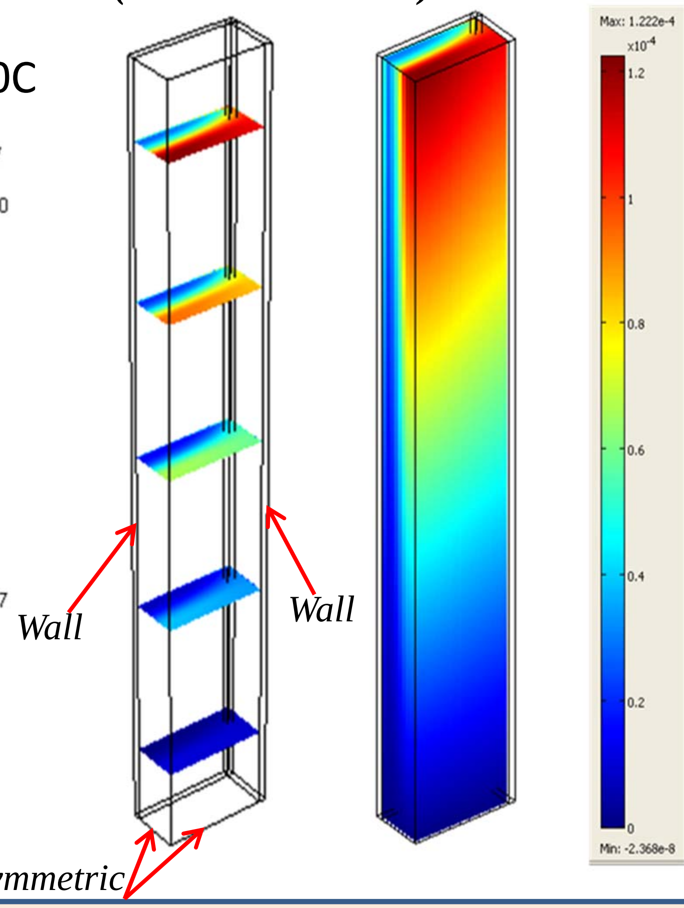
$$\frac{\partial c_1}{\partial t} + \mathbf{u}\nabla c_1 = D_1(T)\nabla^2 c_1 + Q_c(x,y,z)$$

MHD velocity profile

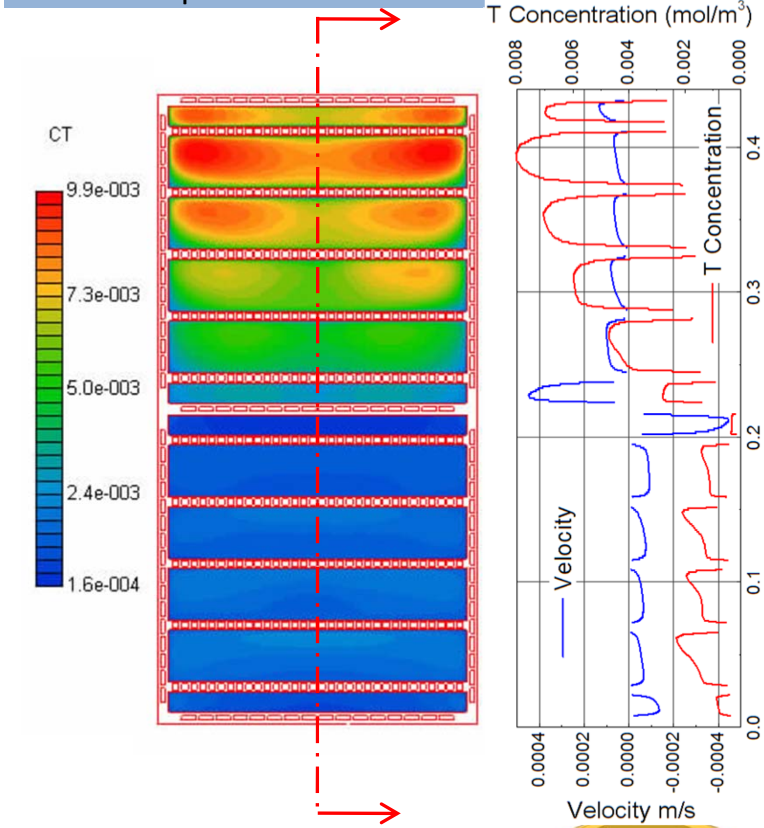
*MHD velocity profile (B=2T, U0=0.07m/s 0.15m*0.06m*1m)*



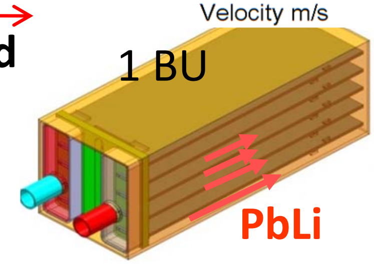
*T concentration in PbLi Quarter of Duct, (0.075m*0.03m*1m)*



HCLL Concepts



2 PbLi BUs analyzed



Lower T concentration near side layer due to locally higher convection effects → Reduced T Permeation

See poster presentation for details

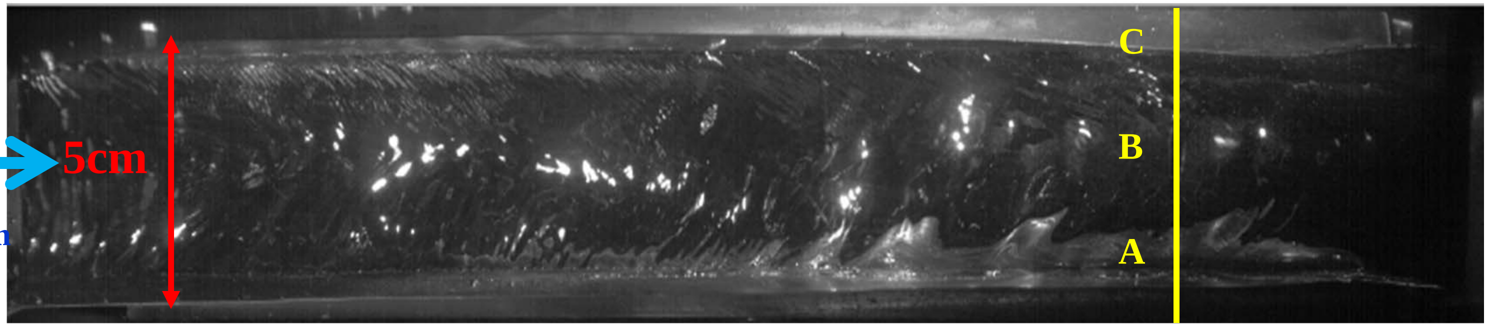
Effects of magnetic fields on free surface LM flow are complicated

Asymmetric surface height variation in the span wise direction

(Decreasing toroidal + locally increasing surface normal fields applied)

2 m/s

2 mm film height

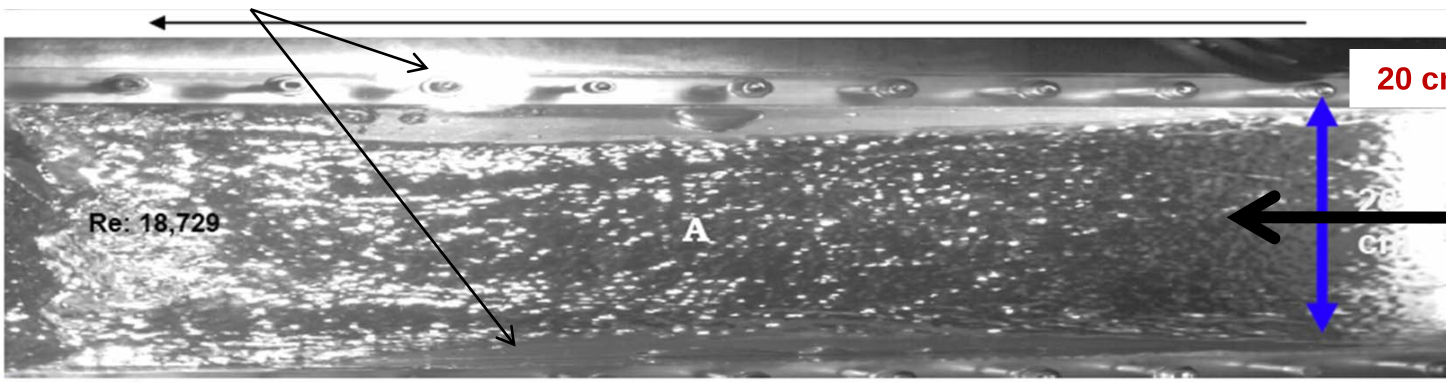


Inductive probe film height at 26cm downstream

A: 6.0mm B: 7.8mm C: 10.0mm

Fast film flow in a surface normal field with gradient shows pinch effect

Pinching off of the walls from self induced MHD interactions



Flow direction

x x x x x x x x

B (into the page, with gradient)

Summary

- **Liquid breeder blanket R&D is on liquid metal PbLi based blankets.** DCLL is selected as an example of a pathway toward higher temperature/higher efficiency but with current generation of ferritic steels.
- **R&D on PbLi blankets covers many important areas: MHD fluid flow / heat transfer / mass transfer modeling and experiments, tritium extraction / transport / permeation / processing, safety, FCI material / component development, radiation effects in FS, integrated modeling**
- **Specifically, thermo-fluid MHD study emphasizes on** understanding **multi-physics, non-linear transport phenomena** associated with **MHD**, heat and mass transfer in flowing liquid breeders in the presence of a space-varying magnetic fields and nuclear heating
- Numerically, improvements are being made in the numerical code (HIMAG) in terms of **enhancing the speed of computation**
    - As an example, Wall function solution is much faster than the normal full simulation. It can be more than 10 times faster; and can use larger time steps (dt=4.0e-2), which makes the speedup closer to 20