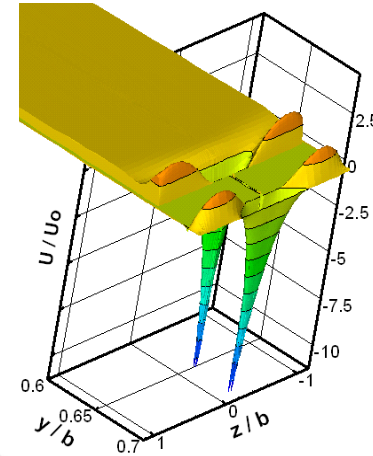
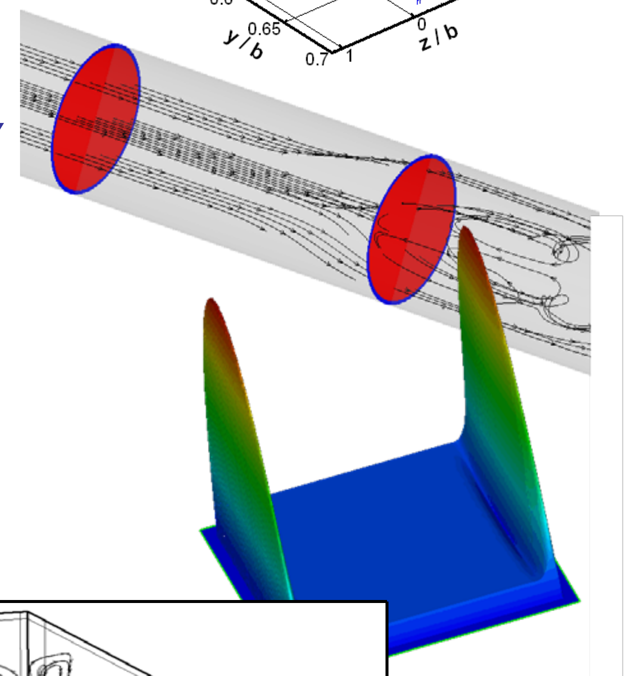
MAGNETOHYDRODYNAMIC EFFECTS IN LIQUID FLOWS



WITH EMPHASIS ON LIQUID METAL FLOW CONTROL IN FUSION ENERGY SYSTEMS



Presented by:

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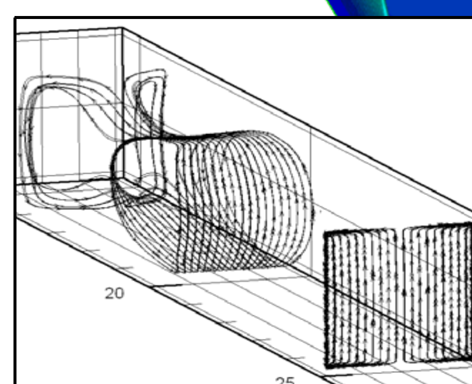

Contributors and sponsors…

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- **R. Munipalli, P. Huang – Hypercomp Inc.**

The support of the *US Department of Energy, Office of Fusion Energy Sciences* for this research is gratefully acknowledged

Outline of Seminar…

- **Introduction to magnetohydrodynamics**
  - What is magnetohydrodynamics? MHD 101
  - Why do we care about MHD? Fusion!
  - Why should you care about MHD?

- **Liquid metal flow and control in distributing/collecting manifolds for fusion**
  - Results of 3D simulations at high magnetic interaction parameter

- **Continuing MHD research and future directions in the UCLA Fusion Science and Technology Center**

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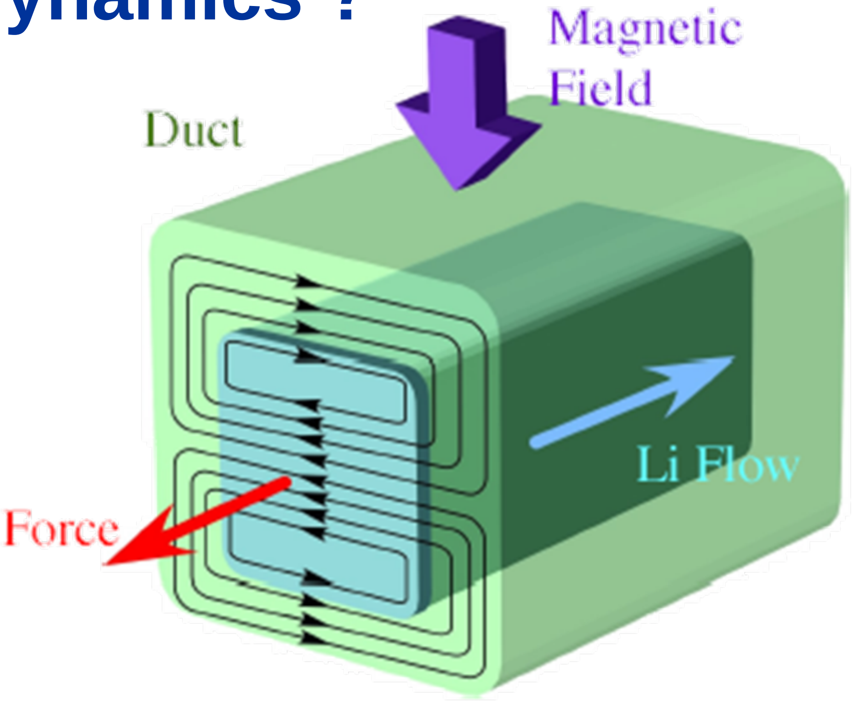
What is magnetohydrodynamics ?



- **Any movement of a conducting material in a magnetic field generates electric currents j, which in turn**
  - induce their own magnetic fields, and
  - Induce j x B forces on the medium known as the *Laplace* or *Lorentz* force.
- ***MHD* describes phenomena in electrically conducting fluids, where the velocity field V, and the magnetic field B, are coupled.**

"The moral is that in MHD one must always be prepared to consider the complete electromagnetic field. The current and magnetic fluxes must have complete paths which may extend outside the region of fluid-mechanical interest into locations whose exact position may be crucial."

J.A. Shercliff "A Textbook of Magnetohydrodynamics", 1965

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An extremely brief history of MHD

- ***Alfvén was the first to introduce the term "MAGNETOHYDRODYNAMICS"***
  - *He described such astrophysical phenomena as an independent scientific discipline.*
  - *The most general name for the field may be*

    "MagnetoFluidMechanics,"

    but the original name

    "Magnetohydrodynamics" or MHD

    is still typically used.

- ***An birth of incompressible fluid MHD is ~1937. Hartmann and Lazarus performed theoretical and experimental studies of MHD flows in ducts.***

- ***Fundamental work by Shercliff (50's-60's), Hunt (60's-70's), Walker (70s-90s), and many others***

Hannes Alfvén (1908-1995), winning the Nobel Prizing for his work on Magnetohydrodynamics

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Incompressible MHD equations

Navier-Stokes equations with the Lorentz force

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \mathbf{g} + \underline{\frac{1}{\rho}\mathbf{j}\times\mathbf{B}}$$

Continuity

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

Energy equation with the Joule heating

$$\rho C_p\left(\frac{\partial T}{\partial t} + (\mathbf{u}\cdot\nabla)T\right) = k\nabla^2 T + q''' + \underline{\frac{j^2}{\sigma}}$$

Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E} \quad \Leftarrow \nabla\cdot\mathbf{B} = 0$$

Ampere's law (Pre-Maxwell)

$$\mathbf{j} = \nabla\times\left(\mathbf{B}/\mu_m\right) \quad \Leftarrow \nabla\cdot\mathbf{j} = 0$$

Ohm's law

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{u}\times\mathbf{B})$$

- 5 equations
- 11 unknowns

- 9 more equations
- 3 more unknowns

B	magnetic field (T)
j	current density (A/m^2)
σ	electrical conductivity ($1/\Omega$.m)
E	electric field (V/m)
μ_m	magnetic permeability (N/A^2)

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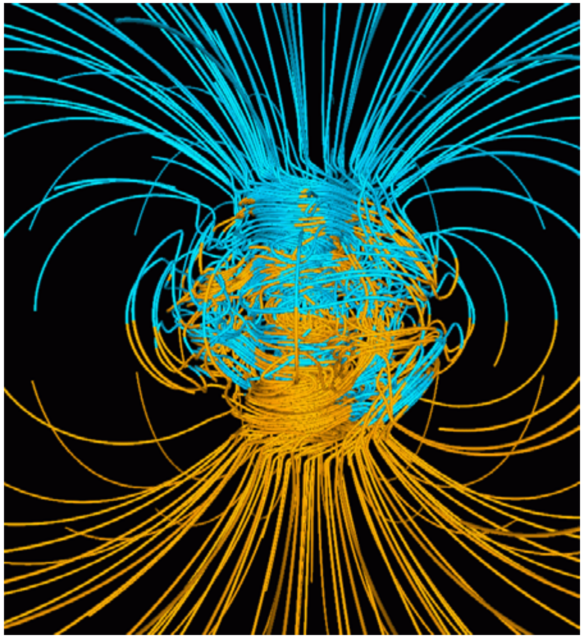
Some incompressible MHD applications

- Astrophysics (planetary magnetic fields)
- MHD pumps (1907)
- MHD generators (1923)
- MHD flow meters (1935)
- Metallurgy (induction furnace and casting of Al and Fe)
- Dispersion (granulation) of metals
- Ship and space propulsion
- Crystal growth
- MHD flow control (reduction of turbulent drag, free surface control, etc.)
- Magnetic filtration and separation
- Jet printers
- Micro-fluidic devices
- Fusion reactors (blanket, divertor, limiter, melt-layers)

GEODYNAMO



A snapshot of the 3-D magnetic field structure simulated with the Glatzmaier-Roberts geodynamo model. Magnetic field lines are blue where the field is directed inward and yellow where directed outward. *Nature*, 1999.

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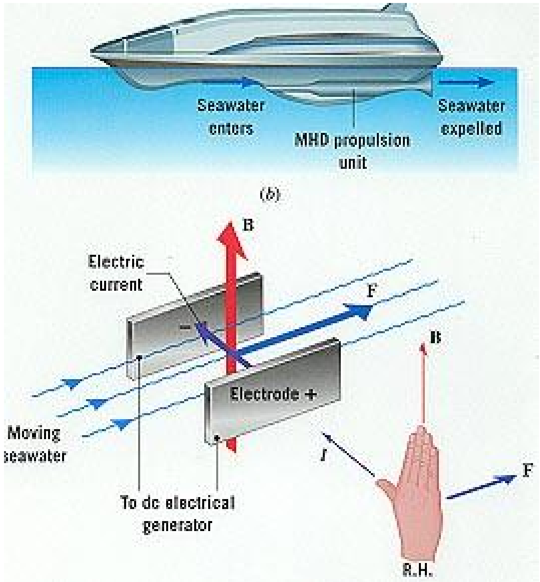
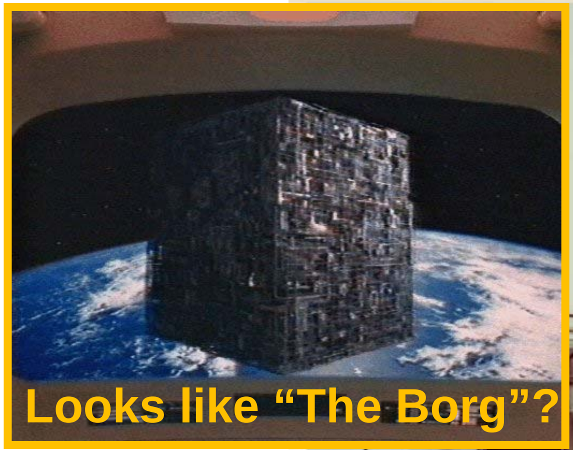
An example of beneficial utilization of MHD: Ship Propulsion

- **In some MHD applications, the electric current is applied to create MHD propulsion force.**
- **An electric current is passed through seawater in the presence of an intense magnetic field. Functionally, the seawater is then the moving, conductive part of an electric motor. Pushing the water out the back accelerates the vehicle.**
- **The first working prototype, the *Yamato 1*, was completed in Japan in 1991.The ship was first successfully propelled 1992. Yamato 1 is propelled by two MHD thrusters that run without any moving parts.**
- **In the 1990s, Mitsubishi built several prototypes of ships propelled by an MHD system. These ships were only able to reach speeds of 15km/h, despite higher projections.**

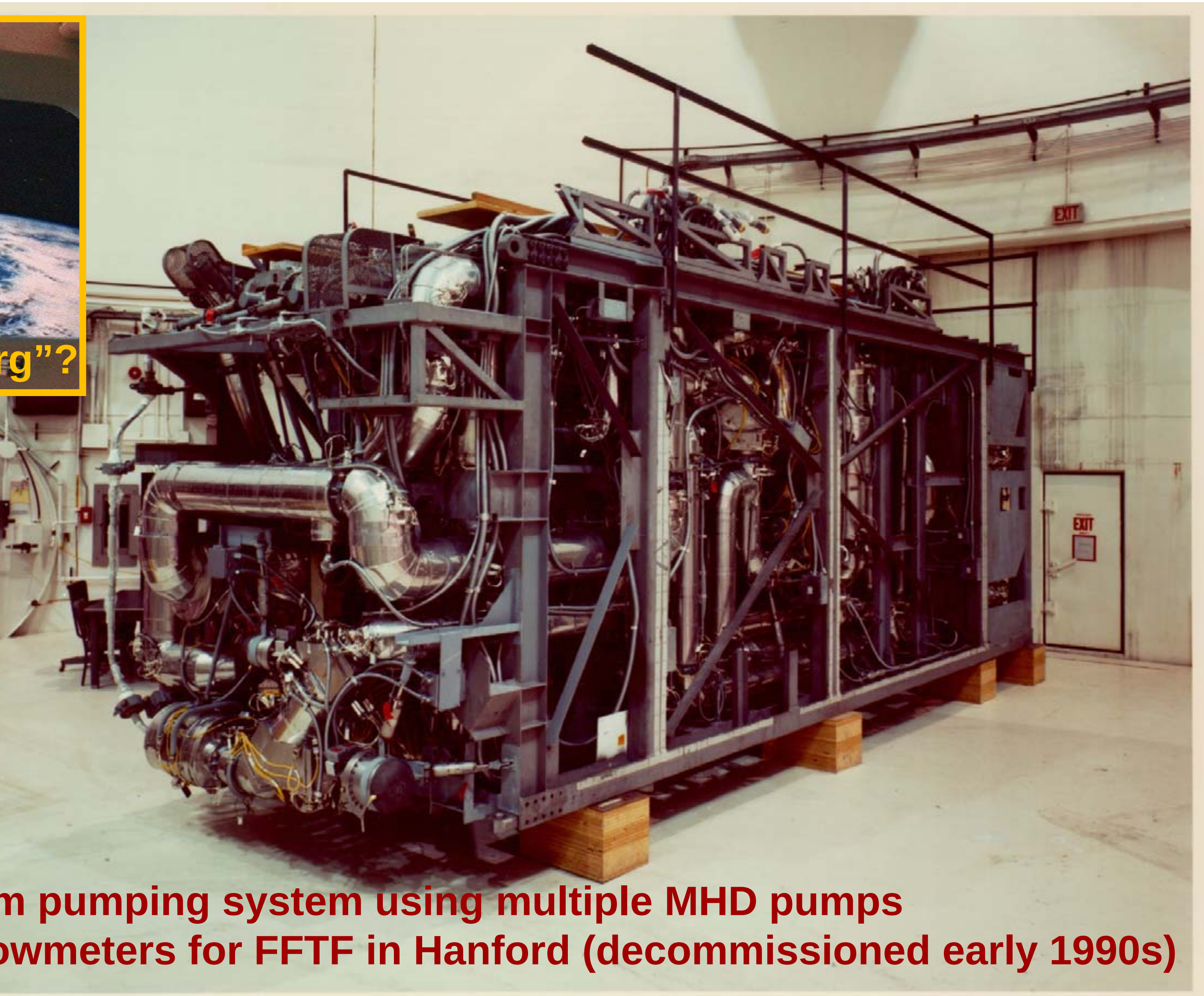


Generation of propulsion force by applying j and B in *Yamato 1* (Mitsubishi, 1991).

Liquid metal MHD pumping, flow measurement, and iron solute control for Fast Reactors



Looks like “The Borg”?



Sodium pumping system using multiple MHD pumps
and flowmeters for FFTF in Hanford (decommissioned early 1990s)

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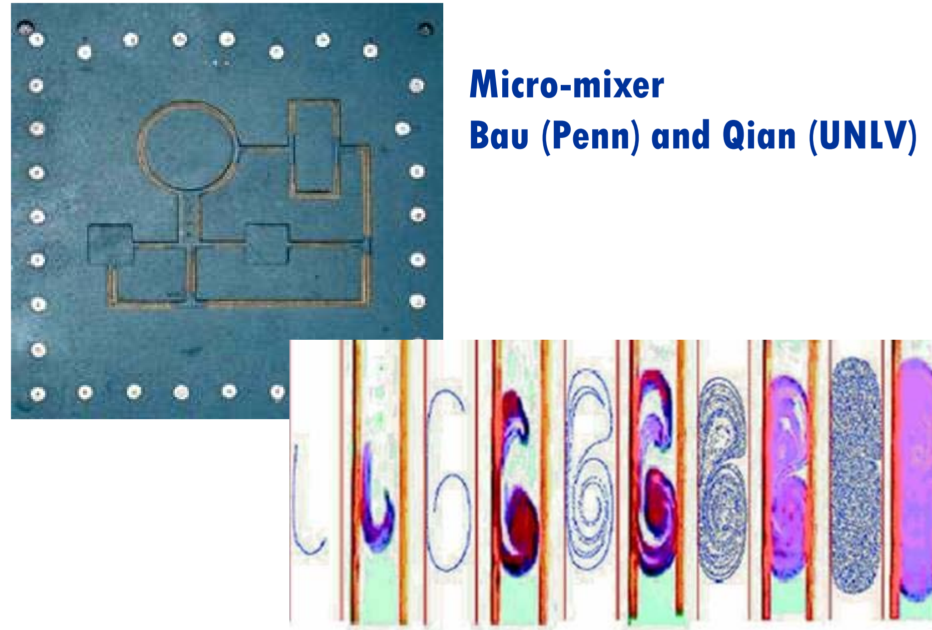
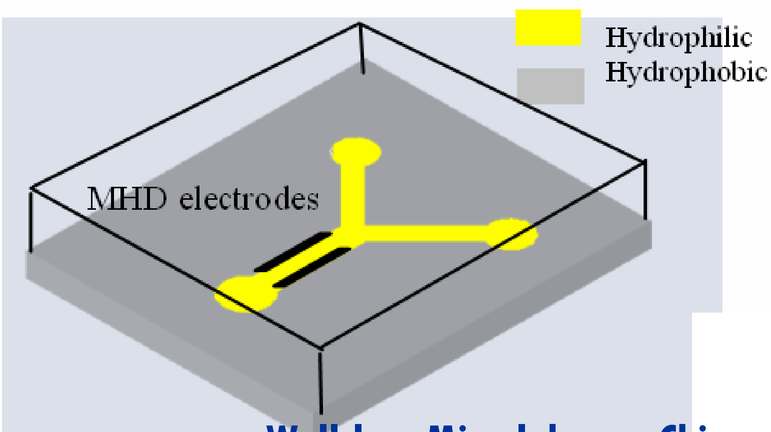
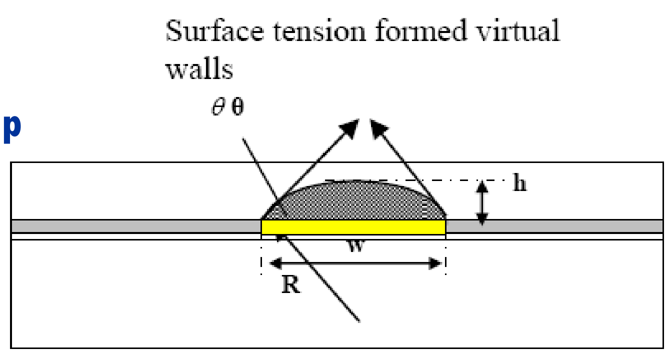
Microfluidic Devices Using MHD pumps and flow control



Micro-mixer
Bau (Penn) and Qian (UNLV)

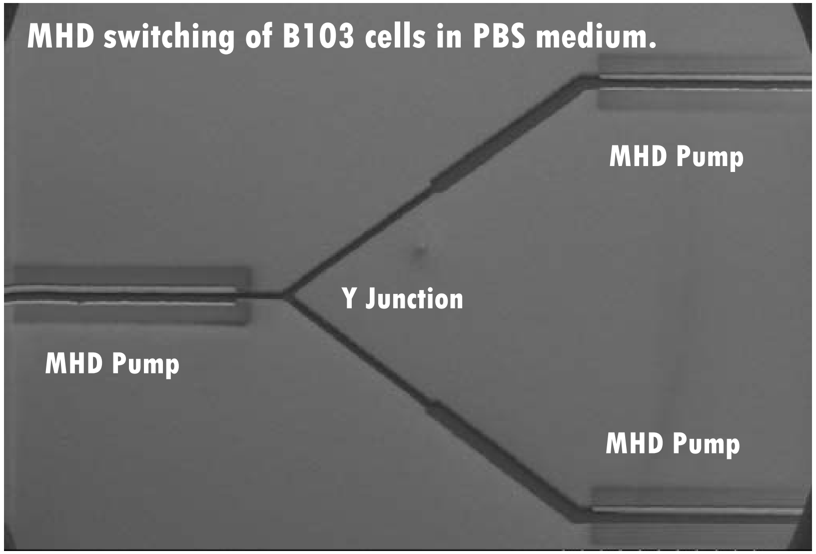


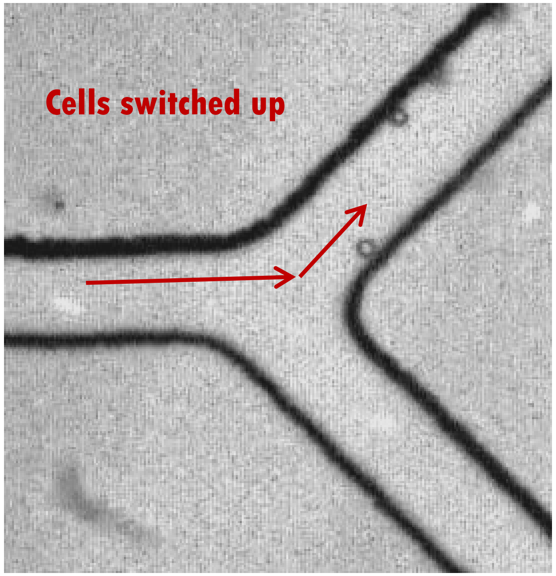
Wall-less Microlab on a Chip
Lee (UCI) and Wang (UCB)

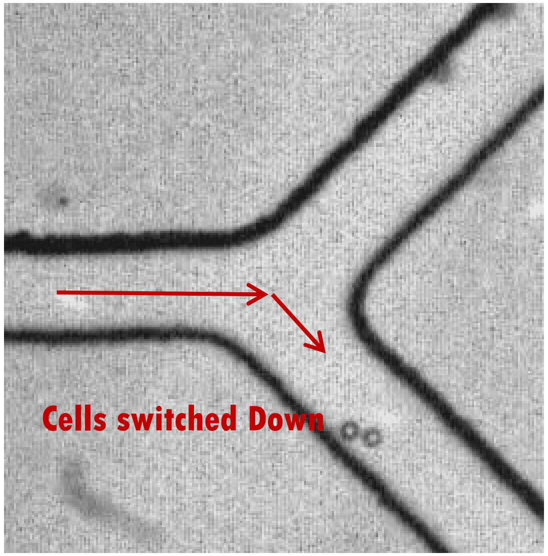


Fast MHD flow control switching in bio-fluidic cell sorting

- **MHD pumps can immediately change the flow pattern by switching the local electrical fields within the microchannels**







- **This instant switching can be extremely useful for high purity cell sorting experiments.**

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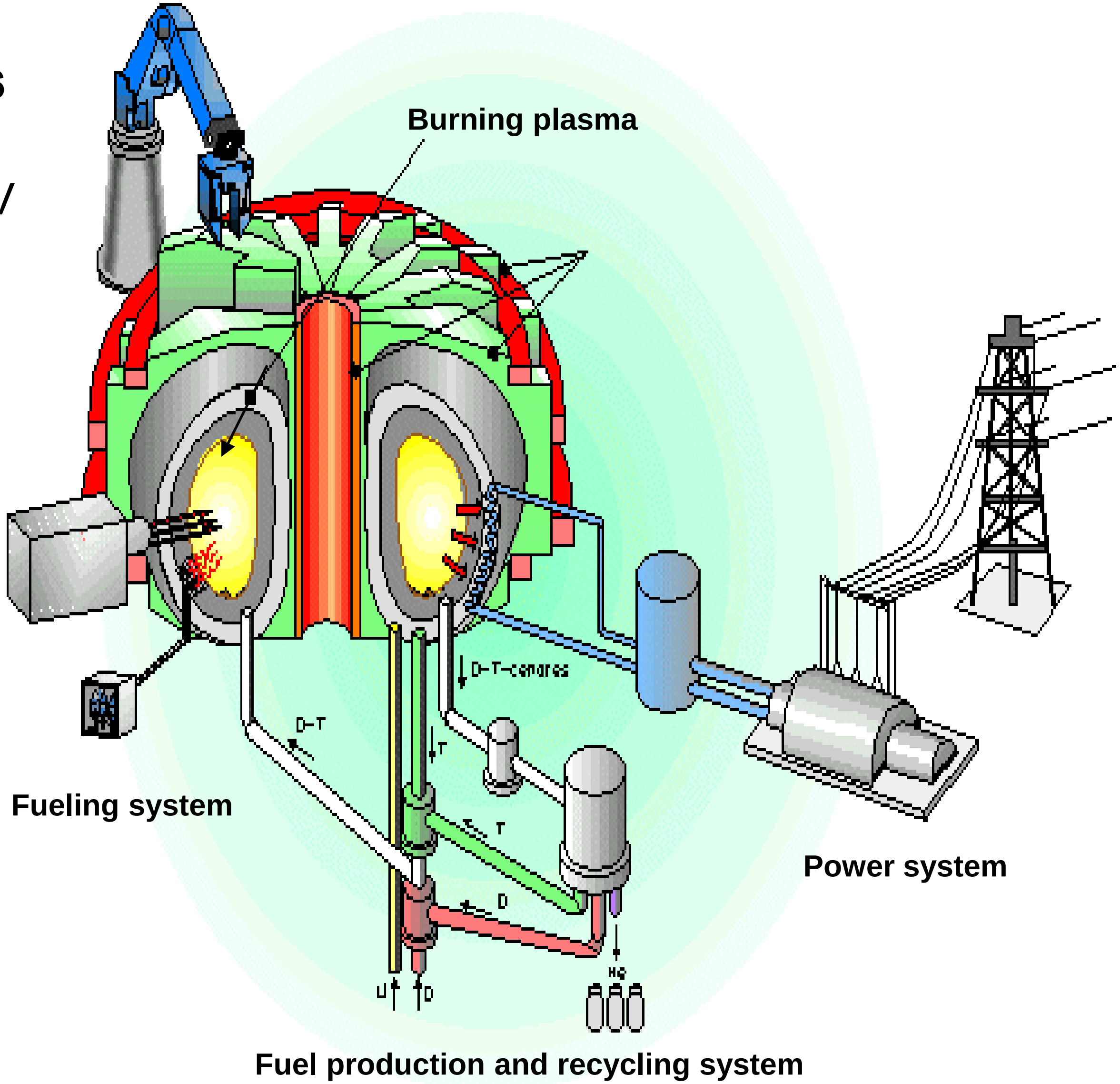
Magnetic-Confinement Fusion Energy

- **Strong magnetic fields used to confine**
  $D + T \Rightarrow \alpha + n + 17.5\ \mathrm{MeV}$
  plasma in toroidal vessel (~8 T on axis)

- **Fusion neutrons captured in the lithium containing "blanket" to:**
  - ✓ extract high grade heat
  - ✓ produce tritium supply by Li(n,α)T reaction
  - ✓ provide shielding



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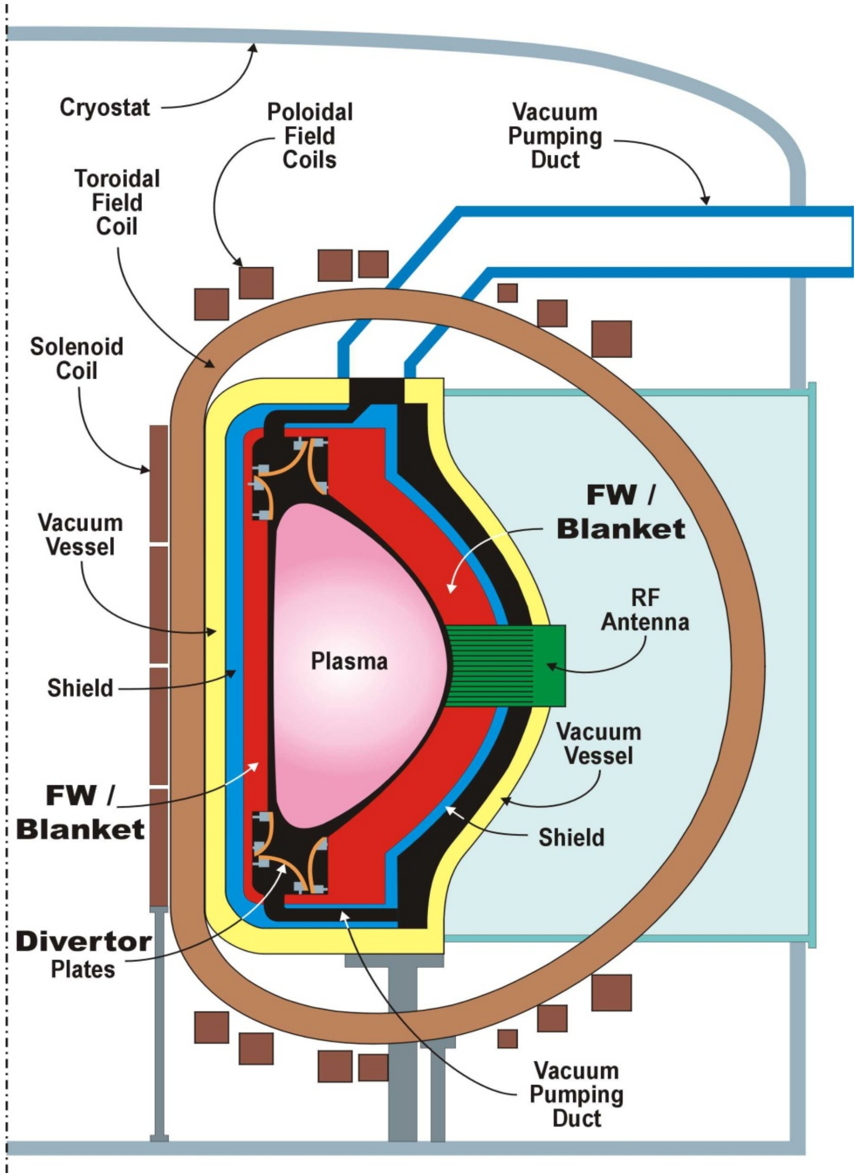
Fusion Reactor Cross-Section, showing nuclear components

- **Blanket/First wall surrounds most of the plasma, with penetrations for various plasma maintenance systems**
- **One blanket system option is to use liquid metal alloy containing Lithium as both breeder and coolant (Li, Li-Pb, Li-Sn)**
- **Blanket is in the same strong magnetic field used to confine the plasma, so MHD effects in a liquid metal blanket are important! Even dominant!**



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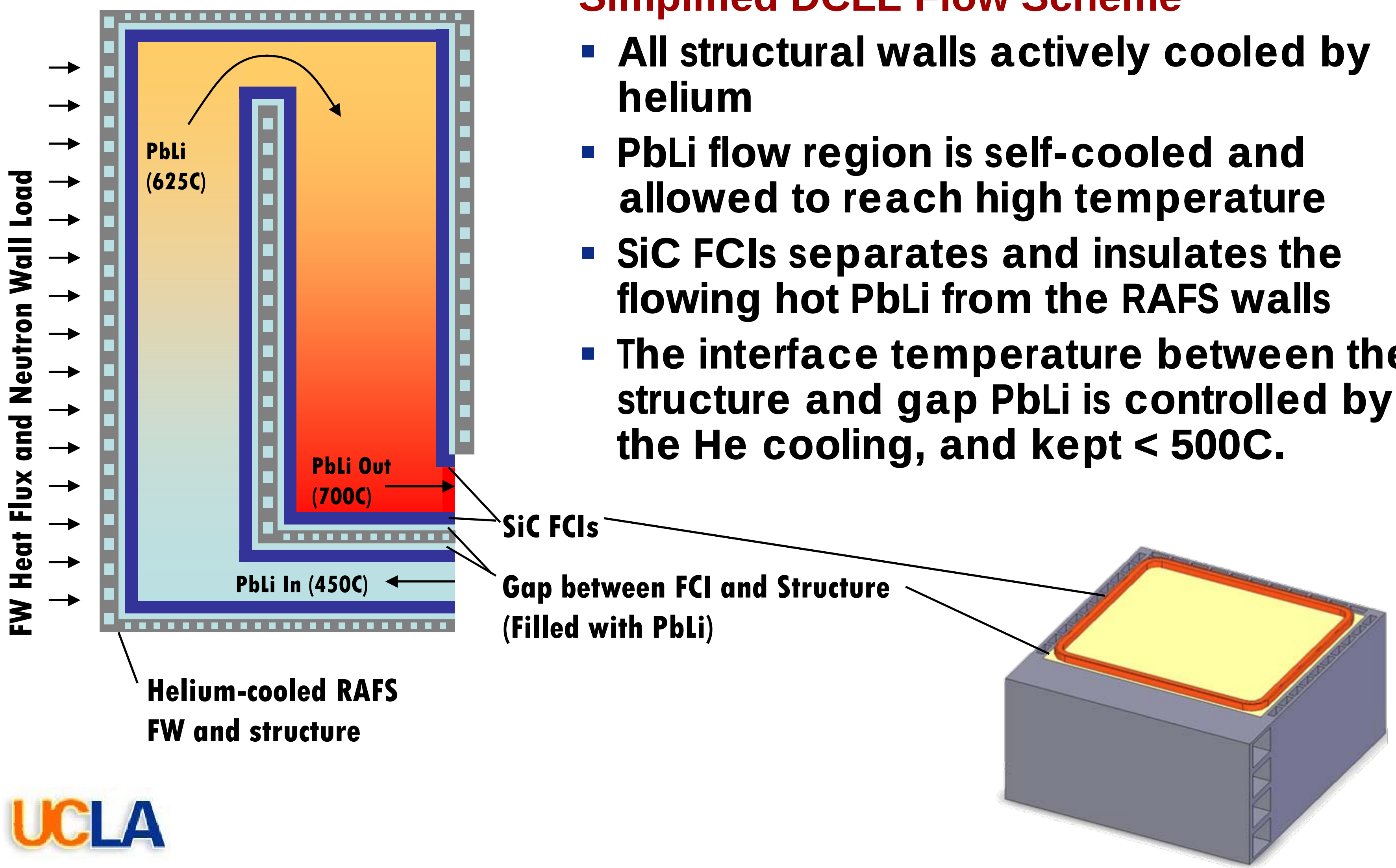
Main blanket option in the US
The Dual-Coolant Lead-Lithium (DCLL) system



Simplified DCLL Flow Scheme

- **All structural walls actively cooled by helium**
- **PbLi flow region is self-cooled and allowed to reach high temperature**
- **SiC FCIs separates and insulates the flowing hot PbLi from the RAFS walls**
- **The interface temperature between the structure and gap PbLi is controlled by the He cooling, and kept < 500C.**

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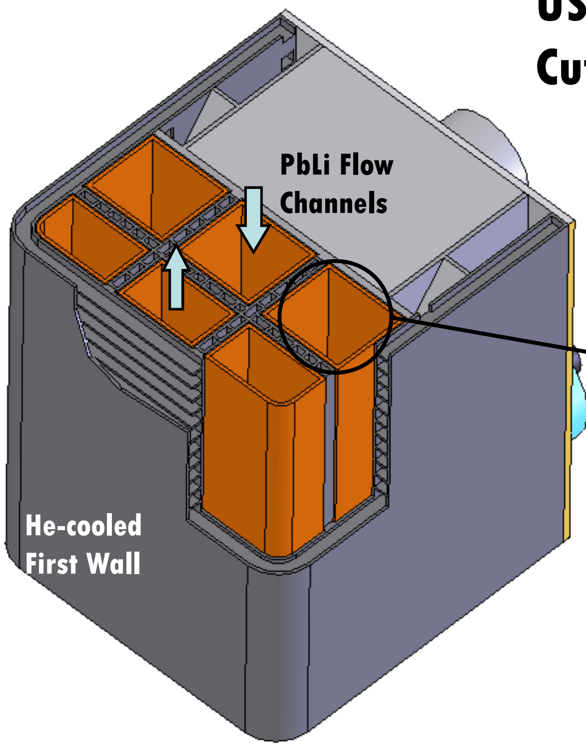
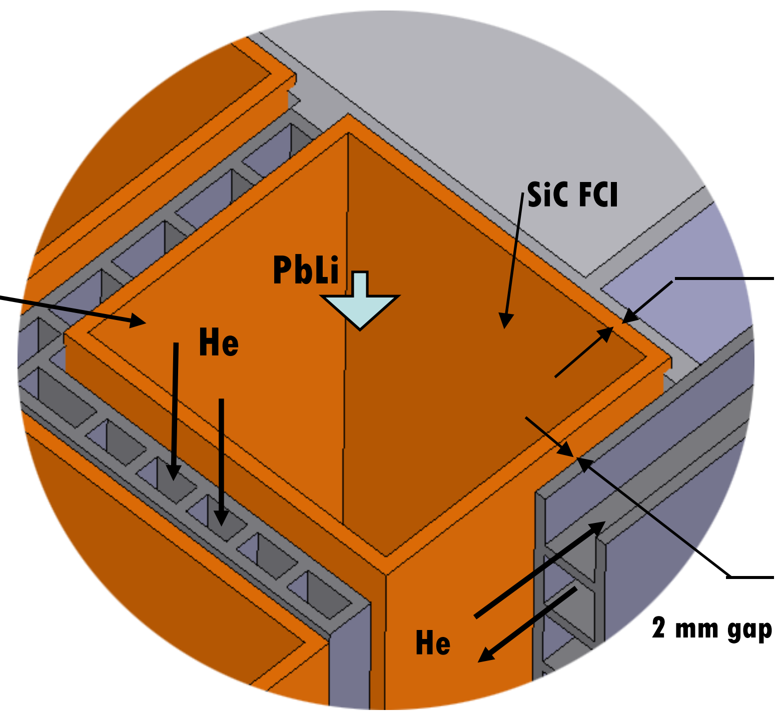
Why is the US (and UCLA) interested in the DCLL?

- DCLL offers a pathway to high outlet temperature and efficiency – Materials issues more tractable!
- We want to test the DCLL in ITER, but we first need to address the MHD issues

US DCLL Test Blanket for ITER – Cutaway Views





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Basic scaling parameters and typical simplifications for LM blanket systems

Reynolds number

$$\mathrm{Re} = \frac{Inertia\ \ forces}{Viscous\ \ forces} = \frac{U_0 L}{\nu}$$

Hartmann number

$$Ha \equiv M = \left(\frac{Electromagnetic\ \ forces}{Viscous\ \ forces} \right)^{1/2} = B_0 L \sqrt{\frac{\sigma}{\nu\rho}}$$

Magnetic Reynolds number

$$\mathrm{Re}_m = \frac{Convection\ of\ \mathbf{B}}{Diffusion\ of\ \mathbf{B}} = \frac{Induced\ \ field}{Applied\ \ field} = \frac{U_0 L}{\nu_m} = \mu_0 \sigma U_0 L$$

Stuart number (or Interaction parameter)

$$N \equiv St = \frac{Electromagnetic\ \ forces}{Inertia\ \ forces} = \frac{Ha^2}{\mathrm{Re}} = \frac{\sigma B_0^2 L}{\rho U_0}$$

- **$\mathrm{Re}_m << 1$**
  Induced magnetic field is small compared to applied field, $B \approx B_{applied}$

  &

  Electric field can be expressed as gradient of a potential, $E = -\nabla\phi$

- **$Ha/\mathrm{Re} > 0.005$**
  Core Flow is generally laminar

Incompressible MHD equations

Navier-Stokes equations with the Laplace force

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \mathbf{g} + \frac{1}{\rho}\mathbf{j}\times\mathbf{B}_a$$

Continuity

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

Energy equation with the Joule heating

$$\rho C_p\left(\frac{\partial T}{\partial t} + (\mathbf{u}\cdot\nabla)T\right) = k\nabla^2 T + q''' + \frac{j^2}{\sigma}$$

- **5 equations**
- **8 unknowns**

Ohm's law

$$\mathbf{j} = \sigma(-\nabla\phi + \mathbf{u}\times\mathbf{B}_a)$$

Conservation of current

$$\nabla\cdot\mathbf{j} = 0 \;\Rightarrow \nabla\cdot\sigma\nabla\phi = \nabla\cdot\sigma(\mathbf{u}\times\mathbf{B}_a)$$

- **4 more equations**
- **1 more unknown**

$\mathbf{B}_a$ applied magnetic field (T)

$\mathbf{j}$ current density (A/m^2)

σ electrical conductivity (1/Ω.m)

ϕ electric potential(V)

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Dimensionless Incompressible MHD equations

Navier-Stokes equations with the Laplace force

$$\frac{1}{N}\left(\frac{\partial \mathbf{u}}{\partial t}+(\mathbf{u}\cdot\nabla)\mathbf{u}\right)=-\nabla p+\frac{1}{Ha^2}\left(\nabla^2\mathbf{u}\right)+\mathbf{j}\times\mathbf{B}_a$$

Continuity

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

Ohm's law

$$\mathbf{j}=(-\nabla\phi+\mathbf{u}\times\mathbf{B}_a)$$

Conservation of current

$$\nabla\cdot\mathbf{j}=0 \quad \Rightarrow \nabla\cdot\nabla\phi=\nabla\cdot\left(\mathbf{u}\times\mathbf{B}_a\right)$$

- **For large N and Ha, one tends to get flows where**

$$\nabla p=\mathbf{j}\times\mathbf{B}_a$$

in a core region, with a large pressure drop that scales like

$$\nabla p\approx k\sigma UB^2$$

p^* **L** σ**UB²**

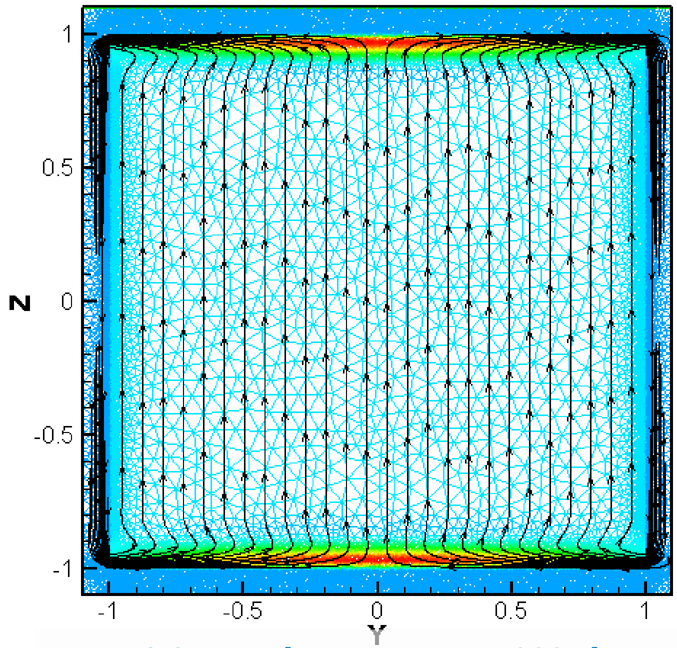
j^* σ**UB**

ϕ^* **LUB**

HyPerComp, Inc.
Leader in High Performance Computing

HIMAG Capability Summary

- **HIMAG is a parallel, unstructured mesh-based MHD solver.**
- **High accuracy at high Hartmann numbers is maintained even on non-orthogonal meshes**
- **HIMAG can model single-phase as well as two-phase (free surface) flows**
- **Multiple conducting solid materials may be present in the computational domain**
- **Heat transfer, natural convection, temperature dependent properties can be modeled (validation continues)**



HIMAG 2D simulation at Ha = 1000 showing good accuracy and current conservation on triangular mesh

- **Extensive validation and benchmarking has been performed for canonical problems. Cases involving Ha > 1000 have never been demonstrated on non-rectangular meshes**

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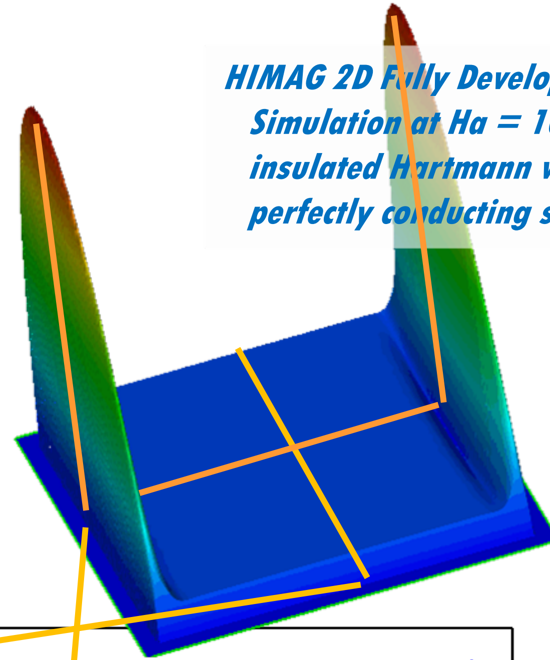
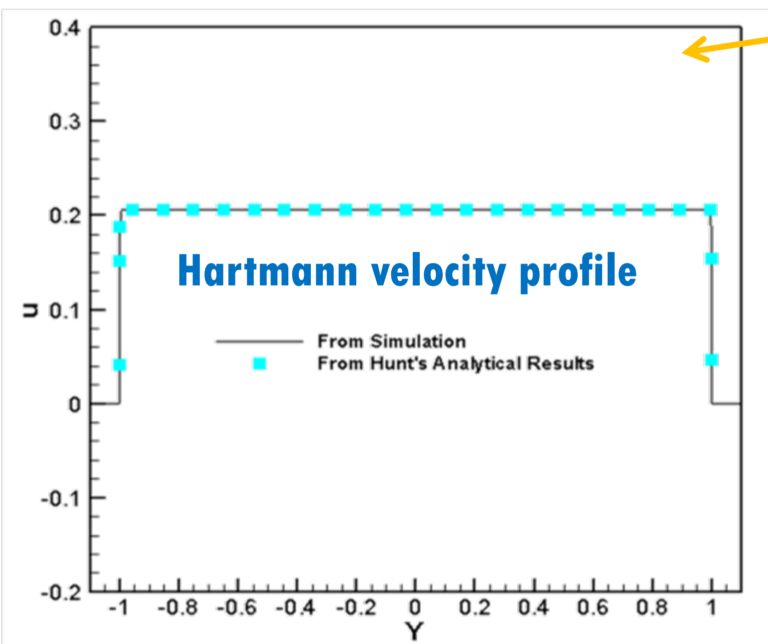
Typical Features of MHD Channel Flows at high Ha and N,

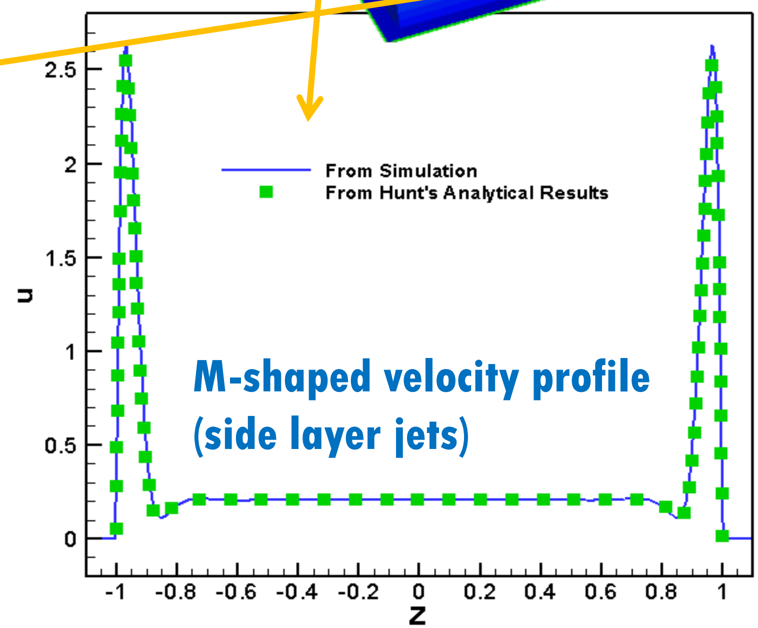
Viscous and inertial effects confined to thin layers

HIMAG 2D Fully Developed Flow Simulation at Ha = 1000, with insulated Hartmann walls and perfectly conducting side walls.



- **Hartmann layer on all walls with a perpendicular component of B, thickness Ha^{-1}**

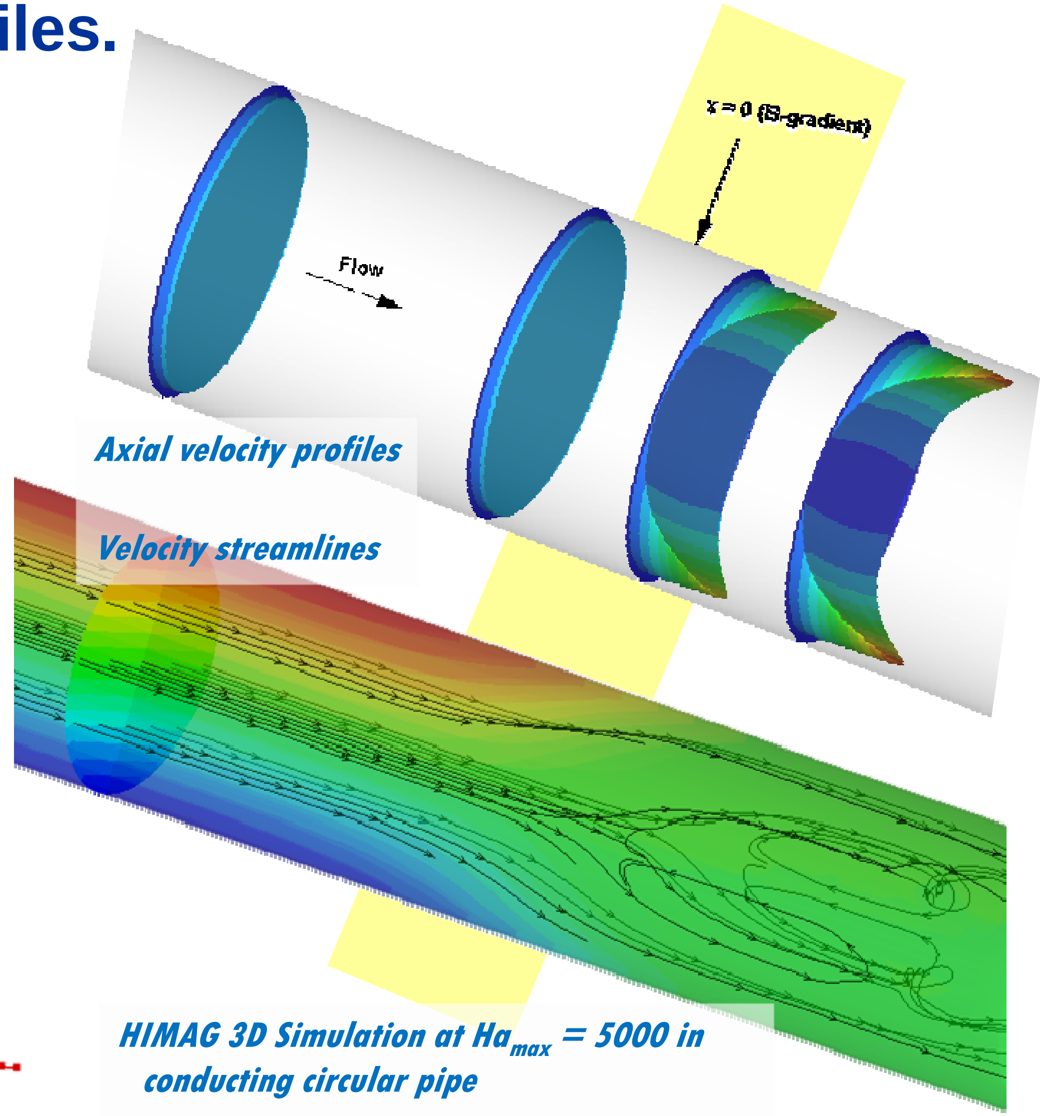




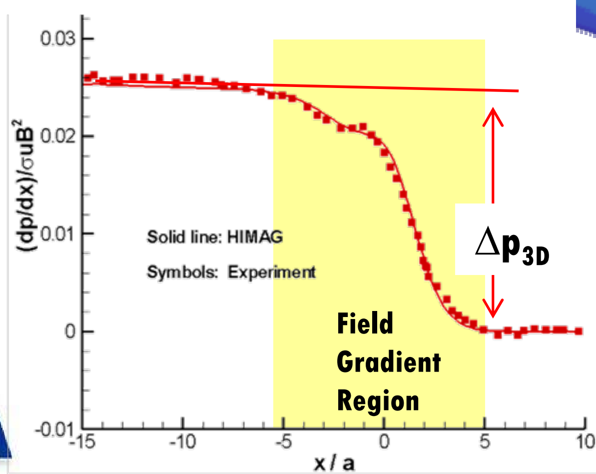
- **Side (Shercliff) layers on walls parallel to B, thickness scales like $Ha^{-1/2}$ and magnitude Ha*cw**

Complex geometry and spatially non-uniform magnetic field MHD flows also trigger 3D effects and M-shaped velocity profiles.

- *The distinctive feature is* ***axial current loops****, which are responsible for extra MHD pressure drop and M-shaped velocity profiles… 3D flow*
- *Such problems are very difficult for analytical studies.*



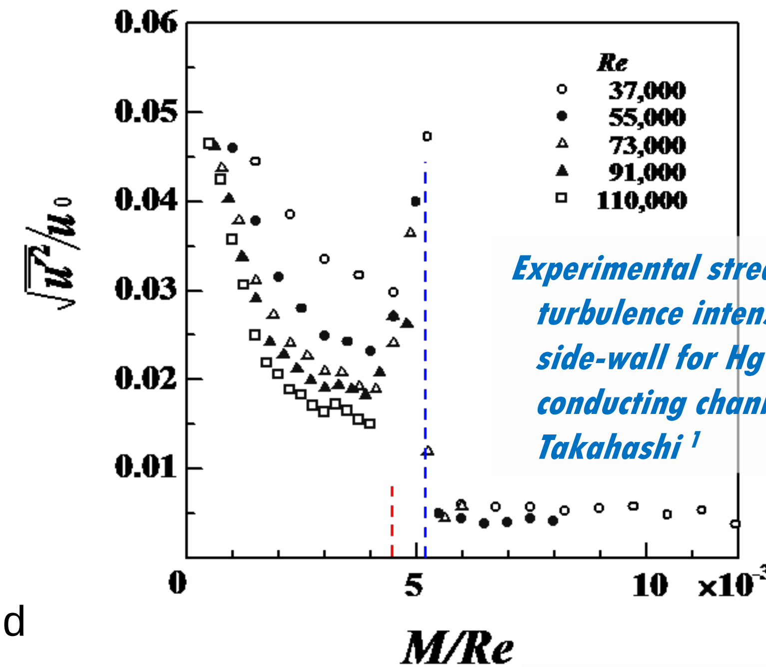
HIMAG 3D Simulation at Ha_{max} = 5000 in conducting circular pipe



(comparison against ANL experiment)

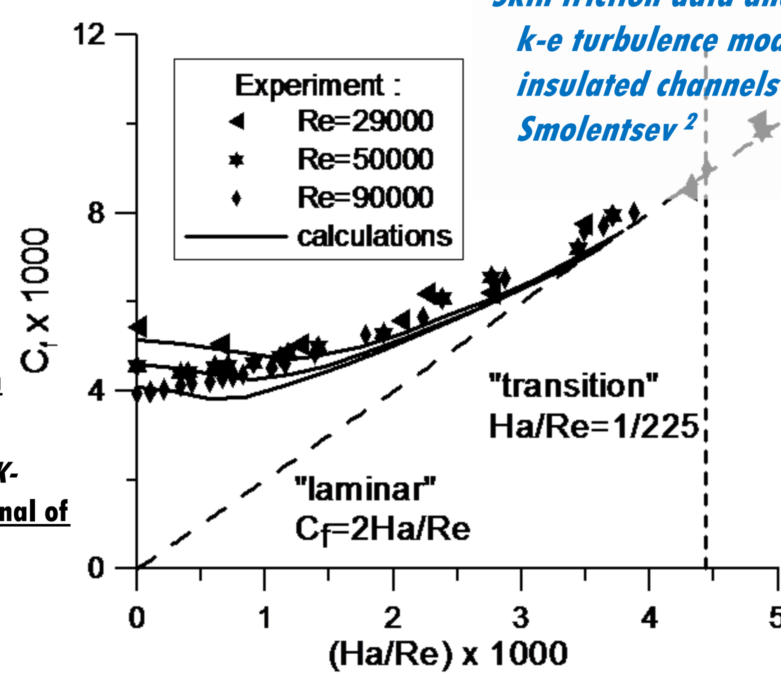
MHD effects modify turbulence, instabilities, and scalar transport

- Radically altered velocity profiles change the source terms for turbulence generation
- Strong energy dissipation via Joule heating competes with turbulence production leading to new turbulence phenomena like quasi-Laminarization and turbulence two-dimensionalization
- Interactions of MHD with buoyancy forces resulting from peaked nuclear heating can drive convection cells and modify thermal transport in ways similar to turbulence



Experimental streamwise turbulence intensity near side-wall for Hg in a conducting channel from Takahashi [1]

Skin friction data and fit to k-e turbulence model in insulated channels from Smolentsev [2]



[1] N. B. Morley, S. Smolenstev, L. Barleon, I. Kirillov, M. Takahashi, *Liquid Magnetohydrodynamics: Recent work and future directions for fusion*, Fusion Engineering and Design, 51-52, 701-713 (2000).

[2] S. Smolentsev, M. Abdou, N. Morley, A.Ying, T. Kunugi, *Application of the K-epsilon Model to Open Channel Flows in a Magnetic Field*, International Journal of Engineering Science, 40, 693-711 (2002).

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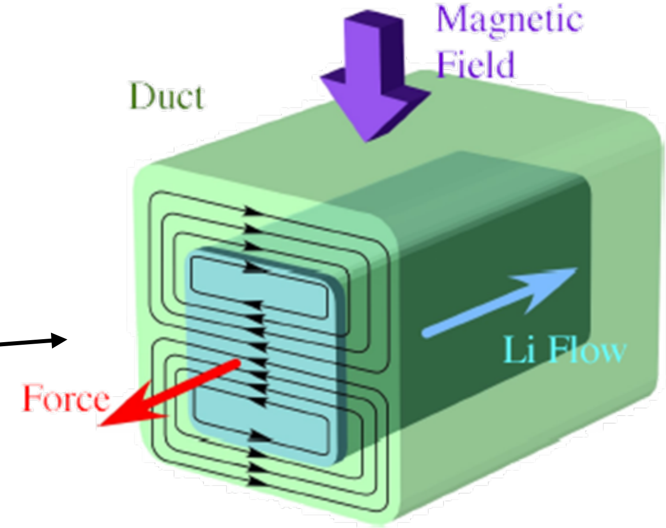
Main Issues for LM Blankets:

Very high pressure drop for electrically conducting ducts and complex geometry flow elements – in general *insulators* are needed for fusion

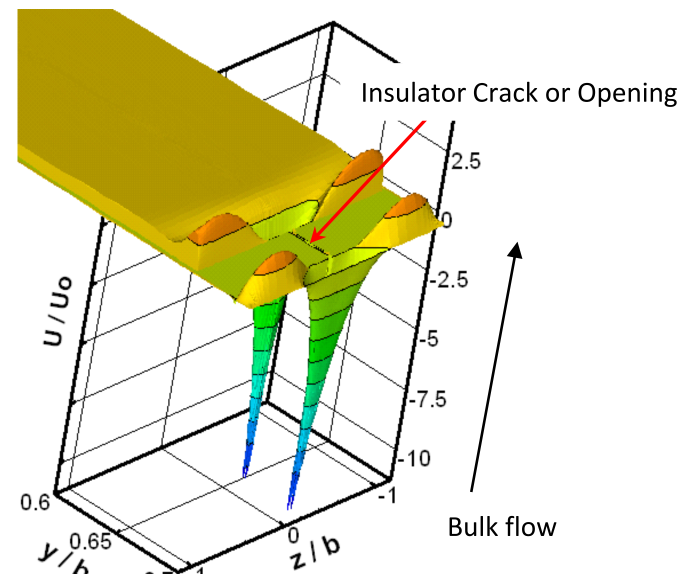
- Unbalanced pressure drops will affect flow distribution between parallel elements fed from a common manifold – flow control is an issue



$$\nabla p \approx \sigma U B^2 \approx (10^6)(10^{-1})(10)^2 \approx 10\,\text{MPa/m}$$

The impact that MHD velocity profiles on the *thermal performance* can be strong.

- Typical MHD velocity profiles in ducts with conducting walls include the potential for very large velocity jets near or in shear layers that form parallel to the magnetic field.
- In channels with insulators these reversed flow regions can also spring up near local cracks.
- Turbulence is reduced or re-oriented with vorticity along field lines



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

S. Smolentsev, N. Morley, M. Abdou, *MHD and Thermal Issues of the SiCf/SiC Flow Channel Insert*, Fusion Science and Technology, 50, 107-119 (2006).

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Current/Recent work in the UCLA Fusion Science and Technology Center

- **Studying MHD effects on…**
  - LM flow and heat transfer in multi-material (e.g. structure, insulators, coolants) closed channels with internal heating
  - LM flows in complex shaped manifolds
  - Electrolyte and molten salt turbulence structure and turbulent heat transfer (Low Ha but high Pr fluids)
  - Free surface film flows on an inclined planes or melted/driven by plasma surface heating or electric current coupling
  - Formation and transport of microbubbles
- **3D finite volume, Lattice Boltzmann, VOF and Level-Set MHD simulation tool development**
- **2 and 3D research codes and models for mixed convection, instabilities, and quasi-2D Turbulence**
- **Experiments in the Magneto-ThermOfluid Research (MTOR) lab on the 1st floor**

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Details available in recent published papers

(MHD specific papers since 2006)

1. N. B. Morley, M.-J. Ni, R. Munipalli and M. A. Abdou, MHD Simulations Of Liquid Metal Flow Through a Toroidally-Oriented Manifold, Fusion Engineering and Design, To appear 2008.
2. M-J Ni, R. Munipalli, N.B. Morley, P. Huang, M.A. Abdou, *Consistent and Conservative Schemes for Incompressible MHD Flow at a Low Magnetic Reynolds Number, Part I: On a Rectangular Collocated Grid System*, Journal of Computational Physics, To appear 2007.
3. M-J Ni, R. Munipalli, N.B. Morley, P. Huang, M.A. Abdou, *Consistent and Conservative Schemes for Incompressible MHD Flow at a Low Magnetic Reynolds Number, Part II: On an Arbitrary Collocated Grid System*, Journal of Computational Physics, To appear 2007.
4. M.J. Pattison, K.N. Premnath, N.B. Morley, *Progress in Lattice Boltzmann Methods for Magnetohydrodynamic Flows in Fusion Applications*, Fusion Science and Technology, To appear 2007.
5. T. Yokomine, H. Nakaharai, J. Takeuchi, T. Kunugi, S. Satake, N B Morley, M A Abdou, *Experimental Investigation of Turbulent Heat Transfer of High Prandtl Number Fluid Flow under the Strong Magnetic Fie*ld, Fusion Science and Technology, To appear 2007.
6. M.-J. Ni, R. Munipalli, N.B. Morley, P. Huang, S. Smolentsev, S. Aithal, A. Ying, M. A. Abdou, Validation strategies in MHD computations for fusion application, Fusion Science and Technology, To appear 2007.
7. J. Takeuchi, S. Satake, T. Kunugi, T. Yokomine, N B Morley, M A Abdou, Development of *PIV technique under magnetic fields and measurement of turbulent pipe flow of Flibe stimulant fluid*, Fusion Science and Technology, To appear 2007.
8. H. Nakaharai, J. Takeuchi, T. Yokomine, T. Kunugi, S. Satake, N.B. Morley, M.A. Abdou. *The influence of a magnetic field on turbulent heat transfer of a high Prandtl number fluid*, Experiments in Thermal Fluid Science, To appear 2007.
9. S. Smolentsev, R. Moreau, *Modeling Quasi-Two-Dimensional Turbulence in MHD Duct Flows*, CTR, Stanford University, Proceedings of the Summer Program 2006.
10. S. Smolentsev, N. B. Morley, M Abdou, and R. Moreau, *Current approaches to modeling MHD flows in the dual coolant lithium-lead blanket*, Magnetohydrodynamics, Vol. 42, No. 2/3, pp. 225-236, 2006.
    S. Smolentsev, N. B. Morley, and M. Abdou, *Magnetohydrodynamic and Thermal Issues of the SiCf/SiC Flow Channel Inserts*, Fusion Science and Technology, Vol. 50, pp. 107-119, 2006.
11. M.-J. Ni, S. Komori, S., and N.B Morley, Direct Simulation of Falling Droplet in a Closed Channel, Journal Heat and Mass Transfer, Vol. 49, pp. 366-376, 2006.
12. S. Smolentsev, M. Abdou, N.B. Morley, M. Sawan, S. Malang, C. Wong, *Numerical analysis of MHD flow and heat transfer in a poloidal channel of the DCLL blanket with a SiCf/SiC flow channel insert*, Fusion Engineering and Design, Vol. 81, pp. 549-553, 2006
13. M.-J. Ni, R. Munipalli, N. B. Morley, M. A. Abdou, *Validation Strategies in Interfacial Flow Computation for Fusion Applications*, Fusion Engineering and Design, Vol. 81, pp. 1535-1541, 2006.
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15. J. Takeuchi, S. Satake, R. Miraghaie, K. Yuki, T. Yokomine, T. Kunugi, N.B. Morley, and M. Abdou, *Study of heat transfer enhancement/suppression for molten salt flows in a large diameter circular pipe: Part one-Benchmarking*, Fusion Engineering and Design,Vol. 81, pp. 601-606, 2006.

Outline of Seminar…

- **Introduction to magnetohydrodynamics**
  - What is magnetohydrodynamics? MHD 101
  - Why do we care about MHD? Fusion!
  - Why should you care about MHD?

➢ **Liquid metal flows in distributing/collecting manifolds for fusion**
  - Results of 3D simulations at high magnetic interaction parameter

- **Continuing MHD research and future directions in the UCLA Fusion Science and Technology Center**

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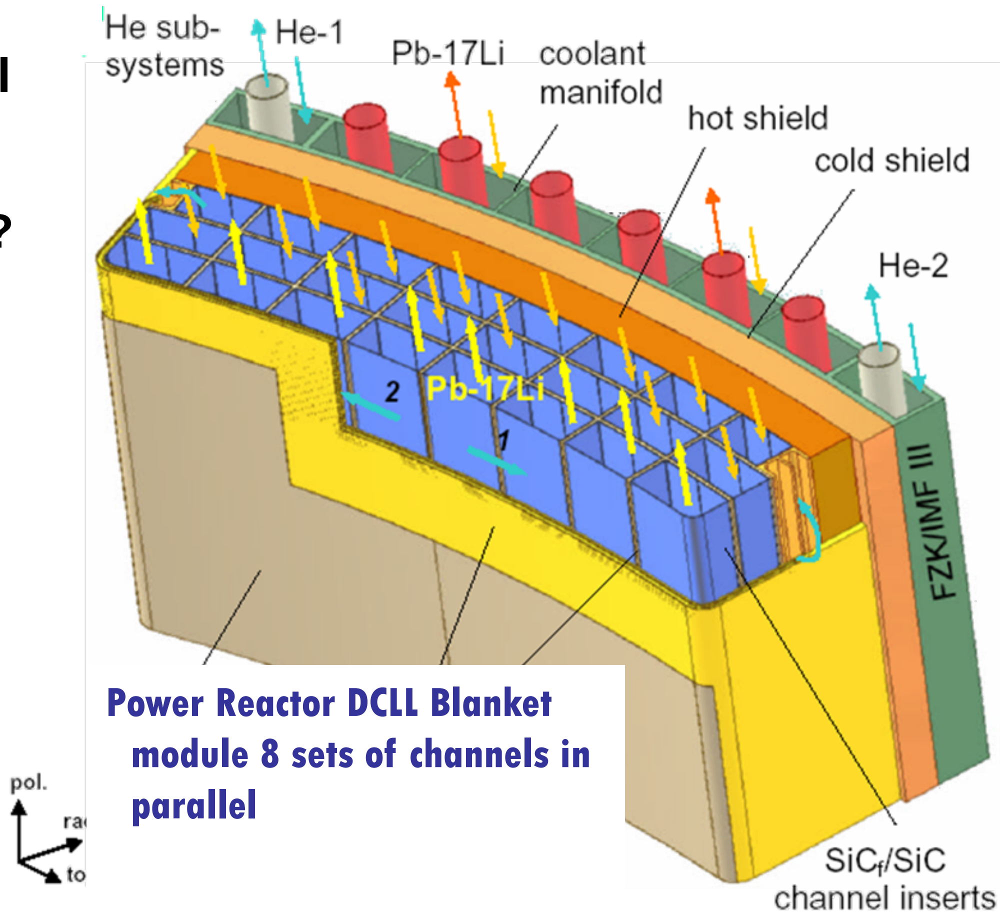
Flow distribution between parallel channels fed from a common manifold

- **Important question for fusion energy applications… how will changes in field and flow conditions affect the flow distribution and heat removal?**
- **What are the flow phenomena and possible sources of flow imbalance?**
- **What are the Manifold region pressure drops (3D)?**
- **What is the Dependence on:**
  - Flow Parameters: Ha, Re, N, aspect ratio
  - Wall conductivities
  - Geometric variations: Manifold length, shape, obstructions
  - 3D magnetic field
  - Up/downstream irregularities



Power Reactor DCLL Blanket module 8 sets of channels in parallel

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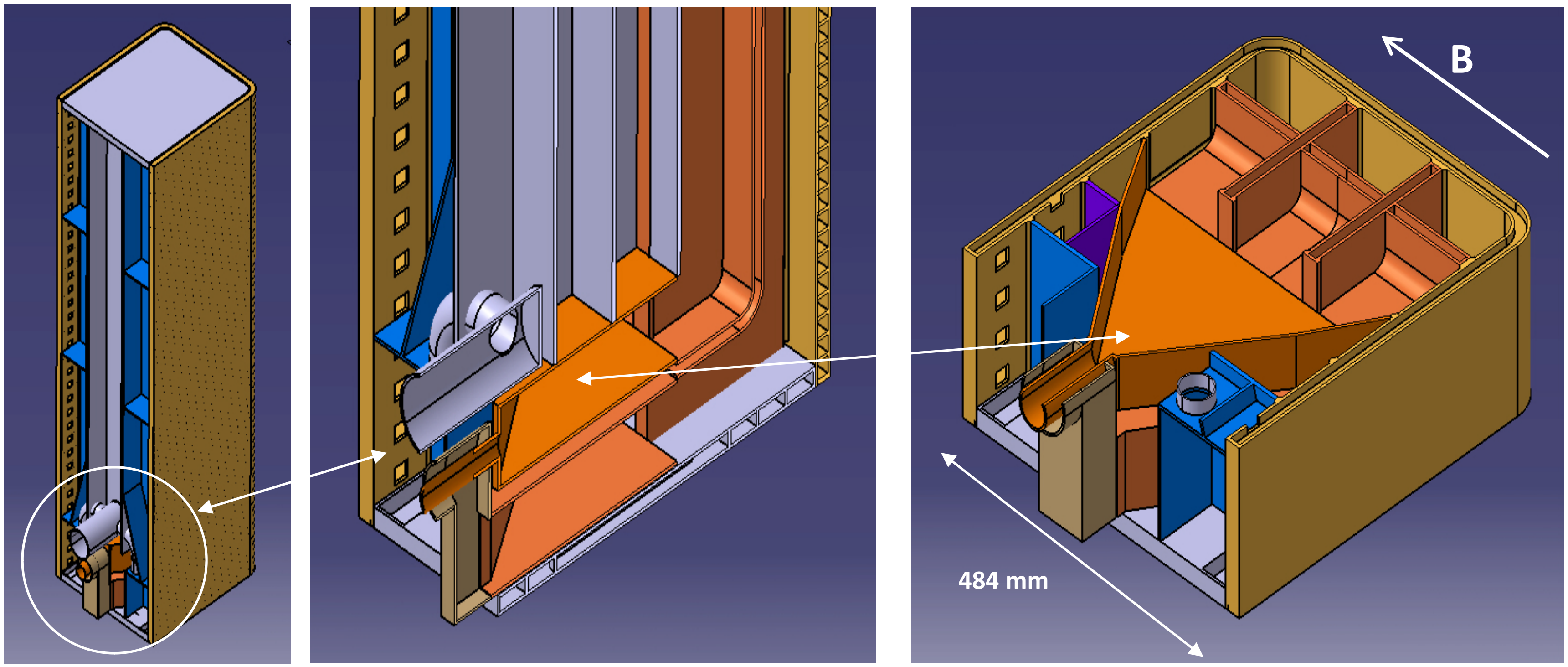
Views of conceived US DCLL ITER Test Blanket Module - Manifold Space



- **Designers conception – our job is to recommend a better design based on MHD considerations**

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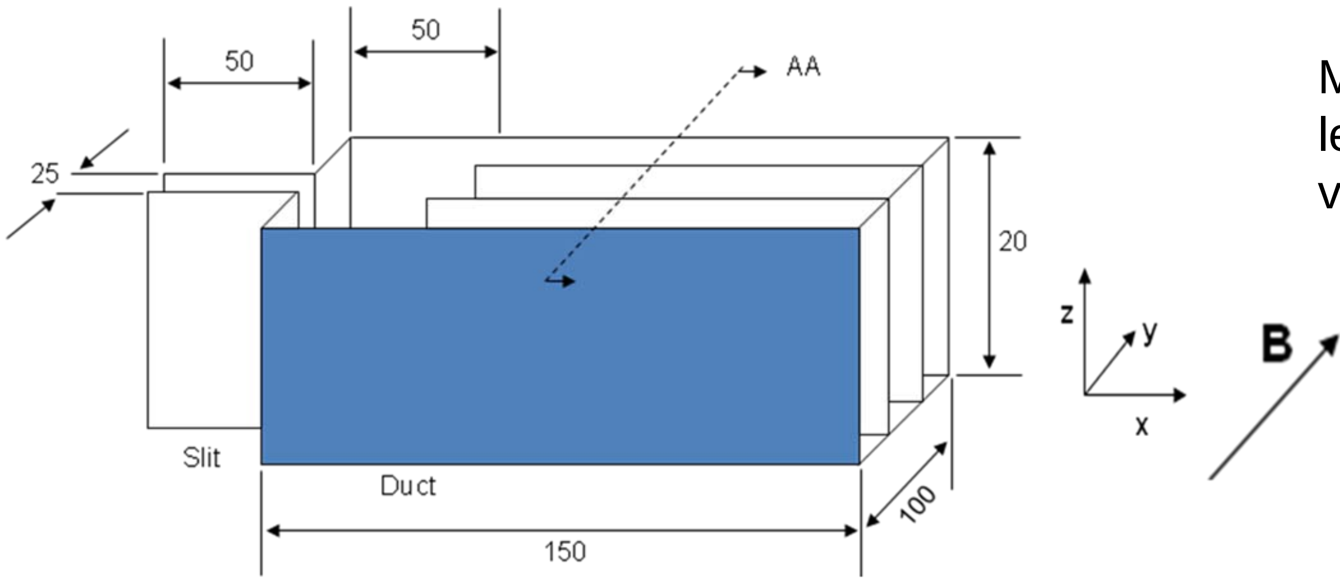
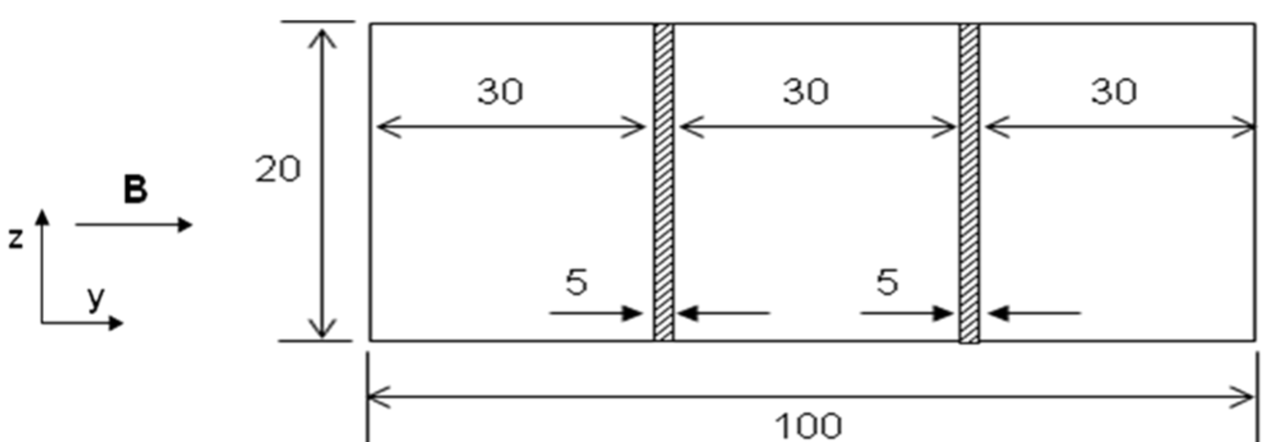
Geometry of ***first*** manifold experiment and Simulations – Abrupt expansion into 3 channels



Many different length and velocity scales



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Typical Manifold Scaling Parameters

		Reactor	US-TBM	UCLA Exp
Manifold expansion width, 2a	**m**	**2**	**0.4**	**0.1**
Manifold expansion height, 2b	**m**	**0.2**	**0.1**	**0.02**
Manifold expansion axial length, L	**m**	**~0.5**	**~0.2**	**.05**
Number poloidal channels		**~8**	**3**	**3**
Flow velocity (in expansion, nominal), u_0	**m/s**	**0.1**	**0.08**	**0.024 ****
Magnetic field (outboard), B	**T**	**4**	**4**	**1.7 ***
Working Liquid Metal		**Pb-Li (550C)**	**Pb-Li (400C)**	**Ga or Hg (RT)**
Hartmann Number (based on a), Ha		**10^5**	**17,000**	**3,000 ***
Reynolds Number (based on a), Re		**10^6**	**10^5**	**3,000 ****
Interaction Parameter, N	**Ha^2/Re**	**10^5**	**3,000**	**3,000 ****
Manifold length ratio	**L/a**	**0.25**	**1**	**1**

Generally dimensionless parameters cited in this presentation are scaled with L = a, i.e. ½ the expansion region dimension along the field

*max SS value
**adjustable value

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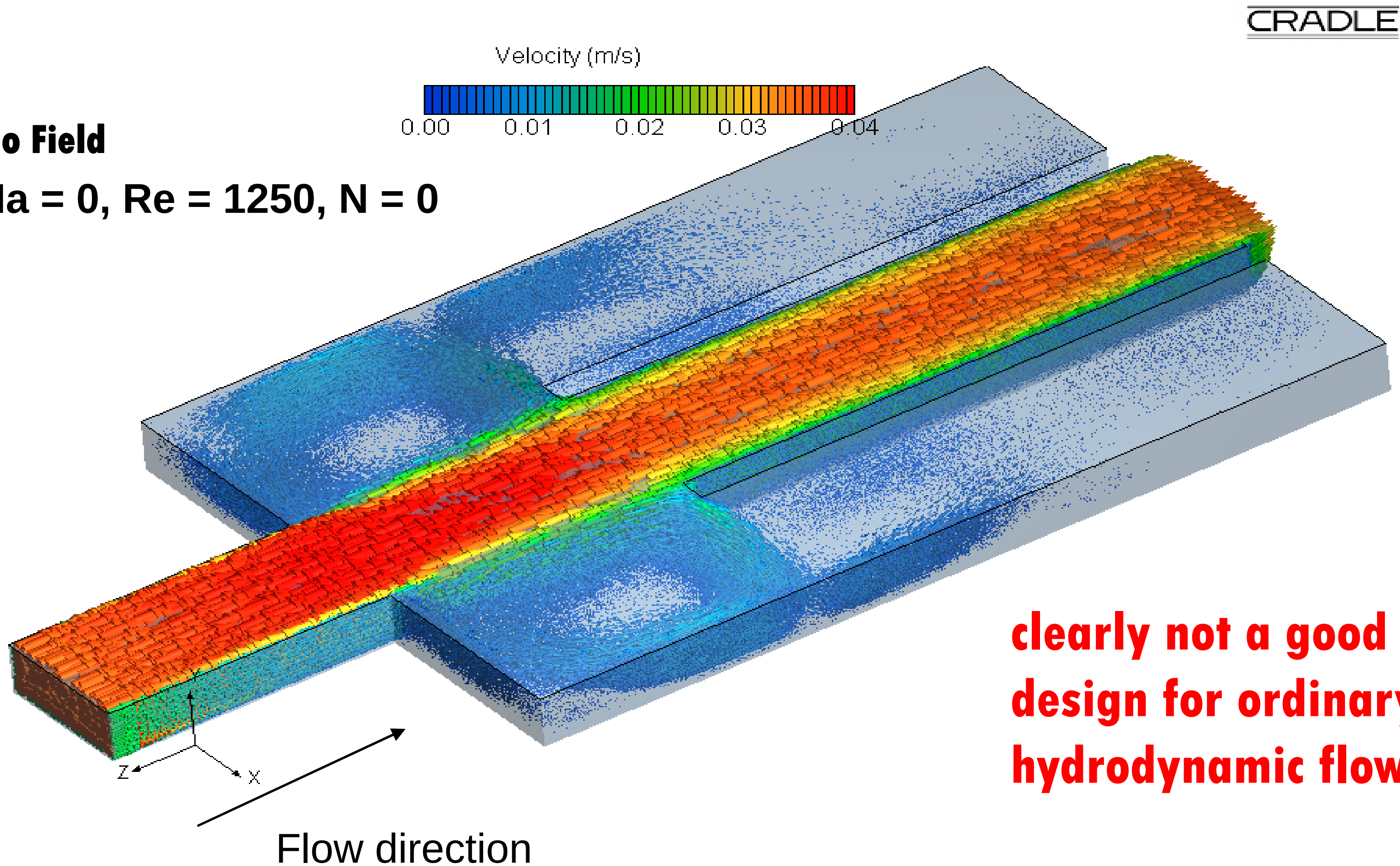
No magnetic field, all flow goes down the center channel

No Field

Ha = 0, Re = 1250, N = 0



clearly not a good design for ordinary hydrodynamic flow

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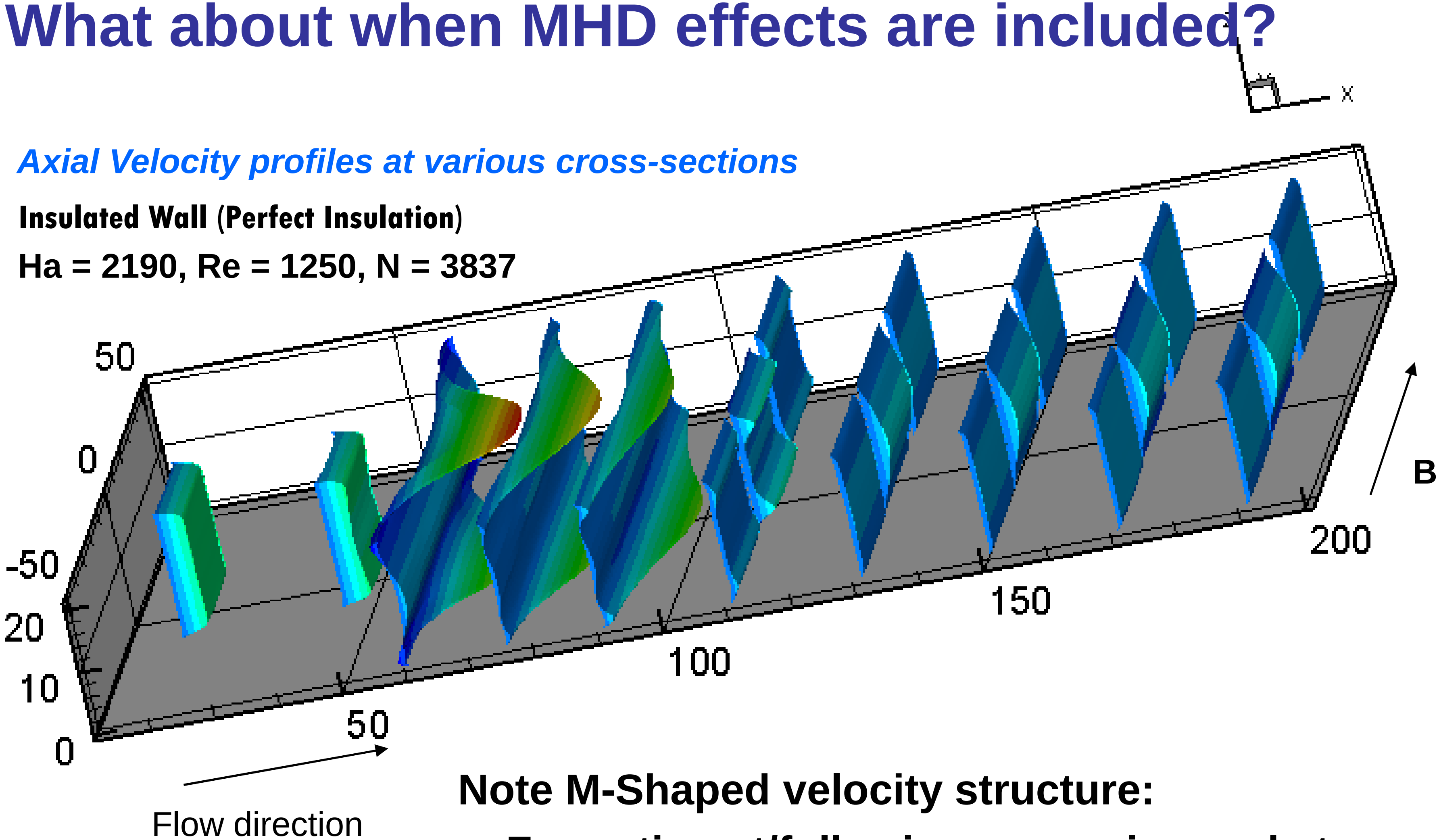
What about when MHD effects are included?

Axial Velocity profiles at various cross-sections

Insulated Wall (Perfect Insulation)

Ha = 2190, Re = 1250, N = 3837



Note M-Shaped velocity structure:

- **Formation at/following expansion and at beginning of parallel channels**
- **Relaxation (diffusion) along field**
- **Center channel behaves differently**

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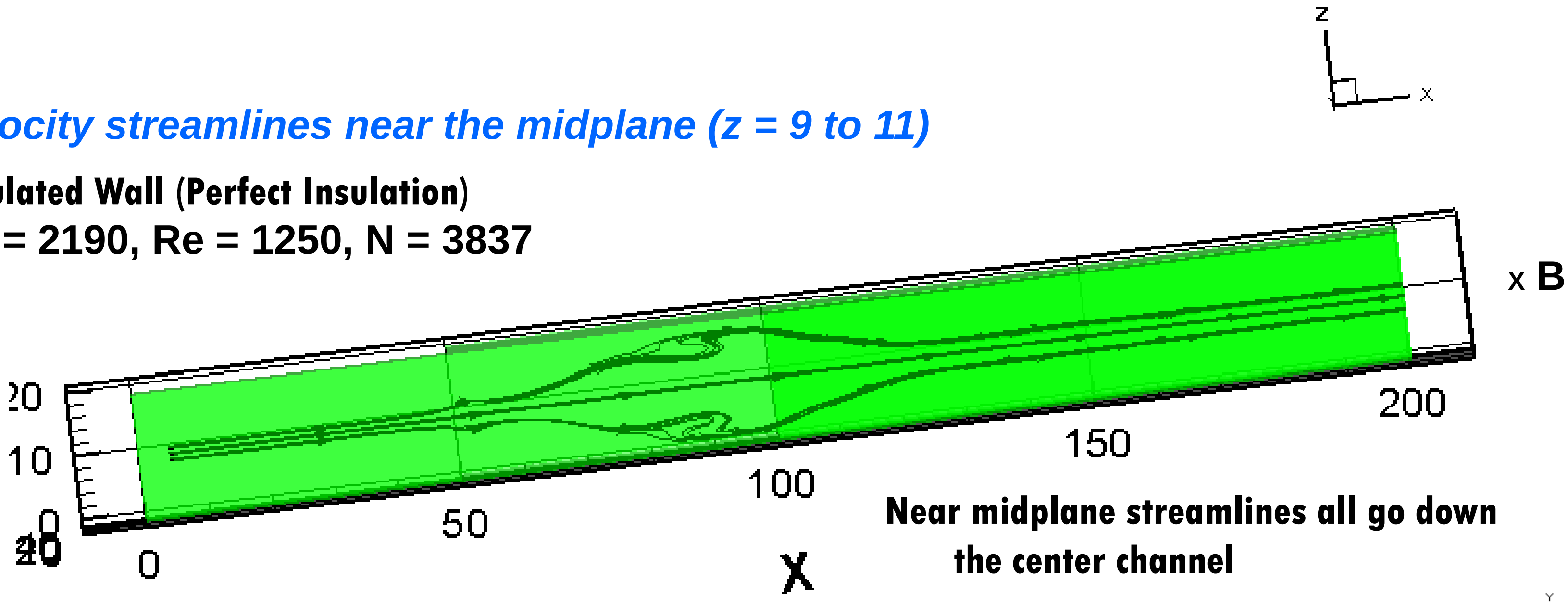
Streamlines show a complex flow pattern in the expansion region

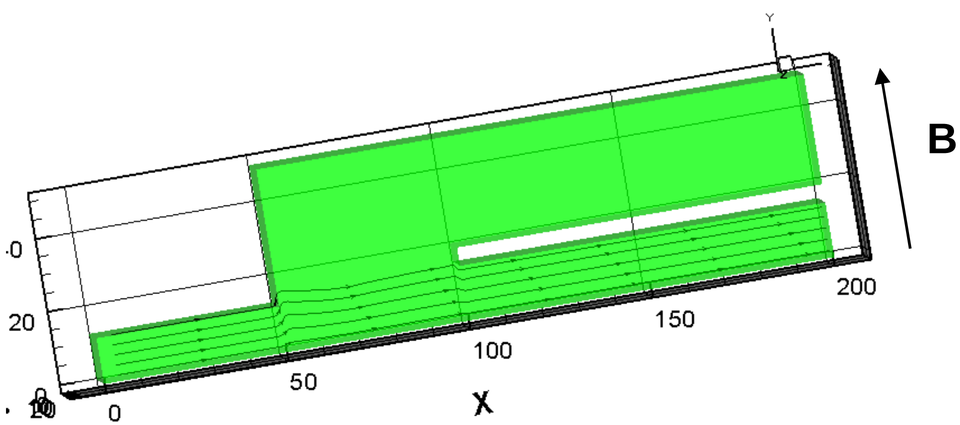
Velocity streamlines near the midplane (z = 9 to 11)

Insulated Wall (Perfect Insulation)

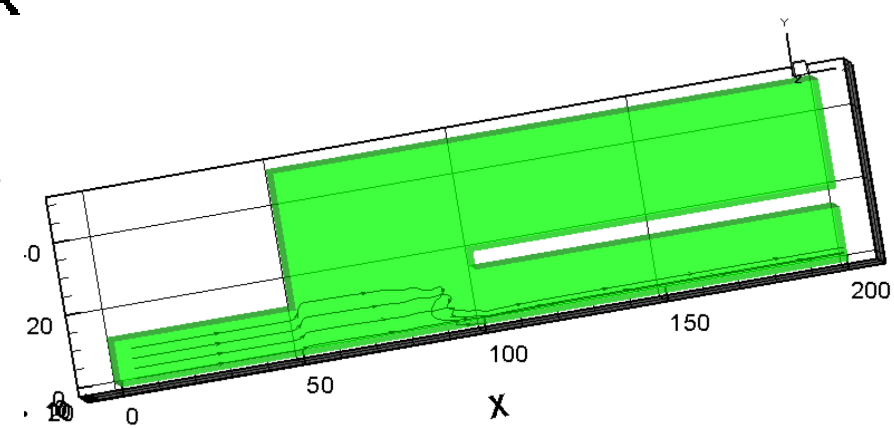
Ha = 2190, Re = 1250, N = 3837



Near midplane streamlines all go down the center channel



Exact midplane (z=10) streamlines are unperturbed



Near midplane (z=11) streamlines caught in 2nd M-shaped structure

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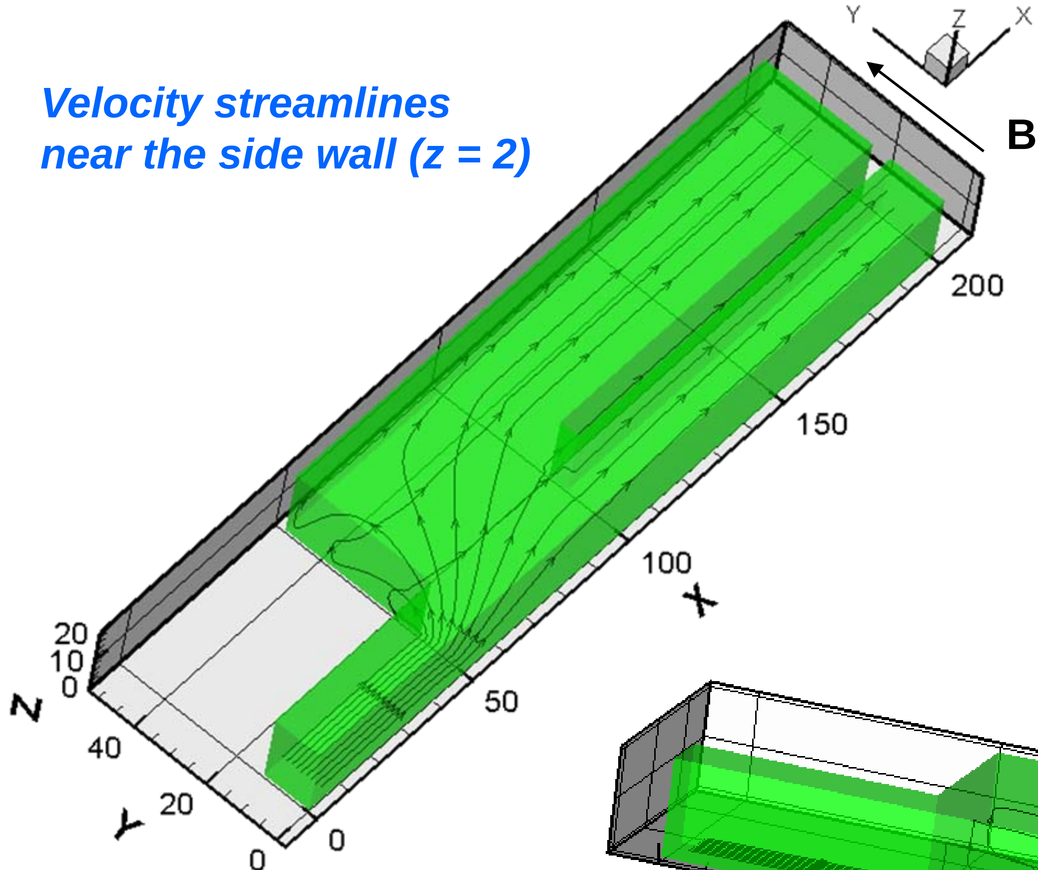
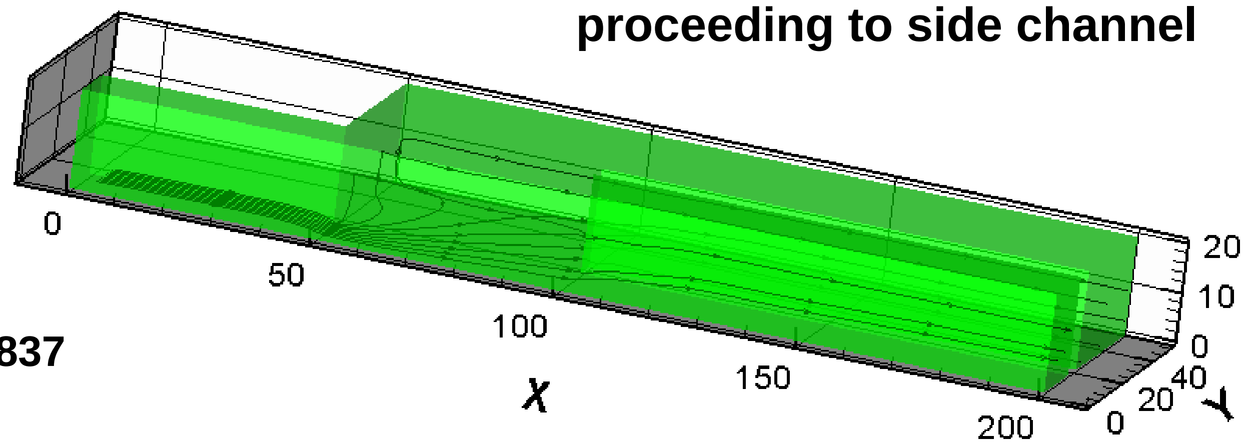
Steamlines near the side-walls are all pulled into 1st M-shape structure

Velocity streamlines near the side wall (z = 2)



3 behaviors observed:

- Steamlines near the center proceed to center channel
- Streamlines between center and Hartmann wall proceed to side channel
- Streamlines near Hartmann wall are pulled back within side layer jet to the expansion wall and move vertically along it before proceeding to side channel



Insulated Wall (Perfect Insulation)

Ha = 2190, Re = 1250, N = 3837

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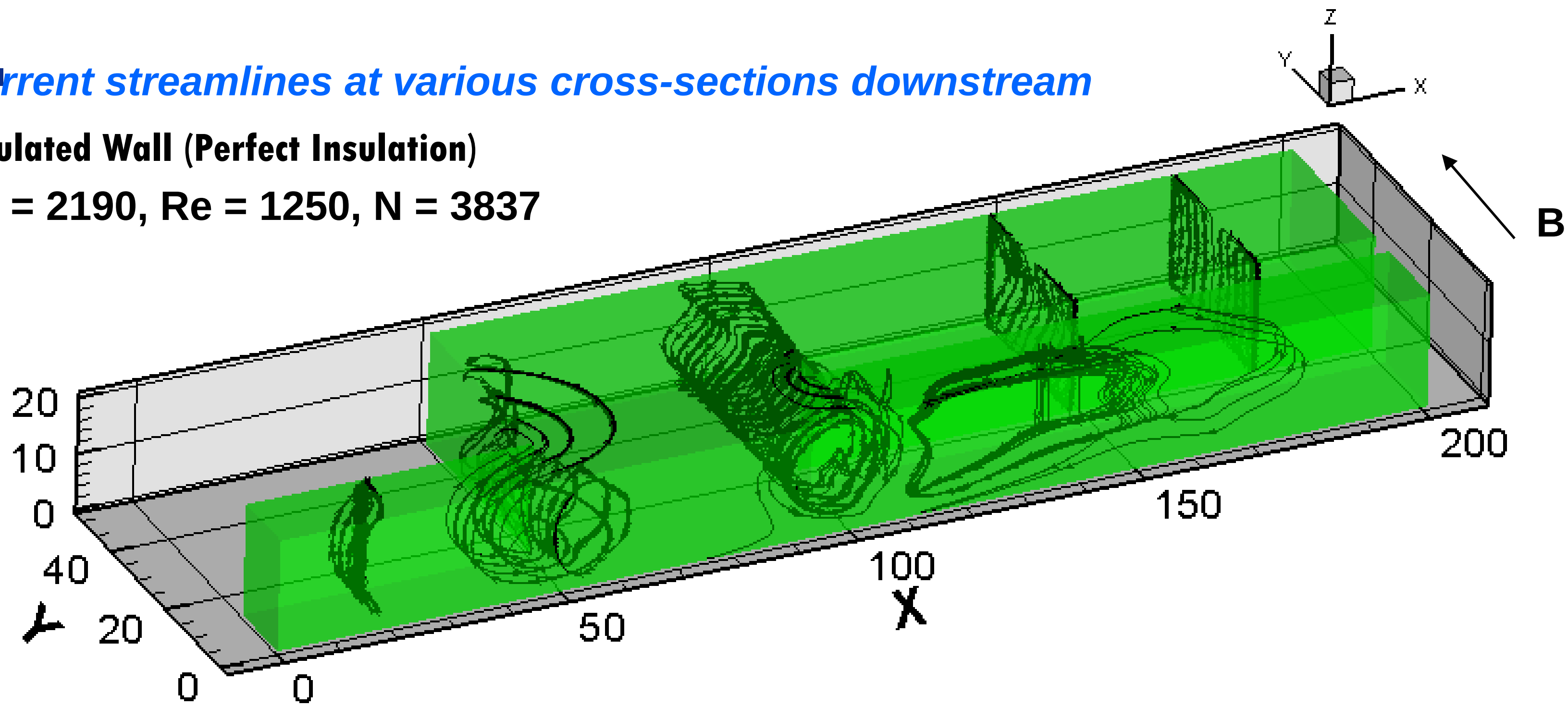
Typical 3D axial current loops are observed – but some strange behavior in the center channel

Current streamlines at various cross-sections downstream

Insulated Wall (Perfect Insulation)

Ha = 2190, Re = 1250, N = 3837



- **Current from high velocity regions close through side-layers and low velocity region – pumping flow**
- **Side channel develops rapidly, but center channel exhibits counter rotating current cells**

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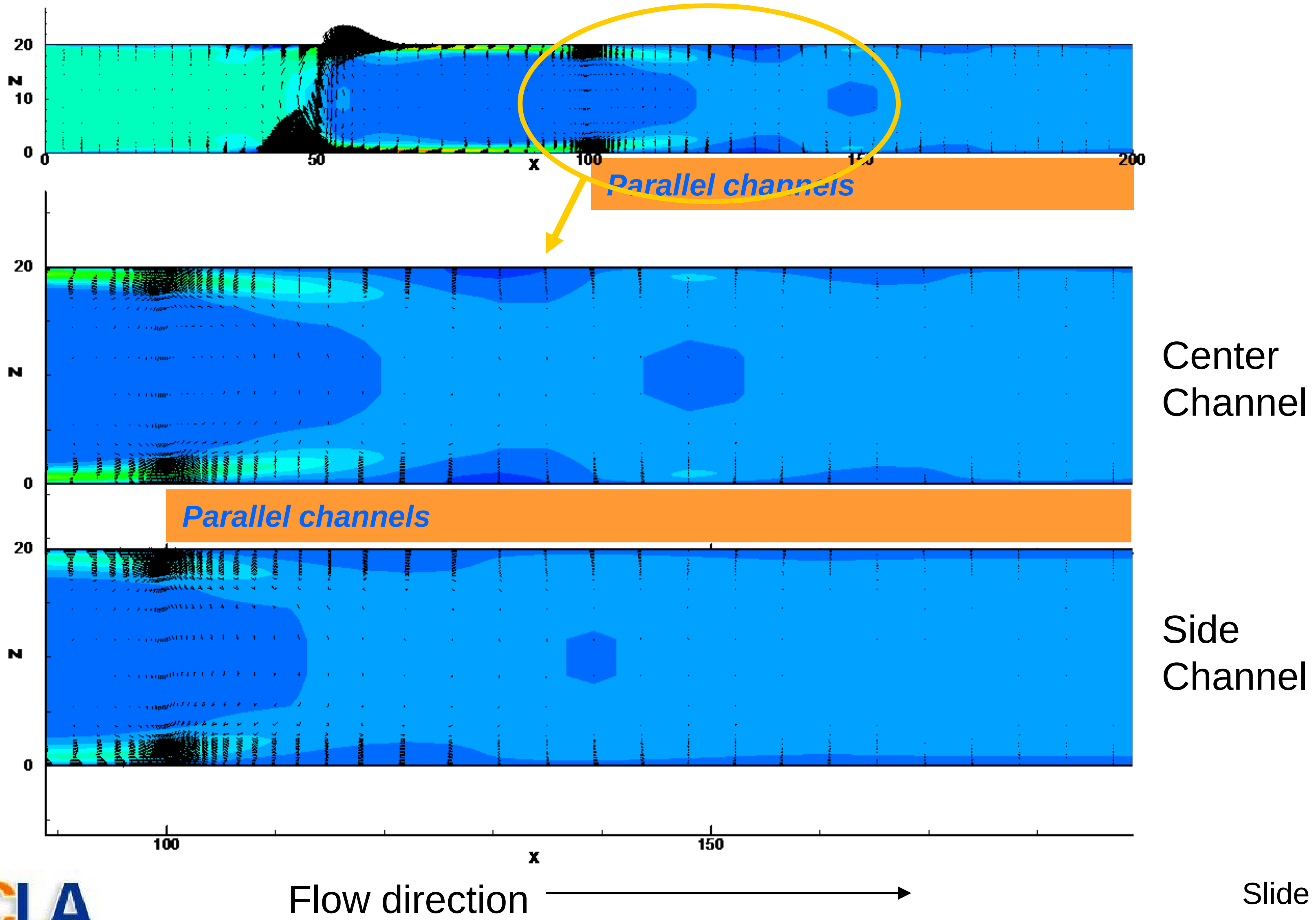
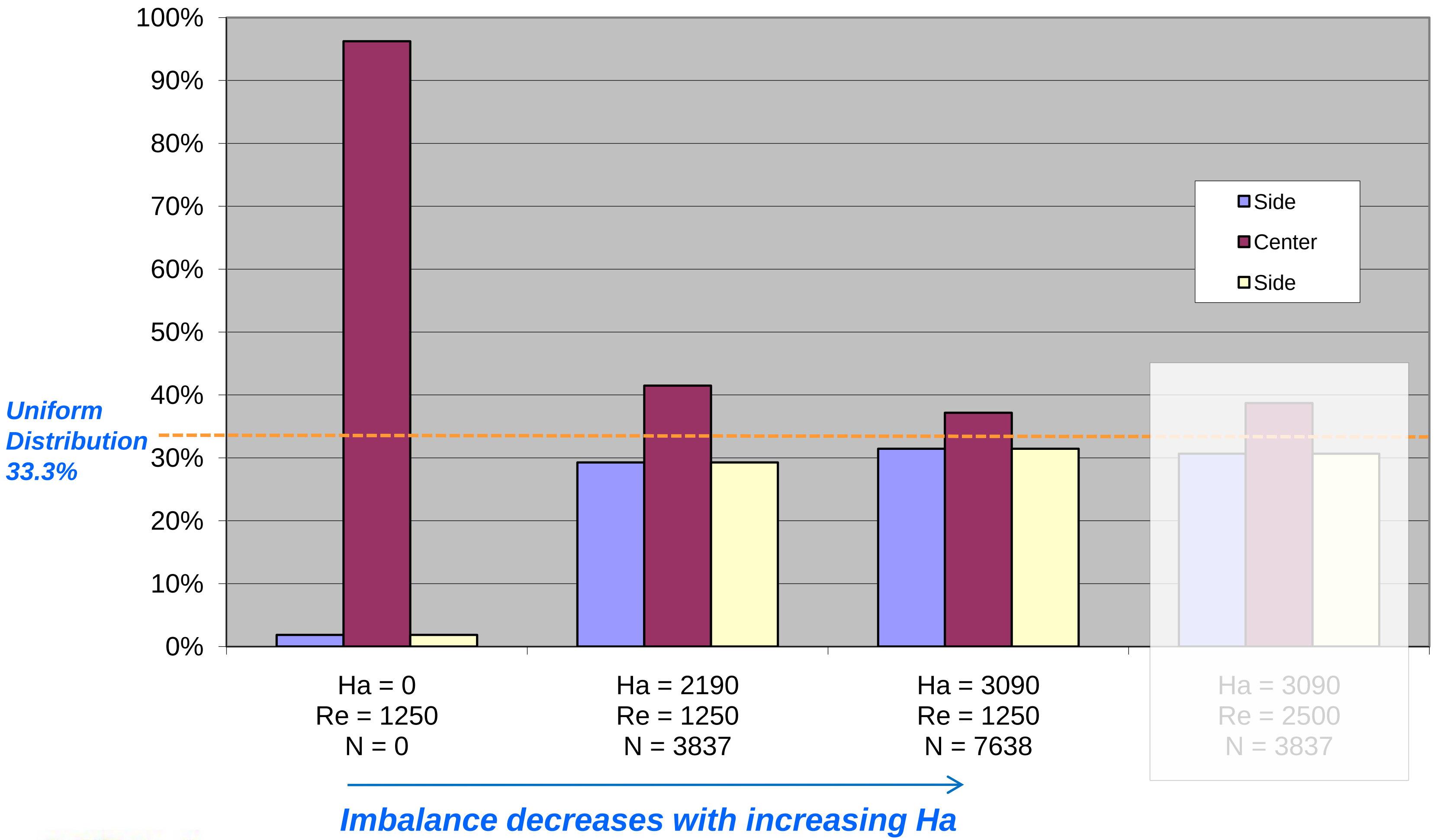
Current Vectors and Axial Velocity Contours



Flow distribution in insulated, abrupt expansion – Increasing Ha *decreases* imbalance



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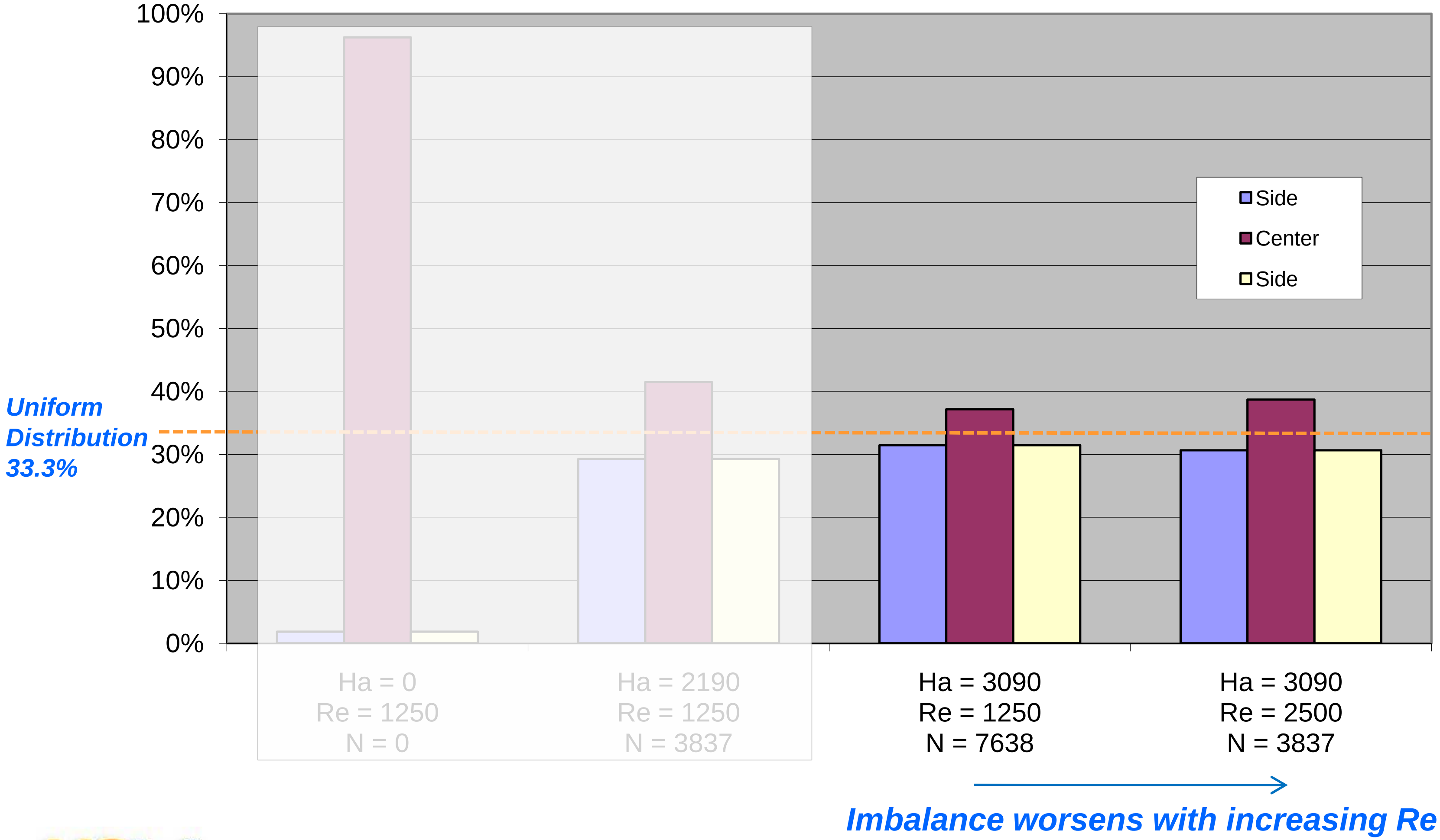
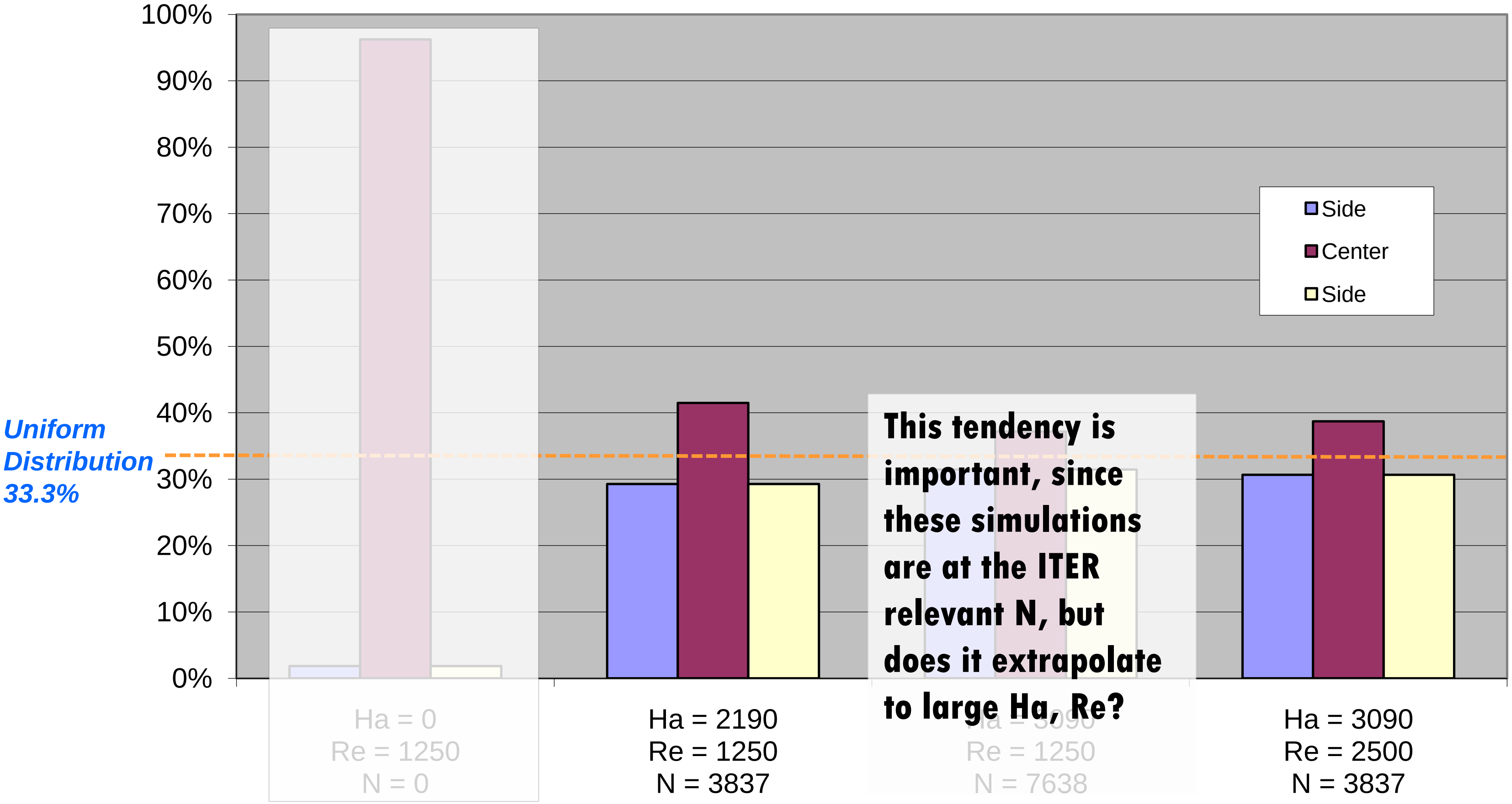
Flow distribution in insulated, abrupt expansion – Increasing Re *increases* imbalance



Flow distribution in insulated, abrupt expansion – Increasing Ha and Re at constant N *decreases* imbalance



Imbalance decreases with increasing Ha, Re at constant Interaction Parameter $N = Ha^2/Re$

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What is the best way to influence the flow balance in an MHD dominated manifold?

- **Can we use conducting walls to reduce M-shape velocity structure and cause it to redistribute more rapidly (in space)**
- **With this orientation of channels and fields, we expect some natural degree of flow balancing**
  - If channels are shorted out through side-layers, then faster channel will pump slower channel
  - Can we encourage this effect by letting the walls be locally conducting?

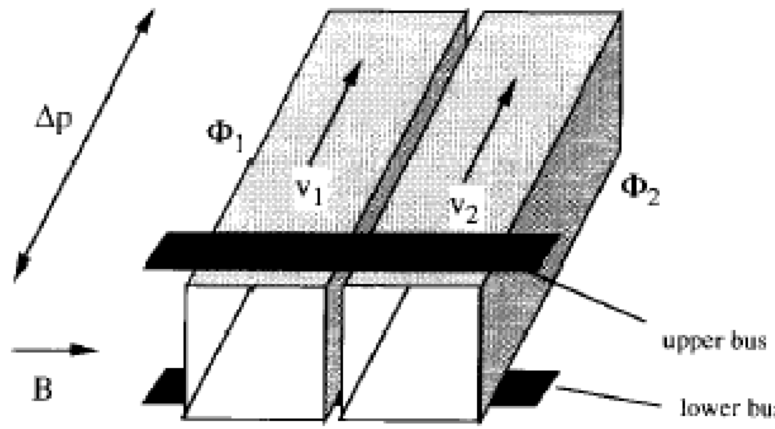
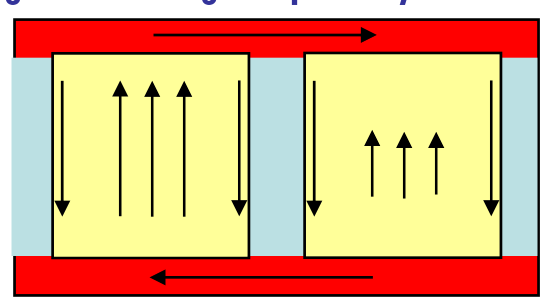


Fig. 7. Locally coupled ducts.

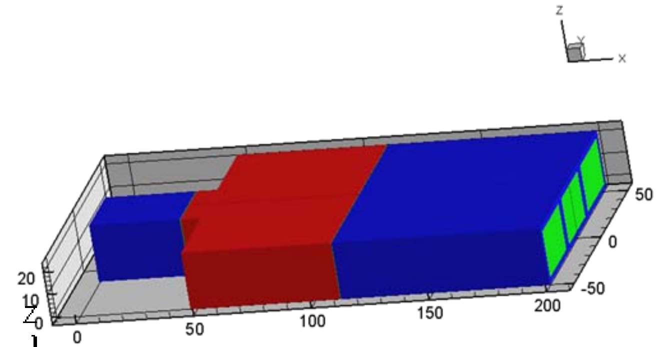
M/ S. Tillack and N. B. Morley, *Flow Balancing in Liquid Metal Blankets,* Fusion Engineering and Design, 27, 735-741 (1995)

Fast channel drives reversed current towards slow channel, reducing its MHD drag and partially alleviating imbalance



$V_1 > V_2$ results in $J_2 < J_1$

All conducting expansion
(don't include a flow channel insert)

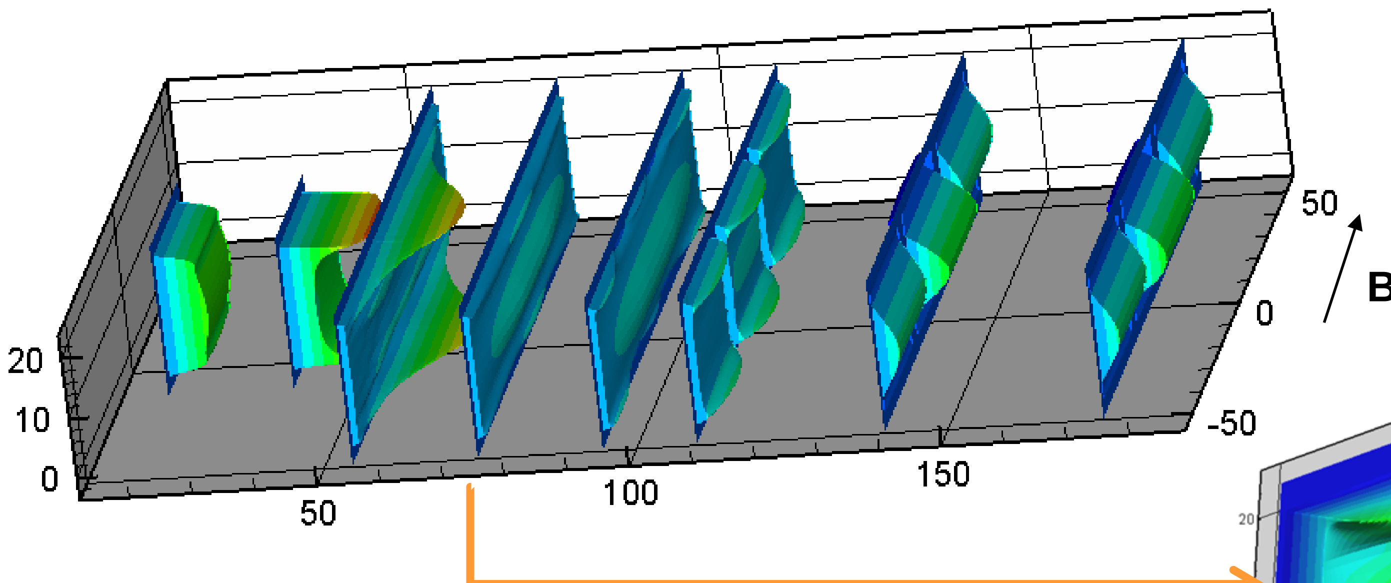


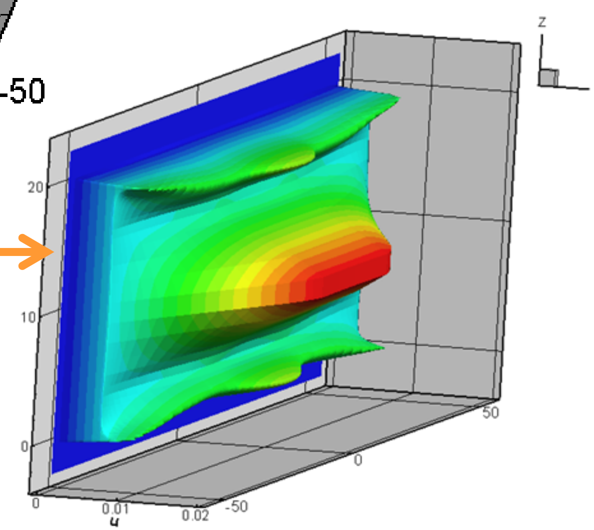
Material conductivity, Cu
Fluid conductivity, Ga-In-Sn
c_w ~ 1.66

Axial Velocity profiles at various cross-sections

All conducting expansion region

Ha = 2190, Re = 1250, N = 3837, c_w = 1.66





- **1st M-Shaped structure dissipates more rapidly and core velocity increases**

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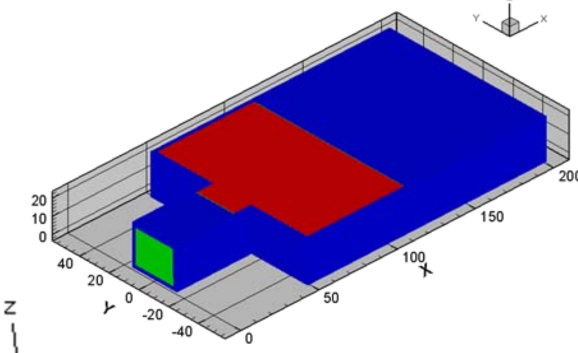
Conducting sidewalls (top/bot) in expansion

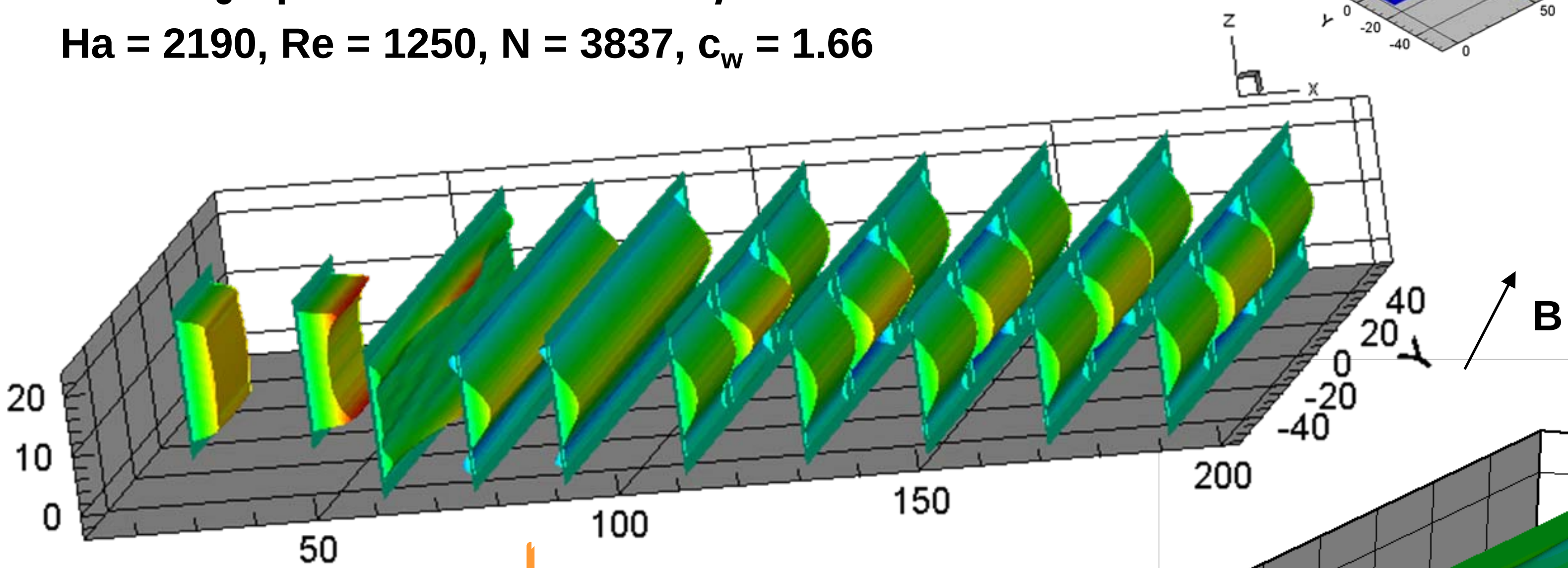
(plating inside of FCI)

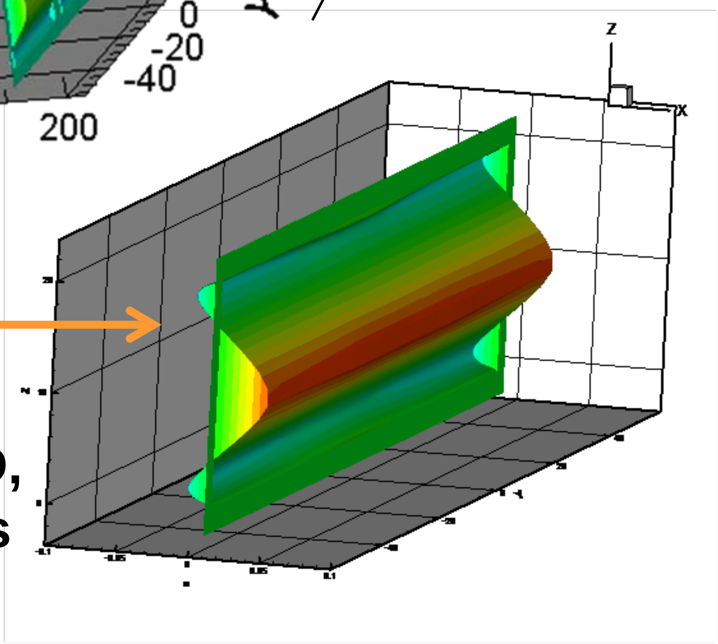


Axial Velocity profiles at various cross-sections

Conducting top and bottom sidewalls only

Ha = 2190, Re = 1250, N = 3837, c_w = 1.66





- **1st M-Shaped structure reduced**
- **All flow moves to core, is nearly 2D, and has reversed flow in sidelayers**

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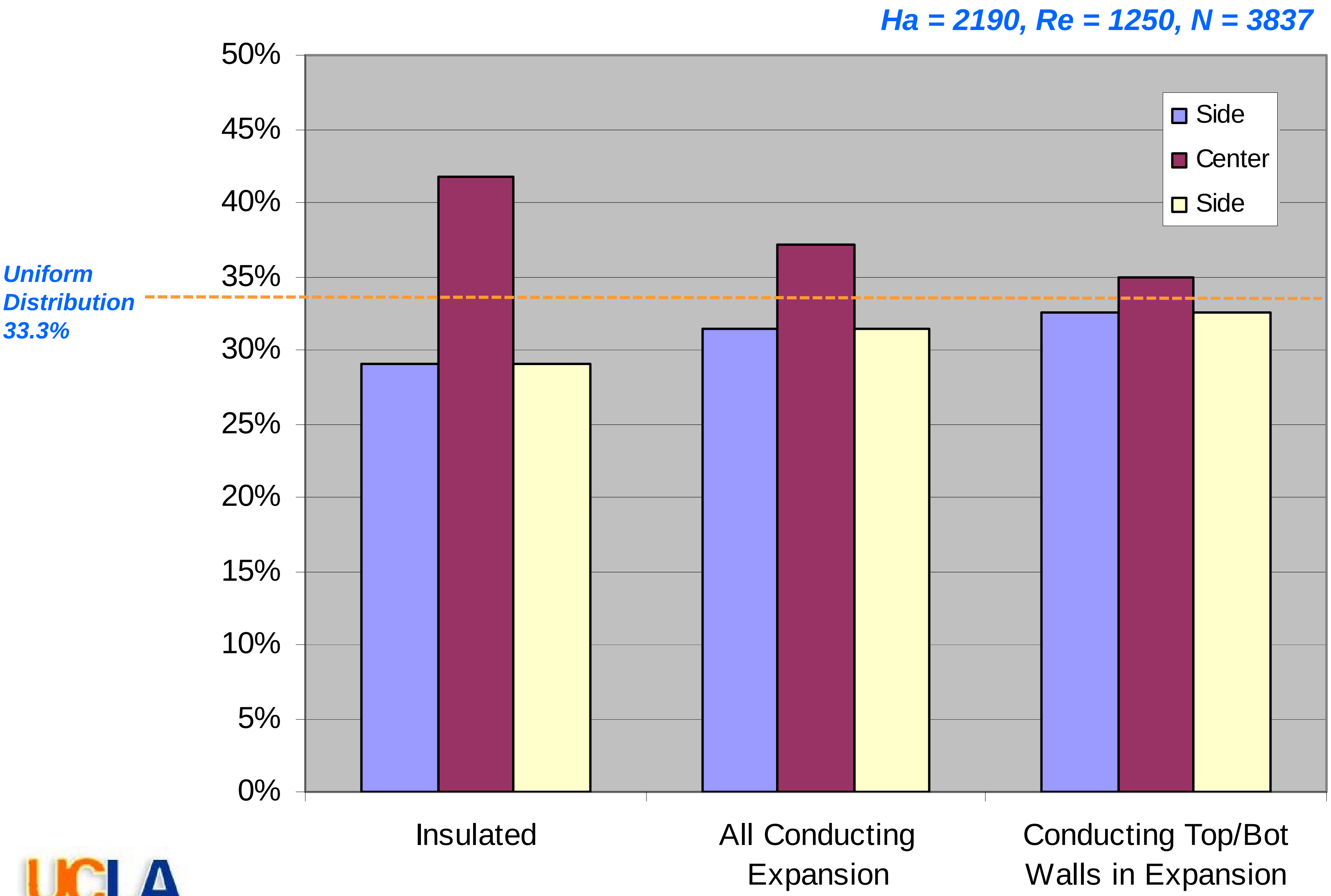
2^{nd} Technique better – flow becomes very nearly balanced



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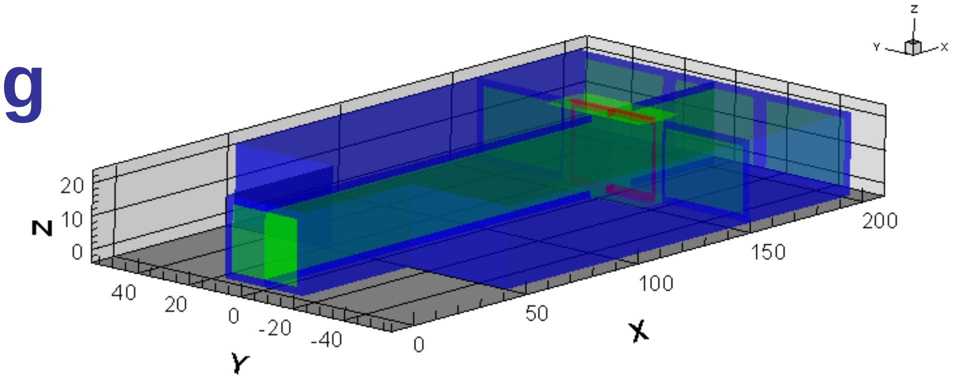
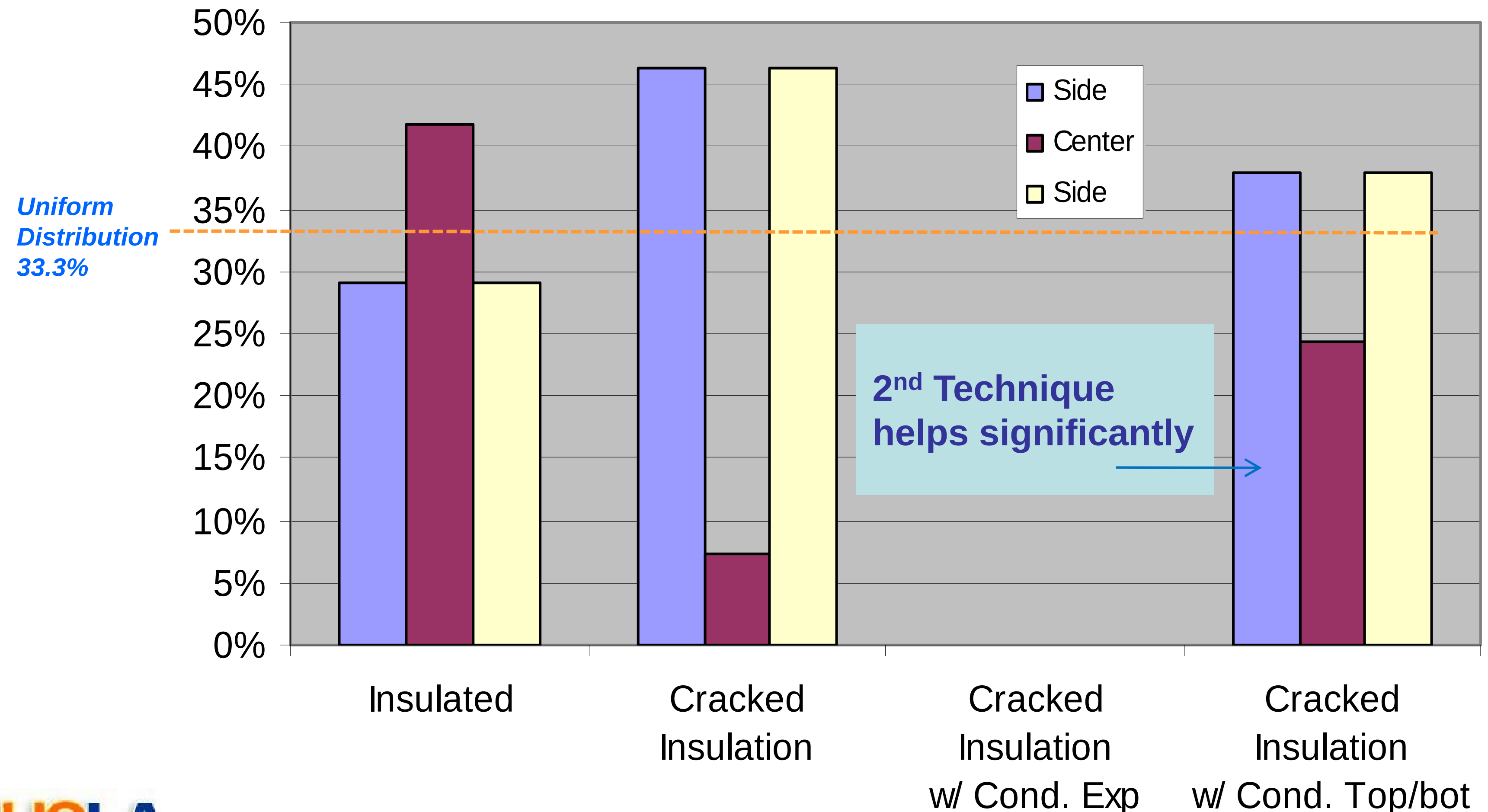
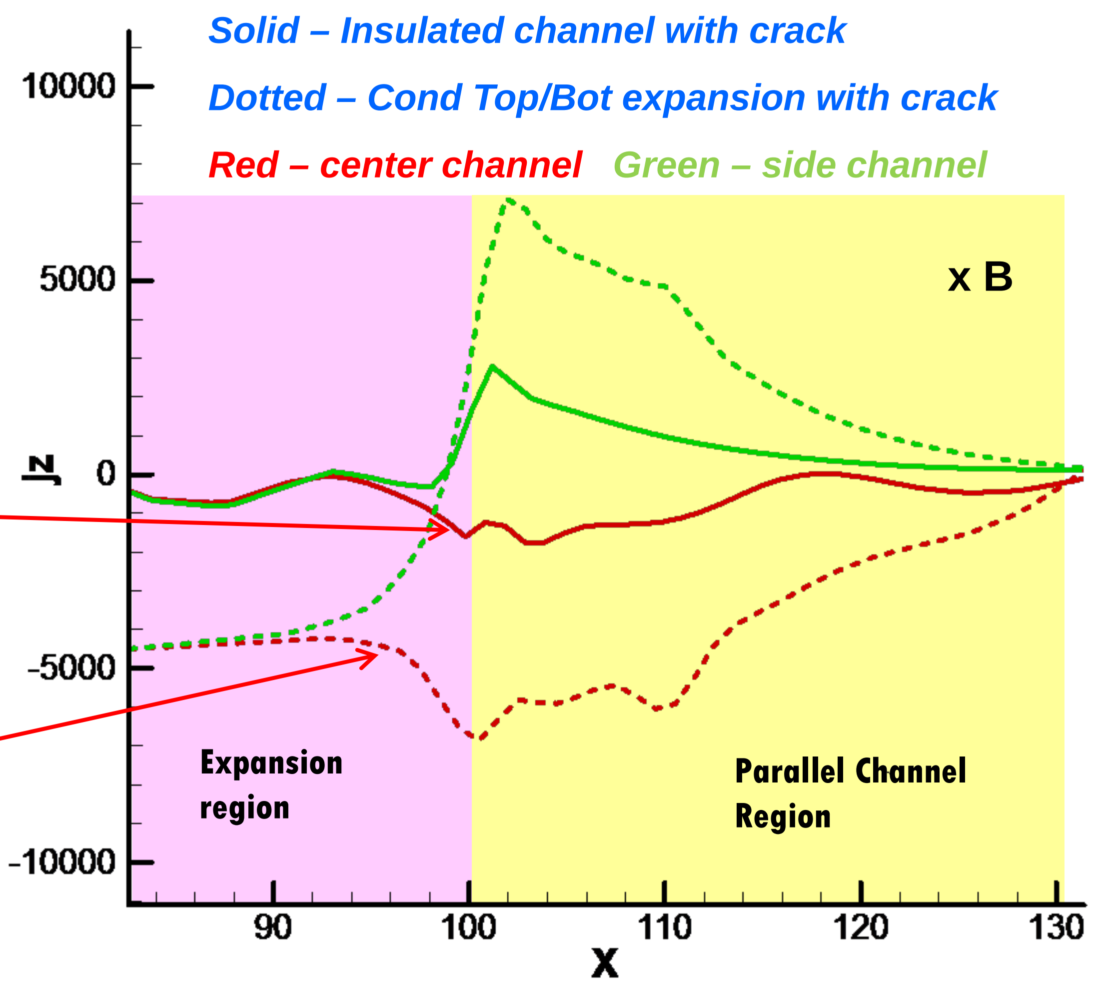
What about correcting for downstream disturbances?





As predicted, the fast channels are pumping the slow channels by driving current that produces positive J x B force

- J_z x B_y represents drag force (so negative Jz is effective pumping)
- Some natural pumping occurs, but
- Cracked center channel is ***strongly*** pumped near the beginning of the parallel channels



Ha = 2190, Re = 1250, N = 3837

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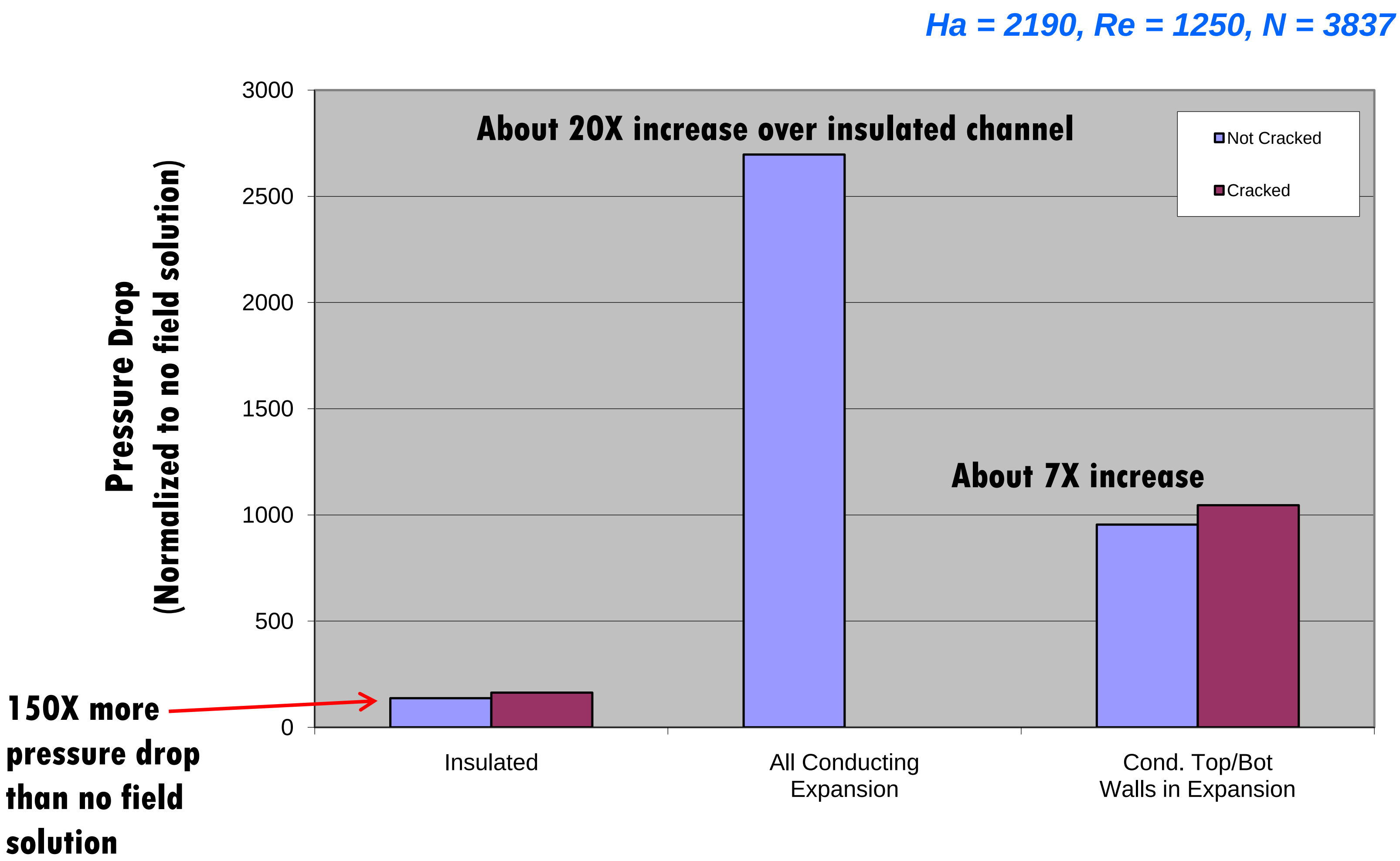
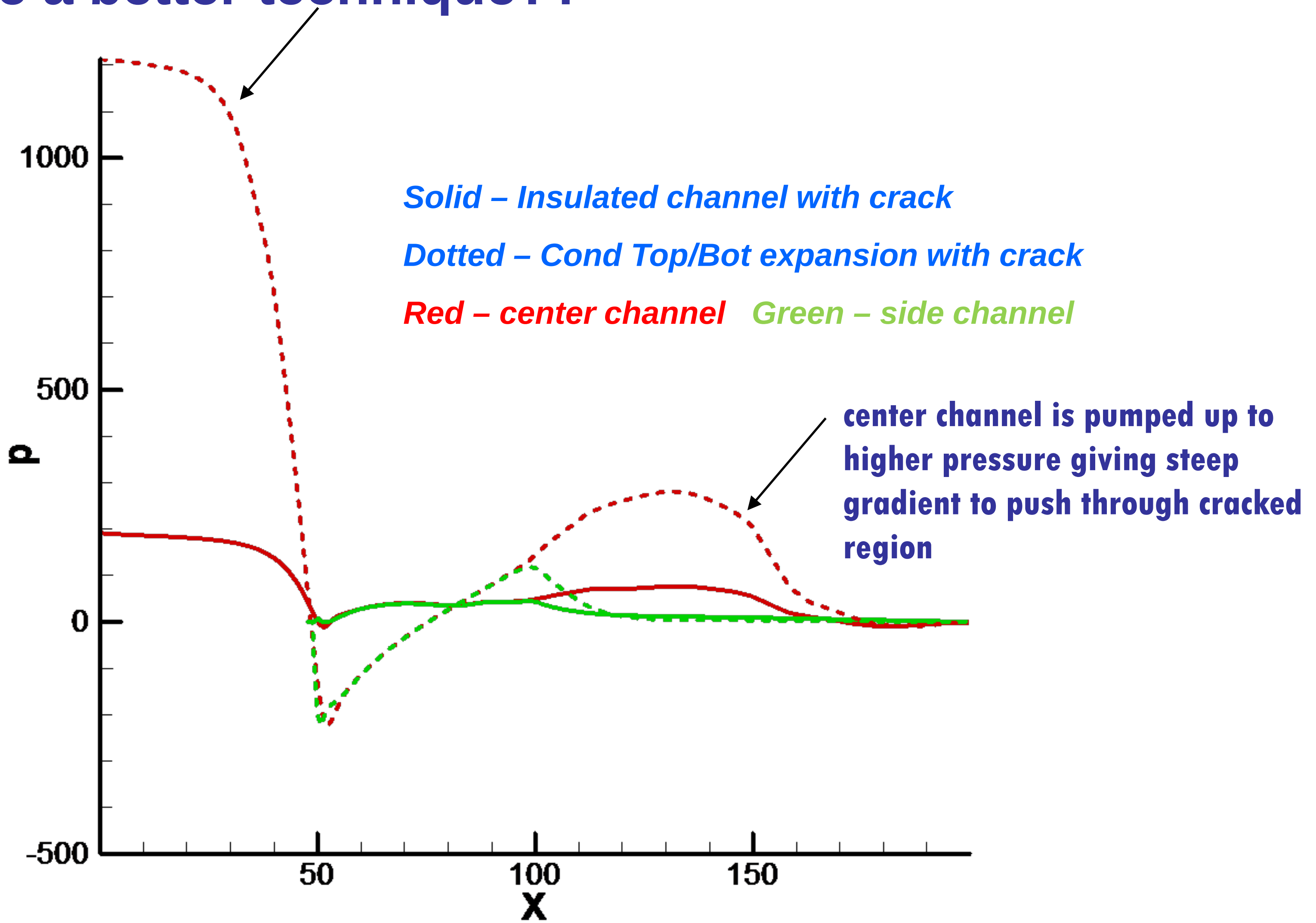
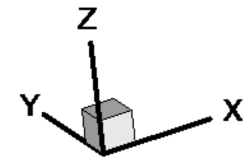
The price you pay… More Pressure Drop



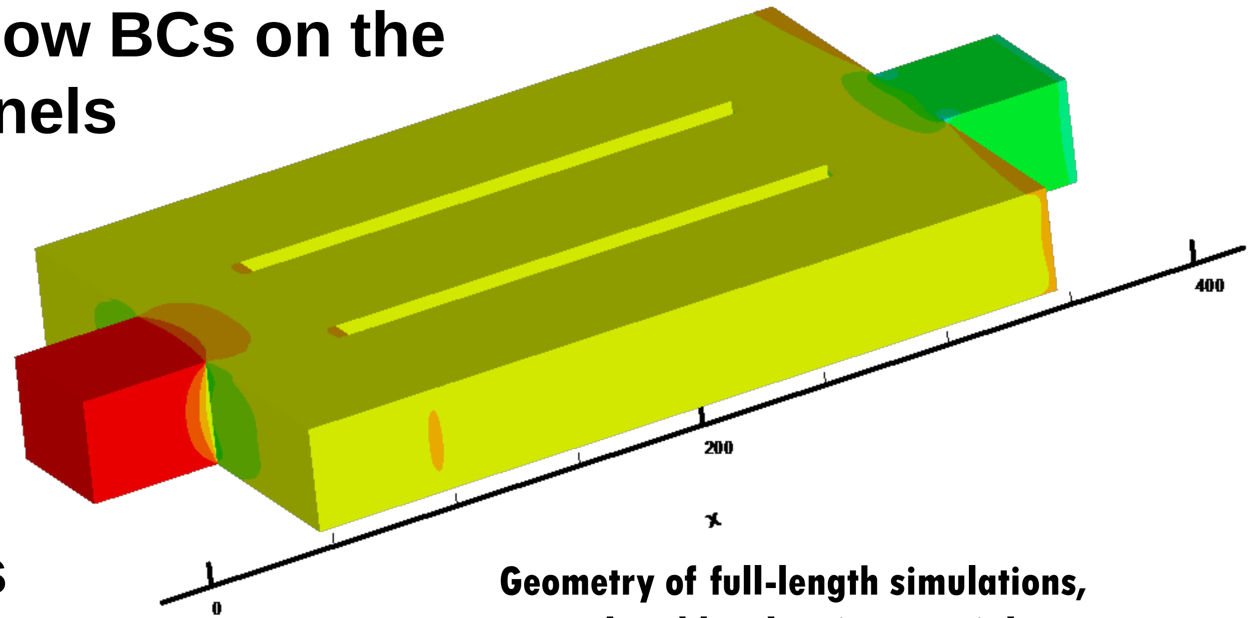
Pressure comparison – Main pressure drop increase comes at transition to conducting wall near expansion. Is there a better technique??



Checking half-length symmetry approximation, is it a good one?



- **The simulations just reported where all for half-length, with p=const outflow BCs on the parallel channels**



Geometry of full-length simulations, colored by electric potential

- **To check this full length simulation was performed as well**

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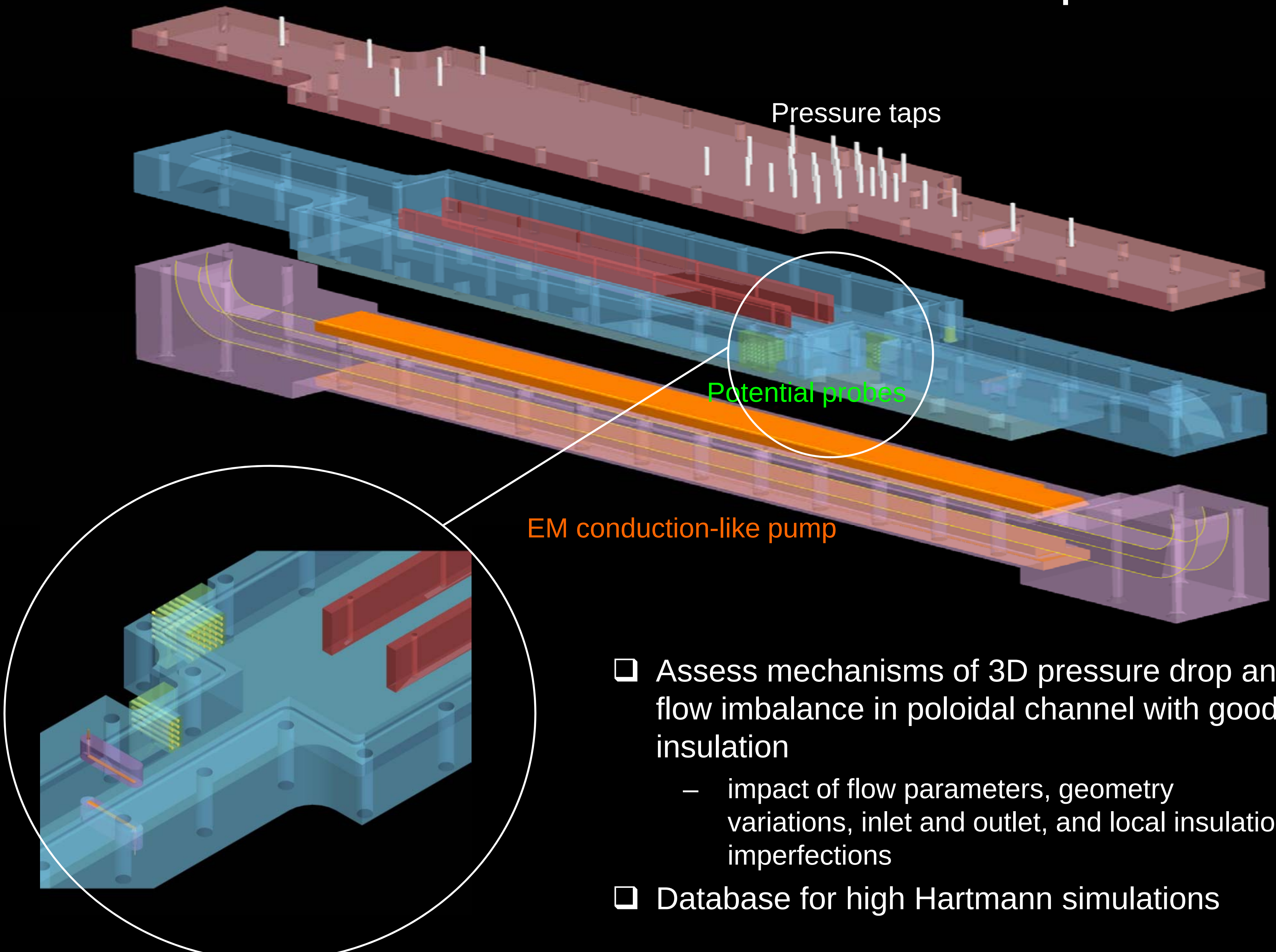
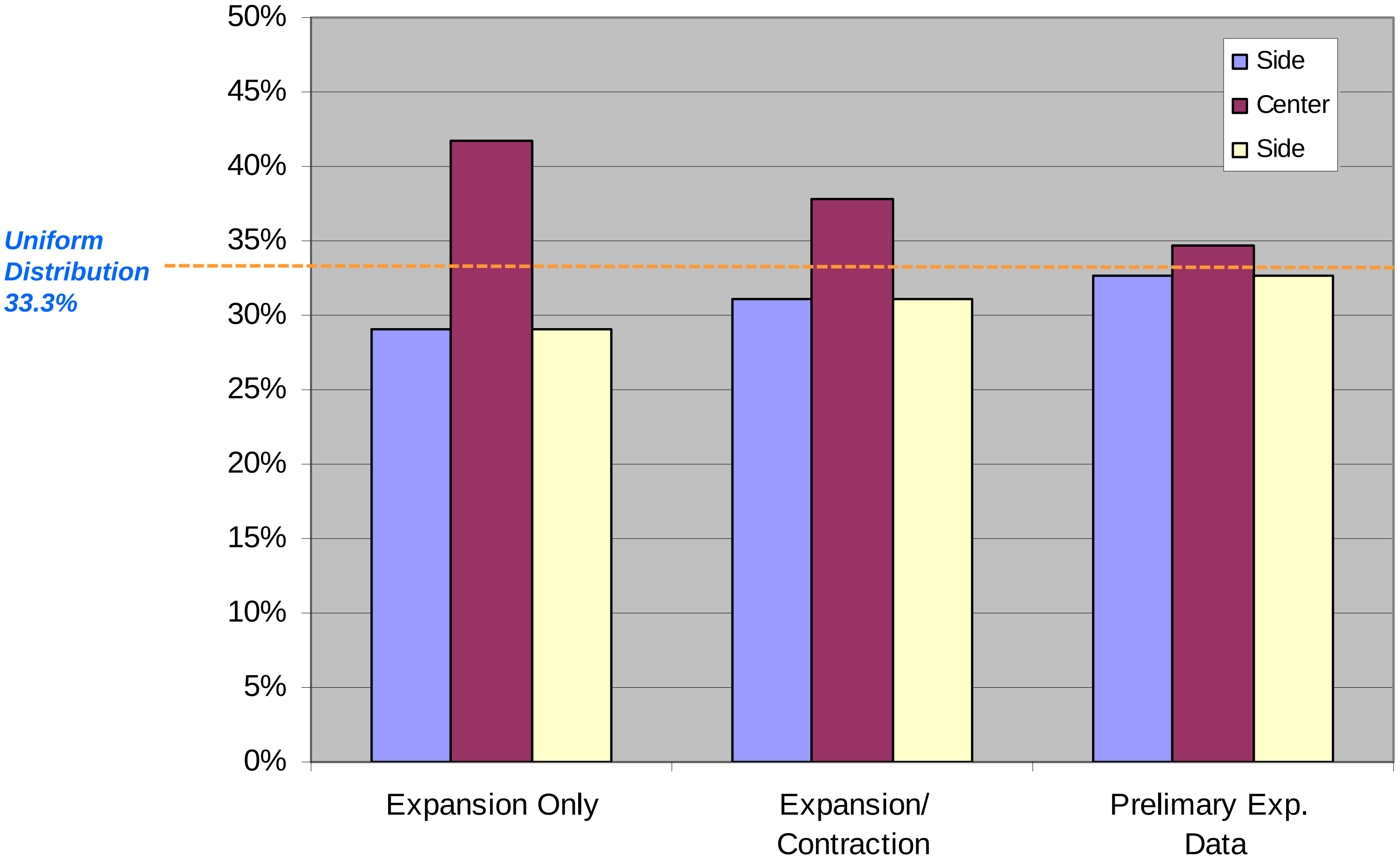
Insulated Manifold Experiment



- ❑ Assess mechanisms of 3D pressure drop and flow imbalance in poloidal channel with good insulation
  - impact of flow parameters, geometry variations, inlet and outlet, and local insulation imperfections
- ❑ Database for high Hartmann simulations

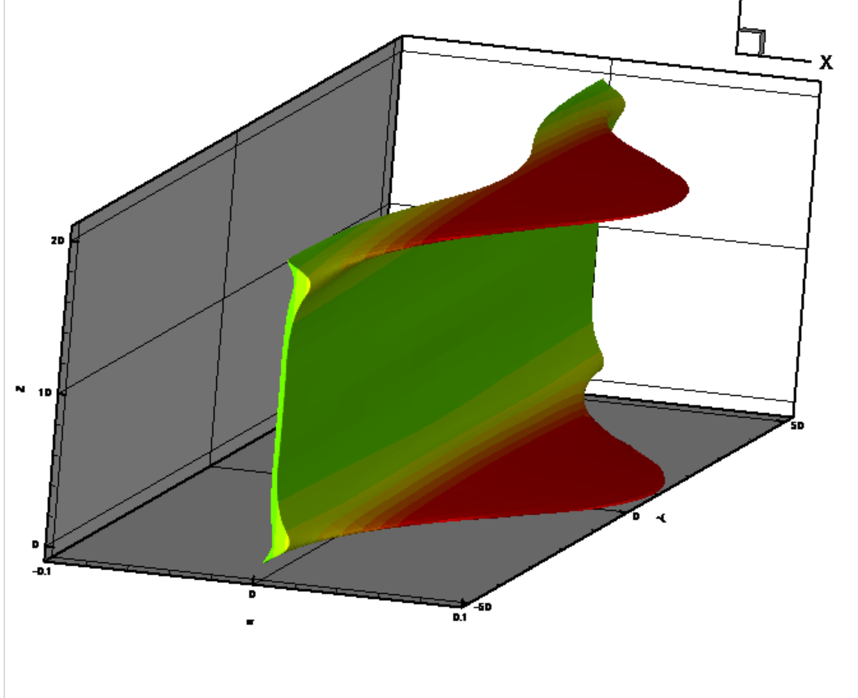
Flow distribution indicates *improved* flow balance when simulating full geometry

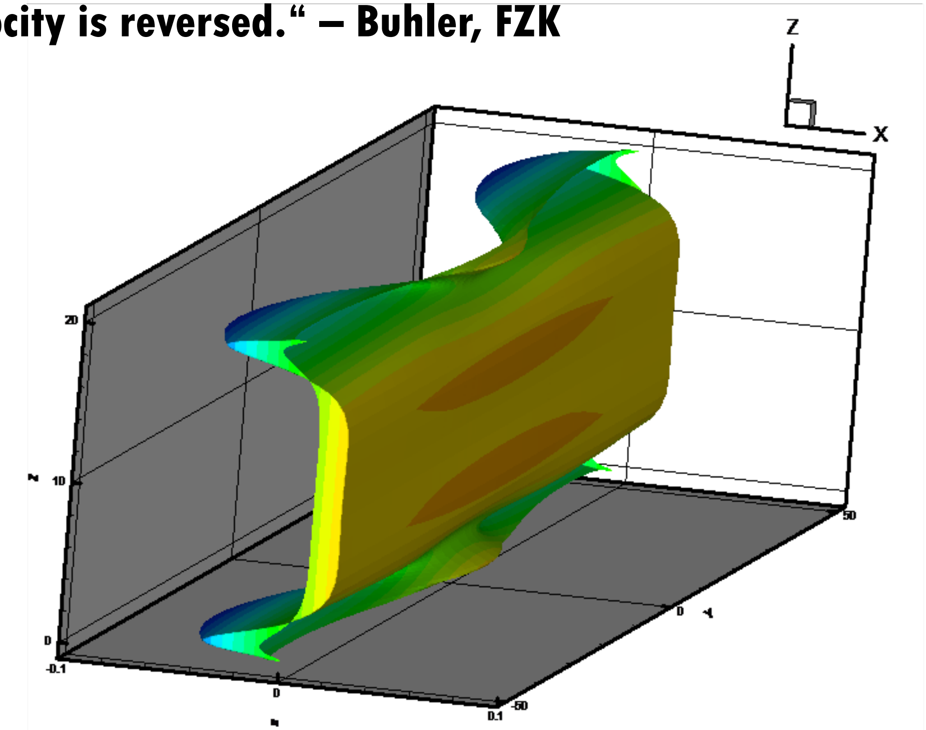


Insulated channels, Ha = 2190, Re = 1250, N = 3837

Comparison of velocity at axial midpoint in expansion vs. contraction region show very different velocities

Expected result for simple expansion…At High Ha and N "the flow problem becomes linear so that the results obtained for an expansion flow apply as well for a flow in a contraction if the velocity is reversed." – Buhler, FZK





- Why? Code wrong or not converged?
- Ha, N not high enough to get completely linear solution?
- Combination of parallel channel region and contraction produce different result?

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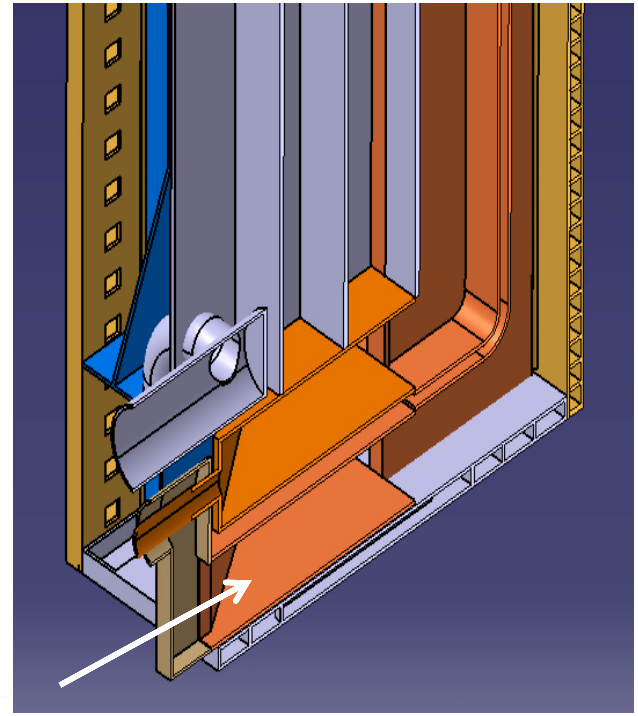
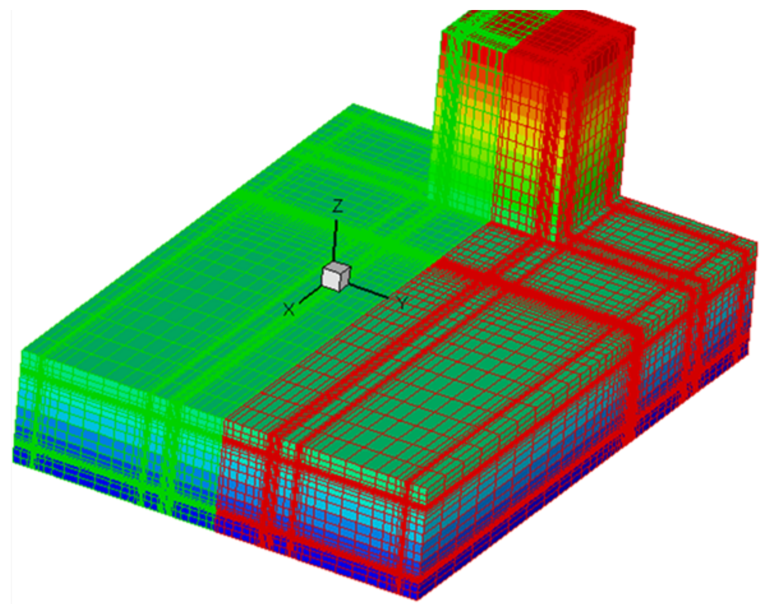
Effects Still to Investigate

- **Detailed validation against experiment**
  - experimental field distribution
  - expansion and contraction
- **Geometric parameters**
- **Tokamak Ha, Re and field distribution**
- **Instabilities** **(see next slide)**
- **Establish approximate model or scaling law**



Manifold with feed from top instead of in-line



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Outline of Seminar…

- **Introduction to magnetohydrodynamics**
  - What is magnetohydrodynamics? MHD 101
  - Why do we care about MHD? Fusion!
  - Why should you care about MHD?

- **Liquid metal flow and control in distributing/collecting manifolds for fusion**
  - Results of 3D simulations at high magnetic interaction parameter

- **Continuing MHD research and future directions in the UCLA Fusion Science and Technology Center**

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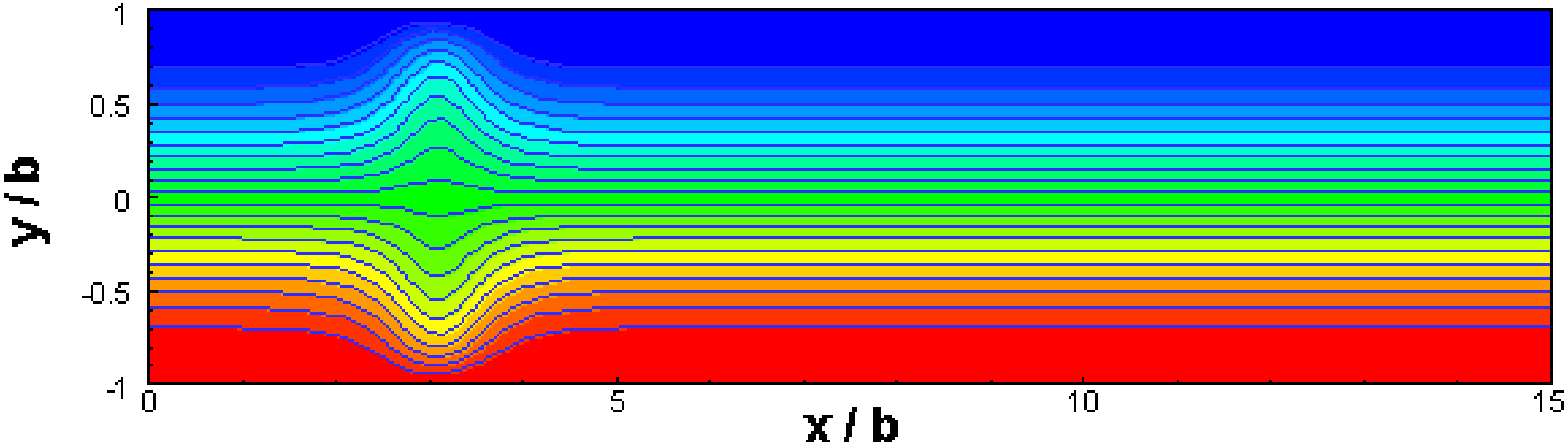
Future MHD research directions in the Fusion Science and Technology Center (1)

Impact of time varying flow phenomena on heat transfer and blanket temperatures

- Instability of strong velocity jets near expansions and FCI overlap regions, cracks
- Buoyancy-driven flow (MHD mixed convection) in strongly neutron heated front channels
- Further simulation, stability analysis, and experiments planned



Flow entering a magnetic field

S. Smolentsev, R. Moreau, Modeling Quasi-Two-Dimensional Turbulence in MHD Duct Flows, CTR, Stanford University, Proceedings of the Summer Program 2006.

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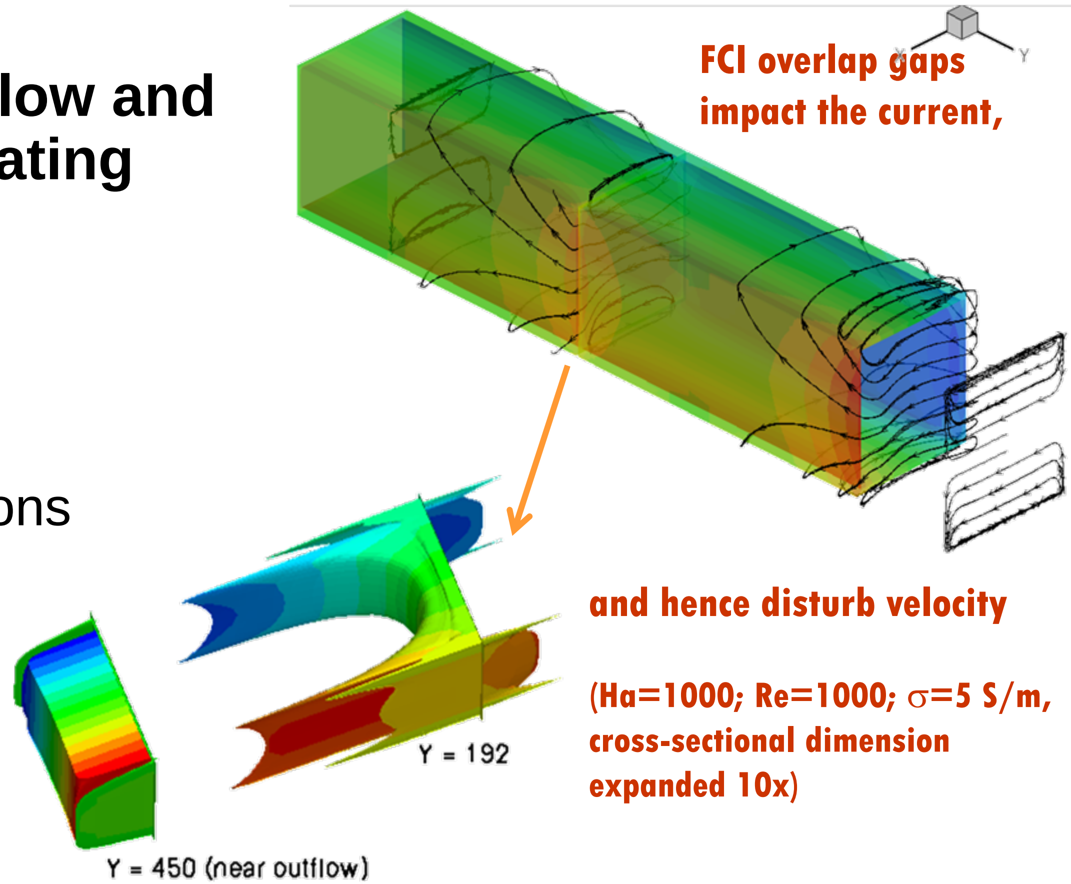
Future MHD directions in the Fusion Science and Technology Center (2)

Impact of 3D effects on flow and heat transfer with insulating flow channel inserts

- FCI overlap regions
- Turns
- Pressure eq. holes
- Cracks and imperfections
- Further simulation and experiments planned



Can such features be used to benefit heat transfer near the first wall in a fusion blanket?

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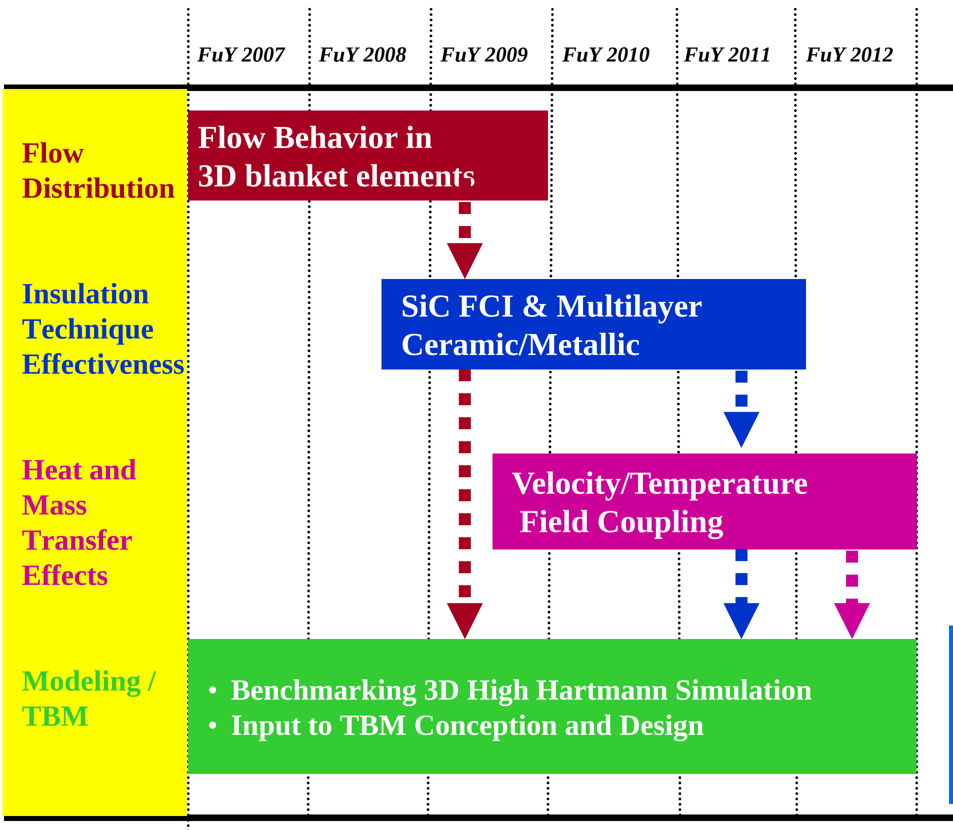
Thank you for your attention ☺



UCLA MTOR Lab.

UCLA – NIFS (Japan)
6 year collaboration schedule

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