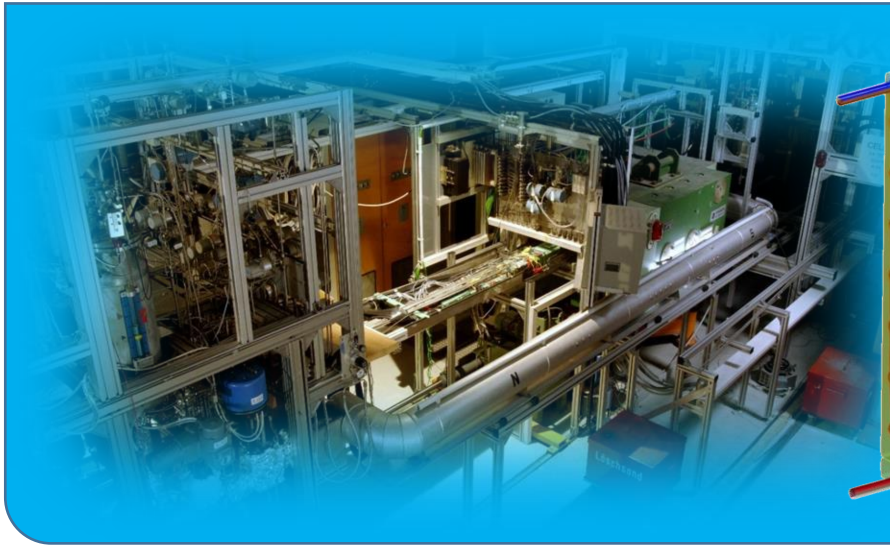
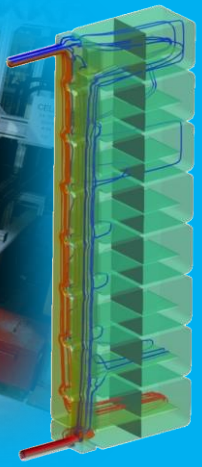
# Liquid metal MHD research at KIT

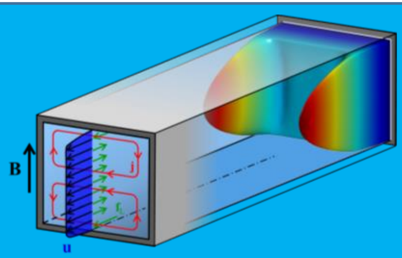
## Fundamental phenomena and flows in complex blanket geometries

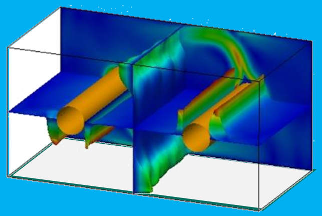

**L. Bühler, and**

**H. J. Brinkmann, C. Courtessole, V. Klüber, C. Koehly, B. Lyu, C. Mistrangelo, J. Roth**

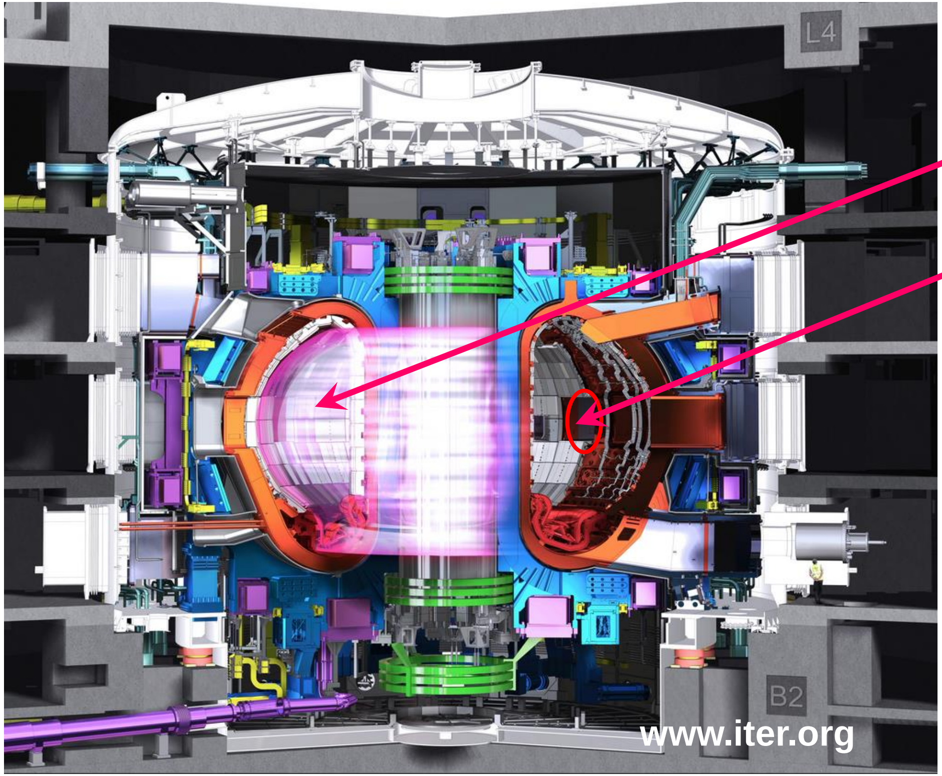







# Motivation – applications in nuclear fusion




*International Thermonuclear Experimental Reactor ITER*

**Fusion plasma in magnetic confinement**

**Blankets around plasma**

- ❑ shielding of radiation
- ❑ breeding of tritium
- ❑ conversion of nuclear power
- ❑ heat removal

**with liquid metal PbLi as breeder and coolant**

**Magnetohydrodynamics (MHD)**

# Overview

## Motivation

## Liquid metal magnetohydrodynamic (MHD) flows

- phenomena
- equations and parameters

## MHD research at Karlsruhe Institute of Technology KIT

- facilities MEKKA and MaPLE supporting theoretical analyses

## Some results

- duct or pipe flow
  - applied example, technological development
  - fundamental research
- Work related WCLL blankets
  - basic research
  - blanket engineering

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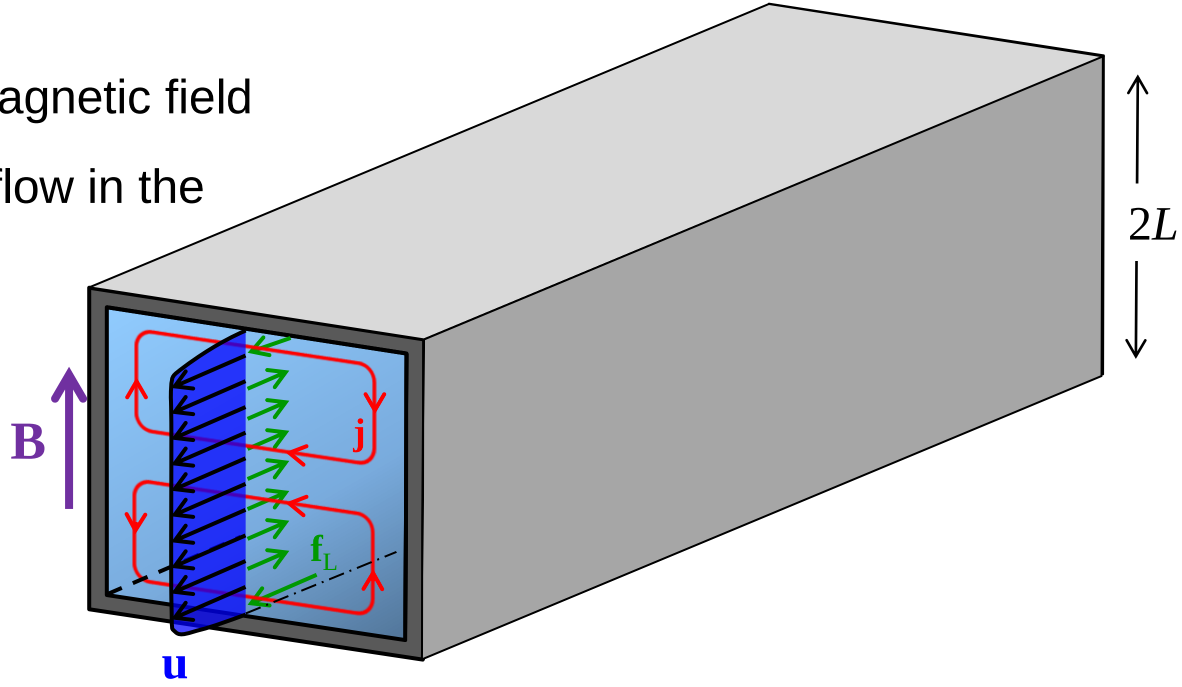
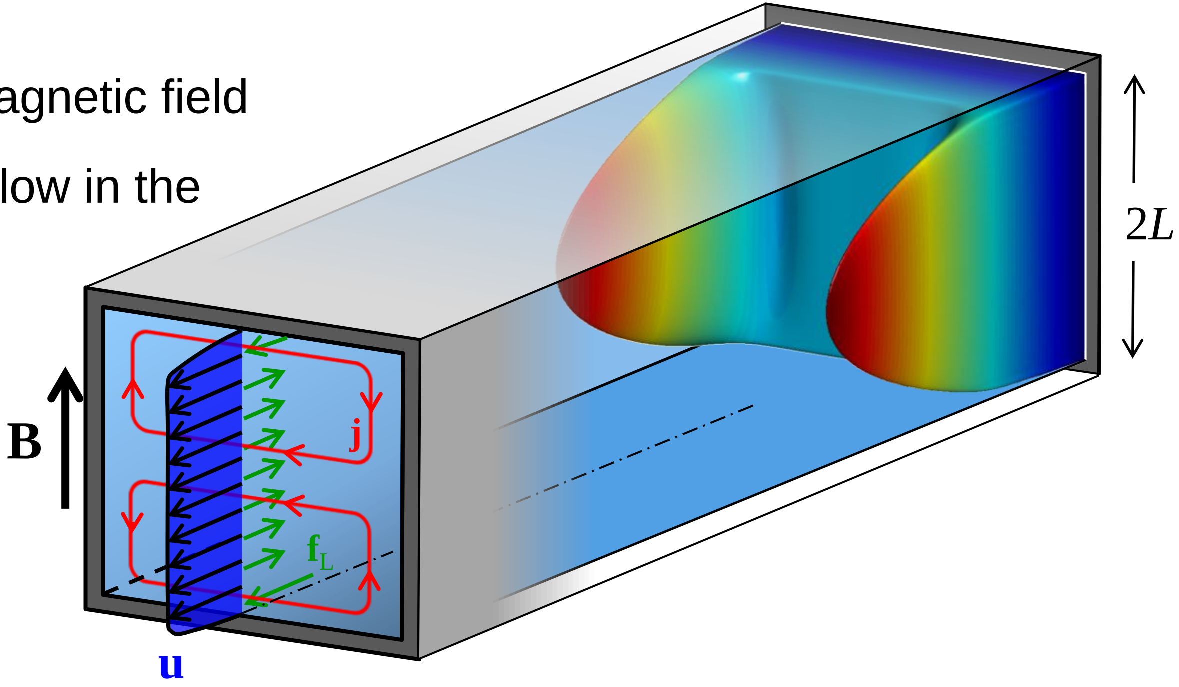
# MHD Phenomena

- Liquid metal flow in a duct
- Flow-induced currents in magnetic field
- Lorentz force opposes the flow in the core → large $\Delta p$



# MHD Phenomena

- ❑ Liquid metal flow in a duct
- ❑ Flow-induced currents in magnetic field
- ❑ Lorentz force opposes the flow in the core → large $\Delta p$
- ❑ Strange velocity profiles
  - ❑ uniform core
  - ❑ thin boundary layers
  - ❑ jets on side walls possible



# Governing equations

Momentum $\rho\left(\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = -\nabla p + \rho\nu\,\nabla^2\mathbf{u} + \mathbf{j}\times\mathbf{B}$

Lorentz force $\mathbf{f}_\mathrm{L}$

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

flow-induced electric field

Ohm's law $\mathbf{j}/\sigma = -\nabla\phi + \mathbf{u}\times\mathbf{B}$

Charge conservation $\nabla\cdot\mathbf{j} = 0$

→ with proper scales for length $L$, velocity $U$, magnetic field $B_0$

# Governing equations, nondimensional

Karlsruhe Institute of Technology

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

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

Ohm's law $$\mathbf{j} = -\nabla\phi + \mathbf{u}\times\mathbf{B}$$

Charge conservation $$\nabla\cdot\mathbf{j} = 0$$

# Parameters

*Interaction parameter* $N = \frac{\sigma L B_0^2}{\rho U}$ *Hartmann number* $Ha = L B_0 \sqrt{\frac{\sigma}{\rho \nu}}$

# Parameters in fusion

Karlsruhe Institute of Technology

*Interaction parameter* $N = \frac{\sigma L B_0^{\ 2}}{\rho U} = \frac{\text{electromagnetic force}}{\text{inertia force}} \approx 10^3 - 2\times 10^5$ *)

*Hartmann number* $Ha = L B_0 \sqrt{\frac{\sigma}{\rho \nu}} = \sqrt{\frac{\text{electromagnetic force}}{\text{viscous force}}} \approx 6\times 10^3 - 3\times 10^4$ *)

**→ electromagnetic force is dominant !!**



*) M. Abdou et al. *Fusion Engineering and Design,* **2015**, 100, 2–43

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  - ❑ applied example, technological development
  - ❑ fundamental research
- ❑ Work related WCLL blankets
  - ❑ basic research
  - ❑ blanket engineering

# MHD platform at KIT: MEKKA & MaPLE

- **MEKKA and MaPLE are unique and complementary facilities** for addressing MHD challenges for liquid metal blankets
  - fusion relevant MHD parameter range
  - big experimental volume for complex geometries
  - experiments for combined MHD and buoyancy effects
- **Fundamental experiments in generic geometries for**
  - improving the understanding of coupled multiphysics phenomena
  - provide insight for blanket designers
- **Development of predictive tools and validation**
  - extension of benchmark database by experiments
- **Technological development under prototypical conditions**
  - test measuring techniques
  - development and test of insulating flow channel inserts (FCI), etc.
- **Validation of design concepts for liquid metal blankets (mock-up tests)**

# MEKKA

**M**agnetohydrodynamische **E**xperimente mit Natrium **K**alium **KA**rlsruhe

# MEKKA

## Liquid metal loop

- Model fluid: eutectic sodium-potassium ($Na_{22}K_{78}$ used as model fluid)
- Inventory 200 l, pump (9 bar, 25 $m^3/h$), thermostat, instrumentation, …
- Advantage of *NaK*: operate at room temperature
  - thermoelectric perturbations are minimized → highly accurate results
  - high ($\sigma/\rho$) → fusion relevant parameters at available magn. field

### Parameters

*Interaction parameter* $N = \frac{\sigma}{\rho}\frac{LB_0^{\ 2}}{U}$

*Hartmann number* $Ha = LB_0\sqrt{\frac{\sigma}{\rho\nu}}$

# MEKKA

## Liquid metal loop

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## Big dipole magnet

- Maximum field: 2.1 T
- Large volume of uniform magnetic field: $800 \times 480 \times 165\ mm^3$
  - experiments in large and complex geometries such as blanket mock-ups

# MaPLE

## MagnetohydrodynamicPbLi Experiments

# MaPLE

- **Built and first operated at UCLA**
  - PbLi flows under transverse magnetic field (prototypical fluid)
- **Upgraded with EUROfusion**
  - for combined MHD and buoyancy effects
- **Main components**
  - PbLi loop (up to 450°C), storage tank (70 l), pump (6 bar, 7.2 $m^3/h$), air cooler (70 kW), ….

# MaPLE

- **Built and first operated at UCLA**
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  - PbLi loop (up to 450°C), storage tank (70 l), pump (6 bar, 7.2 $m^3/h$), air cooler (70 kW), ….
  - Dipole magnet (20 ton, 2 T) with hydraulic positioning frame for various orientations

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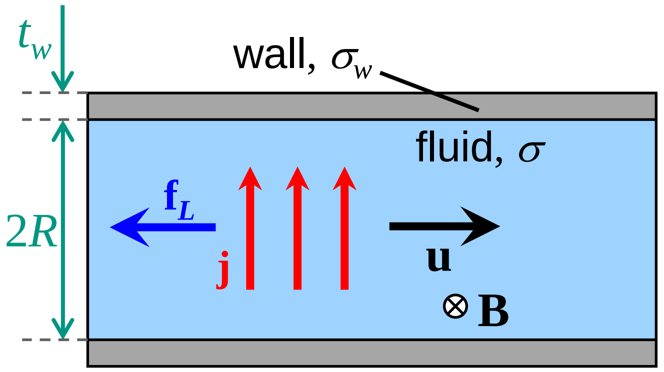
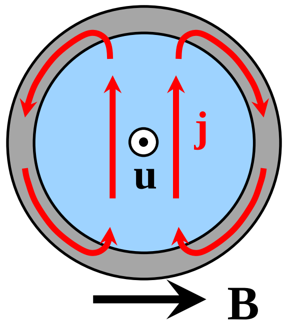
# Insulating Flow Channel Inserts FCIs

# for pressure drop reduction

# MHD flows in conducting and insulating pipes




Chang & Lundgren, 1961; Miyazaki et al., 1983




**Currents find shortcut through walls**

→ high current density **j**

→ strong Lorentz force $\mathbf{f}_L$

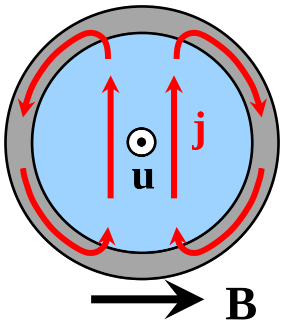
→ large pressure drop $\nabla p \sim \sigma U B_0^2$

**Example in fusion** (PbLi pipe flow: $R$=0.1m, $U$=0.1m/s, $B$=4T, → $Ha \sim 9000$)

| perfectly conducting wall | thin wall, $t_w/R$=0.2 | insulating wall |
|---|---|---|
| $\frac{\partial p}{\partial x} \approx 14 \frac{\text{bar}}{\text{m}}$ | $\frac{\partial p}{\partial x} \approx 3 \frac{\text{bar}}{\text{m}}$ | $\frac{\partial p}{\partial x} \approx 2 \times 10^{-3} \frac{\text{bar}}{\text{m}}$ |

→ insulation is a key for good MHD performance

# MHD flows in conducting and insulating pipes

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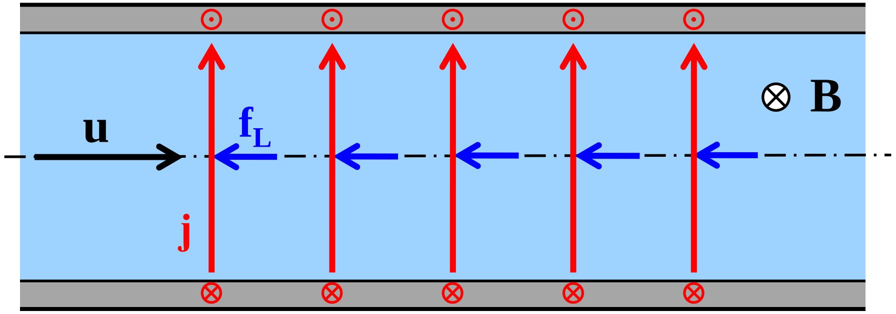
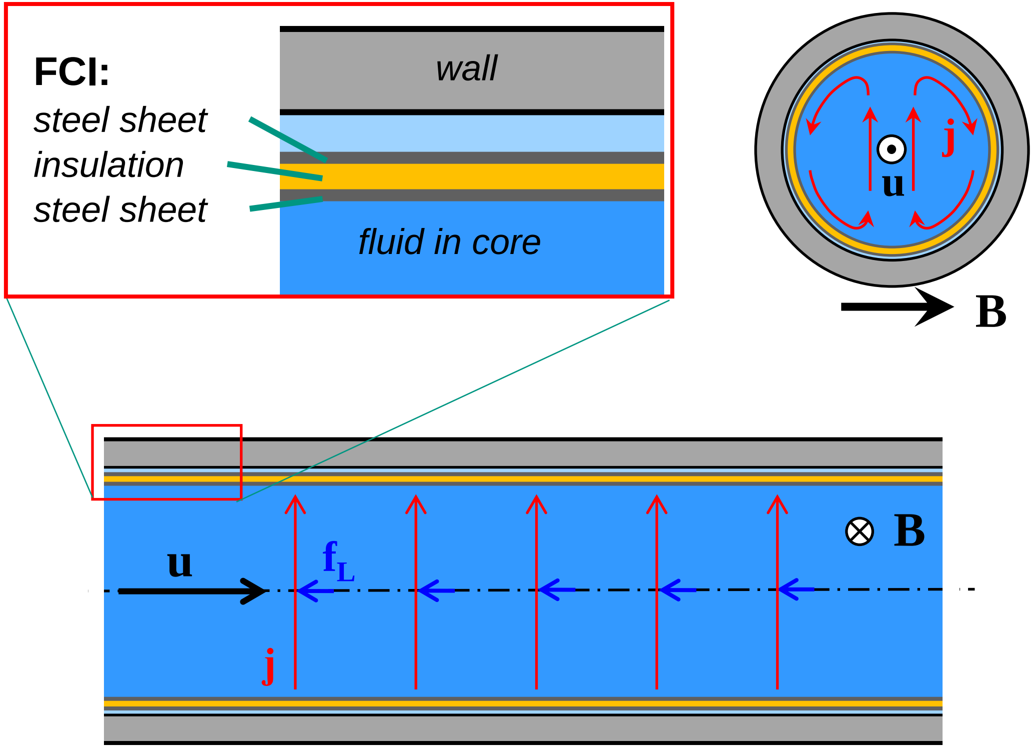


# MHD flows in conducting and insulating pipes




## Sandwich – type FCI

→ insulation is protected by thin sheets

→ FCI fabricated and tested at KIT

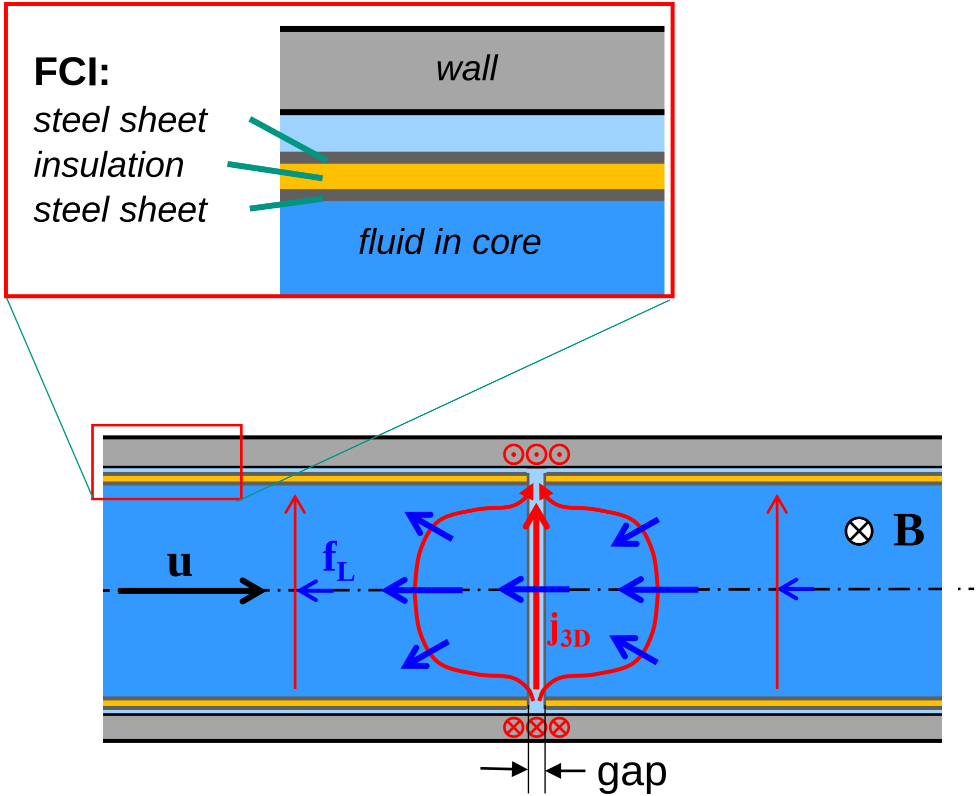
Koehly et al. *Fusion Science and Technology*, **2017**, 72, 660

## Insulating Flow Channel Inserts (FCI)

→ interrupt currents into the wall

→ reduce pressure drop

# MHD flows in conducting and insulating pipes




## Sandwich – type FCI

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## Insulating Flow Channel Inserts (FCI)

→ interrupt currents into the wall

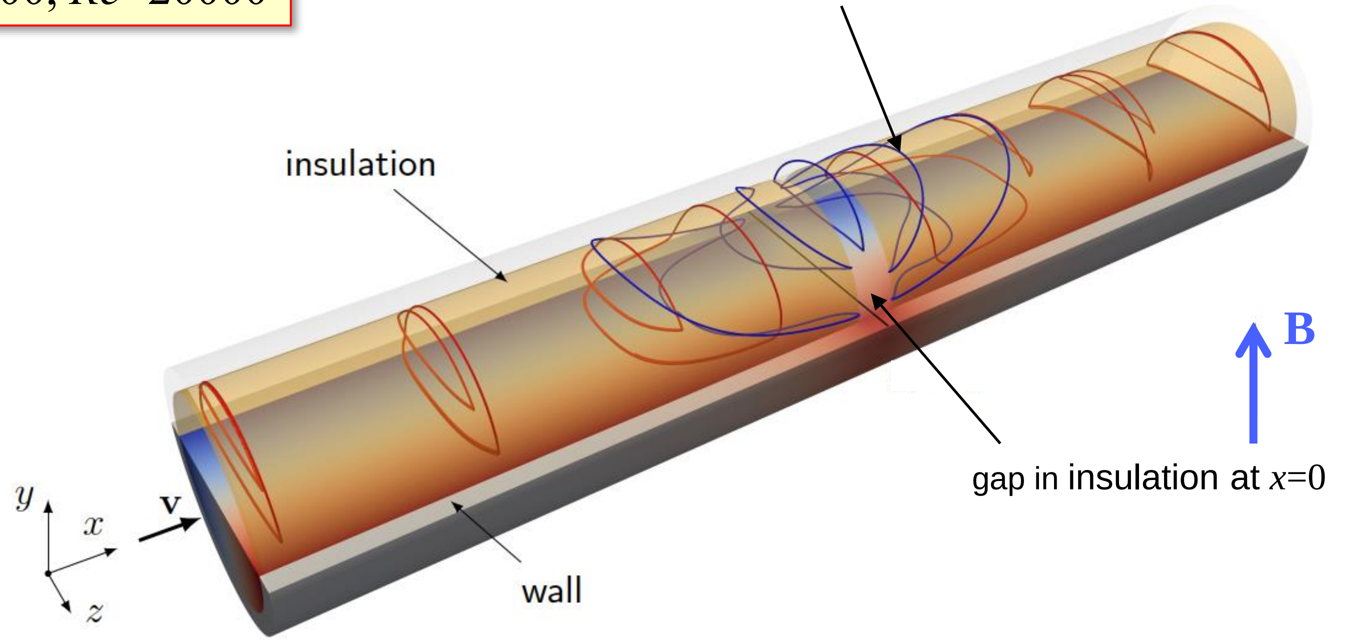
→ reduce pressure drop

→ **gaps between two FCI**

- local leakage currents $\mathbf{j}_{3D}$
- strong local 3D effects

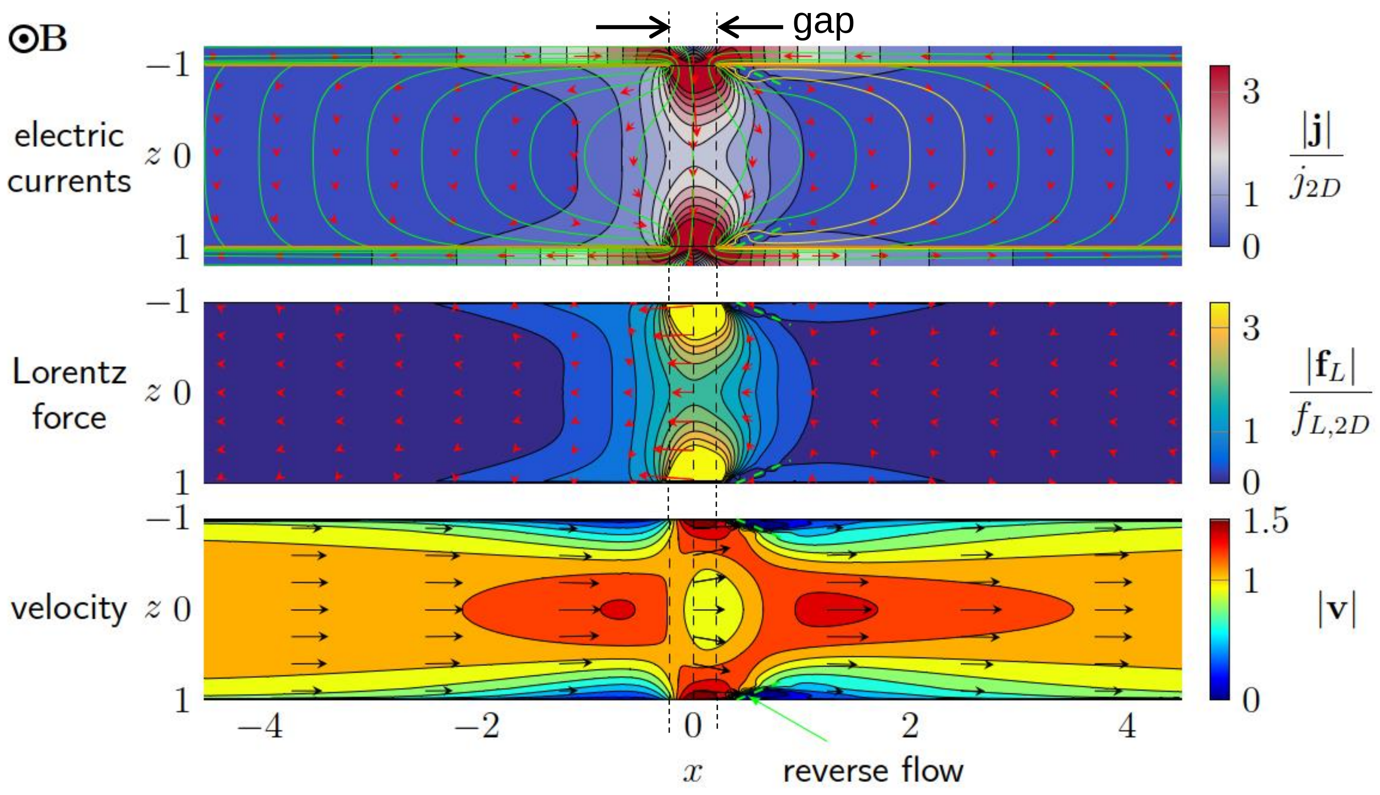
# 3D effects at gaps between two FCIs

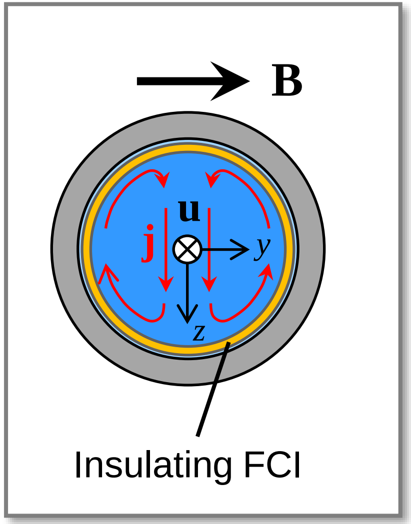
$Ha$=2000, $Re$=20000




**Electric currents and potential near an axial gap between two FCIs**

# 3D effects at gaps between two FCIs

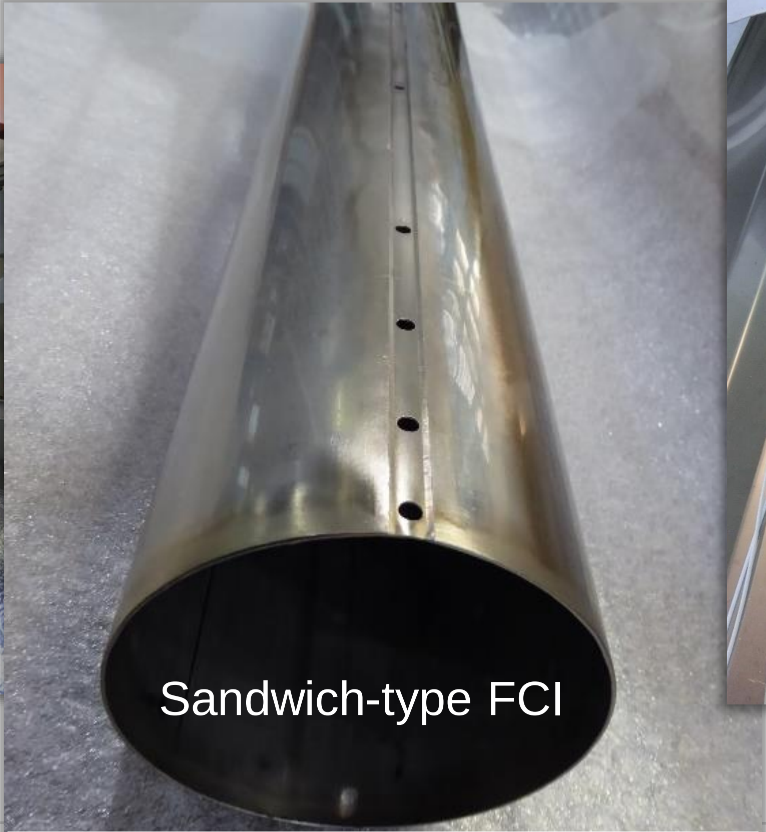



**Flow properties in horizontal symmetry plane** $y = 0$

# Gaps between two FCIs, experiments in MEKKA

Installed in MEKKA loop



Sandwich-type FCI

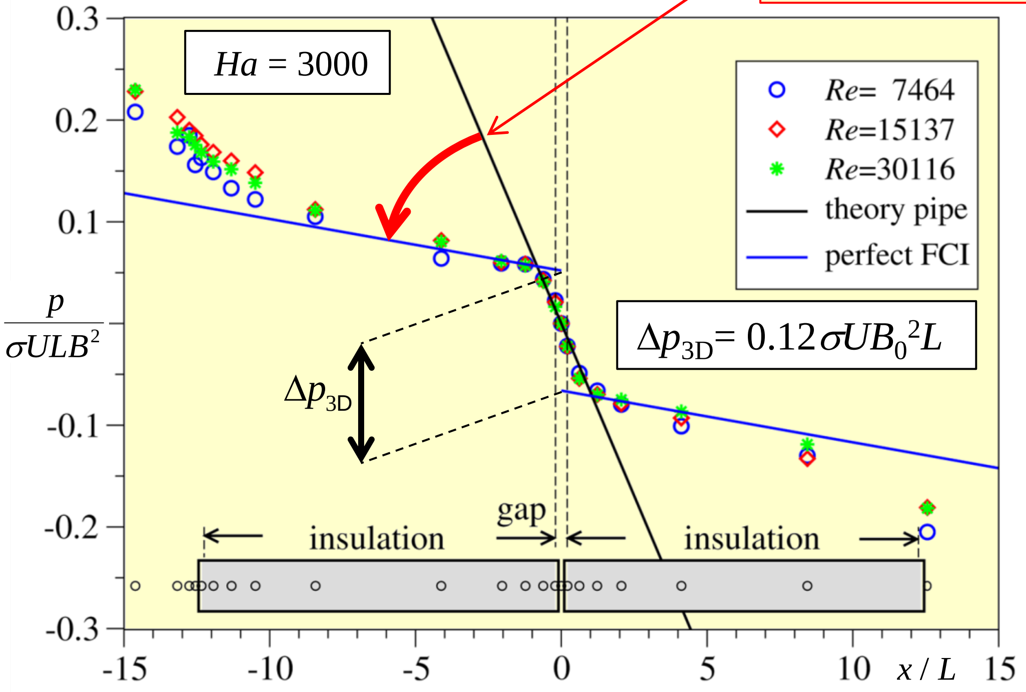
Koehly et al. *Fusion Science and Technology*, **2017**, 72, 660

Instrumented test section

# Gaps between two FCIs, experiments in MEKKA

**Experimental data**

Pressure drop reduction compared to bare pipe flow by factor of 13.3




Pressure distribution $p(x,Re)$ near a junction between two FCIs

## Experiments confirm

- ❑ reduction of pressure gradient for fully developed flow by a factor 13
- ❑ 3D effects near gap between FCIs
- ❑ locally increased pressure drop $\Delta p_{3D}$
- ❑ scaling law for $\Delta p_{3D}$ confirmed for a wide range of $Re$ and $Ha$



Bühler et al. *Fusion Engineering and Design*, **2019**, *146*, 1399

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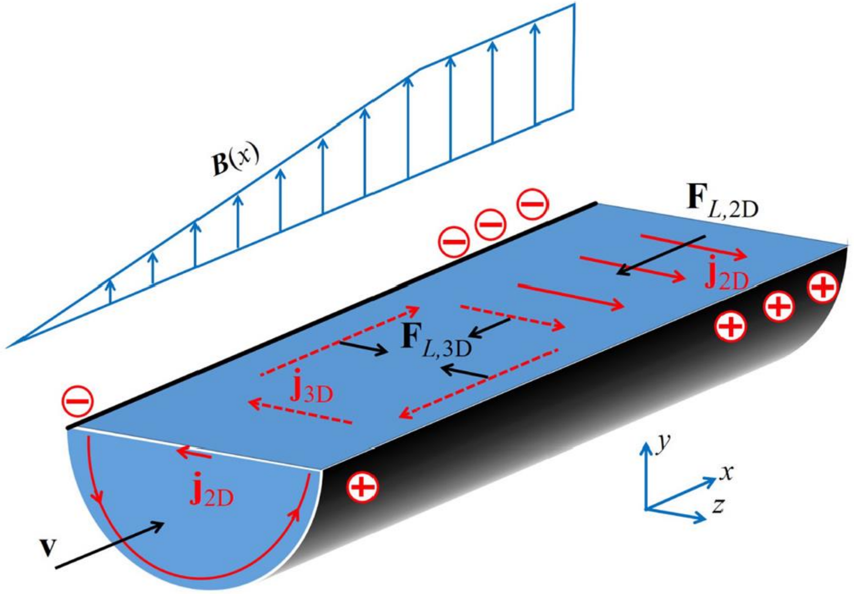
- ❑ **duct or pipe flow**
  - ❑ applied example, technological development
  - ❑ **fundamental MHD problem**
- ❑ Work related WCLL blankets
  - ❑ basic research
  - ❑ blanket engineering

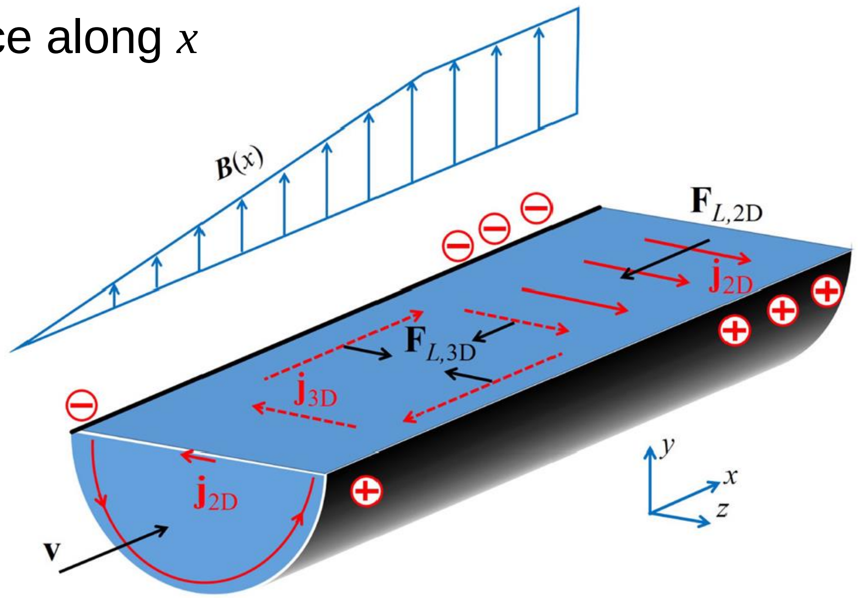
# MHD flow in a non-uniform magnetic field B(x)



# Flow in non-uniform B-field

## Flow into a magnet

- ❑ turbulent flow at high *Re* entering a magnet
- ❑ increasing transverse potential difference along *x*
  - → 3D current loops
  - → extra Lorentz forces






complementary to Picologlou & Reed, *Kluwer*, **1989**, 71-77

# Flow in non-uniforr

## Flow into a magnet

- turbulent flow at high *Re* enter
- increasing transverse potentia
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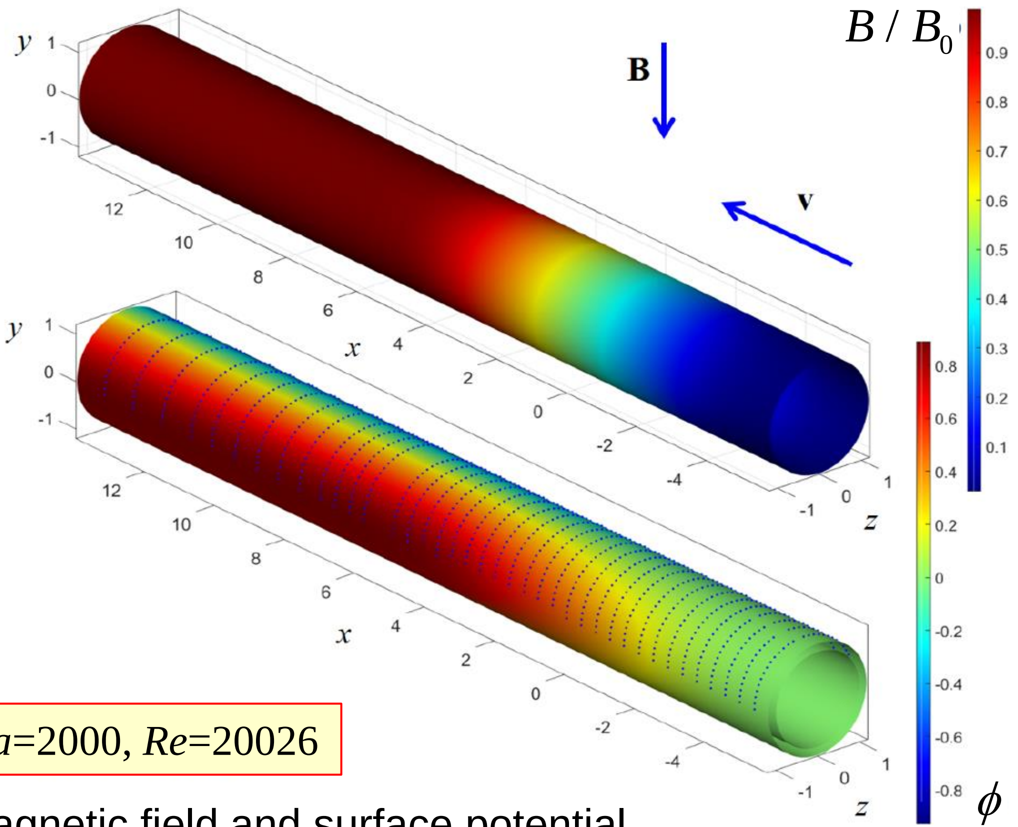
- experiments
  - → yield potential data on surface

**MEKKA experiment at KIT**




Magnetic field and surface potential

# Flow in non-uniform B-field

## Flow into a magnet

- turbulent flow at high *Re* entering a magnet
- increasing transverse potential difference along $x$
  - → 3D current loops
  - → extra Lorentz forces
- experiments
  - → yield potential data on surface
- asymptotic theory
  - → reconstruction of 3D velocity from measured surface data

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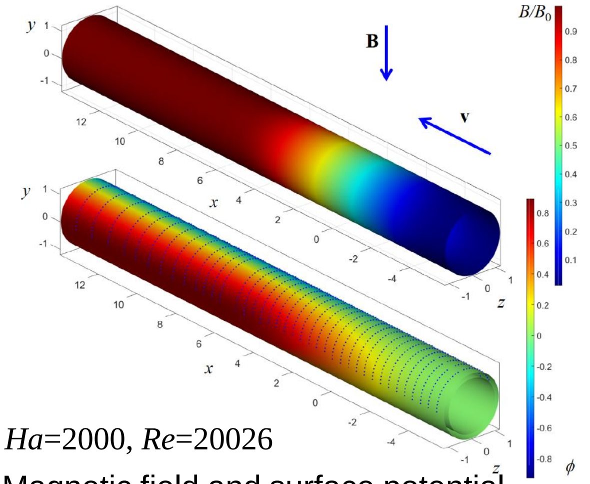


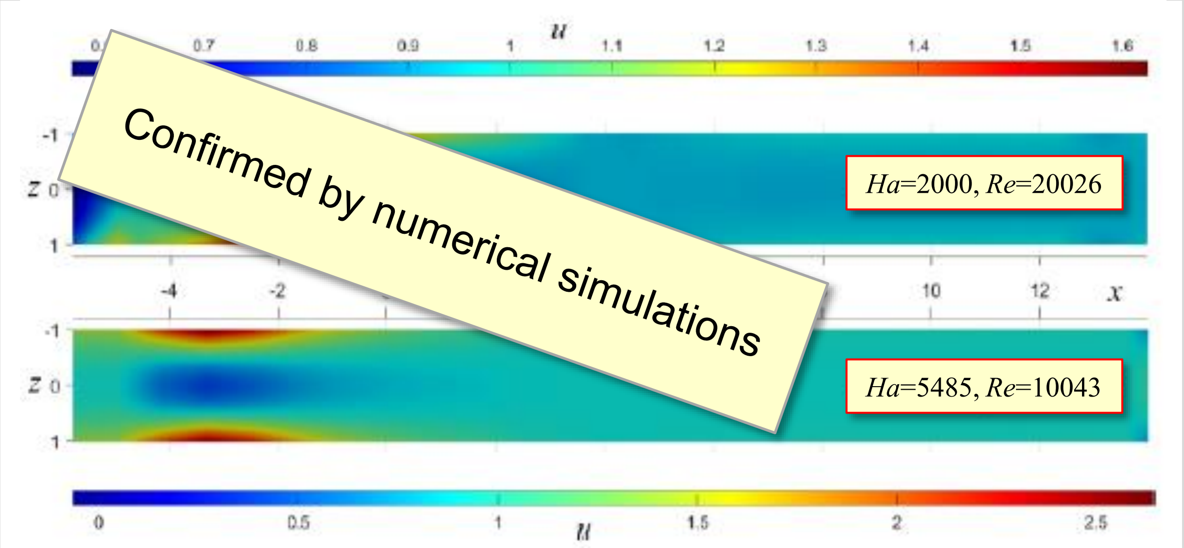

*Ha*=2000, *Re*=20026
Magnetic field and surface potential

$$u(y,z) \approx B^{-1} \frac{\partial \phi}{\partial z}$$

# Flow in non-uniform B-field

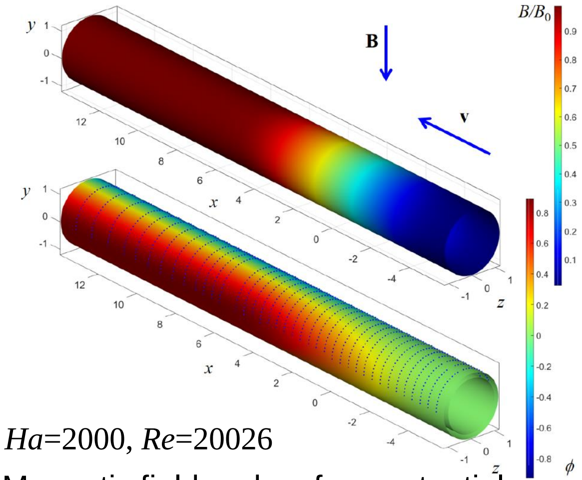
**near entrance to B-field**

- ❑ high velocity at sides
- ❑ reduced velocity in center




Velocity distribution at $y$=0 reconstructed from experimental data

**MEKKA experiment at KIT**

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Magnetic field and surface potential

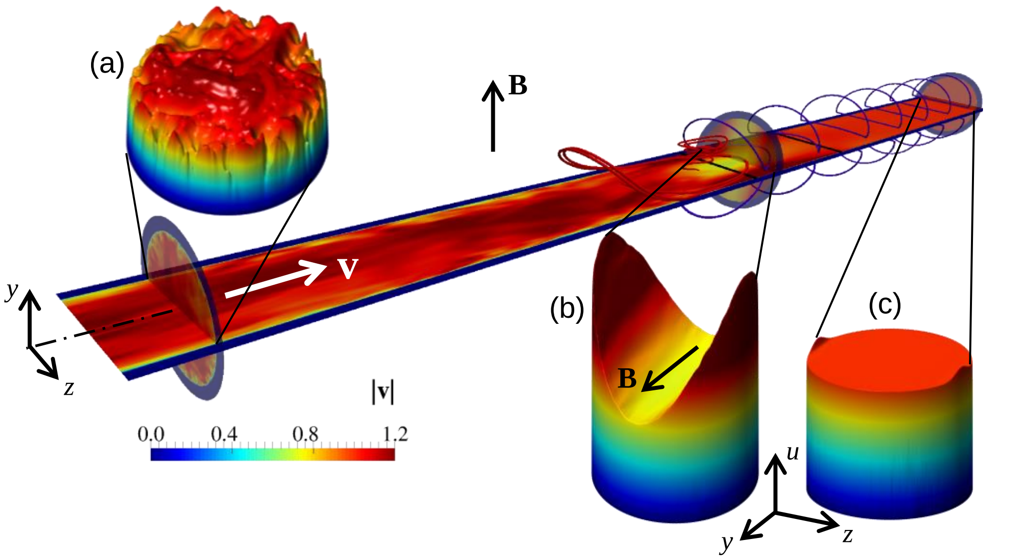
$$u(y,z) \approx B^{-1}\frac{\partial \phi}{\partial z}$$



Bühler et al. *Fusion Engineering and Design*, **2021**, 168, 112590

# Flow in non-uniform B-field

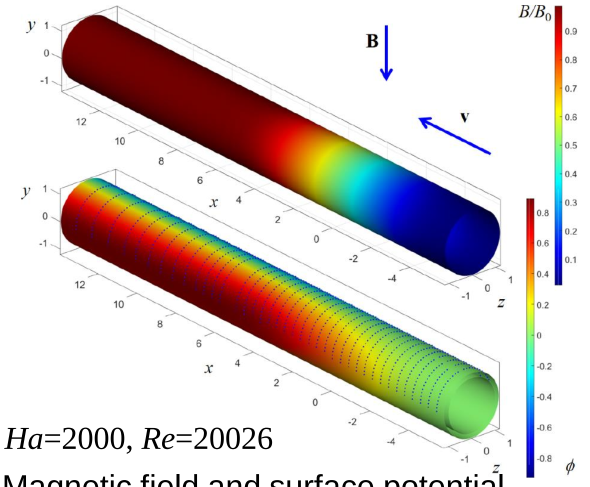
Numerical simulation of turbulent flow entering a magnetic field




Current lines and velocity profiles for *Ha*=2000, *Re*=20000

Klüber et al. Fusion Engineering and Design, **2020**, 156, 111659

## MEKKA experiment at KIT

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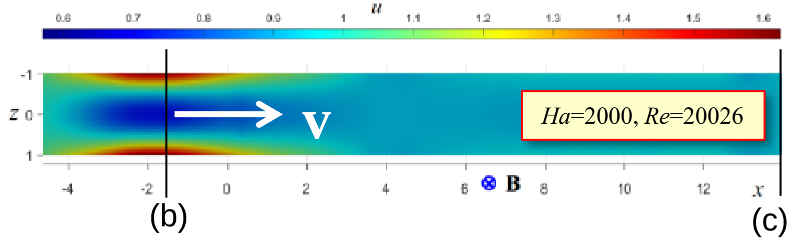


Velocity at *y*=0 reconstructed from experimental data

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Karlsruhe Institute of Technology

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# Magneto convective heat transfer at cooling pipes



Leo Bühler and KIT MHD Team

# Magneto-convection

Karlsruhe Institute of Technology

**Experimental and theoretical results are available for**

- ❑ Rayleigh – Bénard convection (differentially heated horizontal layer of fluid)
- ❑ differentially heated vertical gap
- ❑ heat transfer in pipe and duct flow

Zikanov et al. Mixed convection in pipe and duct flows with strong magnetic fields, *Applied Mechanics Reviews*, **2021**, 73, 010801-1-35

**Lack of knowledge on**

- ❑ MHD flows around obstacles with heat transfer (cooling pipes)

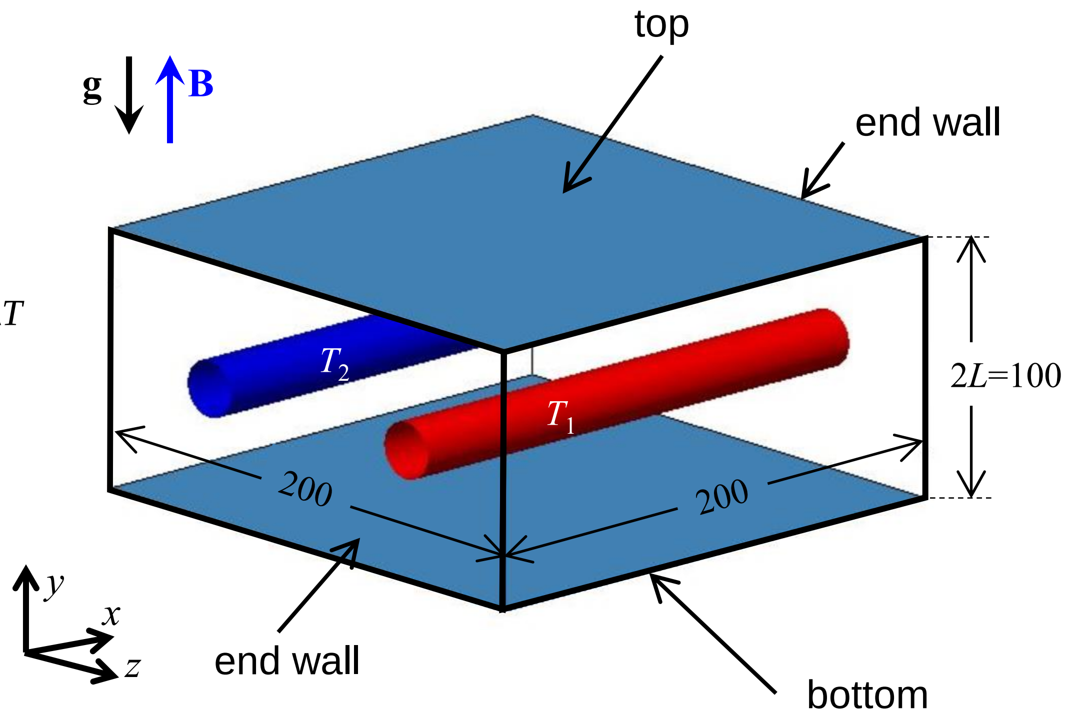
  → need for analyses → definition of a generic problem

# Magneto-convection around obstacles

## Definition of generic problem

- adiabatic box filled with GaInSn
- electrically insulating walls
- differentially heated cylinders $T_{1,2} = \bar{T} \pm \Delta T$
- Parameters:

$$Gr = \frac{g\beta\Delta T L^3}{\nu^2},\ Ha = BL\sqrt{\frac{\sigma}{\rho\nu}}$$

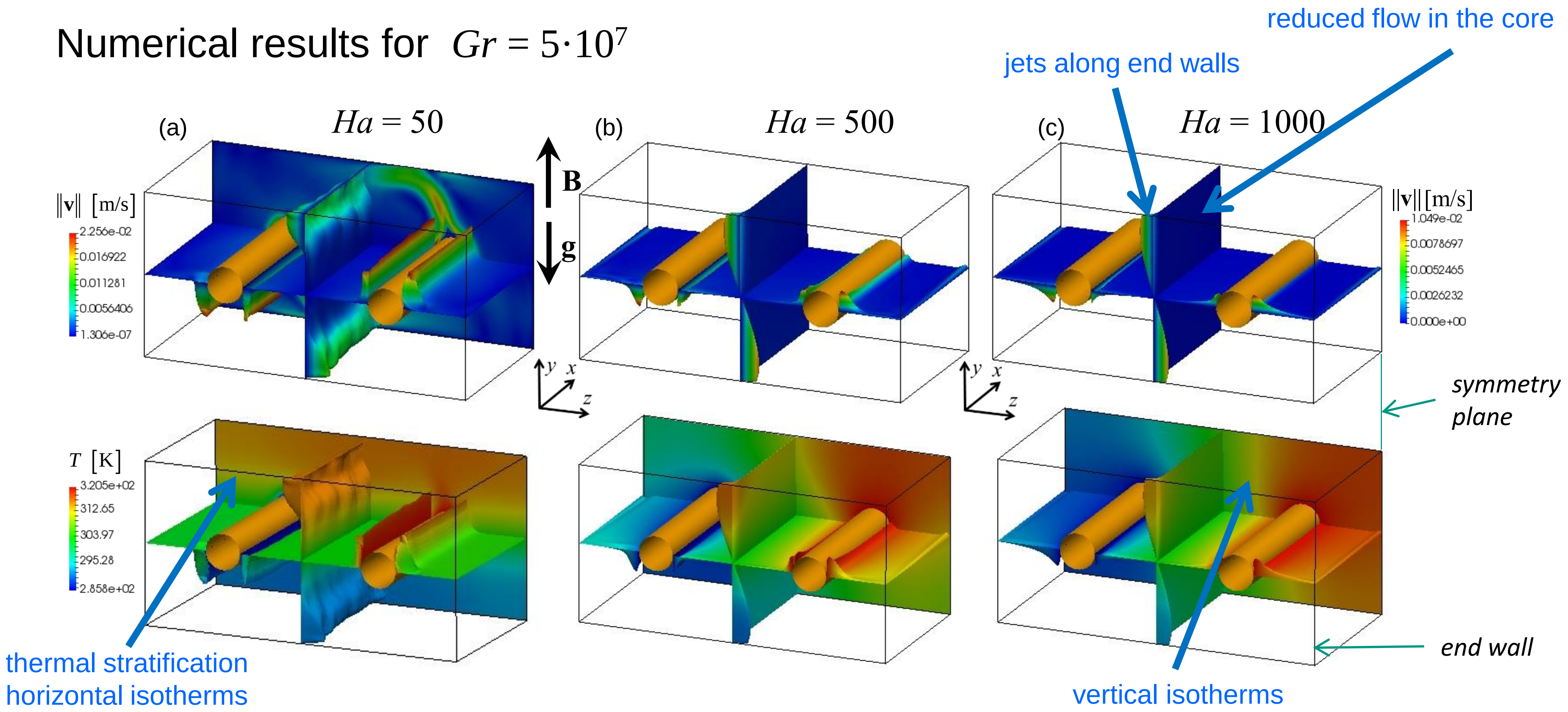





Koehly et al. *Fusion Science and Technology*, **2019**, 75, 1010

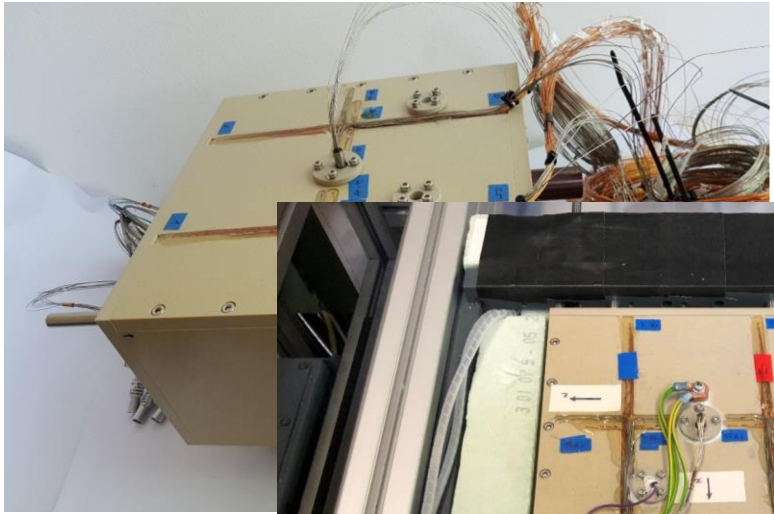
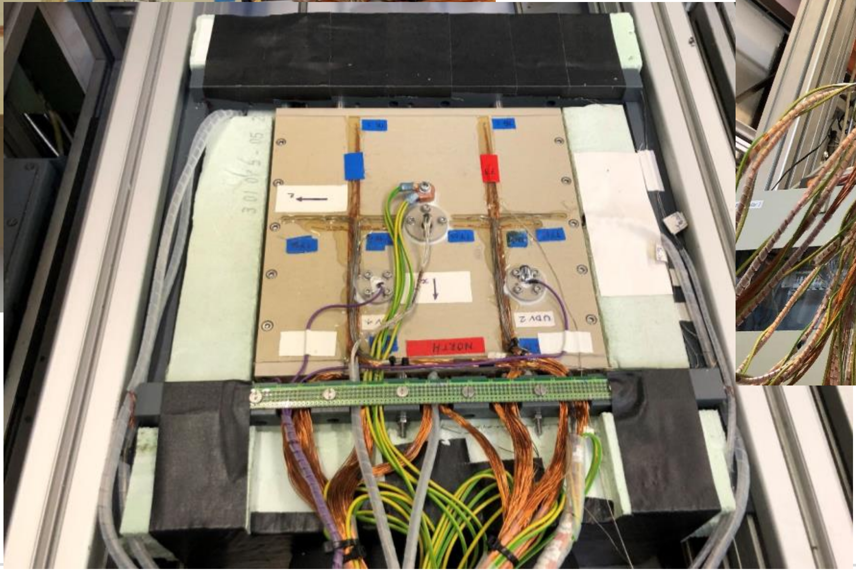
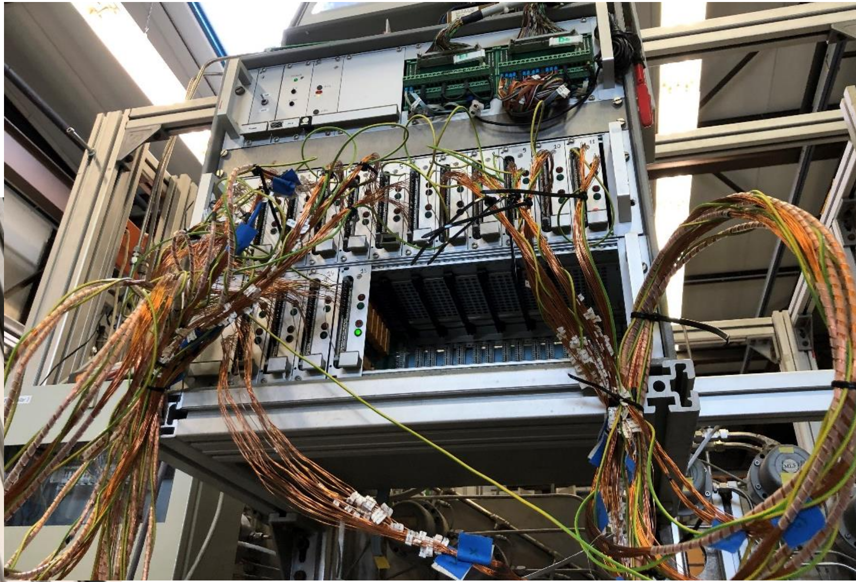
# Magneto-convection around obstacles

Numerical results for $Gr = 5 \cdot 10^7$



# Magneto-convection around obstacles

## Experiments

# Magneto-convection around obstacles

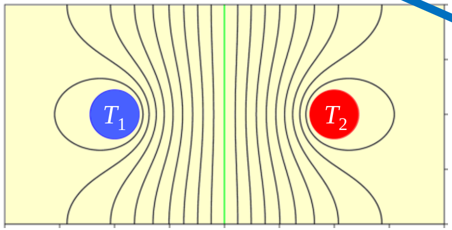
## Heat transfer quantified by Nusselt number

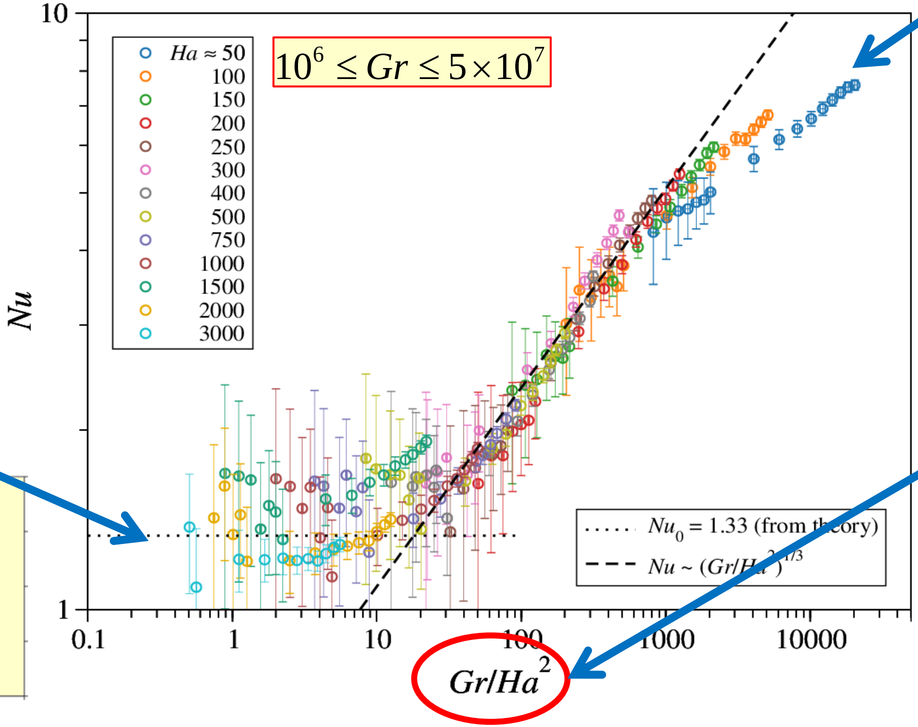
$$q'' = h\,\Delta T$$

$$Nu = \frac{hL}{k}$$

vertical isotherms
heat conduction

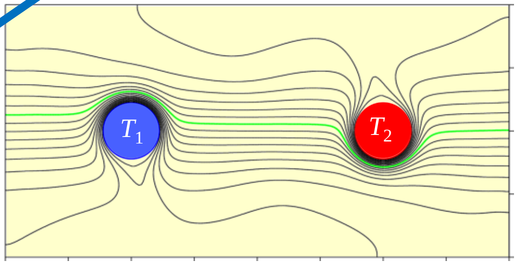
**-- no flow --**




thermal stratification
horizontal isotherms

**-- strong convection --**




results depend on combination of *Gr* and *Ha*

$$\frac{Gr}{Ha^2} = \frac{\text{buoyancy force}}{\text{electromagnetic force}}$$



Courtessole et al, **2023** submitted to *Journal of Fluid Mechanics*

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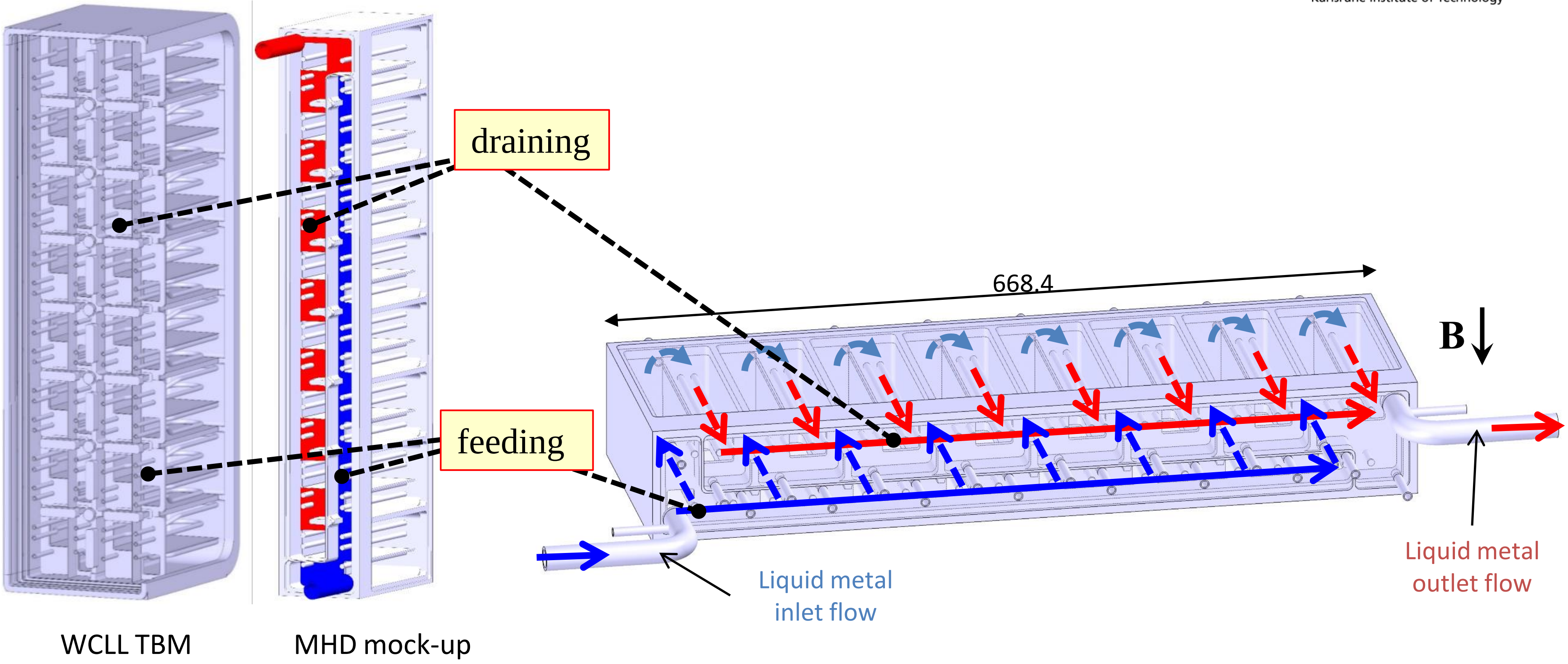
# Flow in a complex WCLL TBM-like geometry

# TBM mock-up in MEKKA






Koehly et al. *Fusion Engineering and Design*, **2023**, 192, 113753

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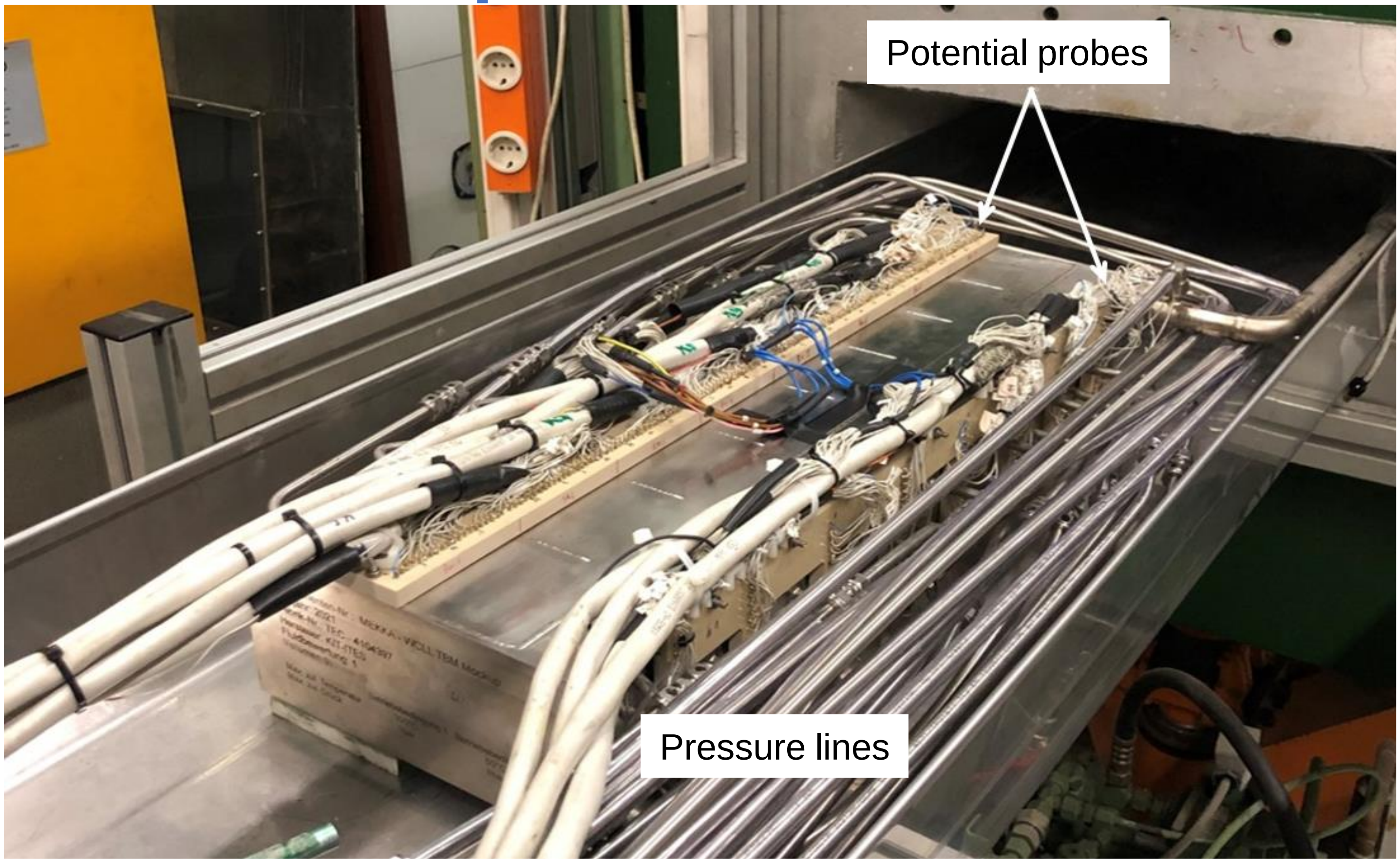




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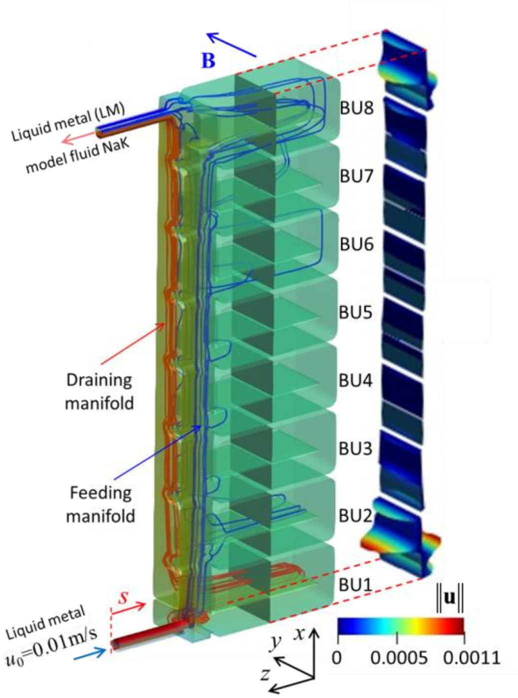
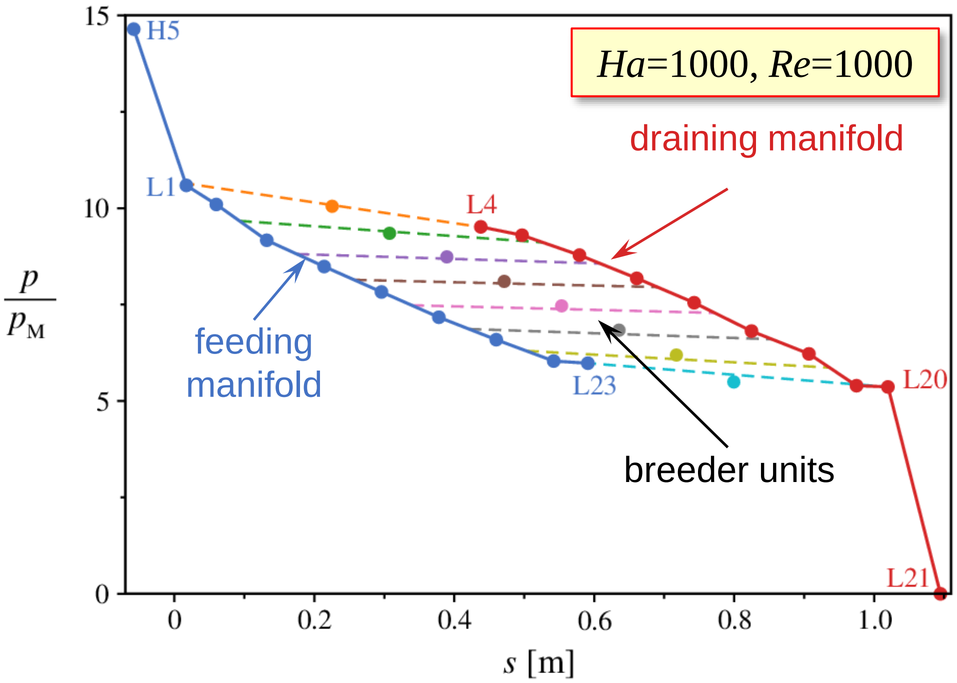
# Experiments in MEKKA and simulations

Karlsruhe Institute of Technology




Numerical simulation: Flow paths along manifolds and BUs and radial velocity profiles in middle plane

Measured pressure distribution along typical flow paths

Mistrangelo et al. *Fusion Engineering and Design*, **2023**, 193, 113752

Courtessole et al. **2023** *this conference*, PS-135

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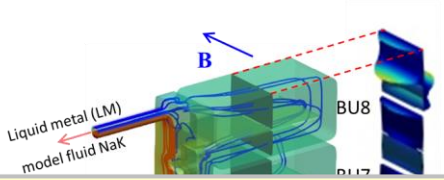


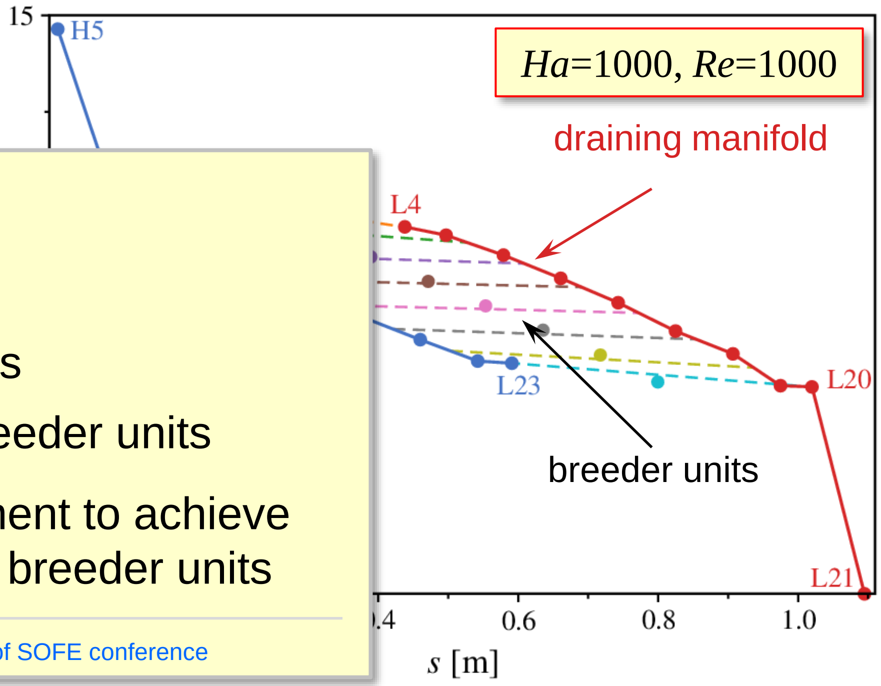


**Results**

- total pressure drop is acceptable
- major pressure drop occurs in manifolds
- non-uniform flow distribution among breeder units
- suggestions made for design improvement to achieve more homogeneous flow partitioning in breeder units

Bühler & Mistrangelo, 2023 *IEEE Transactions on Plasma Science*, Proc. of SOFE conference

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# Summary and future plans

## MHD research at Karlsruhe Institute of Technology KIT

- MEKKA and MaPLE
- Development of predictive tools
- Study of MHD flows for fusion relevant parameters
  - basic research
  - applied engineering problems

## Outlook

- Full commissioning of MaPLE
  - first experiments in a circular pipe → pressure drop → potential data, → $\mathbf{B}(x)$
  - mixed convection MHD heat transfer → horizontal, inclined, vertical ducts
- Scaled blanket mock-up test in MEKKA magnet with PbLi from MaPLE

**Results will support theoretical developments and blanket engineering**

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