Magnetohydrodynamic flow in the helium-cooled lead-lithium test blanket for ITER.

Mock-up experiments, comparison with numerical simulations and further requirements on the way to ITER

L. Bühler, S. Horanyi, C. Mistrangelo

- Helium cooled lead lithium blanket
- Mock-up experiments
- Numerical simulations
- Summary & conclusions
Liquid metal flows in fusion blankets

**Blanket**
- Radiation shielding
- Breeding of tritium
  \[ ^6\text{Li} + \text{n} \rightarrow \text{He} + \text{T} + \text{energy} \]
- Cooling of the first wall
- Conversion of nuclear power
- Heat removal

Requirements can be accomplished with Li-containing liquids as breeder and coolant

International Thermonuclear Experimental Reactor
\[ \Rightarrow \text{Magnetic confinement of plasma} \]

**Liquid metal magnetohydrodynamics (MHD)**
Magnetohydrodynamic equations

Conservation of

– Momentum

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

– Mass & Charge

\[
\nabla \cdot \mathbf{v} = 0, \quad \nabla \cdot \mathbf{j} = 0
\]

Ohm’s law

\[
\mathbf{j} = -\nabla \phi + \mathbf{v} \times \mathbf{B}
\]

Dimensionless groups

**Interaction parameter**

\[
N = \frac{\sigma L B^2}{\rho u_0}
\]

el. magn. force

\[\text{inertia force}\]

**Hartmann number**

\[
Ha^2 = \frac{\sigma L^2 B^2}{\rho \nu}
\]

el. magn. force

\[\text{viscous force}\]

**Reynolds number**

\[
Re = Ha^2 / N
\]

\[\text{inertia force} / N \]

\[\text{viscous force}\]

Fusion (ITER)

\[N \approx 10^5\]

\[Ha \approx 10^4\]
**Helium Cooled Lead Lithium Blanket**

**HCLL is a Separately-cooled blanket**
- Liquid metal is used only as breeder
- Heat is removed by helium

**HCLL blanket features**
- Modular concept
- Stiffening plates form a grid of rectangular cells → breeder units (BU)
Helium Cooled Lead Lithium Blanket

Blanket ↔ MHD issues

- Gap at BP → ♦ Change of cross-section
  ♦ Expansion along $B$ lines
- Rectangular ducts → ♦ High aspect ratio
  ♦ Leak of currents

Diagram:
- First wall (FW)
- Back plate (BP)
- He inlet pipe and manifold
- PbLi inlet gap
- Cooling plates (CP)
- Pol
- Rad
- Tor
Helium Cooled Lead Lithium Blanket

Blanket ↔ MHD issues

- Gap at BP → ♦ Change of cross-section
  ♦ Expansion along B lines
- Rectangular ducts → ♦ High aspect ratio
  ♦ Leak of currents
- Gap at FW → ♦ Inertia effects
Helium Cooled Lead Lithium Blanket

**Blanket ↔ MHD issues**

- **Gap at BP**
  - ♦ Change of cross-section
  - ♦ Expansion along $B$ lines

- **Rectangular ducts**
  - ♦ High aspect ratio
  - ♦ Leak of currents

- **Gap at FW**
  - ♦ Inertia effects
Helium Cooled Lead Lithium Blanket

Blanket ↔ MHD issues

- Gap at BP → ♦ Change of cross-section
  ♦ Expansion along B lines
- Rectangular ducts → ♦ High aspect ratio
  ♦ Leak of currents
- Gap at FW → ♦ Inertia effects
- Manifolds → ♦ High velocity
  ♦ Long path
- Circular pipes
Helium Cooled Lead Lithium Blanket

Blanket $\leftrightarrow$ MHD issues

- Gap at BP $\rightarrow$ ♦ Change of cross-section
  ♦ Expansion along $B$ lines
- Rectangular ducts $\rightarrow$ ♦ High aspect ratio
  ♦ Leak of currents
- Gap at FW $\rightarrow$ ♦ Inertia effects
- Manifolds $\rightarrow$ ♦ High velocity
  ♦ Long path
- Circular pipes
- Electric flow coupling

- Flow distribution (corrosion, tritium permeation)
- Pressure drop
HCLL mock-up experiments

MHD model experiments for ITER test blanket module
HCLL mock-up experiments

- Mock-up scaled 1:2 compared to original TBM (4 breeder units)
- Model fluid: sodium potassium alloy NaK ($\sigma = 2.88 \times 10^6 \, 1/\Omega m$)

Objectives

- Measurements of pressure and electric potential
- Comparison with theory
- Scaling laws for pressure
HCLL mock-up experiments

- Mock-up **scaled 1:2** compared to original TBM (4 breeder units)
- **Model fluid**: sodium potassium alloy NaK ($\sigma = 2.88 \times 10^6$ $\Omega m$)

**Manufactured mock-up**

### Experiment features

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ (tor) [mm]</td>
<td>45</td>
</tr>
<tr>
<td>$a$ (pol) [mm]</td>
<td>409</td>
</tr>
<tr>
<td>$b$ (rad) [mm]</td>
<td>173</td>
</tr>
<tr>
<td>$B_{\text{max}}$ [T]</td>
<td>2.1</td>
</tr>
<tr>
<td>$Q$ [m$^3$/h]</td>
<td>$0 \div 25$</td>
</tr>
<tr>
<td>$c = \frac{\sigma_w t_w}{\sigma L}$</td>
<td>$0.015 \div 0.026$</td>
</tr>
<tr>
<td>$Ha$</td>
<td>$0 \div 5500$</td>
</tr>
<tr>
<td>$N$</td>
<td>$10 \div 10^5$</td>
</tr>
</tbody>
</table>
Pressure measurements

Magnet

Hartmann wall

Pressure taps

Pressure pipes

Inlet pipe

Manifolds

Exit pipe

x, rad

y, pol

z, tor
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\[ Ha = 500 \]

**Pressure distribution**

**Inlet pipe and manifold**

**First Wall**

**Manifolds**

- Pressure taps

\[ Ha = 500 \]

\[ Re = 1097 \]
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\( Ha = 500 \)

Pressure distribution

- Inlet pipe and manifold
- BU1

\( Ha = 500 \)

\( Re = 1097 \)
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\[ Ha = 500 \]

Pressure distribution

Inlet pipe and manifold

BU1-BU2

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BU1</td>
<td>Inlet pipe and manifold</td>
</tr>
<tr>
<td>BU2</td>
<td>Outlet manifold</td>
</tr>
<tr>
<td>BU3</td>
<td>Pressure distribution in the mock-up</td>
</tr>
<tr>
<td>BU4</td>
<td>First Wall</td>
</tr>
</tbody>
</table>

Manifolds

- Pressure taps
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\[ Ha = 500 \]

First Wall

Manifolds

Pressure distribution

- Pressure taps
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\[ Ha = 500 \]

Pressure distribution

- Inlet manifold (B-C) \(\rightarrow\) Outlet manifold (H-I)
- First wall (E-F/M-N)
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\[ \text{Ha} = 500 \]

First Wall

Manifolds

- Inlet manifold (B-C) → Outlet manifold (H-I)
- First wall (E-F/M-N)
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\( Ha = 500 \)

Pressure distribution

- Inlet manifold (B-C) \( \rightarrow \) Outlet manifold (H-I)
- First wall (E-F/M-N)
Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\[ Ha = 500 \]

**Pressure distribution**

- \( \Delta p_{BP} \) Inlet manifold (B-C)
- \( \Delta p_{FW} \) Outlet manifold (H-I)
- \( \Delta p_{BP} \) Gap at BP (B-D)
- \( \Delta p_{FW} \) Gap at FW (E-F)

\[ \Delta p \text{ Total (A-I)} \]

- Inlet manifold (B-C) \( \rightarrow \) Outlet manifold (H-I)
- First wall (E-F/M-N)
Contributions to the total pressure drop

- Identify critical elements/locations
- Defining scaling laws

Main pressure drop in manifolds
All \( \Delta p \) contributions increase linearly with \( N^{-1} \)
For \( N^{-1} \to 0 \) inertia effects reduce
Strong inertia effects are present at the FW

\[ \Delta p_{\text{Total}} = \Delta p_{\text{M1}} + \Delta p_{\text{M2}} + \Delta p_{\text{BP}} + \Delta p_{\text{FW}} \]

\( Ha = 500 \)

- Pressure taps
- First Wall
- Manifolds

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Pressure distribution in the mock-up

- Selection of characteristic flow paths
- Measurement of pressure differences

\[ p_0 = \sigma u_0 B^2 L \]

\[ Ha = 5000 \]

- Pressure taps

For ITER conditions \( \Delta p \) is inertialess
Contributions to the total pressure drop

- Identify critical elements/locations
- Defining scaling laws

\[ \text{Re/Ha} = 5000 \]

For ITER conditions, \( \Delta p \) is inertialess.
Non-dimensional pressure drop scales as

\[ \Delta p = \Delta p_0 + A N^{-1} + B N^{-1/3} \]
Electric potential measurements

Potential $\phi$ serves for code validation, physical interpretation as hydrodynamic streamfunction.

According to Ohm’s law, $j = -\nabla \phi + \mathbf{v} \times \mathbf{B}$

with $j << 1 \Rightarrow u \approx -\frac{\partial \phi}{\partial y}, \quad v \approx \frac{\partial \phi}{\partial x}$

Color indicates electric potential on the walls.
Electric potential measurements

Potential \( \phi \) serves for code validation, physical interpretation as hydrodynamic streamfunction.

According to Ohm’s law, \( j = -\nabla \phi + v \times B \)

with \( j \ll 1 \) \( \Rightarrow \) \( u \approx -\frac{\partial \phi}{\partial y} \) \( v \approx \frac{\partial \phi}{\partial x} \)

Potential sensors

Pressure taps

MHD mock-up with instrumentation for potential measurements
Measured surface potential

Hartmann wall

Measured electric potential for $Ha = 3000, Re = 1000$

Calculated contours of potential on the MHD mock-up surface (cooling plates omitted)

Contours of measured electric potential on the MHD mock-up surface
Potential measurements indicate flow distribution
- Lines of constant color are streamlines
- Fully developed flow conditions along A-A

Assumption for numerical calculations

Measured electric potential for $Ha = 3000$, $Re = 1000$

Contours of measured electric potential on the MHD mock-up surface
Experiments and numerical results

Full electrical coupling
- 4 breeder units
- 24 sub-channels
- 96 boundary layers

Contours of measured electric potential on the MHD mock-up surface
Experiments and numerical results

Contours of calculated electric potential on the MHD mock-up middle plane (AA).

Full electrical coupling
- 4 breeder units
- 24 sub-channels
- 96 boundary layers

Contours of measured electric potential on the MHD mock-up surface
Experiments and numerical results

Comparison of potential profiles along the Hartmann wall

Contours of calculated electric potential on the MHD mock-up middle plane (AA).

Full electrical coupling

- 4 breeder units
- 24 sub-channels
- 96 boundary layers

Comparison

- Validity of FDF assumption (weak Re - dependence)
- Good quality of measuring technique for potential
Experiments and numerical results

- Comparison
  - Validity of FDF assumption (weak $Re$ - dependence)
  - Good quality of measuring technique for potential

Full electrical coupling
- 4 breeder units
- 24 sub-channels
- 96 boundary layers

Contours of calculated radial velocity on the MHD mock-up middle plane (AA).

Comparison of potential profiles along the Hartmann wall
Experiments and numerical results

Contour of calculated radial velocity on the MHD mock-up middle plane (AA).

Full electrical coupling
- 4 breeder units
- 24 sub-channels
- 96 boundary layers

Velocity
- Uniform velocities in central sub-channels of BUs
- Weak effect of cooling plates
- Higher velocity at the stiffening plates
Experiments and numerical results

Calculated current streamlines on the MHD mock-up middle plane (AA).

- Current density
  - Currents cross cooling plates:
    - Strong electric coupling through cooling plates (uniform flow partition)
  - In SPs currents flow tangentially:
    - Weak electric coupling between BUs
Conclusions

- **HCLL blanket and MHD issues:**
  Complex 3D MHD flows through geometries with different-cross sections, large aspect-ratio rectangular ducts, long manifolds, electric flow coupling
  \[ \Rightarrow \text{Influence on pressure and flow distribution} \]

- **Methods for MHD flow analysis:**
  Asymptotic method, numerical simulations, experiments
  \[ \Rightarrow \text{Application to MHD flow in fusion blankets} \]

- **Experiments in a mock-up of a HCLL blanket:**
  Measurements of pressure differences and surface electric potential for \( Ha = 0 \div 5500, N = 10 \div 10^5 \)
Conclusions

- **Pressure measurements:**
  - Significant pressure drop along feeding/drainage pipes and manifolds
  - Pressure in breeder units is practically constant
  - Inertia effects can occur at manifolds and first wall gap

- **Electric potential measurements:**
  - Overview on flow distribution
  - Data for code validation

- **Numerical results:**
  - Good comparison with measured $\phi$ distribution in the central cross-section
  - Yield insight for better understanding
  - Weak electric coupling between breeder units
  - Strong coupling in sub-channels (uniform flow partition)
Further requirements on the way to ITER

Numerical simulation tools required for prediction of MHD flows in ITER

- ITER relevant parameters not yet reached, but expected for the next few years
- Validation is mandatory

Future experiments should

- support ITER TBM design activities (e.g. modified geometry of gaps at the first wall, influence of helium channels on MHD flow) and operating strategies (required flow rates and pressure heads, emergency draining time etc)
- assess the feasibility of the foreseen measuring techniques in terms of functionality of single sensors and global integration of instrumentation in the TBM
- study phenomena that cannot be measured in ITER
- pay attention to fundamental MHD effects as support for ITER data understanding
Experiments and numerical results

Calculated current streamlines on the MHD mock-up middle plane (AA).

**Current density**
- In cooling plates currents enter perpendicularly:
  - Strong electric coupling through cooling plates (uniform flow partition)

- In SPs currents flow tangentially:
  - Weak electric coupling between BUs

\[ \begin{align*}
  &\text{Current density} \\
  &\text{In cooling plates currents enter perpendicularly:} \\
  &\Rightarrow \text{Strong electric coupling through cooling plates} \\
  &\text{(uniform flow partition)} \\
  &\text{In SPs currents flow tangentially:} \\
  &\Rightarrow \text{Weak electric coupling between BUs}
\end{align*} \]