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MaPLE: A versatile facility for investigating MHD convective flows

C. Koehly *, C. Courtessole, L. Bühler

Karlsruhe Institute of Technology, Karlsruhe, Germany

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ABSTRACT

With MaPLE (Magnetohydrodynamic PbLi Experiment), KIT provides an experimental research facility to investigate magnetohydrodynamic (MHD) effects affecting liquid metal blankets of future fusion reactors using the prototypical liquid metal PbLi. The facility is designed to enable heat transfer studies in free, forced, or mixed magneto-convective flows in simple ducts and more complex typical geometries relevant to liquid metal breeder blankets. It features a versatile infrastructure that allows experimental examination of flows at any orientation with respect to gravity under a transverse magnetic field, as those occurring in a fusion blanket. While MaPLE has been primarily designed to explore the combined MHD and buoyancy effects, the facility can also support the development of measuring techniques at high temperatures and strong magnetic fields. In synergy with the well-established MEKKA facility, which offers an even larger experimental magnetic volume, MaPLE is also suited for analyzing PbLi flows in complex geometries such as scaled mock-ups of fusion blankets. Identified as one of EUROfusion Technological Hubs, MaPLE will support the development of breeding blankets the European demonstration fusion power plant DEMO, and the international ITER project. The main features and characteristics of the facility are described in this paper, and the roadmap for the first experimental campaigns is presented.

1. Introduction

In proposed liquid metal blanket concepts for fusion reactors, the eutectic lead-lithium alloy (PbLi) is foreseen as a breeder material, neutron multiplier, and heat transfer fluid. The high electric conductivity of PbLi results in induced electric currents and strong Lorentz forces, when the fluid moves in the plasma-confining magnetic field. This leads to large magnetohydrodynamic (MHD) pressure drops and flow patterns that are very different from those observed in comparable hydrodynamic flows. Several experimental and theoretical studies on transport phenomena in fusion-relevant liquid metal flows have already been published as summarized in the comprehensive review paper by Zikanov et al. [1]. However, some fundamental and practical aspects still need to be investigated for applications in liquid breeder blankets. One main objective is to analyze the effect of buoyancy forces on MHD flows using the prototypical fluid PbLi. Moreover, there is a demand for developing diagnostic tools suited for high-temperature PbLi. To address these issues, MaPLE (Magnetohydrodynamic PbLi Experiment) was developed at the University of California, Los Angeles [2,3]. The PbLi loop has been upgraded with EUROfusion support [4] and eventually transferred to KIT where it was adapted to comply with European standards and to meet the requirements for upcoming experimental campaigns.

Studying the impact of buoyancy forces on a liquid metal MHD flow and their influence on the associated heat and mass transfer in blanket-relevant conditions is a difficult task. The main impediments are:

- The limited experimental volume and strength of available magnetic fields in laboratories.
- The use of the prototypical fluid PbLi requiring complex experimental setups to perform experiments at temperatures higher than the melting point of the alloy with additional difficulties associated with heat losses or thermoelectric perturbations.
- The impossibility of generating volumetric heating in liquid metals in non-nuclear facilities. Available engineering options such as induction heating cannot be applied since they would completely modify the MHD flow patterns.

The experimental facility MaPLE has been designed for investigations of MHD flows subject to combined effects of buoyancy forces, electromagnetic forces, viscous and inertia forces. Those forces are related with respect to each other via the nondimensional Grashof,

* Corresponding author.
E-mail address: christina.koehly@kit.edu (C. Koehly).

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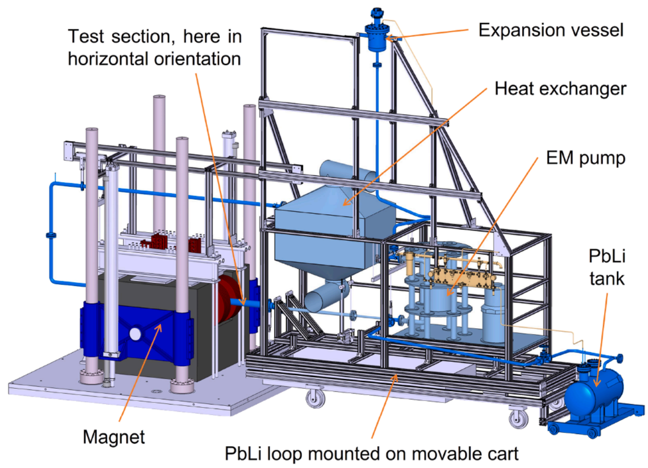

Fig. 1. MaPLE facility at KIT.

Hartmann and Reynolds numbers

$$Gr = \frac{g\beta q'' L^4}{\lambda\nu^2}, Ha = LB\sqrt{\frac{\sigma}{\rho\nu}}, Re = \frac{u_0 L}{\nu}$$

Here, Gr, Ha^2, and Re denote the ratios of buoyant, electromagnetic, and inertia forces to the viscous force, respectively. The variables u_0, L, and q'' stand for typical velocity, length, and applied wall heat flux. B is the strength of the applied magnetic field, g stands for gravity, and the fluid properties of PbLi are given by the reference density ρ, thermal expansion coefficient β, kinematic viscosity ν, heat conductivity λ, and specific electrical conductivity σ. MaPLE is capable of reaching values of these parameters $Ha = 1600$, $Re = 35{,}000$. With a reasonable and realistic wall heat flux of $10\mathrm{W/cm^2}$ and channel dimension $L = 0.025$ m, Grashof numbers of about $Gr = 5 \times 10^7$ may be achieved.

The facility is quite flexible and allows for various test sections or mock-ups to be connected to the liquid metal loop in arbitrary orientation with respect to gravity. This unique capability is essential when buoyancy is expected to play a major role.

The facility will be used to measure MHD pressure drop in PbLi flows, distribution of electric potential as an indicator for flow patterns and temperatures, from which the heat transfer coefficients can be evaluated. Since measuring those properties is non-trivial at high temperatures and in strong magnetic fields, MaPLE will also support the development and testing of measuring techniques (e.g. pressure, flow rate, electric potential, etc.). Moreover, data generated in MaPLE experiments will extend the database for code validation of buoyant heat transfer simulations in the fusion-relevant parameter range.

The choice of the liquid alloy PbLi allows MHD experiments to be carried out with the prototypical fusion fluid foreseen in breeding blankets. Other surrogate fluids could be NaK [5] or GaInSn [6] as used in the MEKKA facility. The lower density and higher electrical conductivity of NaK results in higher Hartmann numbers closer to fusion applications and provides good electrical contact with metal walls. Due to its high affinity for oxygen, the operation of a NaK loop requires great care and safety precautions. GaInSn is a good alternative for experiments in insulating channels but its tendency of poor wetting and formation of contact resistance at fluid-wall interfaces is problematic when flows in electrically conducting ducts are of interest [7]. Mercury has been also used for MHD experiments [8], but it suffers from similar problems (poor electrical contact) and additional high toxicity. Motivation for using PbLi is to gain experience in long-term operation of PbLi circuits and in measuring techniques to be used when investigating combined MHD and heat transfer with buoyancy effects using the prototypical fusion fluid.

The present paper depicts the main features and characteristics of the MaPLE facility as well as the roadmap for the first experimental campaigns. Advantages and prospects will be addressed.

Fig. 2. MaPLE magnet at KIT.

2. MaPLE facility

The MaPLE facility consists mainly of two key components (see Fig. 1):

- A normal-conducting dipole electromagnet installed on a hydraulic positioning frame.
- A PbLi loop sitting on a movable cart.

2.1. MaPLE magnet

The MaPLE magnet is a normal-conducting dipole magnet that was designed and fabricated by Princeton Plasma Physics Laboratory (PPPL) in 2004 as part of the Japan-USA collaborative program JUPITER-II [9]. It is constructed from 10 water-cooled copper coils and 224 hot-rolled steel plates (1/4-in. thick) stacked together to form the ferromagnetic core. The magnet exhibits a 150 mm wide air gap open to one side, which allows easier instrumentation of test sections. The copper coils are located as close as possible to the test volume in two groups straddling the air gap. Each coil is formed by winding 16 turns of insulated square copper conductor with a circular cooling hole to obtain the maximum magnetization current of 480,000 ampere-turn at 3kA, required to generate a transverse magnetic field with a maximum strength of 2T. The coils are cooled down by water and connected to a chilled water system shared with the MEKKA facility [5], which is able to extract up to 500 kW when operating at the maximum field strength.

The MaPLE magnet is installed on a hydraulic positioning frame. Four hydraulic cylinders allow lifting the 20-ton magnet up to 2 m. The magnet is mounted between two crossheads and can rotate around a horizontal axis by ±90°. Fig. 2 shows the magnet in lifted and tilted position.

The MaPLE magnet has been fully commissioned. The distribution of the magnetic field between the pole faces of the dipole was measured using a 3-component Hall probe mounted on a multi-axis linear traversing mechanism and connected to a gaussmeter (FW Bell). The coordinate system employed for the measurements is centered in the middle of the magnetic gap with coordinates x and z parallel, and y perpendicular to the pole faces. The origin of the axial coordinate $x = 0$ is in the axial center of the magnetic gap. Since the magnet has a

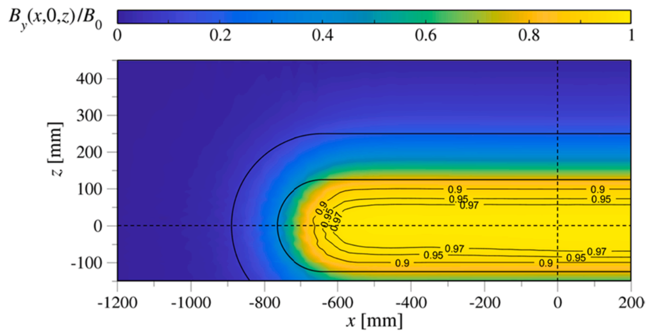

Fig. 3. Map of measured transverse magnetic field component $B_y(x,0,z)$ in the symmetry plane of the magnet (y = 0) for $B_0 = 0.5$T.

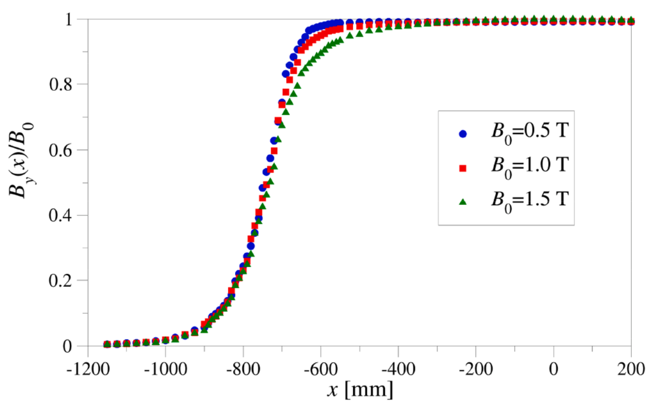

Fig. 4. Transverse magnetic field component $B_y(x,0,0)$ on the axis of the magnet.

Table 1
PbLi material parameters for 300 °C [10].

Melting point, T_m [°C]	235
Density, ρ [kg/m^3]	9838
Kinematic viscosity, ν [m^2/s]	2.14×10^{-7}
Electric conductivity, σ [1/(Ω m)]	8.83×10^{5}
Thermal conductivity, λ [W/(m K)]	20.4

symmetric built-up, it is sufficient to consider only one side (here, $x < 0$) in more detail. The magnetic gap has been mapped for several values $0 < B_0 = B_y(0,0,0) < 1.8$T in steps of $\Delta B_0 = 0.1$T One result of those measurements obtained for $B_0 = 0.5$T is displayed in Fig. 3. The figure shows that, for the chosen parameters, the magnetic field is quite uniform with deviations from B_0 smaller than 3 % in a region of about $|x| < 600$ mm, $|y| < 50$ mm, $|z| < 60$ mm.

The results of some detailed measurements along the symmetry axis of the magnet are shown in Fig. 4. It could be observed that the magnetic field rises to maximum values in a region of -1000mm $< x < -600$ mm. The results further highlight, that the transition to higher magnetic field values depends on B_0, caused by the fact that some parts of the iron core already experience the beginning of magnetic saturation. This is important when future experimental MHD results in the non-uniform field region are compared with numerical simulations.

2.2. MaPLE PbLi loop

The MaPLE liquid metal loop enables MHD experiments with the prototypical eutectic lead-lithium alloy $Pb^{84.3}Li^{15.7}$. Some thermophysical properties of PbLi are summarized in Table 1. This operating fluid supports experimental campaigns for component testing,

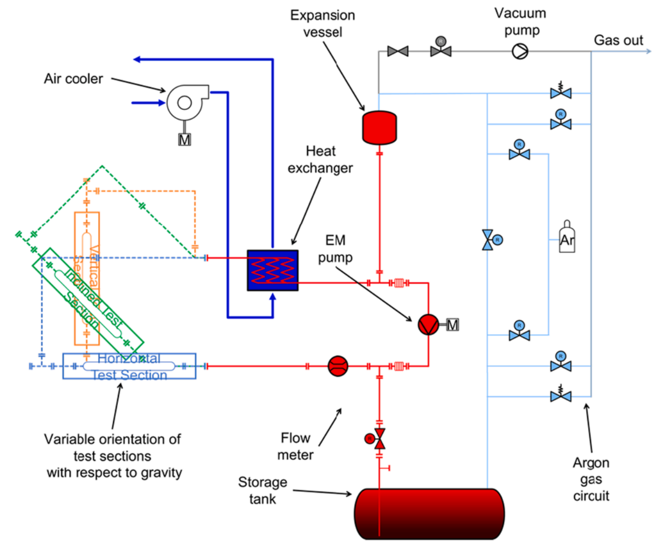

Fig. 5. MaPLE loop at KIT.

Table 2
Main parameters of the MaPLE PbLi loop.

PbLi inventory	70 L, extendable up to 115L
Operating Temp	400 °C max.
Permanent Magnet Pump	Pressure head: up to 6 bar at 5kg/s
Flow reversal capable	
Air-cooler	70 kW capacity
Test Sections	Variable orientation: −90° to 90°

instrumentation development, and code validation under reactor-typical conditions. Eutectic PbLi is solid at room temperature. Therefore, the entire loop must be kept above the melting point of the alloy at all times during the operation of the facility. The loop has been designed to operate up to 400 °C. The maximum temperature is specified to comply with national standards for pressure vessel equipment. Initial experiments in MaPLE are planned to operate at a temperature of 300 °C close to conditions in a water-cooled lead lithium blanket. All components and pipes are equipped with either mineral-insulated heating cables or flexible heating tapes controlled individually with feedback from several thermocouples. Heat losses are minimized with the use of jacketing and thick layers of insulation around all pipes and components, thus reducing the required heating power during experiments.

The MaPLE loop is designed as a flexible liquid metal circuit and features test sections that can easily be exchanged. It sits on a cart-on-track conveyor, which allows moving the loop with an installed test section in or out of the magnetic gap (see Fig. 1). This ensures easier preparation of the test section and maintenance operations. The entire flow circuit is made of stainless steel. The MaPLE loop consists of a storage tank, an electromagnetic pump, a flow meter, an exchangeable test section, a PbLi-air heat exchanger, and an expansion vessel. The loop benefits from the sectional build-up of all its components to ensure easy maintenance and replacement of each element; each section being connected to the next one by a set of flanges sealed with graphite gaskets. Additionally, the flow circuit can quickly and easily be reconfigured. In particular, it is foreseen to install test articles with different orientations with respect to gravity (horizontal, inclined, vertical) as seen in Fig. 5.

The main operation parameters of MaPLE PbLi loop are summarized in Table 2. The facility has a maximum PbLi inventory of 115L , but the storage tank is currently filled with 70 L, which is sufficient for the planned experimental campaigns including PbLi experiments in larger blanket module mock-ups. It is equipped with two level sensors used to monitor the minimum and maximum level of liquid metal, as well as a multipoint thermocouple probe.

The liquid metal flow is driven by a permanent magnet pump (PMP) developed by SAAS GmbH, Germany. Samarium-Cobalt magnets are mounted on a rotor that, when spun, induces eddy currents and Lorentz forces in the electrically conducting fluid. The developed pressure head is adjusted by varying the rotation speed of the magnetic core. The flow direction can be reversed by changing the rotation direction of the rotor. The pump is designed for a maximum pressure head of up to 6 bar at a mass flow rate of 5kg/s.

For conducting magneto-convection experiments, large amounts of heat need to be introduced into the test section to generate substantial buoyancy forces. To ensure that the temperature of the liquid metal remains constant at the inlet of the test section, the loop features a heat rejection system consisting of a cross-flow liquid metal-air heat exchanger in which PbLi flows in a bundle of six finned tubes enclosed in a stainless-steel box with an upward airflow. The air cooler has a heat removal capacity of 70 kW. For isothermal experiments, it can be removed and replaced by a simple pipe.

The expansion tank of the liquid metal circuit is installed at the highest point of the loop. Like the storage tank, it encompasses several level sensors and a multipoint thermocouple probe for assessing the height of the free surface of the liquid metal within the expansion volume.

In order to prevent oxidation of PbLi, the circulation loop is permanently kept under an inert atmosphere of argon. The cover gas in the expansion tank is also used to adjust the pressure of liquid metal in the loop. The expansion and storage tanks are connected to a vacuum pump to evacuate residual air that is introduced into the flow circuit when test sections are swapped. Before heating the facility, the atmosphere is flushed several times with argon. Then, to fill up the loop, differential argon pressure is applied between the storage and the expansion volume. The argon and vacuum circuits are controlled by several solenoid valves and equipped with pressure transducers to monitor gas pressure in the expansion vessel and in the storage tank. For draining, a pressure equalization valve is installed between the expansion vessel and storage tank (see Fig. 5). Except during filling operation, this valve is normally open in case of emergency draining

The loop is remotely operated from a distant control room. All components – e.g. pump, air-cooler, electromagnetic flowmeter – and sensors such as pressure transducers, thermocouples, etc., are connected to a data acquisition and control system (DACS) designed to ensure the safe operation of the facility. For instance, the system can de-energize a specific heating element in case of overheating or automatically drain the entire loop if the temperature of a section of the flow circuit drops under a given limit.

3. Instrumentation

Performing MHD liquid metal experiments at high temperatures with PbLi requires special measuring techniques to produce accurate results. To that extent, the facility is equipped with many sensors monitoring various process variables such as temperature, flow rate, pressure, etc., and test sections equipped with specific instrumentation.

Level sensors. To monitor the level of liquid metal in the storage tank and the expansion vessel, electrodes of different lengths that are electrically insulated from the steel vessels, are inserted through the lids of the tanks. They detect the position of the free surface of liquid metal when PbLi comes in contact with them. In particular, these sensors are used to monitor the minimum and maximum levels in the storage tank and expansion vessel, which are critical for the safe operation of the facility, for instance, to avoid overfilling the facility.

Temperature measurements. The entire loop counts about 160 type-K thermocouples. Each heated section is associated with at least two thermocouples to control the heating power injected and to monitor the heater temperature for safety reasons. The tank as well as the

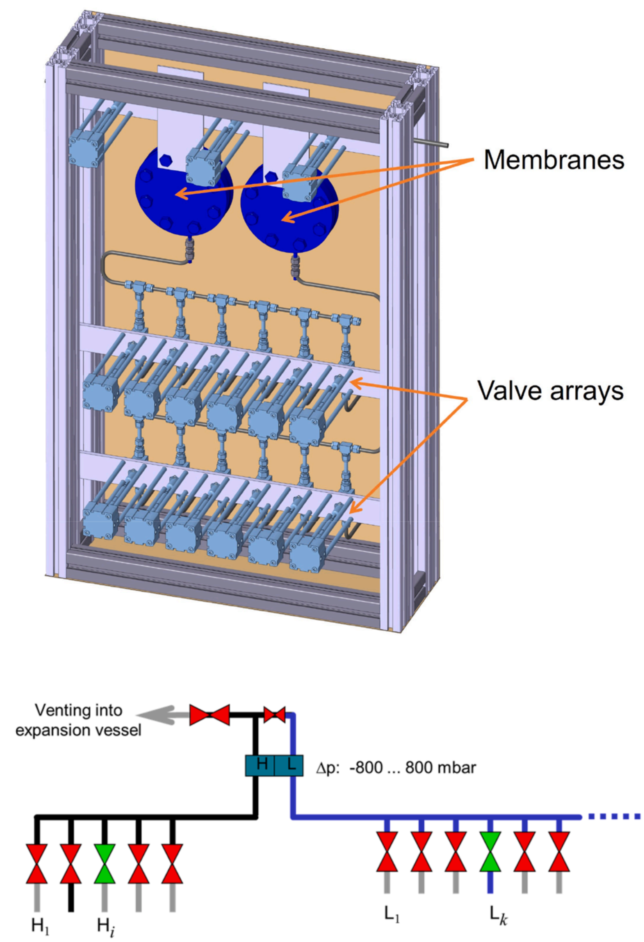

Fig. 6. CAD view of MaPLE differential pressure multiplexer (top); Schematics of pressure taps connection with pressure transducers (bottom).

expansion vessel are equipped additionally with multipoint thermocouples probes, which measure the temperature distribution along their heights at several points. The reading of these probes is interpreted to roughly define the level of the liquid metal in the tank and in the expansion volume. Temperatures in the liquid metal loop can be determined with uncertainty <1 °C.

Flowmeter. Liquid metal flow rates are measured by a homemade electromagnetic flowmeter. It measures the potential difference $\Delta\phi$ induced orthogonally to a locally applied transverse magnetic field and to the flow direction. The voltage, which is proportional to the velocity, is measured between two stainless steel electrodes that are welded to the pipe in the center of a permanent magnet/yoke assembly.

Pressure measurement. The loop is equipped with several pressure transducers to monitor gas and liquid metal pressure in the system. Argon pressure in the storage and expansion tanks is measured by two digital sensors (PX319, Omega Engineering, Inc.) as well as two analog manometers for redundancy. In addition, two high-temperature piezoresistive pressure transducers (IE Impact, Gefran S.p.A.) are installed in the liquid metal at the inlet and outlet of the pump to watch the pressure in the loop and determine the pressure head delivered by the pump.

During experimental campaigns, pressure differences are recorded between pressure taps located along the test section. To avoid multiplying the number of pressure sensors needed to measure several pressure drops, a differential pressure multiplexer was developed. It relies on a single high-temperature pressure transmitter using oil as a coupling medium (SITRANS P320, Siemens AG) associated with a set of pneumatically actuated valves and allows the connection of up to 12 pressure

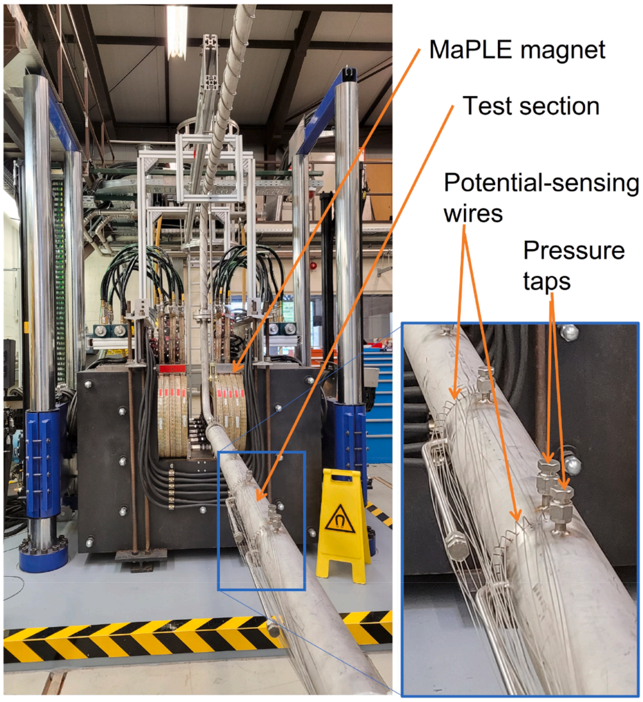

Fig. 7. Test section built for investigating PbLi MHD flow in a circular pipe installed in front of the magnet before being equipped with heaters and thermally insulated.

taps. This differential pressure measurement system is shown in Fig. 6. During experiments, the entire box holding the piping system and the pressure transmitter is kept at 300 °C. Measurements can be performed in the range from -800mbar to 800mbar by switching valves connected to preselected pressure taps.

Electric potential. Distributions of electric potential are commonly measured in MHD experiments as the potential gradient may be directly interpreted as a velocity signal since, according to Ohm's law

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

in a magnetic field

$$\mathbf{B} = B_0\widehat{\mathbf{y}}.$$

Velocity components perpendicular to B may be determined as

$$u \approx \frac{1}{B_0}\frac{\partial\phi}{\partial z} \text{and} w \approx -\frac{1}{B_0}\frac{\partial\phi}{\partial x}.$$

Advantages of measuring the circumferential distribution of wall potential has been highlighted by Picologlou and Reed [11] since "voltages are essentially constant along magnetic field lines. Hence, wall voltage distributions are translated into voltage distributions in the fluid."

In order to record the potential distribution on the surface of the test section, arrays of stainless steel electrodes can be laser-welded onto the outer wall of the test article. To minimize thermoelectric contributions to the recorded signals, all the connections between the stainless steel electrodes and the copper wires plugged into a nano-voltmeter are done far away from the test section and kept at the same temperature. With this system, electric potential differences can be resolved with errors smaller than $\pm 0.1\mu$V.

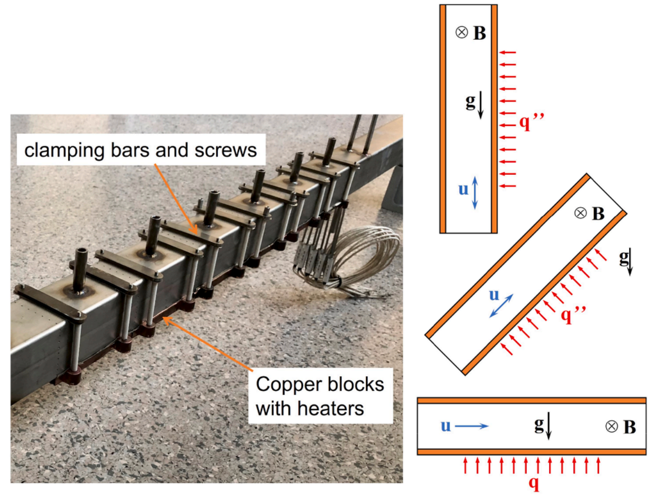

Fig. 8. Rectangular test section for MHD mixed-convection experiments (buoyancy-assisted or buoyancy-opposed) at various orientations.

4. Roadmap for first experiments

4.1. MHD flow in a circular pipe

The first experimental campaign will examine PbLi flow in an electrically conducting circular pipe in uniform and non-uniform magnetic fields. The test section is manufactured from stainless steel with specific electrical conductivity $\sigma = 1.02\times10^6\ \Omega^{-1}\mathrm{m}^{-1}$ at 300 °C [12]. For that purpose, a 76 mm circular test section with 2 mm thick walls has been designed, manufactured, and installed in the MaPLE loop (Fig. 7). This type of flow is well-known as there exist proven literature data from asymptotic analysis for fully developed pipe flow in uniform magnetic fields [13]. The phenomena expected in non-uniform fields are also well understood as demonstrated by very good comparisons of numerical simulations with available experimental data [14–16]. This experiment was selected for these reasons as it aims to validate newly installed measuring techniques at high temperatures. Pressure distribution in the pipe will be recorded via six pressure taps welded on the test section and connected to the differential pressure measurement system described above. Surface potential distributions will also be measured by three sets of 20 electrodes installed at different axial locations. The data collected will expand the existing database for 3D MHD flows in strong non-uniform magnetic fields and serve for code validation.

4.2. MHD heat transfer in a rectangle duct

Mixed magneto-convective flows will be investigated in a simple rectangular duct at various orientations of the test section with respect to gravity. A $50\times50\mathrm{mm}^2$ test section with 2 mm thick walls was designed and fabricated for the experimental campaign (see Fig. 8). To generate buoyancy forces in the liquid metal, a uniform surface heat flux is applied on one sidewall between

-300mm $< x <$ 300 mm, where the magnetic field in uniform and the MHD flow is fully developed. All other walls are adiabatic. The test channel will be instrumented with pressure taps, electrodes, and thermocouples. Experiments will be performed for various Hartmann, Reynolds, and Grashof numbers to determine the combined influence of magnetic field, inertia, and buoyancy on the flow and the associated heat transfer. Several flow orientations could also be investigated by tilting the test section at different angles and reversing the flow direction of the liquid metal.

This experiment is of particular interest since it represents the experimental verification for numerical simulations that have already been performed in a first code-to-code benchmark for the vertical

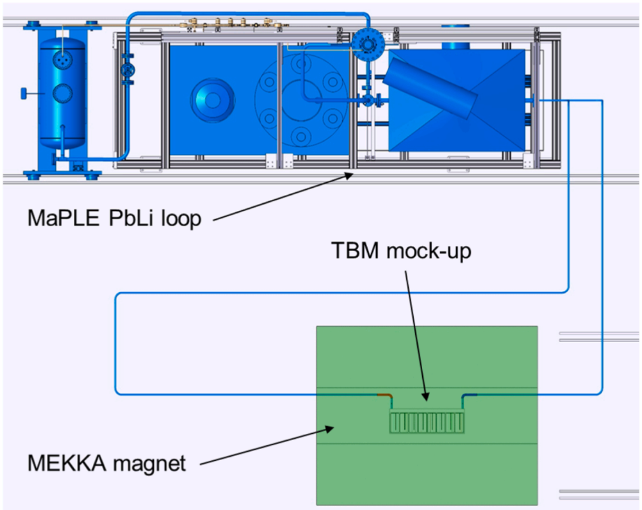

Fig. 9. Top view of the laboratory: MaPLE in synergy with the MEKKA facility.

orientation [17,18]. It will also provide empirical data for another ongoing benchmark activity related to MHD mixed-convection in a horizontal test section.

4.3. PbLi flow in a scaled WCLL TBM mock-up

Experimental and numerical data obtained recently at KIT in a scaled mock-up of the water-cooled lead-lithium (WCLL) test blanket module (TBM) for ITER show that manifolds are responsible for most of the pressure drop occurring in the module and significantly affect flow partitioning among breeder units [19–21]. This experimental work was performed using the model fluid NaK in the MEKKA facility. The latter is particularly suited for reaching fusion-relevant flow parameters due to the high electric conductivity and low density of the model fluid NaK and the extensive experimental space in the magnet (uniform field in $800\times165\times483$ mm^3) that can host large test sections such as scaled mock-up of blanket modules. To transpose experimental results obtained with NaK to other fluids such as PbLi, well-established scaling laws based on similarity principles can be used for simple geometries. Those relations have been applied so far to predict the pressure drop of PbLi flow in fusion blanket modules from comparable model experiments. However, since the geometry of real blanket designs and their scaled models are quite complex, the above-mentioned correlations require experimental confirmation since they have been developed under different assumptions.

To investigate suitable similarity principles when transferring data from NaK to PbLi applications, it is planned to repeat the former NaK experiment in the same mock-up geometry with PbLi supplied from the MaPLE loop. Here, the synergy between both facilities available at KIT – MEKKA with the larger magnet with the available blanket mock-up, and MaPLE providing the PbLi flow – will be exploited (Fig. 9). The feasibility of such an experiment is currently explored under the EUROfusion research program.

5. Conclusions

With MaPLE expanding the capability of the liquid metal MHD laboratory, KIT possesses a unique experimental platform to conduct MHD research for fundamental and applied problems relevant to nuclear fusion technology. Alongside MEKKA, which is best suited to reach very large Hartmann numbers or to conduct experiments in complex geometries, MaPLE allows experiments to be performed with the prototypical breeder alloy PbLi that is foreseen in liquid metal blankets. It provides a unique tool for studying the combined effects of buoyancy, electromagnetic, inertia, and viscous forces thanks to the ability to work at arbitrary orientations of test sections with respect to gravity. The facility offers a versatile platform that will be used for the determination of magneto-convective heat transfer, MHD pressure drop and flow distribution, development for measuring techniques at high temperatures, etc. Results gained with MaPLE will support blanket design activities and expand the experimental database for PbLi flows for the validation of predictive numerical tools.

CRediT authorship contribution statement

C. Koehly: Writing – original draft, Visualization, Resources, Investigation, Conceptualization. **C. Courtessole:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Investigation, Data curation, Conceptualization. **L. Bühler:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors do not have permission to share data.

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