

Experiments and Facilities to Explore Multiple Effects in Liquid Metal Blankets in the US/UCLA- EUROfusion Collaboration

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EUROfusion

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OUTLINE

- Need for Multiple Effect Experiments and Modelling
- Scientific Challenges in design of multiple-effect Laboratory Facilities
- Major challenges in modelling multiple-effect phenomena in 3-D complex geometry
- Highlights of the MaPLE–U Facility and the US/UCLA- EUROfusion Collaboration

Fusion Nuclear Environment is Complex & Unique

Neutrons (*flux, spectrum, gradients, pulses*)

- Bulk (volumetric) Heating
- Radiation Effects
- Tritium Production
- Activation and Decay Heat

Heat Sources (*thermal gradients, pulses*)

- Bulk (neutrons)
- Surface (particles, radiation)

Particle/Debris Fluxes (*energy, density, gradients*)

Magnetic Fields (*3-components, gradients*)

- Steady and Time-Varying Field

Mechanical & Electromagnetic Forces

- Normal (*steady, cyclic*) and Off-Normal (*pulsed*)

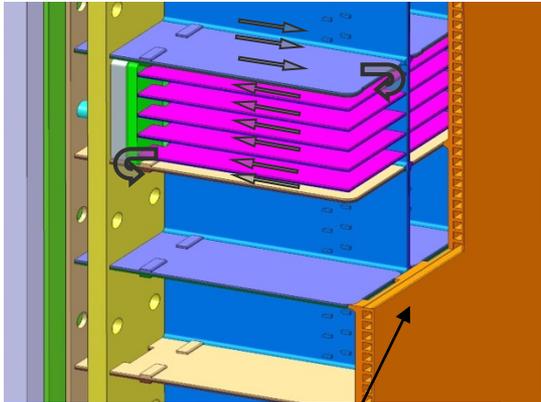
Combined Loads, Multiple Environmental Effects

- Thermal-chemical-mechanical-electrical-magnetic-gravitational-nuclear interactions and multiple/synergistic effects
- Interactions among physical elements of components

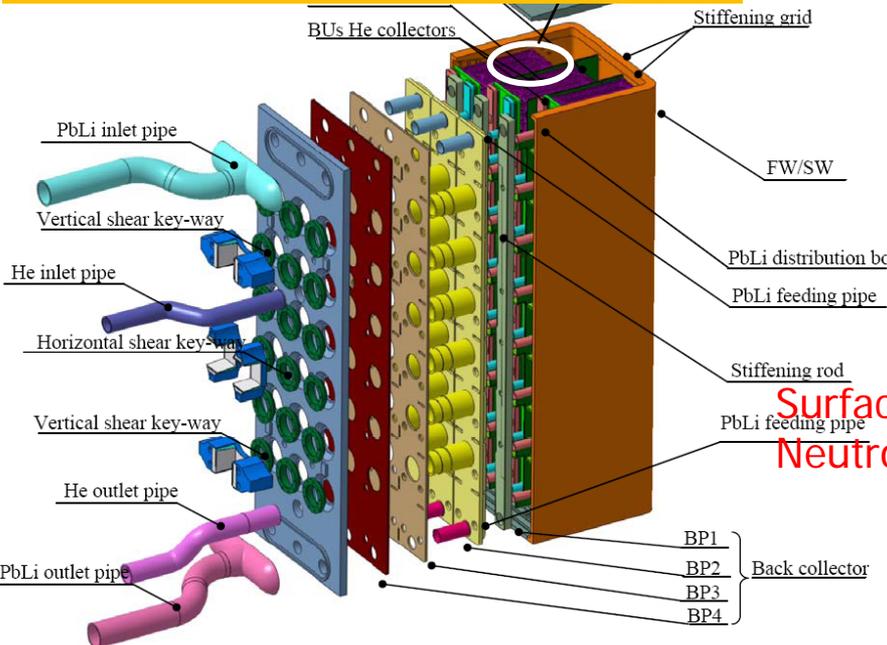
Multiple functions, materials,
and many interfaces in highly
constrained system

Blanket/FW systems are complex and have many functional materials, joints, fluids, and interfaces

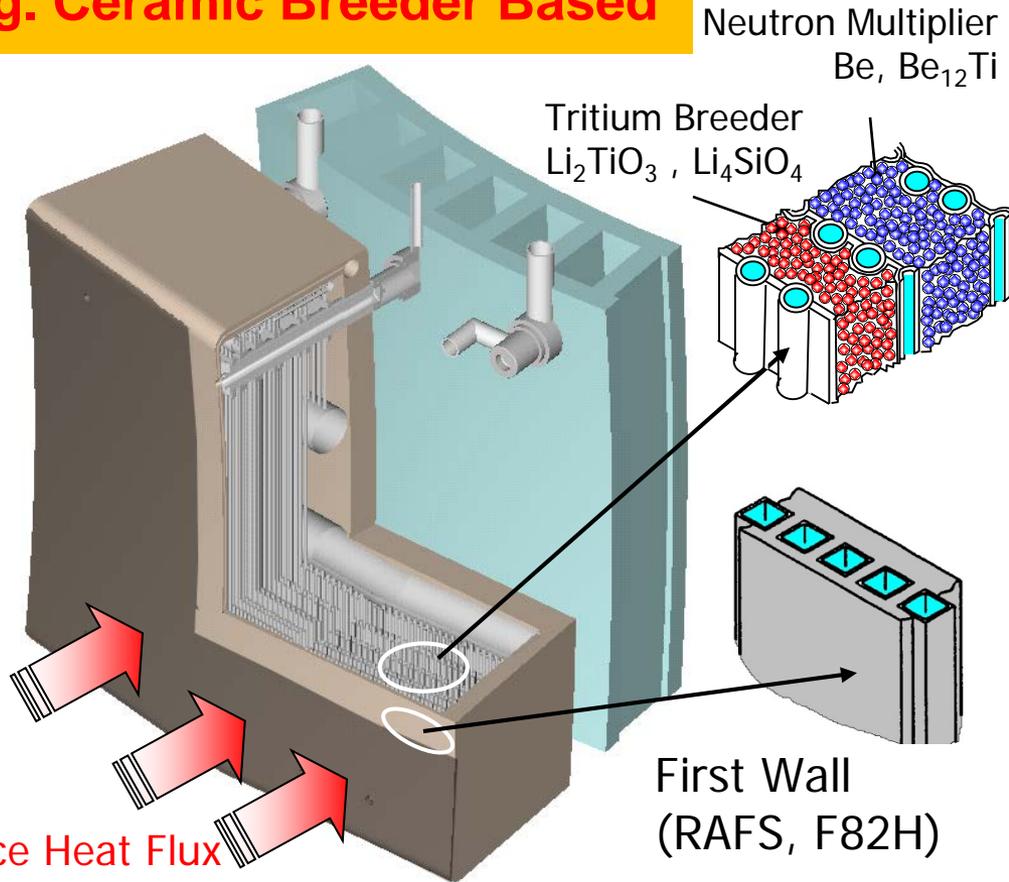
Li, PbLi,
Li-Salt flow



E.g. Liquid Breeder Based



E.g. Ceramic Breeder Based



Coolants: He, H₂O,
or liquid metal or salt

Key challenges that must be carefully considered in planning a credible pathway for FNST & Fusion Development

- **The Fusion Nuclear Environment**: Multiple field environment (neutrons, heat/particle fluxes, magnetic field, etc.) with high magnitude and steep gradients experienced by complex Blanket/FW
 - *lead to yet undiscovered new phenomena due to multiple interactions and synergistic effects*
 - *can not adequately simulate in laboratory facilities or fission reactors*
 - *full simulation to uncover phenomena and quantify behavior requires DT Plasma-based facility (FNSF)*
- **Nuclear heating** in a large volume with steep gradients
 - *drives temperatures and most FNST phenomena*
 - *cannot simulate in laboratory facilities or fission reactors*
 - *can be simulated only in DT Plasma-based facility (FNSF)*
- **Complex configuration** with FW/Blanket/Divertor inside the vacuum vessel. Makes the fusion system not fault tolerant and challenging to maintain. RAMI is a central issue

Recent research results (at UCLA) have shown clearly that the blanket/FW behavior in the fusion nuclear environment **cannot be predicted by synthesizing results of separate effects**

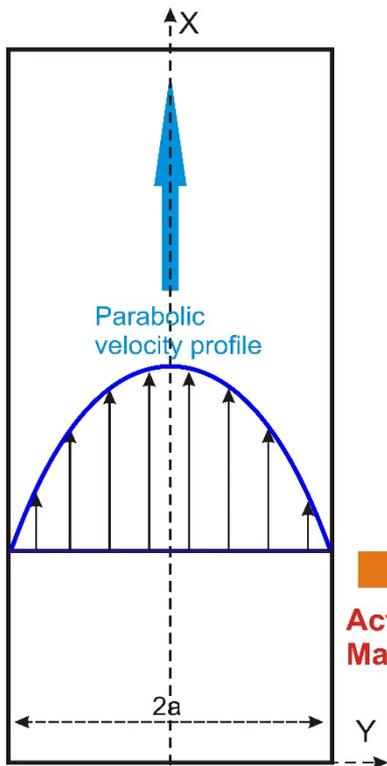
Moving forward with Multiple Effects/Multiple Interactions Experiments and Modelling is NECESSARY to understand and learn the behavior of blankets in the fusion environment

Example: MHD Thermofluids

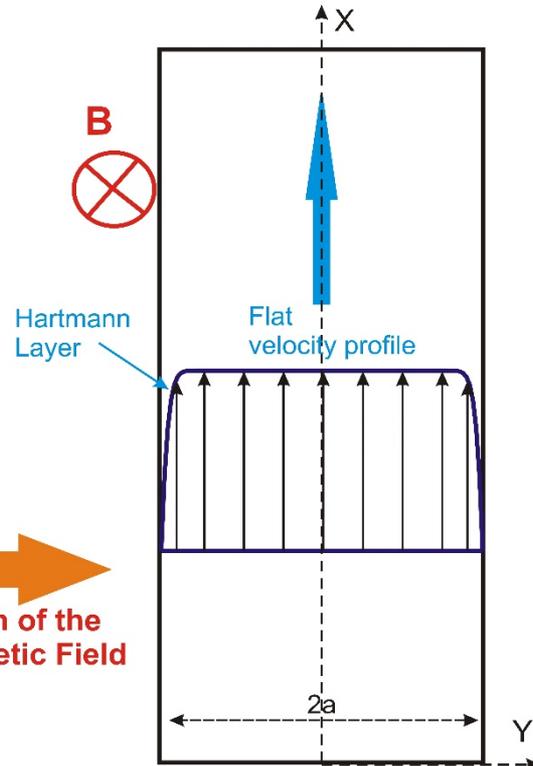
Fusion Researchers for 30 years studied Liquid Metal MHD Flow Behavior in Blankets as if it were PURELY in the Presence of Magnetic Field (i.e. separate effect). So, the common assumption has been:

Flow is *Laminar*: the flow velocity profile is strongly altered by the action of the Lorentz force leading to flat laminar core with very thin Hartmann and side layers

Laminar Velocity Profile



Purely MHD Velocity Profile



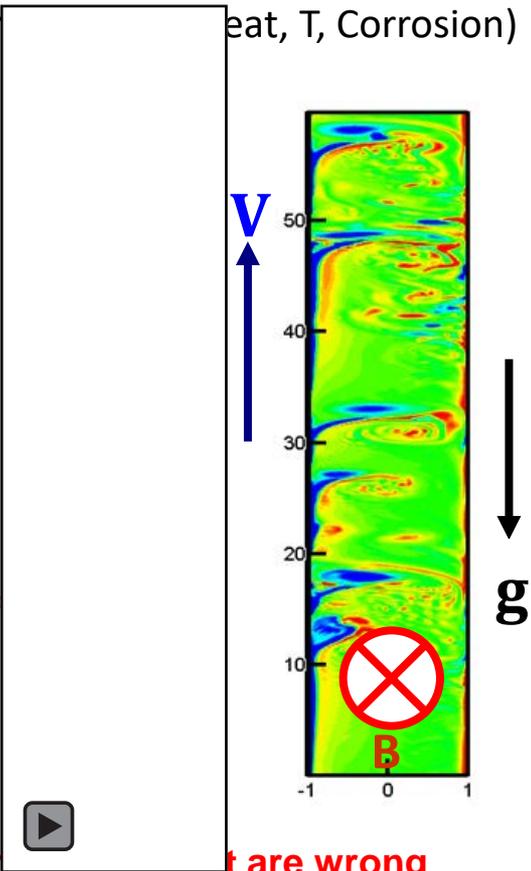
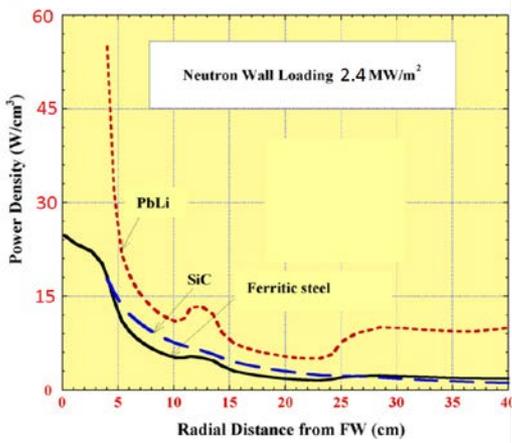
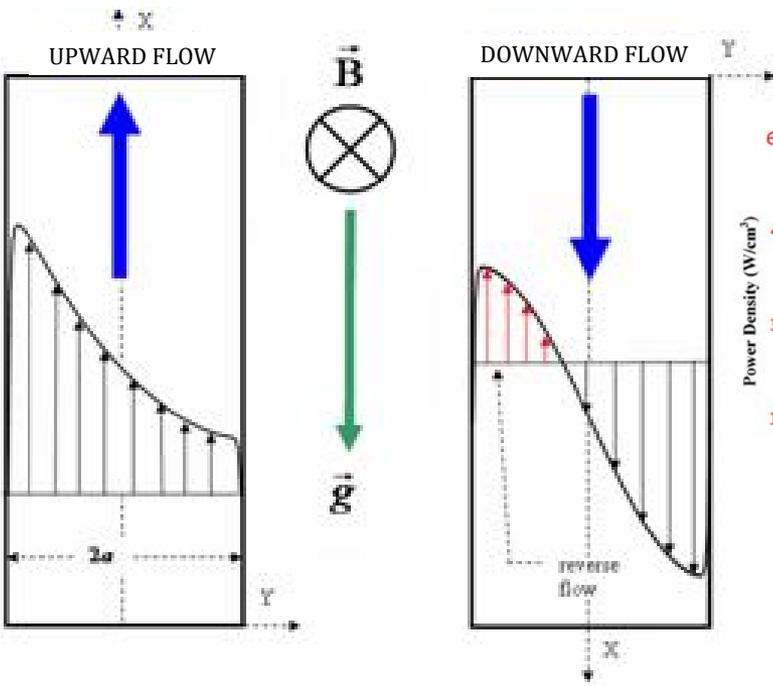
But we just discovered that what we assumed for 30 years is wrong

Discovery: Spatial gradients in nuclear heating & temperature in LM blanket combined with \vec{g} and \vec{B} lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior, Tritium Transport/Permeation and Materials Interactions in the blanket in the fusion nuclear environment

lead to **Buoyant MHD interactions resulting in an unstable “Mixed Convection” flow regime**

Base flow strongly altered leading to velocity gradients, stagnant zones and even “**flow reversal**”

Vorticity Field shows new **instabilities** that affect transport phenomena (Heat, T, Corrosion)



This result is from modeling at limited parameters in idealized geometry.

- Predictions from separate effect tests for the integrated fusion nuclear environment are wrong
- Blankets designed with current knowledge of phenomena and data will not work

What do we need to do to investigate “MHD Buoyant interactions/mixed convection flow” and other phenomena?

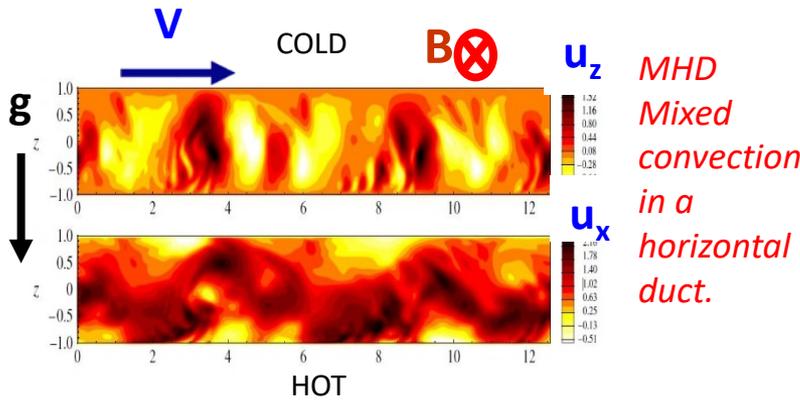
- Need to perform **multiple effects experiments** in which we can observe & characterize MHD mixed convection phenomena & discover new phenomena
- Need major initiatives to perform **more integrated phenomenological and computational modeling** using high speed computation (e.g. solve simultaneously Energy, Maxwell, and Navier-Stokes equations in a coupled manner, push for high performance parameters e.g. Ha, Gr, Re)

Requirements in Experiments:

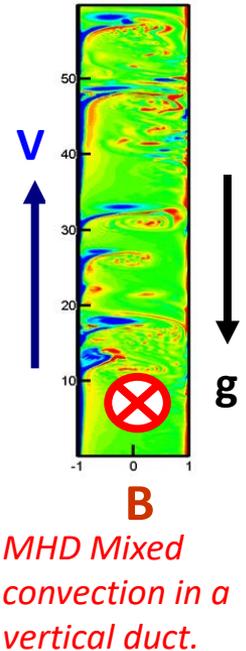
- 1) Simulation of volumetric heating and high temperature with steep gradients
 - 2) Provide flexible orientation of the channel flow w.r.t. gravity
 - 3) Provide sufficient volume inside the magnets to realistically simulate multi-channel flows with multi-material and geometry representation
 - 4) Include representative 3-component magnetic fields with gradients
 - 5) Use Prototypic Materials (e.g. PbLi, RAFM, SiC) and operating conditions (e.g. high T)
 - 6) Develop instrumentation techniques compatible with high-temperature liquid metals
- **Designing Laboratory Facilities that satisfy the above Requirements involves Big challenges** that we must confront. Examples are highlighted in the next several slides (from UCLA research in collaboration with EUROfusion)

MHD Convection Phenomena: Dependence on Gravity Orientation

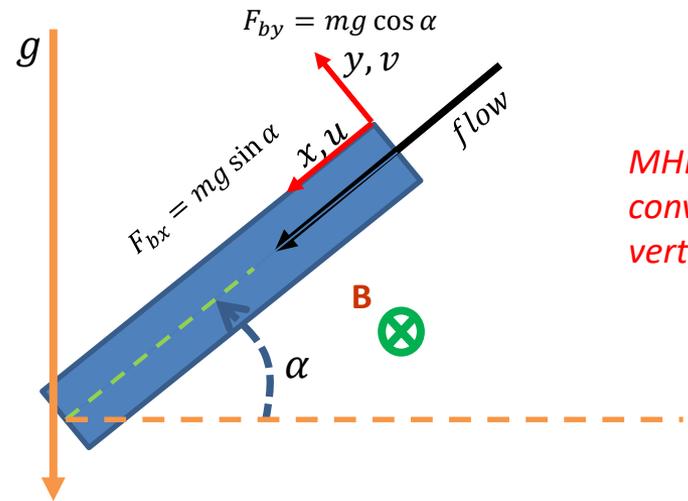
- For **horizontal ducts**, the buoyancy forces are normal to the main flow direction. They induce secondary flows in the form of turbulent “Rayleigh-Benard” convective rolls*.



- For **vertical ducts**, the buoyancy forces act in the main flow direction. Such flows experience “Kelvin-Helmholtz” instabilities and eventually become turbulent**.



- For **inclined ducts**, buoyancy forces act in both the main flow and the cross-stream directions. Given the **non-linear** nature of the flow physics, such flows cannot be predicted purely by the superposition of vertical and horizontal solutions. Detailed investigation of instabilities in inclined ducts is necessary.



Schematic illustrating the angle between the direction of gravity and fluid flow in the case of MHD convective flow in inclined ducts

* Zhang et.al, “Mixed convection in a horizontal duct with bottom heating and strong transverse magnetic field”, J. Fluid Mech. (2014), vol. 757, pp. 33-56.

** Vetcha et.al, “Study of instabilities and quasi-two-dimensional turbulence in volumetrically heated magnetohydrodynamic flows in a vertical rectangular duct”, Phys. Fluids 25, 024102 (2013)

Multiple effects experiments will necessarily be at scaled down conditions from blankets in DEMO. **How do we preserve phenomena?**

- By preserving ratios of forces through the use of relevant non-dimensional parameters

Non-Dimensional Parameters

➤ Reynolds Number, $Re = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{\rho u L}{\mu}$

➤ Hartmann Number, $Ha = \left(\frac{\text{Electromagnetic forces}}{\text{Viscous forces}} \right)^{0.5} = BL \sqrt{\frac{\sigma}{\mu}}$

➤ Grashof Number, $Gr = \frac{\text{Buoyancy forces}}{\text{Viscous forces}} = \frac{g\beta\Delta TL^3}{\nu^2} = \frac{g\beta\dot{q}L^4}{\nu^2\kappa}$

- Need to consider these parameters in a coupled manner
- **What is the “right combinations” of these Dimensionless Parameters to preserve phenomena? **Discovery of the right combinations is R&D by itself.****
- **Examples of coupled parameters we should attempt to preserve in the experiments:**
 - Ha/Re – determines transition to turbulence in Hartmann layers
 - $r = \sqrt{Gr/Ha Re} \left(\frac{a}{b}\right)^2$ - responsible for the shape of velocity and temperature profile in steady mixed-convection flows
 - Ha/\sqrt{Gr} – determines transition from 3D to Q2D in MHD mixed-convection flows

The Blanket in DEMO/Power Reactors is NOT one set of conditions

- The Blanket has many modules, each will have its own MHD thermofluid conditions (e.g. different Ha , Gr) because of variations in magnetic field, neutron wall load and flow orientation w.r.t. gravity (see figure).

- We have a wide range of parameter values, e.g.

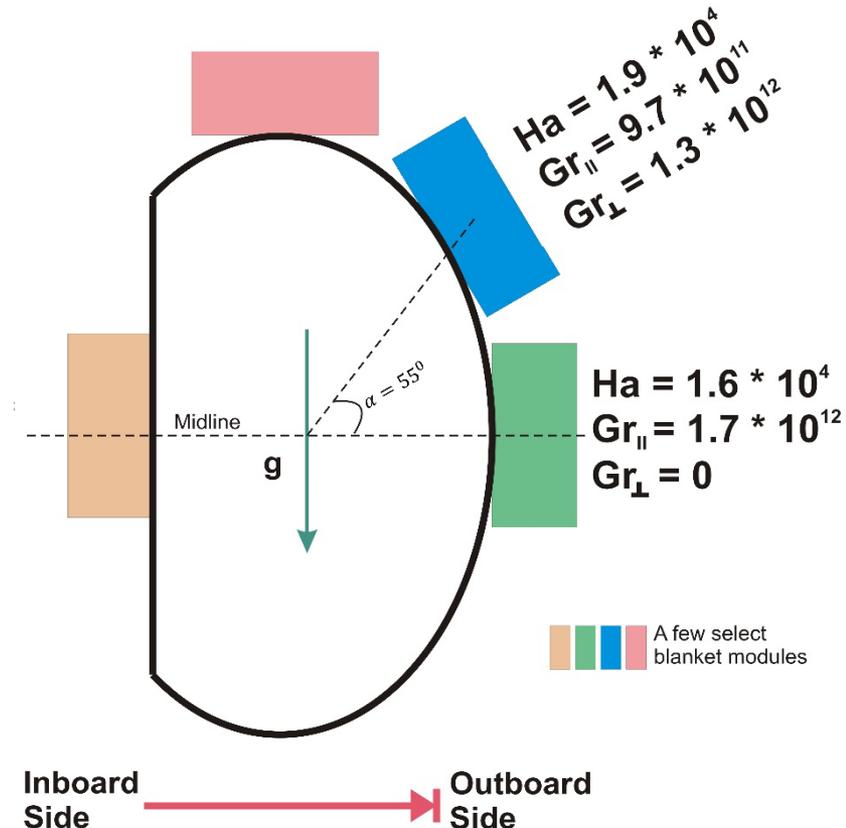
- **Parallel** radial Grashof Number

$$Gr_{\parallel} = Gr_{eq} * \cos(\alpha);$$

- **Perpendicular** radial Grashof Number

$$Gr_{\perp} = Gr_{eq} * \sin(\alpha);$$

- Furthermore, the temperature rise in the flow direction can also be fairly significant. Such an axial ΔT can be used to define an **axial Grashof number**, understanding of which is also paramount in any blanket design efforts.



- **Therefore, each module needs to have its own design**
- **Experiments need to cover the range of conditions & phenomena in various modules.**

ALL Liquid Metal Blankets are Affected by Buoyant forces resulting in MHD Mixed Convection Phenomena

Water- or Helium-Cooled Lead Lithium (WCLL, HCLL)

- **Most affected**
- Forced flow velocity, V_f , is only ~ 1 mm/sec compared to buoyant flow velocity $V_b \sim 20$ cm/sec $(V_b/V_f \sim 200)$

Dual Coolant Lead Lithium (DCLL)

- **Strong effect**
- Forced flow velocity is ~ 10 cm/sec $(V_b/V_f \sim 2)$

Self-Cooled LM

- **Smaller effect** with volumetric heating
- Forced flow velocity is $\sim 0.5 - 1.0$ m/sec $(V_b/V_f \sim 0.2 - 0.4)$
- But **Surface Heating will substantially increase buoyancy effects** (this may help make self-cooled LM blankets feasible again?!)

Non-Linear LM MHD Phenomena is difficult to scale from experiment to DEMO

(Blanket scaling problem similar to plasma physics!)

DEMO BLANKET: $Ha \sim 10^4$, $Gr \sim 10^{12}$, $Re \sim 10^5$

EXPERIMENT: $Ha \sim 10^3$, $Gr \sim 10^9$, $Re \sim 10^5$

Grand Challenge

Since blankets in DEMO/Power Reactors have very high parameters (e.g. Ha , Gr) that cannot be reached in laboratory, **how do we scale results from experiments to predicting Blanket behavior in DEMO?**

- Non-linear phenomena (difficult to scale)
- Higher Ha will suppress turbulence/instabilities
- Higher Gr will enhance buoyancy/instabilities
- **So, what will be the real behavior in the real blanket where both Ha and Gr are high?**

Summary of FNST Multiple Effects/Multiple Interactions Issues and required R&D

Right now, we do not know and cannot predict how the blanket/FW will work in the fusion nuclear environment. This behavior cannot be predicted by synthesizing results of separate effects; and predictions are wrong.

Pathway Issues and Needed R&D:

- **Need to move forward with Multiple Effects/Multiple Interactions Experiments.** We must build a number of new laboratory facilities to do the best possible simulation of the combined effects of the fusion nuclear environment and representative blanket mockups.
- **A sequence of progressively more powerful facilities is needed (\$5M, \$20M, \$50M).** We also need several such facilities with different approaches to simulation to be constructed around the world.

Current status: No such facilities exist in the world. A first-of-a-kind facility is being completed as an upgrade of the MaPLE (Magnetohydrodynamic PbLi Experiment) facility at UCLA, in exemplary partnership with EUROfusion, to study MHD thermofluids multiple-effects, material interactions, and tritium transport & permeation.

- **But full simulations in the Lab is impossible because volumetric heating can be simulated only in DT Plasma-based facility.**
- **Extrapolation from lab facilities to FNSF/DEMO is extremely problematic (non-linear phenomena similar to plasma physics issues). Launching Major 3-D Modelling Initiative is a MUST**

The UCLA – EUROfusion collaborative research on multiple effect LM MHD mixed convection / MaPLE upgrade / 3D Modeling is a major transformative research activity in the world FNST program

- In 2015, a plan was made by UCLA/DOE to upgrade the MaPLE facility at UCLA to provide capabilities for multiple-effects experiments. UCLA-EUROfusion collaboration started
- In 2015-2016, intensive effort was devoted to pre-design/pre-experiment analyses of this first-of-a-kind facility to perform experiments on MHD mixed convection, heat/mass transfer, tritium transport, and materials interactions with prototypical materials and conditions.
- Aggressive construction phase for MaPLE Upgrade in 2017-May 2018. Now getting ready for commissioning and initial operation

UCLA/EUROfusion Collaboration: Researchers

1. Project organization at EUROfusion

- Contact person: **Marco Utili (ENEA)** and **Fabio Cismondi (EUROfusion PMU)**
- EUROfusion team:
 - **(1) Engineering team:**
 - Alessandro Venturini (UniPisa)
 - Rosario Giamusso (ENEA)
 - David Rapisarda (CIEMAT)
 - Belit Garcinuño (CIEMAT)
 - Amelia Tincani (ENEA)
 - **(2) Design and assembly:**
 - Massimo Valdiserri (ENEA)
 - **(3) MHD/Experiment/PbLi blanket team:**
 - Leo Buehler (KIT)
 - Chiara Mistrangelo (KIT)
 - Carlota Soto (CIEMAT)
 - Fernando Ugorri (CIEMAT)

UCLA/EUROfusion Collaboration: Researchers

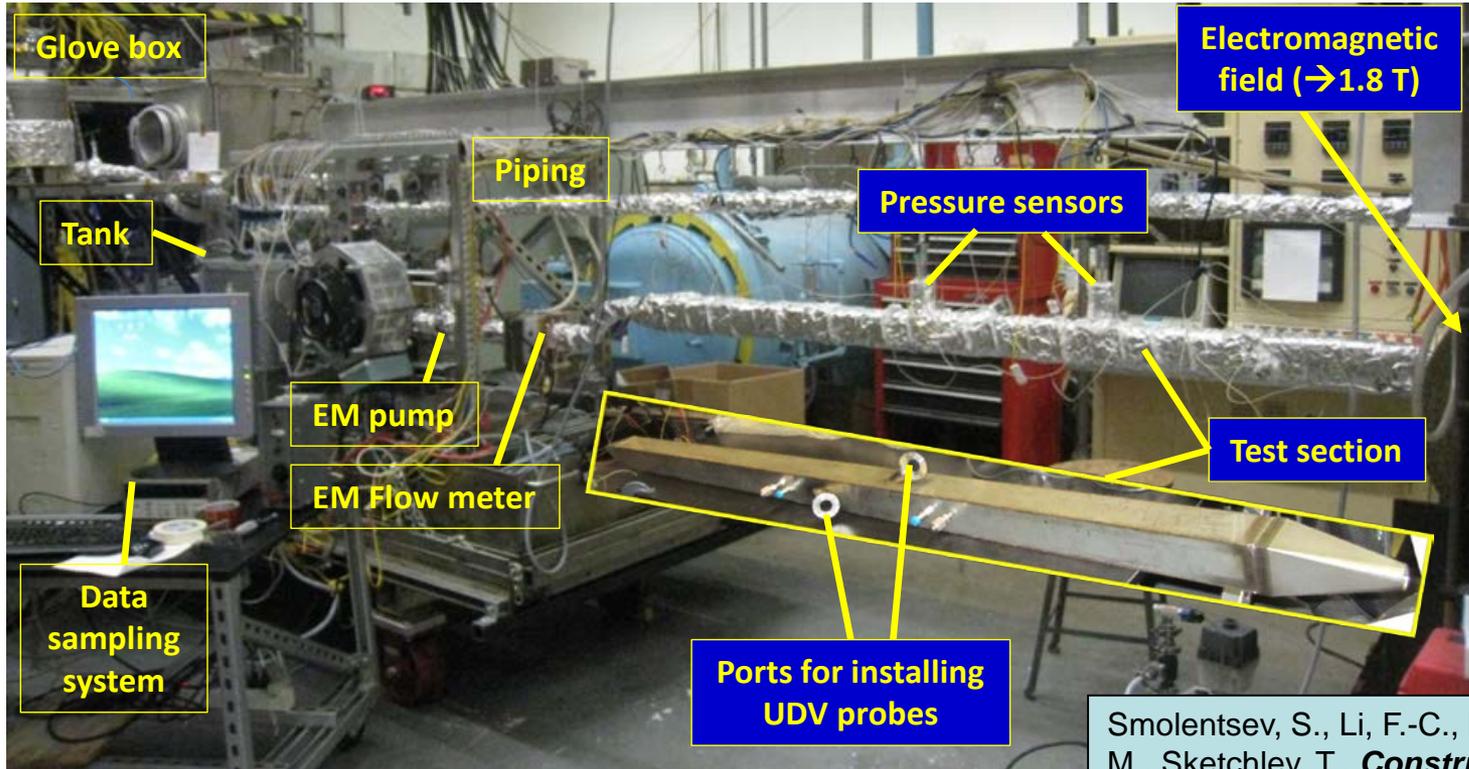
2. UCLA Researchers

A large group of UCLA researchers are involved: both in the *coordination and planning, engineering, design & assembly, AND in the scientific experiments & modeling*

- **MOHAMED ABDOU** – Distinguished Professor of Engineering and Applied Science, UCLA
- **SERGEY SMOLENTSEV** – Leader of MHD Thermofluids Group at Fusion Science and Technology Center, UCLA
- **CYRIL COURTESOLE** – Lead experimentalist at Fusion Science & Technology Center, UCLA
- **NEIL MORLEY** – Senior Researcher at Fusion Science & Technology Center, UCLA
- **ALICE YING** – Blanket Design Specialist, UCLA
- **TOMAS SKETCHLEY** – Lead Laboratory Engineer, UCLA
- **UCLA Ph.D. students:** Yi Yan, Tyler Rhodes, Charlie Kawczynski, Jack Young

MaPLE facility at UCLA prior to the upgrade was successfully used for MHD and Heat Transfer experiments with PbLi from 2011 to 2016

MaPLE Facility (prior to upgrade)

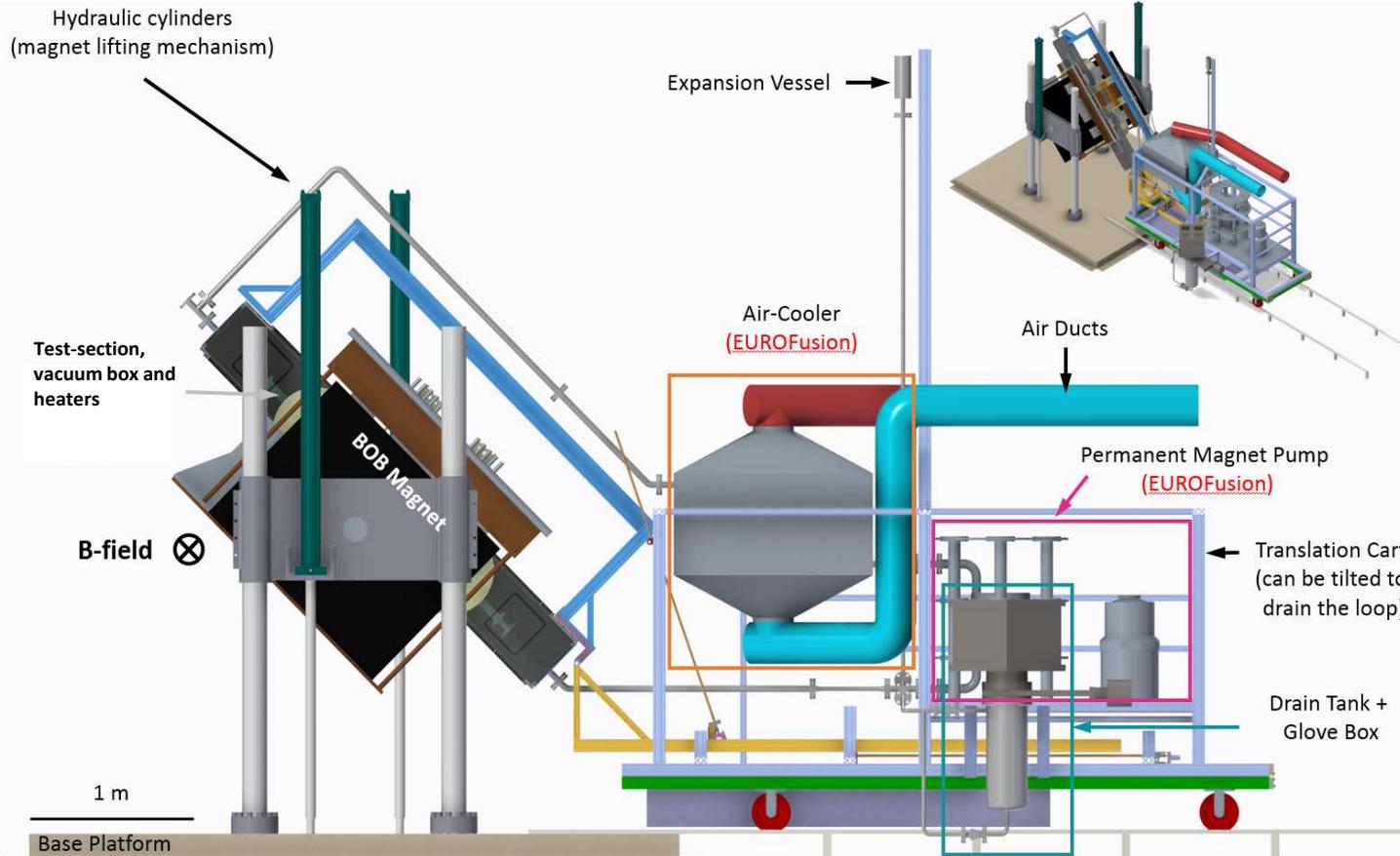


- Q=50 l/min
- M=100 kg PbLi
- B=1.8 T
- V=15x15x80 cm³
- ΔP=0.15 MPA
- T<350°C

Smolentsev, S., Li, F.-C., Morley, N., Ueki, Y., Abdou, M., Sketchley, T., *Construction and Initial Operation of MHD PbLi Facility at UCLA*, *Fusion Eng. Des.* 88, 317-326 (2013).

Main limitation of the MaPLE facility prior to the upgrade was horizontal orientation of the magnet and test-section, and limited heating/cooling Capability

The MaPLE Facility Upgrade (MaPLE-U) has major capabilities to investigate multiple effect LM MHD mixed convection turbulence and instabilities, heat/mass transfer, and material interactions



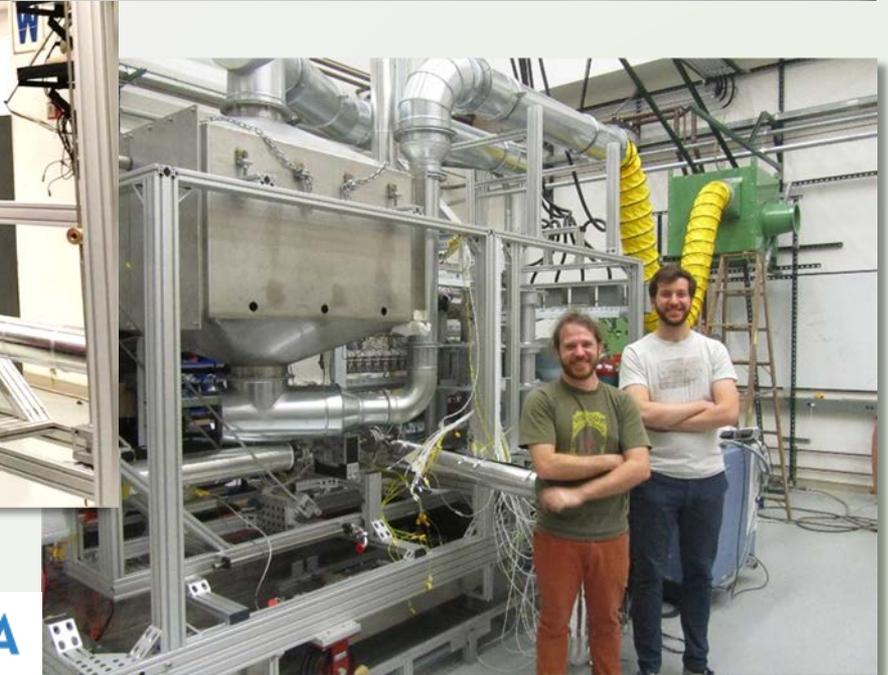
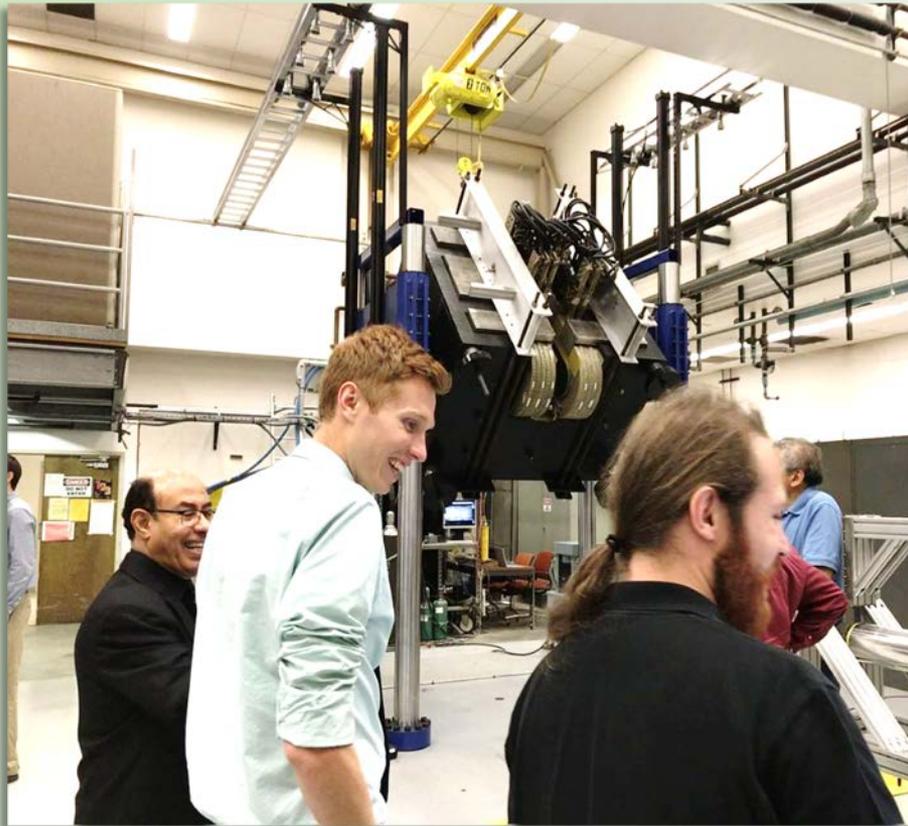
- **Base platform** (11.5 ft x 13 ft, 15000 lb)
- **Lift/tilt mechanism** for the 20-ton BOB magnet with hydraulic motor, hydraulic cylinders and rotation control system: up to 80 inch lift, $-90^\circ < \alpha < 90^\circ$
- **Motor-driven translation cart** to accommodate the PbLi loop, test-section and equipment
 - EM pump (SAAS, Germany): 0.45 MPa /120 LPM
 - Air-cooler: up to 75 kW heat removal
 - Melting/Draining tank with a glove box at the top: 265 kg PbLi
 - Ar-gas purification unit
 - Expansion vessel
 - EM flowmeter
 - Test section with vacuum box and heaters
- **Motor-driven pivot system** to tilt the test-section to the desired angle with respect to gravity

MaPLE-U is a huge step forward

New lift/tilt system, high heating/cooling capability, advanced Control/DAQ system have turned the old MaPLE facility into a unique first-of-a-kind powerful facility (MaPLE-U) for studying multiple effects MHD mixed convection/ turbulence & instabilities, and material interactions

Parameter/capability	MaPLE (2011-2016)	MaPLE-U (2017-)
Flow orientation w.r.t. gravity	Only horizontal	Any orientation from horizontal to vertical
Heating/Cooling capability		75 kW (0.75 MW/m ²) max
Max PbLi inventory	100 kg	265 kg
Max PbLi temperature	350°C	550°C
Max pressure head	0.15 MPa	0.5 MPa
Max PbLi flow rate	50 LPM	120 LPM
Max PbLi velocity	20 cm/s	50 cm/s
Max B-field	1.8 T (15 cm x 15 cm x 80 cm)	2 T (15 cm x 15 cm x 80 cm)
Control/DAQ system	Manual	Fully automated
Safety		Vacuum/safety box

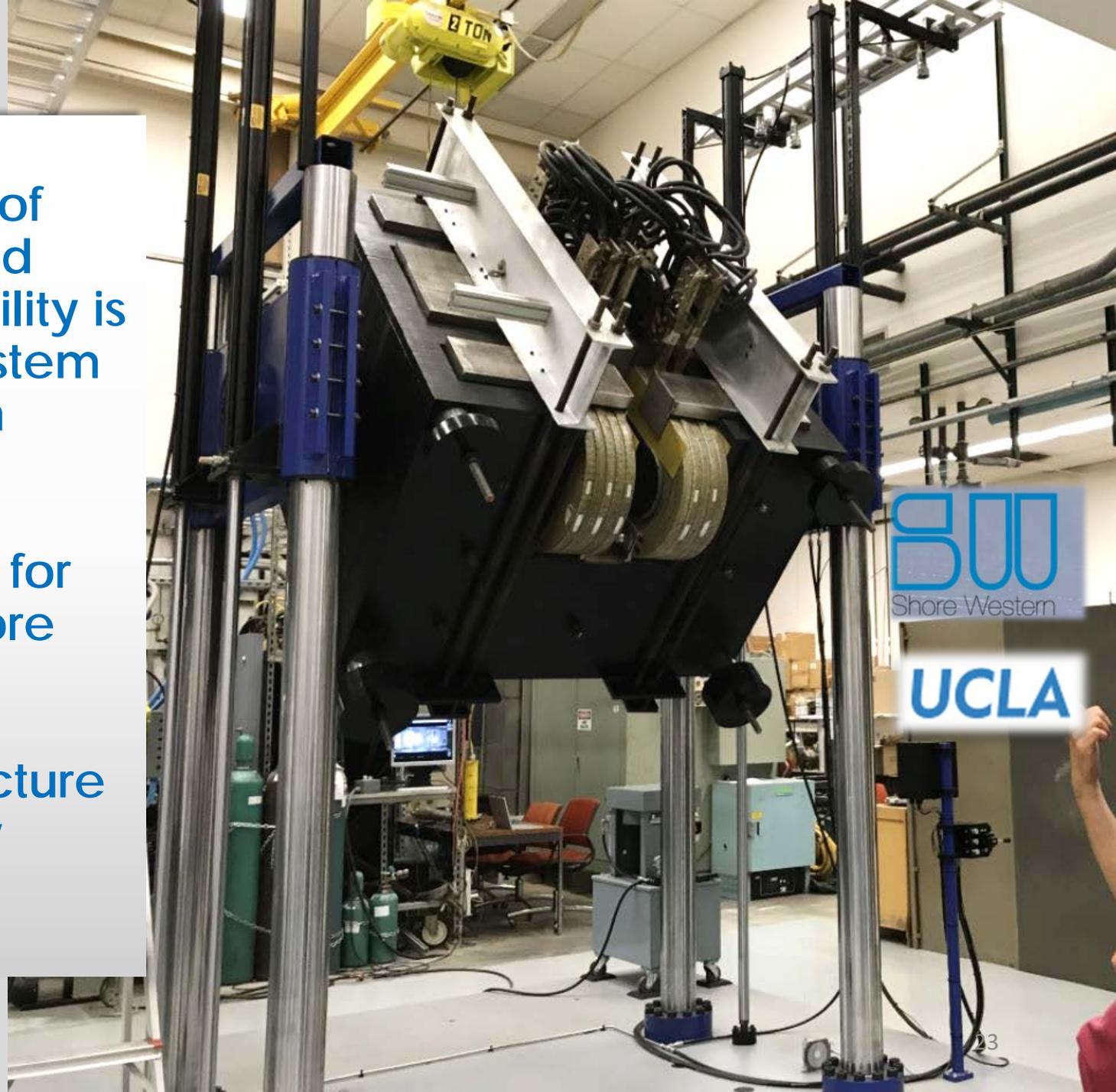
Working together...



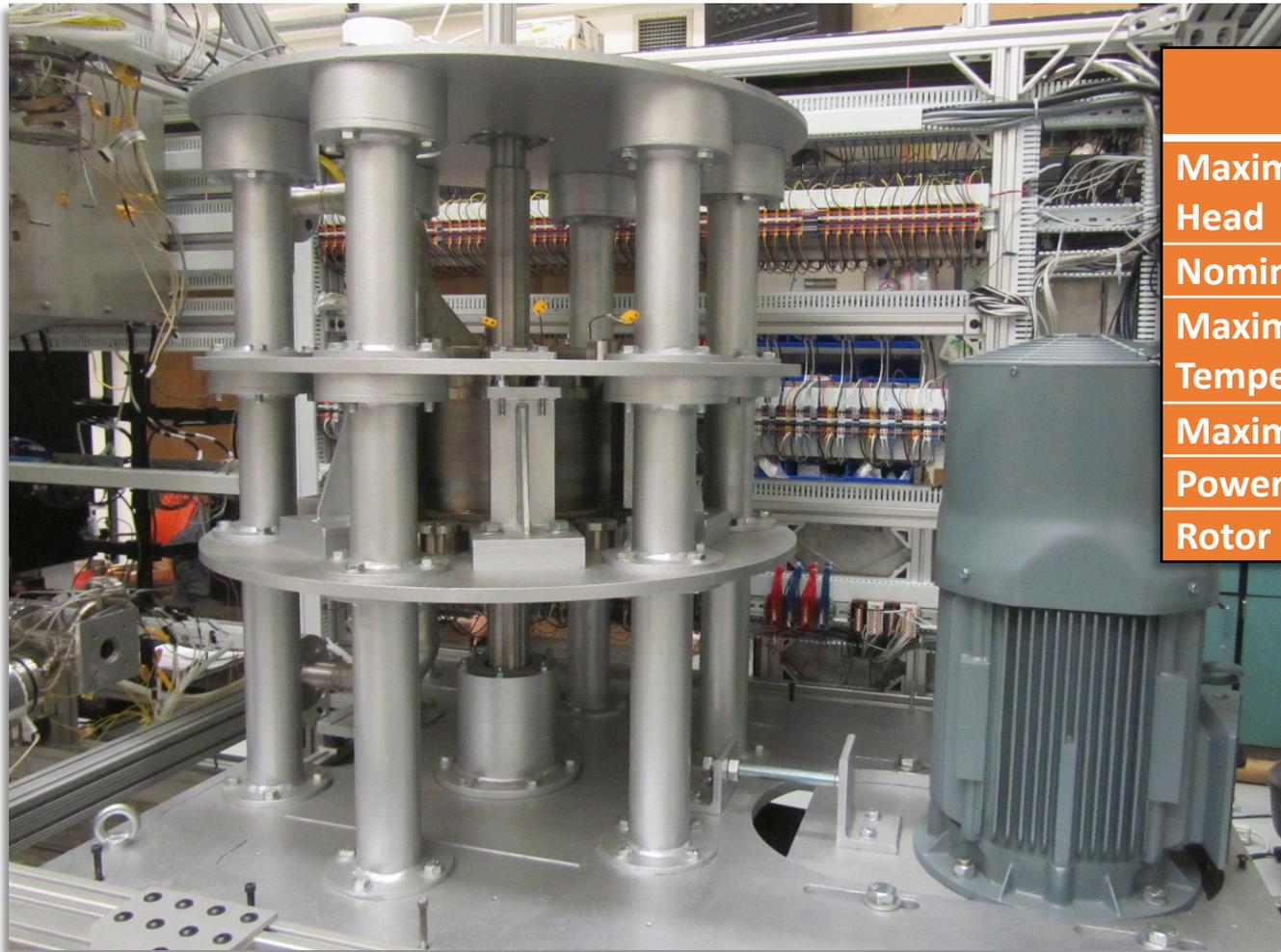
A key component of the upgraded MaPLE-U facility is the lift/tilt system of the 20-ton magnet

Constructed for UCLA by Shore Western

Support structure designed by UCLA Civil Engineering



New Permanent Magnet MHD Pump (PMP) from SAAS, Germany



PMP Parameters	
Maximum Pressure Head	0.5 MPa
Nominal temperature	350 °C
Maximum Working Temperature	550°C
Maximum Flow Rate	120 l/min
Power	18 kW
Rotor Diameter	350 mm

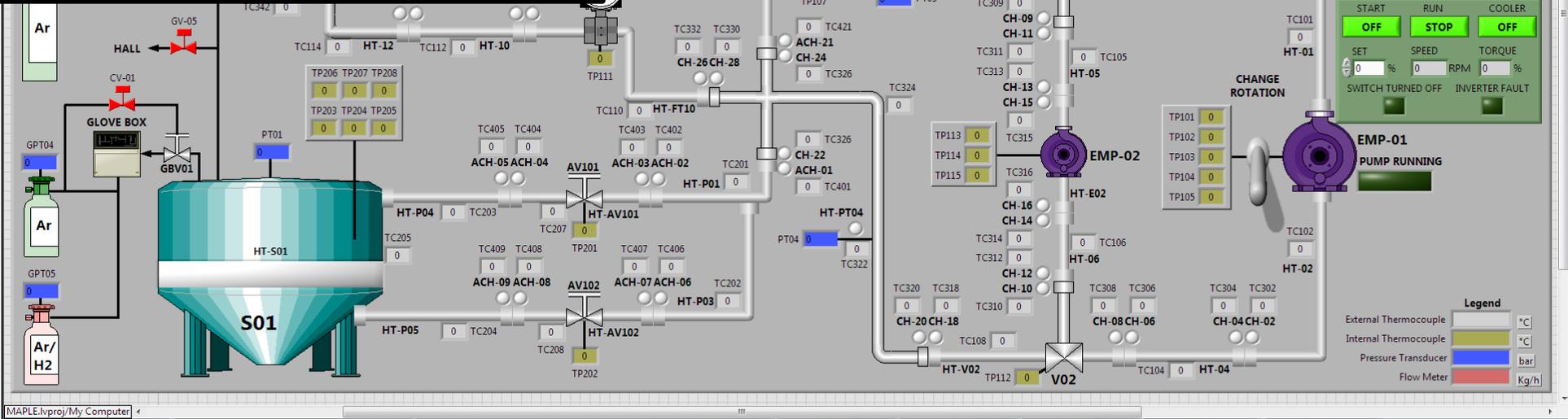
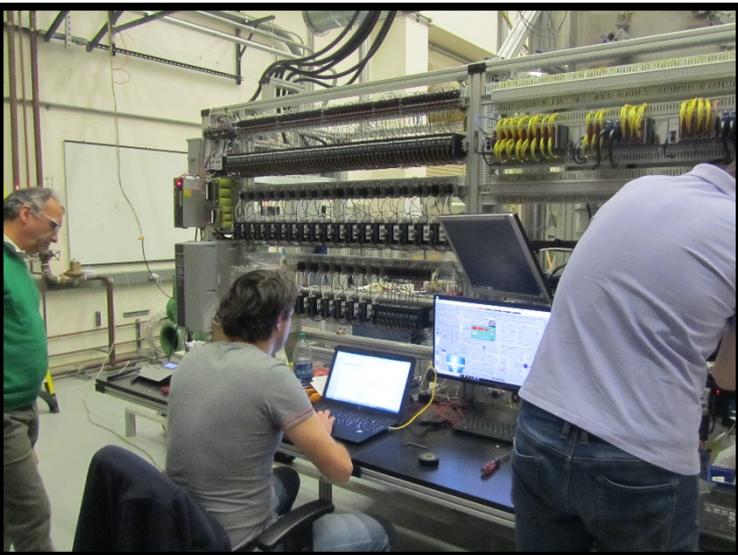
New air cooler (ENEA) – up to 75 kW heat removal



An air cooler was selected as heat rejection system for its simplicity and the capability to remove a large amount of power. In particular:

- ✓ The air cooler is a counter flow PbLi-air heat exchanger, with the liquid metal flowing inside the pipes and the air flowing outside
- ✓ A helical stainless steel sheet is welded on the surface of the tubes to intensify heat transfer
- ✓ The air flow is pumped by a fan, which is controlled by an SCR (silicon-controlled rectifier) using the PbLi temperature at the air cooler outlet as a control signal
- ✓ A heating system is used during the charging phase in order to prevent the alloy to freeze (3- 4 kW)

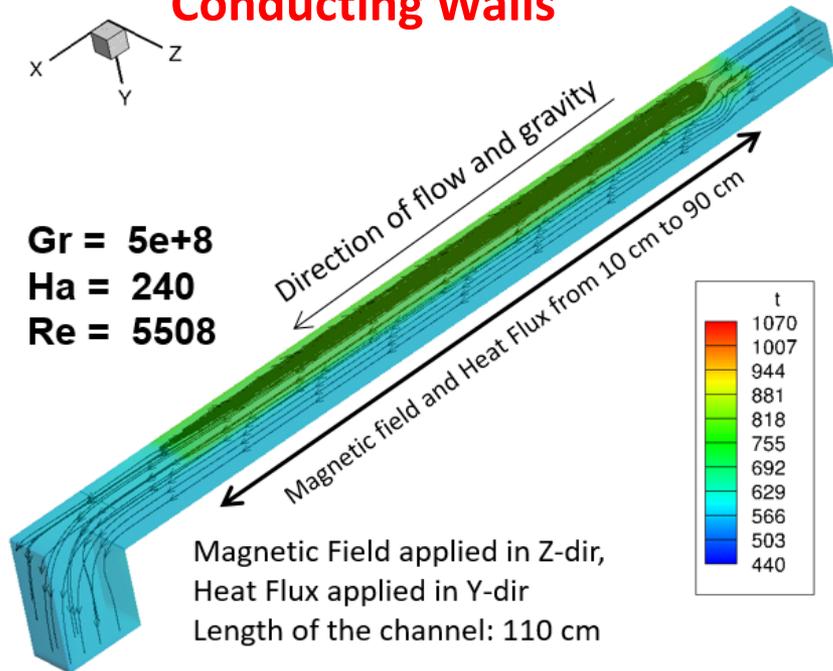
New Control/Data Acquisition system from ENEA



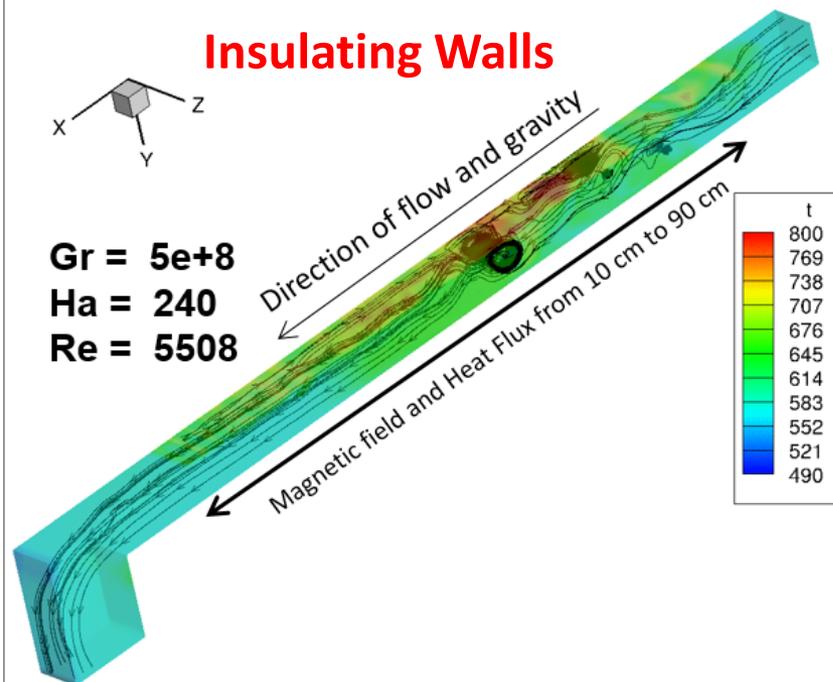
UCLA made major advances in 3-D modelling in the past 18 months in collaboration with HyPerComp (using HIMAG) for predicting mixed convection “downward flows” with B, g, heating, and temperature gradient. This has enabled us to do much more insightful scientific planning of the experimental campaigns

Computation used 1024 nodes at DOE/NERSC cluster with massively parallel computation

Conducting Walls



Insulating Walls



The velocity field shows **instabilities with flow reversals** that affect transport phenomena. These instabilities are **stronger for insulating walls as compared to conducting walls** due to lower Joule dissipation.

The first mixed-convection experiments will be performed by the joint team of UCLA/EUROfusion scientists. They will focus on **vertical flows typical of midplane blankets with the highest NWL**

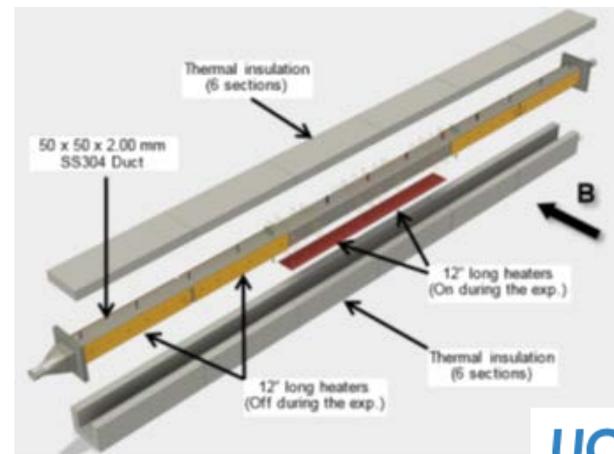
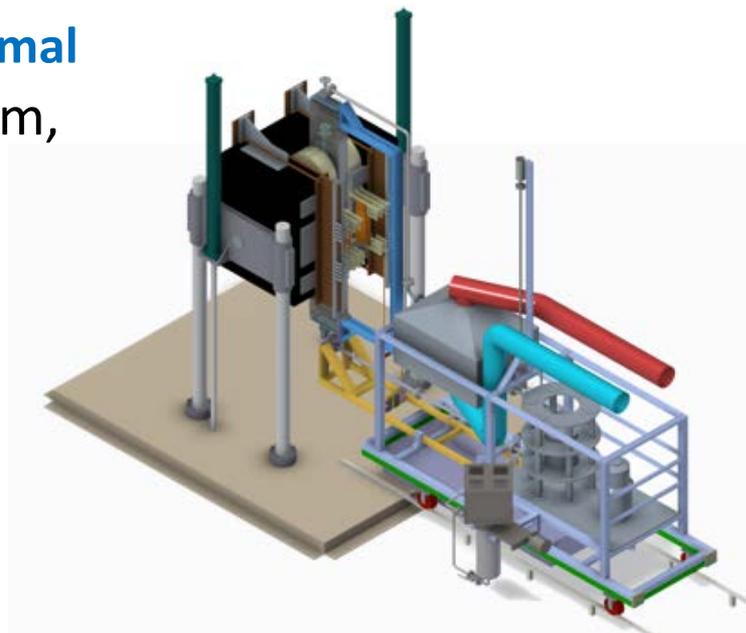
In this orientation the buoyancy forces are maximal

- Vertical SS 304 rectangular duct (5 cm x 5 cm, tw=2 mm, L=1.8 m) heated from one side

This is a **conducting test-article**. Follow on experiments will use a **non-conducting duct**.

- Magnetic field: 0 -1.8 T
- PbLi velocity: 1 -20 cm/s
- Maximum heat flux: 0.2 MW/m²
- Maximum Gr number $\sim 4.4 \times 10^8$
- Diagnostics: surface and submerged thermocouples, potential probes, movable probes

We are looking forward to seeing many important flow phenomena : *flow reversals, bulk and boundary layer instabilities, quasi-two dimensional turbulence, formation of high-velocity near-wall jets, etc.*



Experimental sequence in 2018-2019 and beyond to characterize MHD mixed-convection flows in various conditions

Max parameters: $Ha \sim 10^3$, $Re \sim 10^4$, $Gr \sim 10^9$

Duct: **conducting/insulating**

Flow regime: **upward/downward**

Inclination angle: $\alpha = 0-90^\circ$

Year	Experiment	Facility upgrade / Test-section/ Instrumentation
2018	I. MHD mixed-convection flow in a vertical ($\alpha=90^\circ$) and inclined ($\alpha=45^\circ$) electrically conducting duct	Upgraded MaPLE-U: $q \sim 0.2$ MW/m ² and PbLi T _{max} =500°C. New high-capacity MHD pump. New cooling/heating system. New DACS
2019	II. MHD mixed-convection flow in a non-conducting duct ($\alpha=90^\circ, 45^\circ$) (Non-conducting channel experiments are the most challenging)	New insulating test-section, e.g. Aluminum Nitride, Alumina, SiC or SS coated. (Need walls that are electrically insulated but thermally conducting to allow penetration of heat load) New HT PbLi instrumentation: LEVI probes, transverse electric potential probes.
2019-	III. Complex geometry MHD mixed-convection flows, including flows with insulating FCI	1) Test-section of multiple channels 2) Conducting test-section with insulating FCI

Summary (1 of 2) – Right now, we do not know and cannot predict how the blanket/FW will work in the fusion nuclear environment

- Blankets designed with current knowledge of separate effects phenomena and data will not work. The sources of this problem are:
 1. The fusion nuclear environment has many fields with steep gradients (magnetic, neutrons, nuclear heating), and the blanket has many functions and materials – resulting in many yet undiscovered phenomena caused by multiple and synergistic effects/interactions
 2. Simulation of the full fusion nuclear environment in non-fusion facilities is impossible
 3. Accurate simulations of volumetric nuclear heating and temperature gradients are not possible
 4. The fusion conditions result in very high parameters (e.g. Ha, Gr) not achievable in the lab
 5. Phenomena such as MHD thermofluids is non-linear – so we do not know the scaling laws
- We must build a number of laboratory facilities with strong capabilities to do the best possible simulation of the combined effects of the fusion nuclear environment and representative blanket mockups. **A sequence of progressively more powerful facilities is needed (\$5M, \$20M, \$50M).** We also need a multiple of such facilities with different approaches to simulation to be constructed around the world.
- We will also need to do much more serious modeling with high speed computation initiatives

Summary (2 of 2) – The US/UCLA-EUROfusion Collaboration is pioneering first-of a-kind multiple effect/multiple interaction experiments

- Modelling shows that gradients in volumetric nuclear heating and high temperature in the LM breeder may lead to new phenomena that fundamentally alter our understanding of the MHD thermofluid behavior.
 - For example, buoyant MHD interactions result in mixed convection flow regimes, instabilities and MHD turbulence, which might strongly affect heat transfer, tritium transport/permeation and materials interactions in the blanket
- The US (UCLA) and EUROfusion started a strong collaborative program to study multiple effect phenomena in LM blanket. A key element in this collaboration is the upgrade of the MaPLE (Magnetohydrodynamic PbLi Experiment) facility at UCLA:
 - high temperature PbLi as a working fluid,
 - prototypical materials and conditions,
 - capabilities for heating, generation of temperature gradients,
 - arbitrary orientation of the LM flow with respect to gravity and magnetic field,
 - while utilizing an advanced fluid flow diagnostics and new control and data acquisition system.
- Extensive modelling and analyses have been carried out to design a series of experiments to investigate buoyant MHD interactions, mixed convection flows and other phenomena in different flow regimes and a variety of conditions.
- We are entering very exciting times for Fusion Nuclear Science

THANK YOU