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

<table>
<thead>
<tr>
<th>Neutrons (flux, spectrum, gradients, pulses)</th>
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<tbody>
<tr>
<td>- Bulk (volumetric) Heating</td>
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<tr>
<td>- Tritium Production</td>
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<tr>
<td>- Radiation Effects</td>
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<tr>
<td>- Activation and Decay Heat</td>
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</tbody>
</table>

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<tr>
<th>Heat Sources (thermal gradients, pulses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Bulk (neutrons)</td>
</tr>
<tr>
<td>- Surface (particles, radiation)</td>
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<thead>
<tr>
<th>Particle/ Debris Fluxes (energy, density, gradients)</th>
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<th>Magnetic Fields (3-components, gradients)</th>
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<tbody>
<tr>
<td>- Steady and Time-Varying Field</td>
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</table>

<table>
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<tr>
<th>Mechanical &amp; Electromagnetic Forces</th>
</tr>
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<tr>
<td>- Normal (steady, cyclic) and Off-Normal (pulsed)</td>
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<tr>
<th>Combined Loads, Multiple Environmental Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Thermal-chemical-mechanical-electrical-magnetic-gravitational-nuclear interactions and multiple/synergistic effects</td>
</tr>
<tr>
<td>- Interactions among physical elements of components</td>
</tr>
</tbody>
</table>

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. Ceramic Breeder Based**
  - Neutron Multiplier: Be, Be$_{12}$Ti
  - Tritium Breeder: Li$_2$TiO$_3$, Li$_4$SiO$_4$
- **E.g. Liquid Breeder Based**
  - Coolants: He, H$_2$O, or liquid metal or salt
- **First Wall (RAFS, F82H)**
- **Surface Heat Flux Neutron Wall Load**
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
  - cannot 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.

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 \( \mathbf{g} \) and \( \mathbf{B} \) 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)

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**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.

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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

<table>
<thead>
<tr>
<th>Non-Dimensional Parameters</th>
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<tbody>
<tr>
<td>➢ Reynolds Number, ( Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{\rho u L}{\mu} )</td>
</tr>
<tr>
<td>➢ Hartmann Number, ( Ha = (\frac{Electromagnetic\ forces}{Viscous\ forces})^{0.5} = BL\sqrt{\frac{\sigma}{\mu}} )</td>
</tr>
<tr>
<td>➢ Grashof Number, ( Gr = \frac{Buoyancy\ forces}{Viscous\ forces} = \frac{g\beta \Delta T L^3}{\nu^2} = \frac{g\beta q L^4}{\nu^2 \kappa} )</td>
</tr>
</tbody>
</table>

- 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
    \[ Gr_{\parallel} = Gr_{eq} \cdot \cos(\alpha); \]
  - Perpendicular radial Grashof Number
    \[ Gr_{\perp} = Gr_{eq} \cdot \sin(\alpha); \]

- Furthermore, the temperature rise in the flow direction can also be fairly significant. Such an axial \( \Delta T \) 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.

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* Smolentsev et.al, “Inboard DCLL blanket with sandwich flow channel insert using the EU DEMO1 as a reference plant layout”, Internal Report UCLA.
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 $\sim 1$ 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 $\sim 10$ 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!)

**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?

**DEMO BLANKET:** Ha~$10^4$, Gr~$10^{12}$, Re~$10^5$

**EXPERIMENT:** Ha~$10^3$, Gr~$10^9$, Re~$10^5$
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 Urgorri (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 COURTESSOLE** – 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

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

- \( Q = 50 \, \text{l/min} \)
- \( M = 100 \, \text{kg PbLi} \)
- \( B = 1.8 \, \text{T} \)
- \( V = 15 \times 15 \times 80 \, \text{cm}^3 \)
- \( \Delta P = 0.15 \, \text{MPa} \)
- \( T < 350 \, ^\circ \text{C} \)

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°<α<90°
- **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

Upgrading the MaPLE facility is in its final phase at UCLA. First experiments on MHD mixed convection will be started soon by the UCLA-EUROfusion team.
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.

<table>
<thead>
<tr>
<th>Parameter/capability</th>
<th>MaPLE (2011-2016)</th>
<th>MaPLE-U (2017-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow orientation w.r.t. gravity</td>
<td>Only horizontal</td>
<td>Any orientation from horizontal to vertical</td>
</tr>
<tr>
<td>Heating/Cooling capability</td>
<td>75 kW (0.75 MW/m²) max</td>
<td>75 kW (0.75 MW/m²) max</td>
</tr>
<tr>
<td>Max PbLi inventory</td>
<td>100 kg</td>
<td>265 kg</td>
</tr>
<tr>
<td>Max PbLi temperature</td>
<td>350°C</td>
<td>550°C</td>
</tr>
<tr>
<td>Max pressure head</td>
<td>0.15 MPa</td>
<td>0.5 MPa</td>
</tr>
<tr>
<td>Max PbLi flow rate</td>
<td>50 LPM</td>
<td>120 LPM</td>
</tr>
<tr>
<td>Max PbLi velocity</td>
<td>20 cm/s</td>
<td>50 cm/s</td>
</tr>
<tr>
<td>Max B-field</td>
<td>1.8 T (15 cm x 15 cm x 80 cm)</td>
<td>2 T (15 cm x 15 cm x 80 cm)</td>
</tr>
<tr>
<td>Control/DAQ system</td>
<td>Manual</td>
<td>Fully automated</td>
</tr>
<tr>
<td>Safety</td>
<td></td>
<td>Vacuum/safety box</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Pressure Head</td>
<td>0.5 MPa</td>
</tr>
<tr>
<td>Nominal temperature</td>
<td>350 °C</td>
</tr>
<tr>
<td>Maximum Working Temperature</td>
<td>550°C</td>
</tr>
<tr>
<td>Maximum Flow Rate</td>
<td>120 l/min</td>
</tr>
<tr>
<td>Power</td>
<td>18 kW</td>
</tr>
<tr>
<td>Rotor Diameter</td>
<td>350 mm</td>
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</table>
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.

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:

- Vertical SS 304 rectangular duct (5 cm x 5 cm, \( t_w = 2 \) mm, \( L = 1.8 \) m) heated from one side
- Magnetic field: 0 - 1.8 T
- PbLi velocity: 1 - 20 cm/s
- Maximum heat flux: 0.2 MW/m\(^2\)
- 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

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
<th>Facility upgrade / Test-section/ Instrumentation</th>
</tr>
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<tbody>
<tr>
<td>2018</td>
<td>I. MHD mixed-convection flow in a vertical ($\alpha = 90^\circ$) and inclined ($\alpha = 45^\circ$) electrically conducting duct</td>
<td>Upgraded MaPLE-U: $q \sim 0.2$ MW/m² and PbLi $T_{max} = 500^\circ$C. New high-capacity MHD pump. New cooling/heating system. New DACS</td>
</tr>
</tbody>
</table>
| 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