Examples of Scientific Discoveries and the Role of International Collaboration from Fusion Energy R&D

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Examples of Scientific Discoveries and the Role of International Collaboration from Fusion Energy R&D

- Scientific discovery is essential to advancing humankind
- Fusion research has made major advances through important scientific discoveries over decades
- International collaboration has also been very strong in fusion research and played a key role in accelerating the development of fusion
- This Lecture will give examples of major scientific discovery at UCLA in fusion science and technology and exemplary US/UCLA–European collaboration to utilize this discovery

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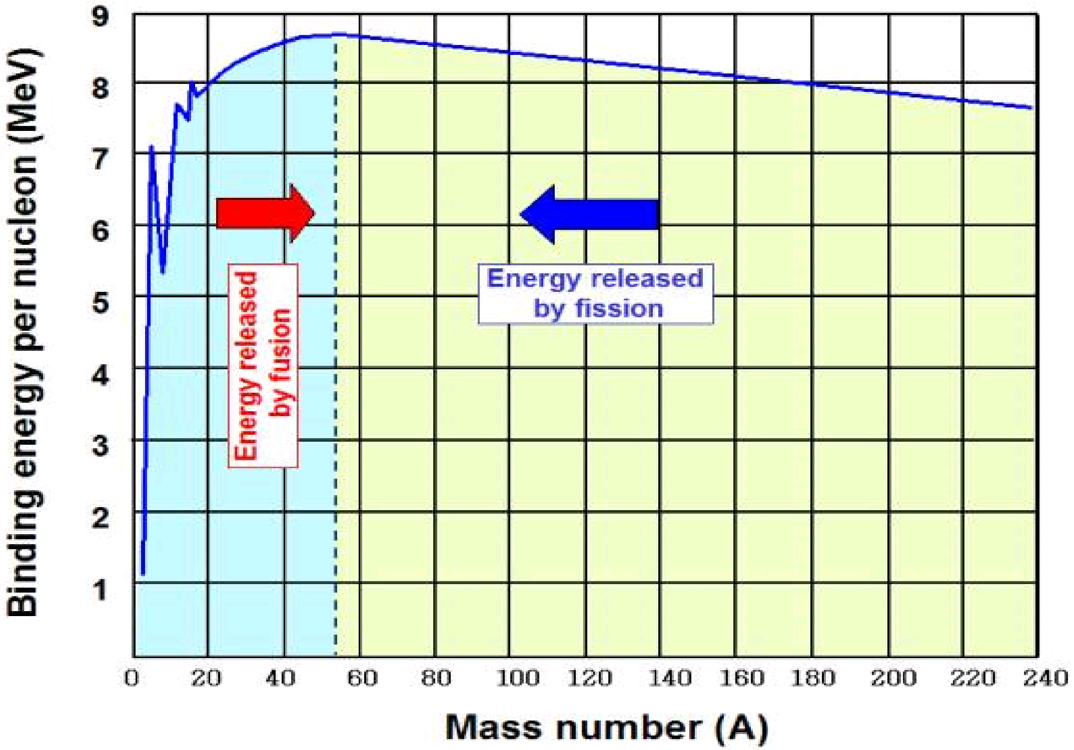
What is nuclear fusion?

- **Fusion powers the sun and stars:** **Fusion is the energy-producing process taking place in the core of the sun and stars. Fusion research is akin to "creating a star on earth"**
- **Two light nuclei combine to form a heavier nuclei, converting mass to energy - the opposite of nuclear fission where heavy nuclei split**
- **In nuclear (fission and fusion), mass is converted to energy , Einstein's famous Eq.**

  $E = mC^2$

  Small mass → Huge energy

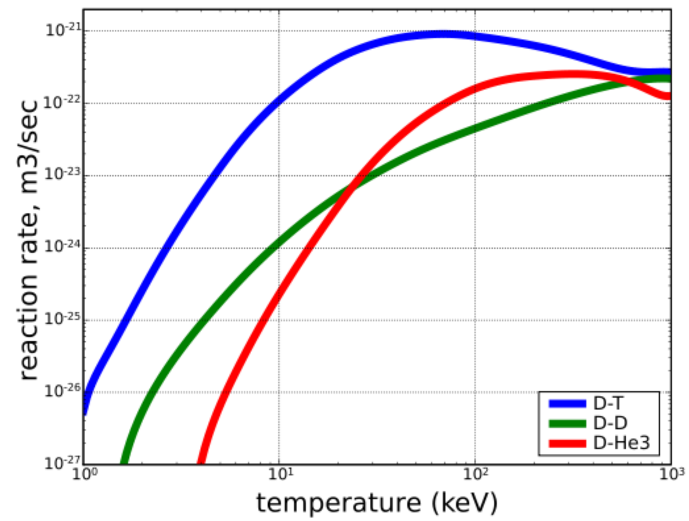


In contrast to fossil fuels (oil, gas, coal) where chemical energy is stored, and huge mass needed to "store" energy

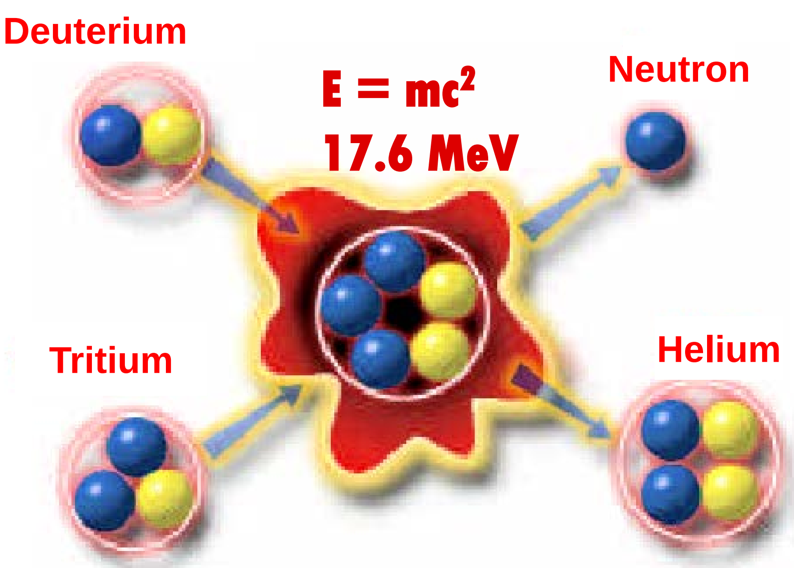
A number of fusion reactions are possible based on the choice of the light nuclides

The World Program is focused on the

Deuterium (D) - Tritium (T) Cycle



- **D-T Cycle is the easiest to achieve: attainable at lower plasma temperature because it has the largest reaction rate and high Q value.**



80% of energy release (14.1 MeV) → Used to breed tritium and close the DT fuel cycle

Li + n → T + He

Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)

Incentives for Developing Fusion

- Sustainable energy source

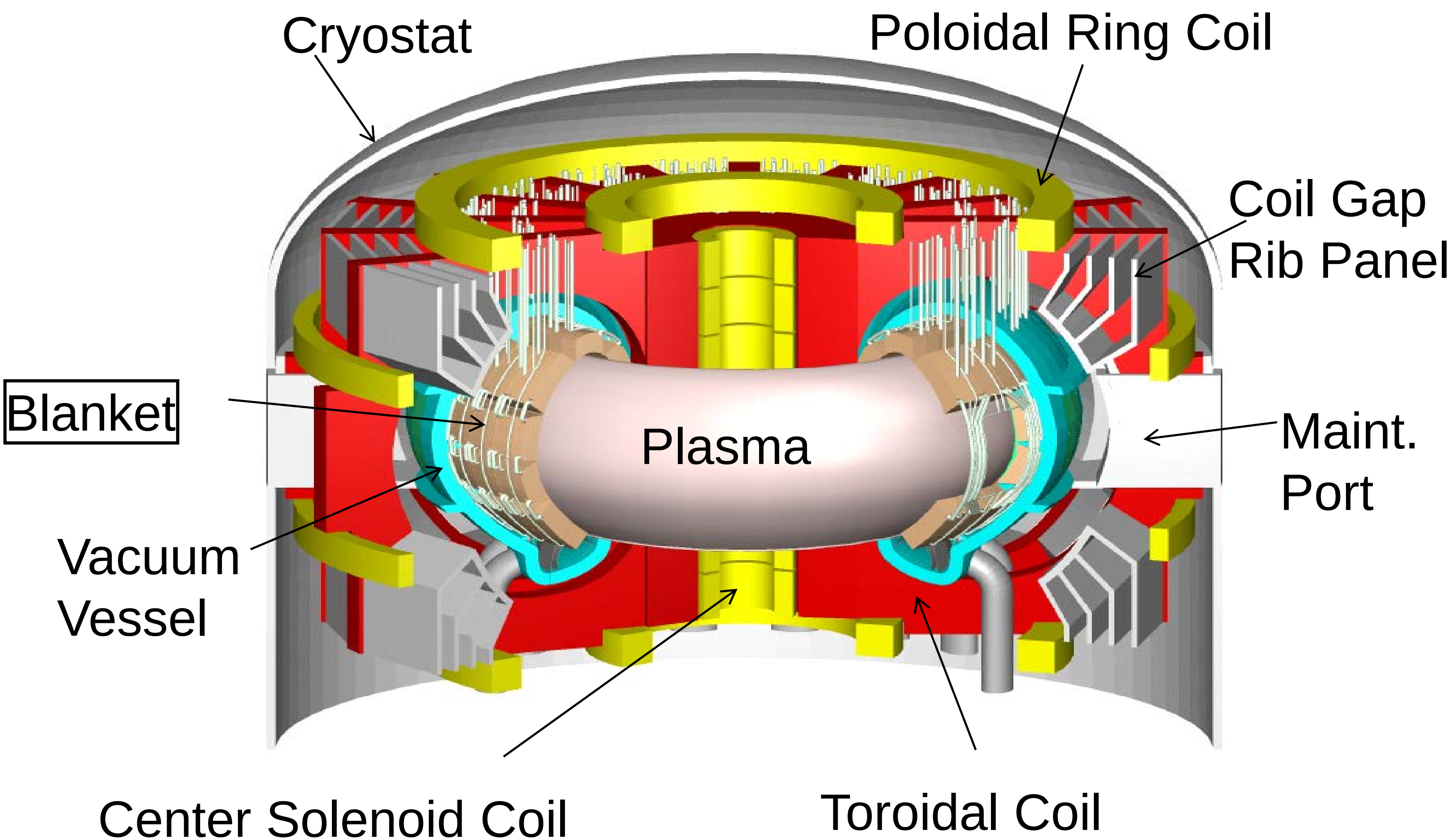
  Fusion fuels are widely available and abundant. Deuterium can be distilled from all forms of water, while tritium will be produced during the fusion reaction as fusion neutrons interact with lithium.

- No emission of Greenhouse or other polluting gases
- No risk of a severe accident – No risk of meltdown
- No long-lived radioactive waste

Fusion energy can be used to produce electricity and hydrogen, and for desalination.

The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2050(?)

Plans for DEMO are based on Tokamaks

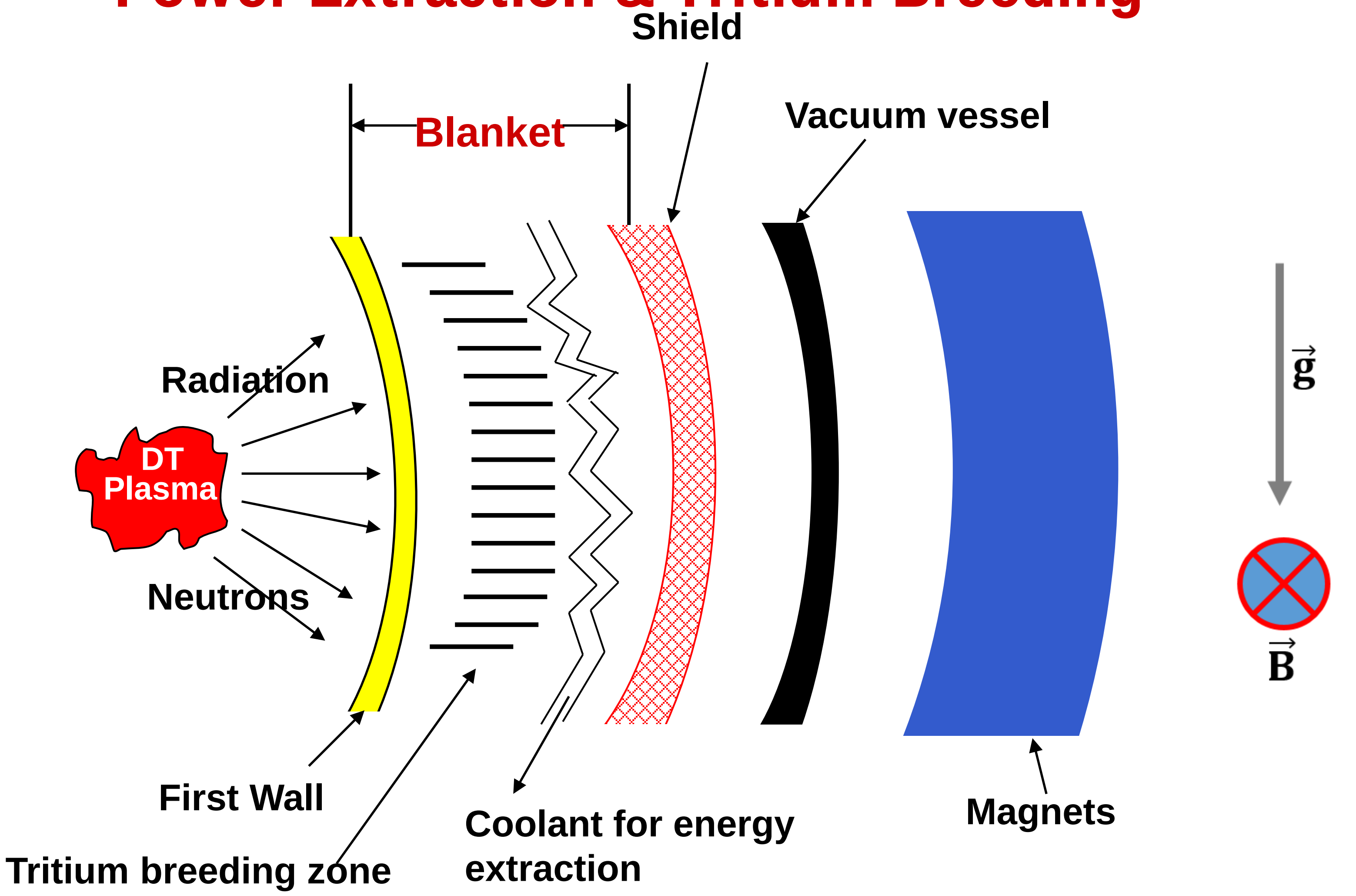


(Illustration is from JAEA DEMO Design)

ITER

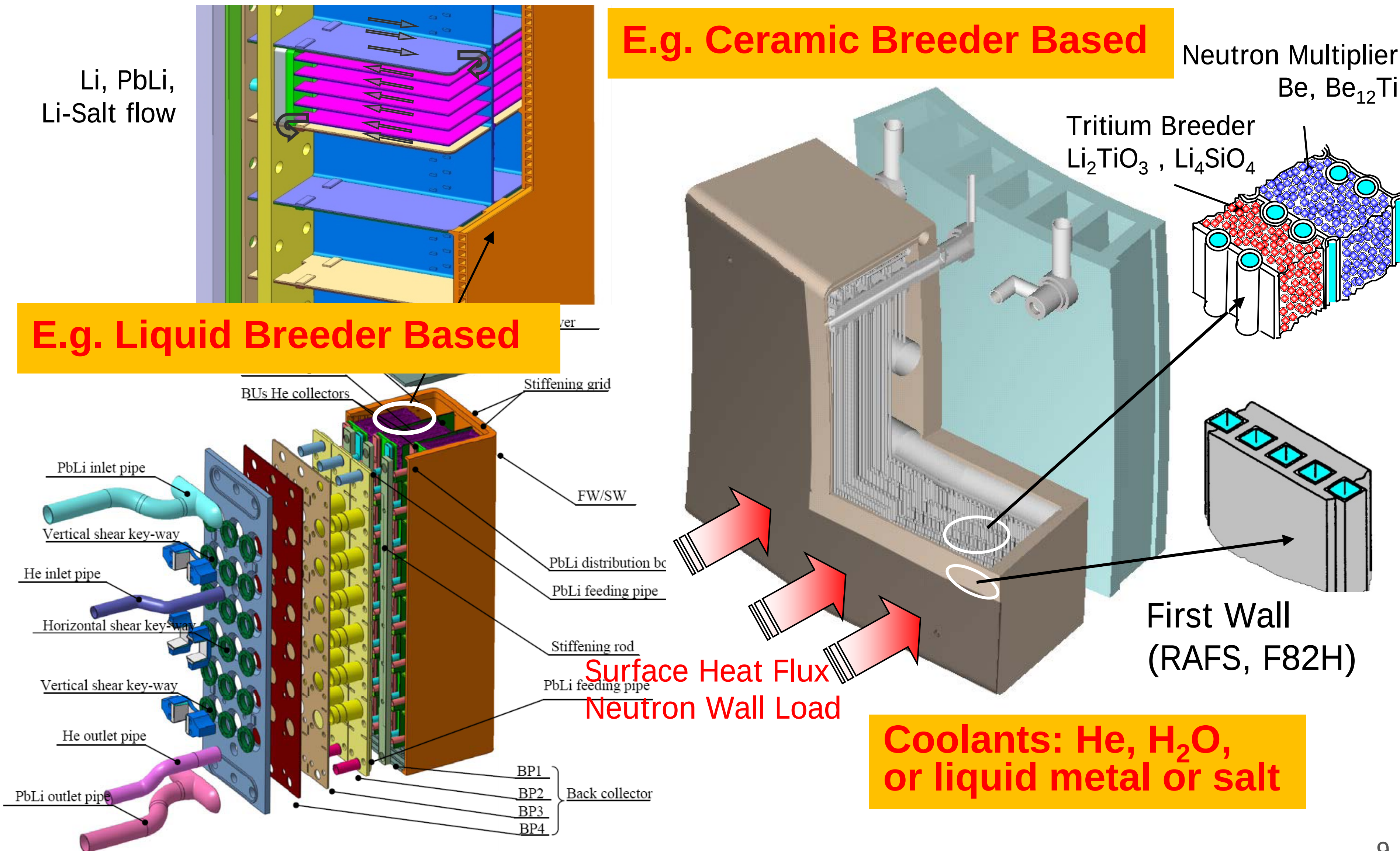
- Fusion Research is very challenging – it started ~ 50 years ago. The **next step** in fusion development, a device called ITER, is now under construction in Southern France.
- **ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea, and India. – represent half the world's population**
- ITER will produce **500 MW** of fusion power
- Cost is ~25 billion dollars.
- ITER will begin operation (first plasma) ~ 2025 (DT in 2036)
- *ITER will demonstrate the **science of burning plasma and** plasma-support technologies (magnets, plasma heating/fueling). But it will not demonstrate fusion nuclear science and technology (e.g. blankets for heat extraction and tritium breeding) – these need R&D parallel to ITER*

The Blanket is a KEY component in fusion reactors. Its primary functions are to provide for: Power Extraction & Tritium Breeding



Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. He-cooled Li ceramics are also candidates.

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



Coolants: He, H_2O, or liquid metal or salt

Fusion Nuclear Environment is Complex & Unique

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

- Bulk (volumetric) Heating
- Tritium Production
- Radiation Effects
- 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)*

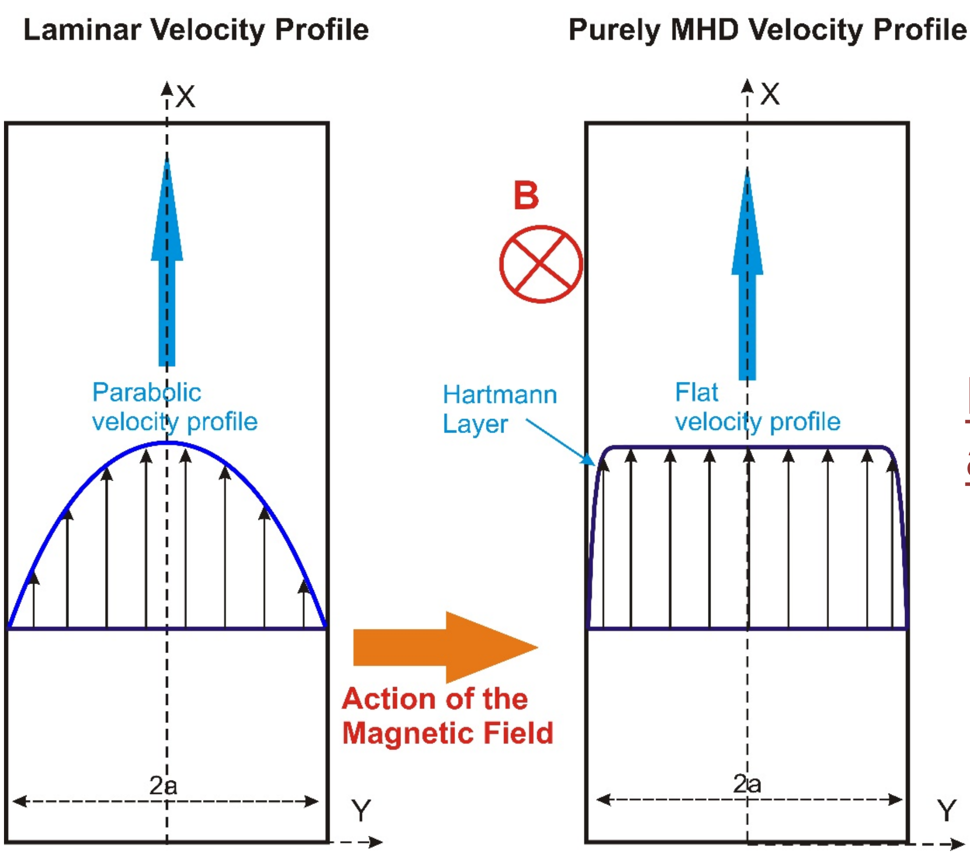
Multiple functions, materials, and many interfaces in highly constrained system

Combined Loads, Multiple Environmental Effects

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

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

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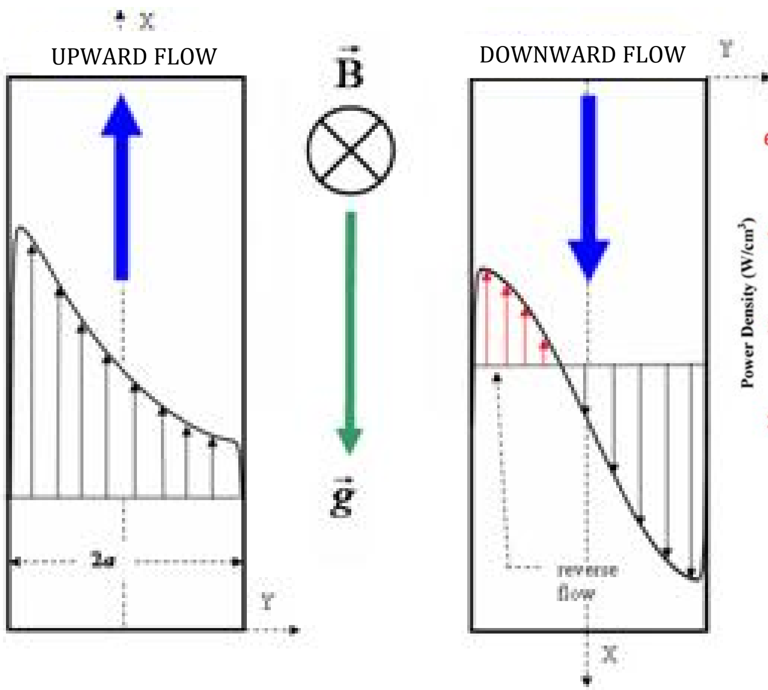
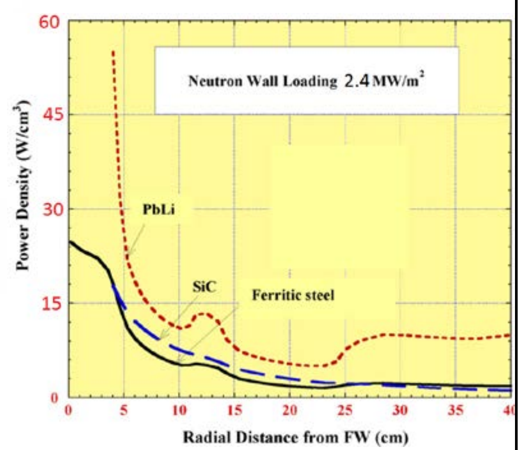
UCLA Discovery: Spatial gradients in nuclear heating & temperature in LM blanket combined with $\vec{g}$ and $\vec{B}$ lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior, Tritium Transport/Permeation and Materials Interactions in the blanket in the fusion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

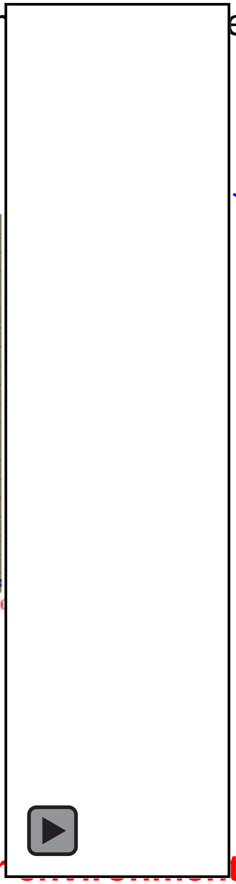
lead to **Buoyant MHD interactions resulting in an unstable "Mixed Convection" flow regime**

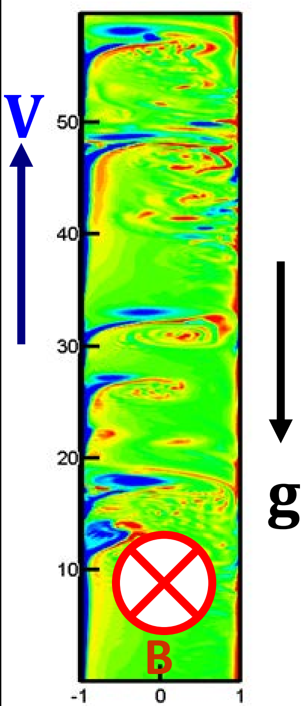
Base flow strongly altered leading to velocity gradients, stagnant zones and even "**flow reversal**"

Vorticity Field shows new **instabilities** that affect transport ph eat, T, Corrosion)









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

- **Predictions from separate effect tests for the integrated fusion nuclear t are wrong**
- **Blankets designed with current knowledge of phenomena and data will <u>not</u> 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)

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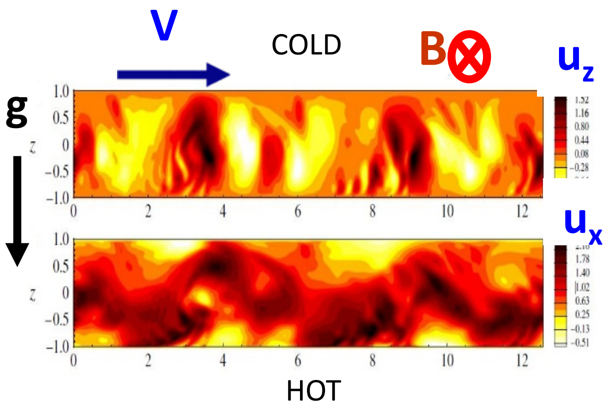
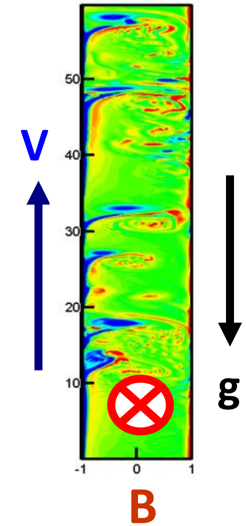
MHD Convection Phenomena:
Dependence on Gravity Orientation

- 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*.



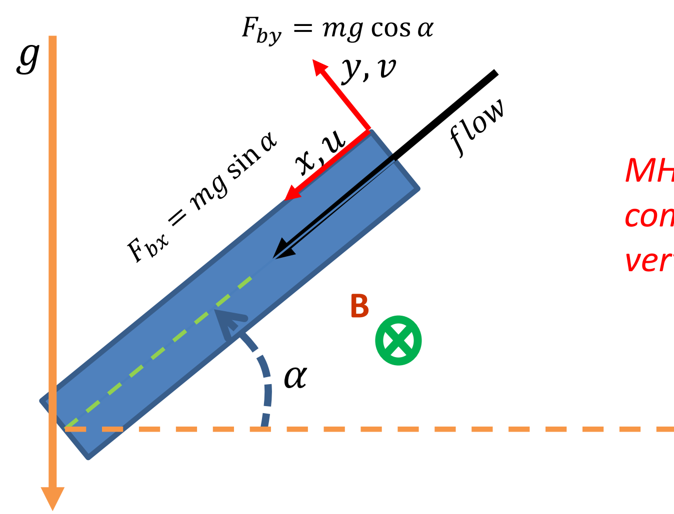
MHD Mixed convection in a horizontal duct.

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



MHD Mixed convection in a vertical duct.

- 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 <u>scaled down</u> 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, $Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{\rho u L}{\mu}$
➢ Hartmann Number, $Ha = \left(\frac{Electromagnetic\ forces}{Viscous\ forces}\right)^\wedge 0.5 = BL\sqrt{\frac{\sigma}{\mu}}$
➢ Grashof Number, $Gr = \frac{Buoyancy\ forces}{Viscous\ forces} = \frac{g\beta \Delta T L^3}{\nu^2} = \frac{g\beta \dot{q} L^4}{\nu^2 \kappa}$

- 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

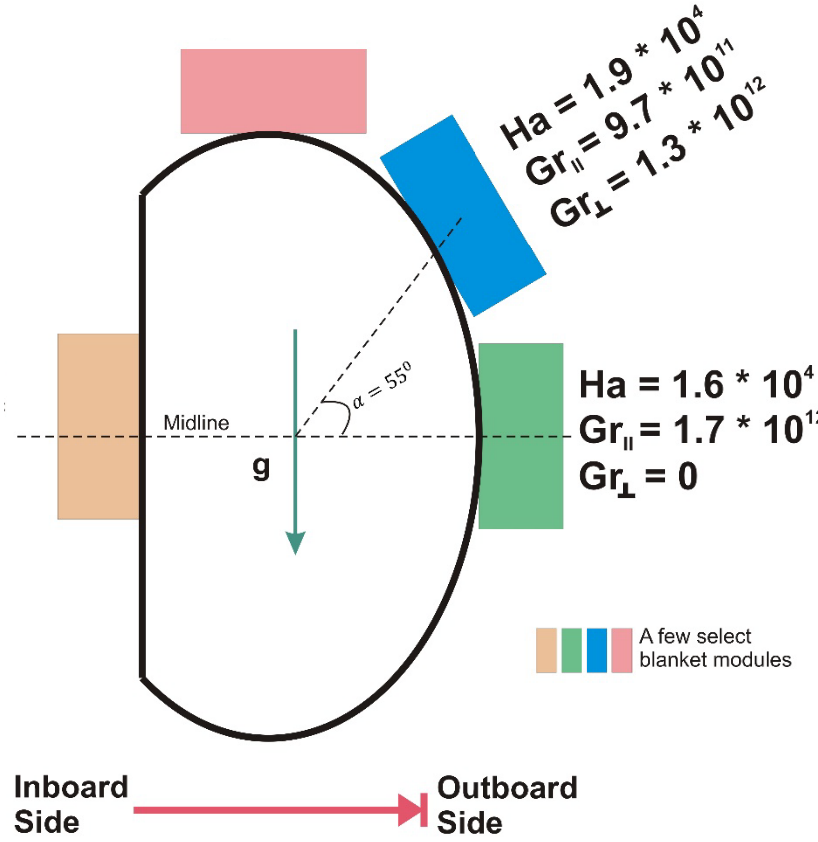
- The Blanket has many modules, each will have its own MHD thermofluid conditions (e.g. different Ha, Gr) because of variations in magnetic field, neutron wall load and flow orientation w.r.t. gravity (see figure).
- We have a wide range of parameter values, e.g.
  - **Parallel radial Grashof Number**

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

  - **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.**

- *Rapisarda et.al, "*Overview of DCLL research activities in the EU/Spain*", Pulsed Power Conference & Symposium on Fusion Engineering – PPC 2015 SOFE, Austin, Texas.
- *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 ~ 1 mm/sec compared to buoyant flow velocity V_b ~ 20 cm/sec **(V_b/V_f ~ 200)**

Dual Coolant Lead Lithium (DCLL)

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

Self-Cooled LM

- **Smaller effect** with volumetric heating
- Forced flow velocity is ~ 0.5 – 1.0 m/sec **(V_b/V_f ~ 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~10^4, Gr~10^{12}, Re~10^5

EXPERIMENT: Ha~10^3, Gr~10^9, Re~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?**
- **This is another compelling reason why major advances in modelling are needed to plan and extrapolate results from laboratory experiments**

What Does the UCLA Discovery on Multiple Effects/Multiple Interactions Issues in LM Blankets mean?

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 existed in the world prior to 2018. A first-of-a-kind facility has been constructed in 2018 at UCLA in exemplary partnership with EUROfusion. The facility is called MaPLE-U (Magnetohydrodynamic PbLi Experiment- Upgrade). The objectives of MaPLE-U are to 1- study MHD thermofluids multiple-effects, material interactions, and tritium transport & permeation, and 2- provide realistic data for design of LM Blankets.

- 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

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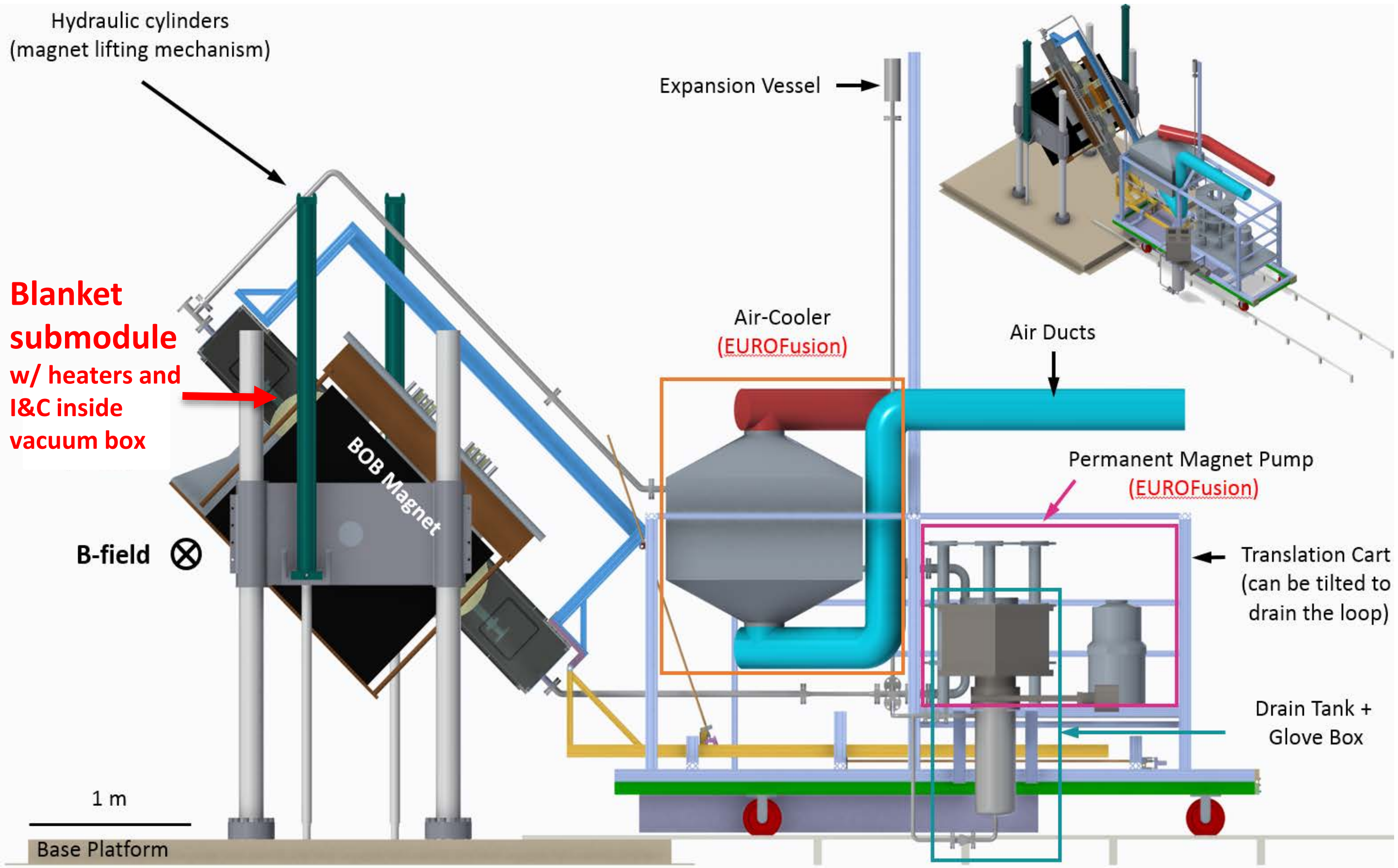
Recent Major Achievements in the UCLA-EUROfusion Collaboration

- Completed fabrication, construction, and commissioning of the MaPLE-U Facility at UCLA. Started operation in August 2018. This is a first-of-a-kind facility in the world to study multiple effect phenomena in fusion LM blankets

- First Experiment on mixed convection in MaPLE-U successfully started in August 2018. These experiments showed the existence of Flow Reversal. This is direct experimental proof of our modelling prediction and of the underlying scientific motivation for constructing MaPLE-U and for the UCLA-EUROfusion Collaboration Program.

- Major Improvements in modelling, utilization of models for design of experiments, and for pre-, parallel-, and post-experiment analysis were made.

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



MaPLE-U has 4 Major Sections:

1- **Magnet** Assembly with Lift/tilt mechanism

2- **Loop** with Motor-driven translation cart that has EM pump , Air cooler , and auxiliary systems

3- Advanced **DACS**

4- **Test Blanket Submodule** with heaters and instrumentation inside vacuum box with Motor-driven pivot system to tilt it to the desired angle with respect to gravity

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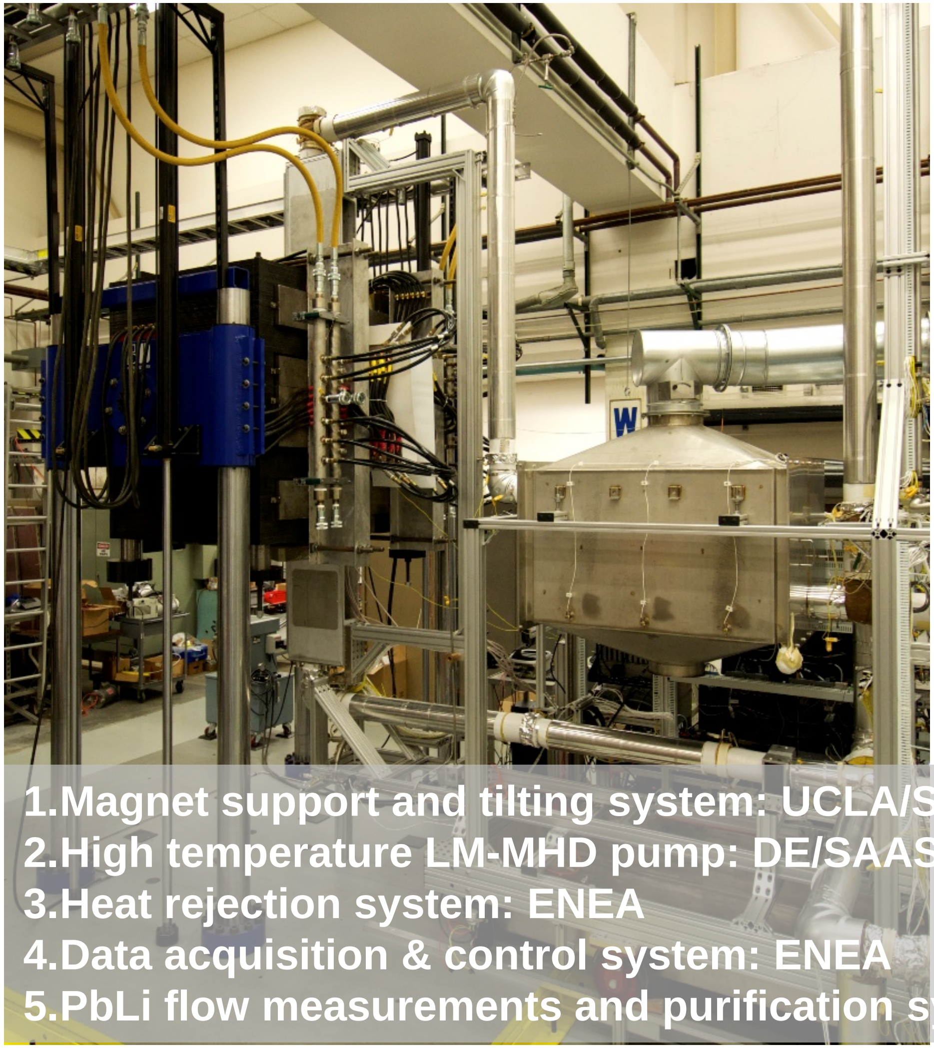
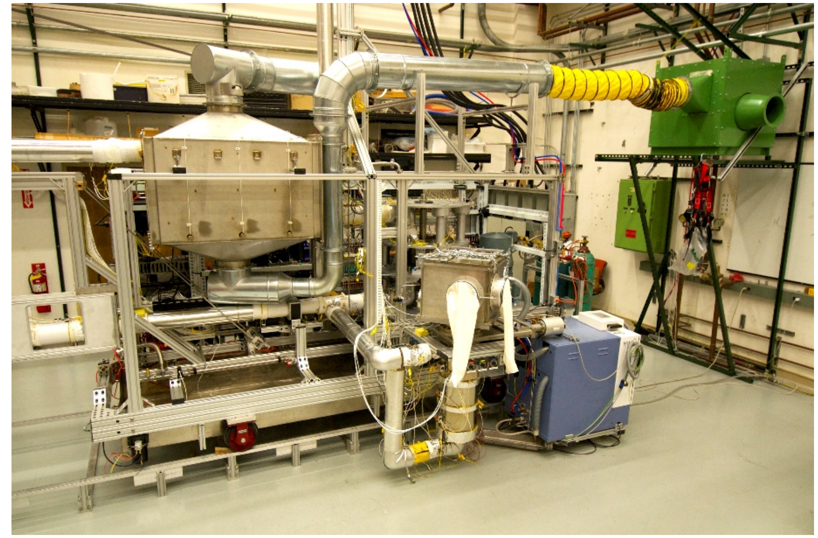
Simplified Analogy: The Magnet, heaters, and vacuum box simulate a fusion test facility (e.g. FNSF). The test blanket submodule simulates a blanket module to be tested in FNSF. The Loop represents the external heat transport/auxiliary system. As expected in FNSF, the test blanket submodules have many issues and expected high failure rates

With UCLA and EUROfusion working together, new PbLi technology has been developed, MaPLE-U is completed, and operational





1. Magnet support and tilting system: UCLA/Shore Western
2. High temperature LM-MHD pump: DE/SAAS
3. Heat rejection system: ENEA
4. Data acquisition & control system: ENEA
5. PbLi flow measurements and purification system: UCLA

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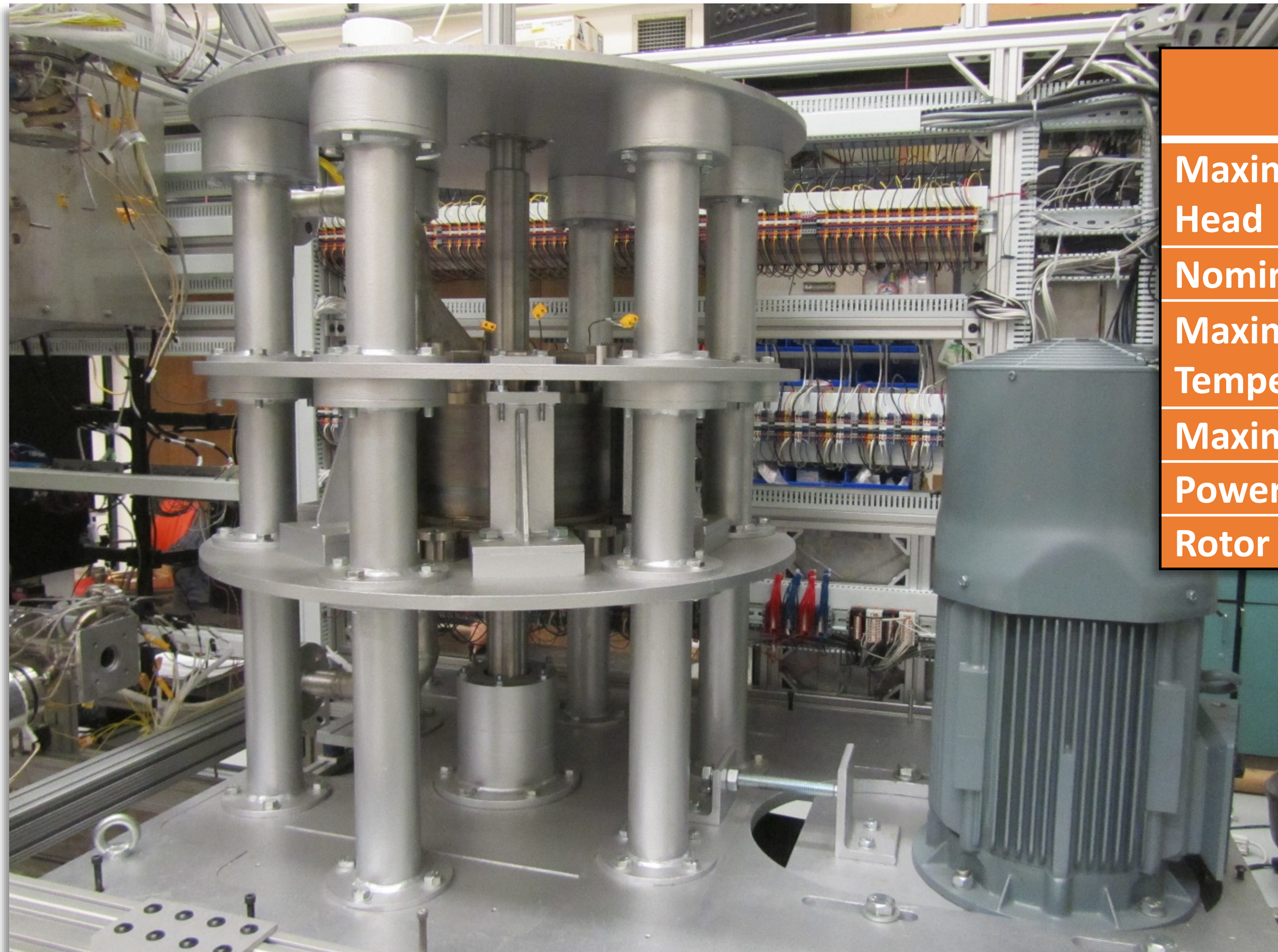
A key component of the upgraded MaPLE-U facility is the lift/tilt system of the 20-ton magnet

Constructed for UCLA by Shore Western

Support structure designed by UCLA Civil Engineering

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



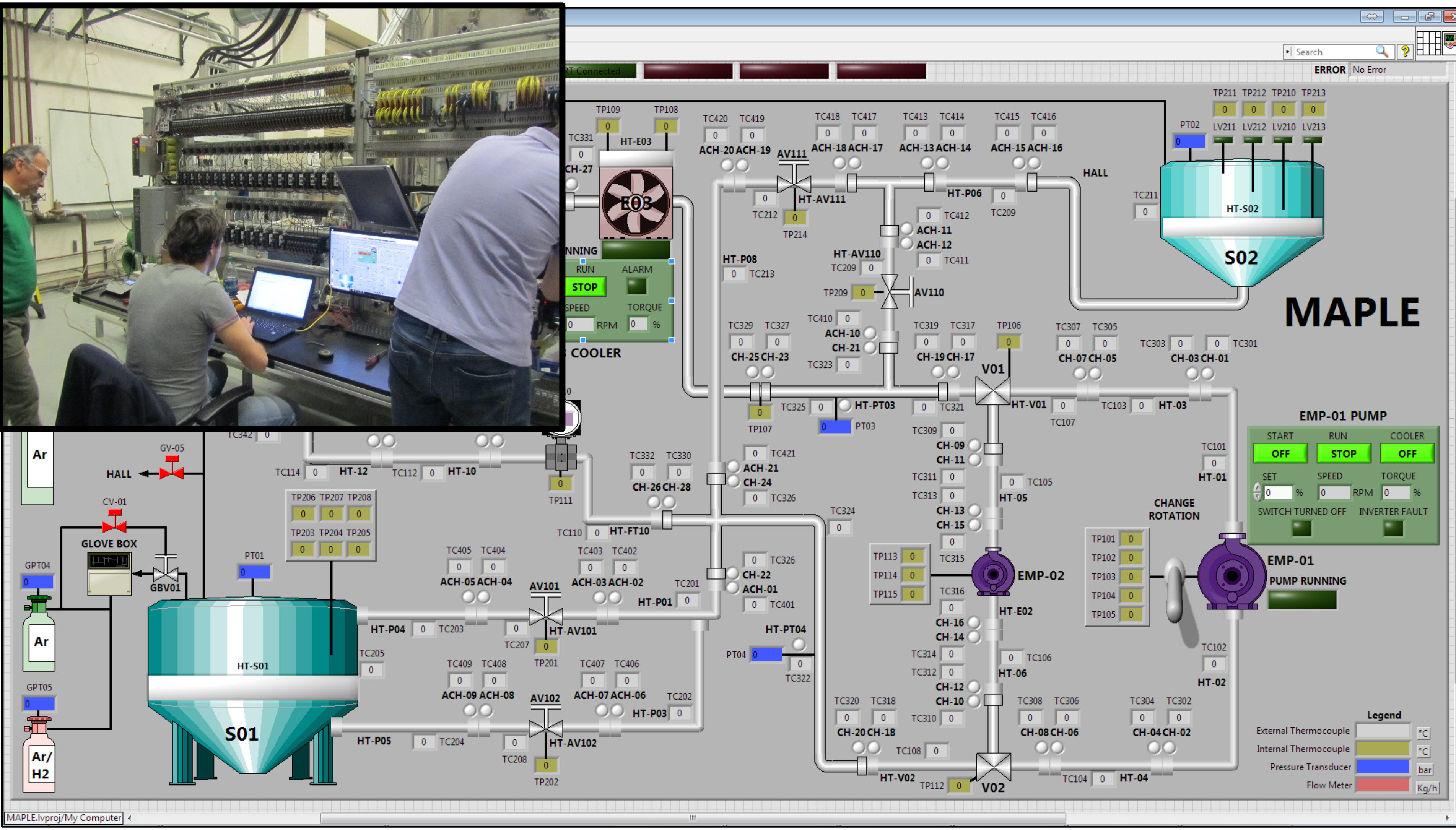
PMP Parameters	
Maximum Pressure Head	0.5 MPa
Nominal temperature	350 °C
Maximum Working Temperature	550°C
Maximum Flow Rate	120 l/min
Power	18 kW
Rotor Diameter	350 mm

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



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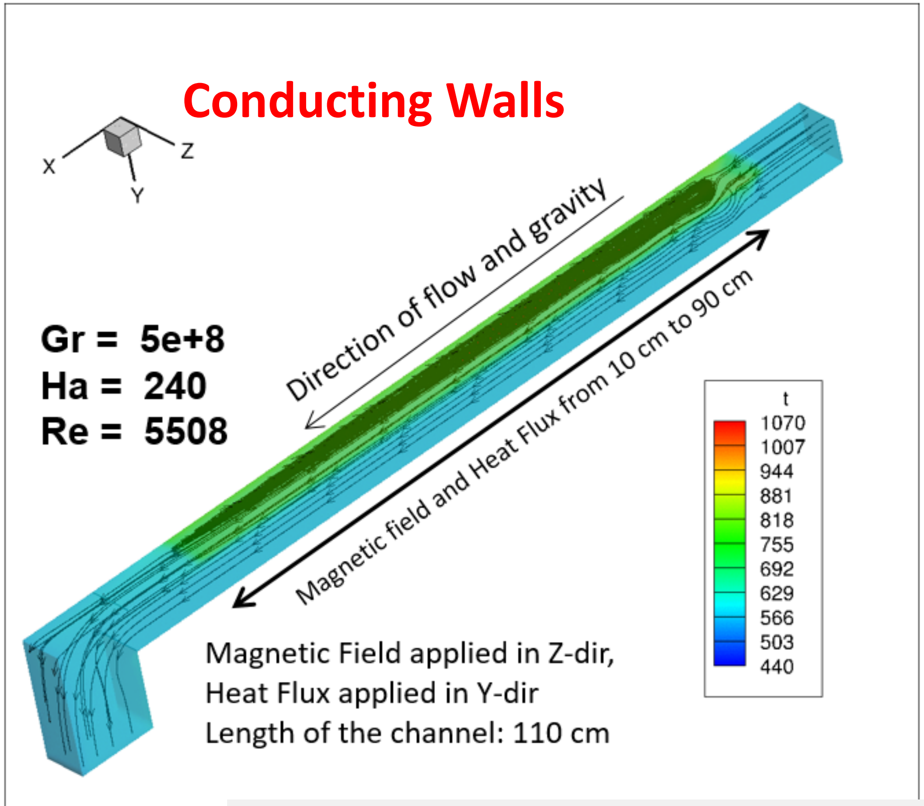
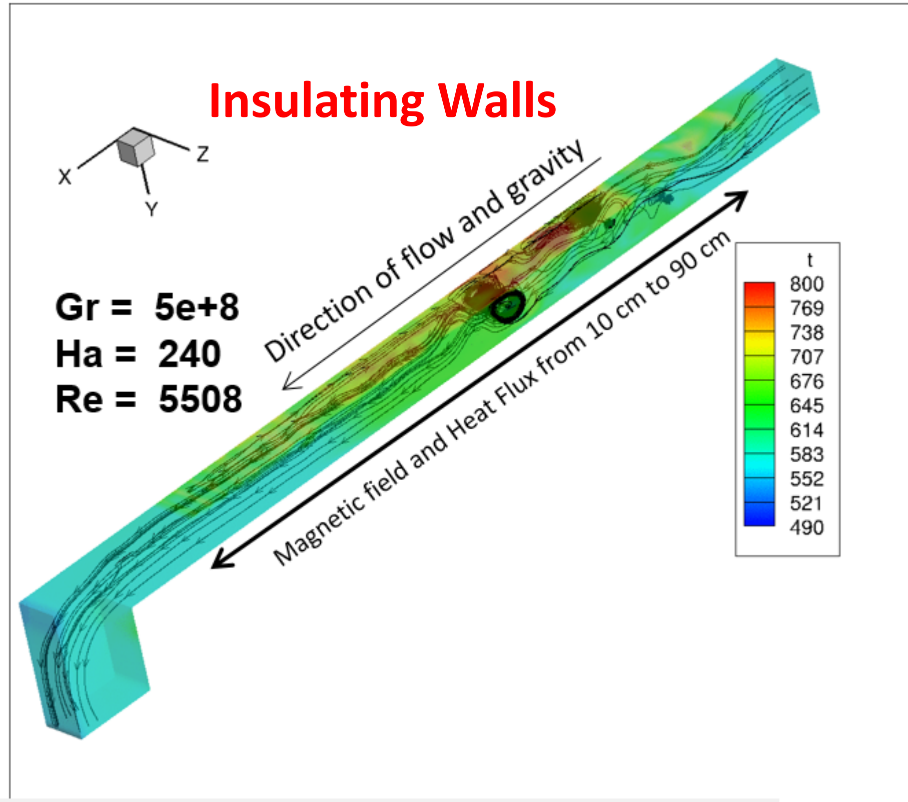
UCLA also made major advances in 3-D modelling in collaboration with HyPerComp (using HIMAG) for predicting mixed convection “downward flows” with B, g, heating, and temperature gradient. This has enabled us to do much more insightful scientific planning of the experimental campaigns

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.**

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FNST research requires advancing the state-of-the-art, and developing highly integrated predictive capabilities for many cross-cutting scientific and engineering disciplines

- neutron/photon transport
- neutron-material interactions
- plasma-surface interactions
- heat/mass transfer
- MHD thermofluid physics
- thermal hydraulics
- tritium release, extraction, processing and control
- gas/radiation hydrodynamics
- phase change/free surface flow
- structural mechanics
- radiation effects
- thermomechanics
- chemistry
- radioactivity/decay heat
- safety analysis methods and codes
- engineering scaling
- failure modes/effects and RAMI analysis methods
- design codes

Resolving the challenging FNST issues will require "ingenuity" and "time". FNST needs to attract and train bright young scientists and engineers in many technical disciplines .

Examples of Scientific Discoveries and the Role of International Collaboration from Fusion Energy R&D

- Scientific discovery is essential to advancing humankind
- Fusion research has made major advances through important scientific discoveries over decades
- International collaboration has been very strong in fusion research and played a key role in accelerating progress
- This Lecture gave examples of major scientific discovery at UCLA in fusion technology and exemplary US/UCLA – EUROfusion collaboration to utilize this discovery
- Much more scientific discoveries, innovative ideas, and enhanced international collaboration are needed to confront the challenges in development of Fusion Nuclear Science and Technology

THANK YOU

谢谢