Examples of Advances on Key Issues of Fusion Nuclear Technology

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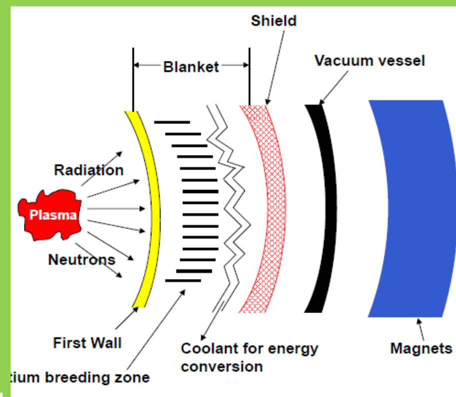
Key Technical Challenges beyond ITER

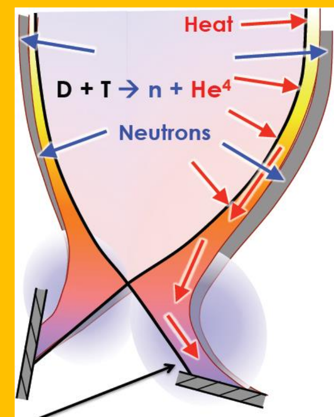
FNST: Fusion Nuclear Components (In-Vessel Components: Blanket/FW, Exhaust/Divertor) and associated technical disciplines (Materials, RAMI, Tritium)

Blanket / FW

- Most important/challenging part of DEMO
- Strict conditions for T self-sufficiency with many physics & technology requirements
- Multiple field environment, multiple functions, many interfaces
- Serious challenges in defining facilities and pathway for R&D



Exhaust / Divertor



- High heat and particle fluxes and technological limits: challenge to define a practical solution
- Both solid and liquid walls have issues
- Huge T inventory in Exhaust for low T burn fraction

Materials

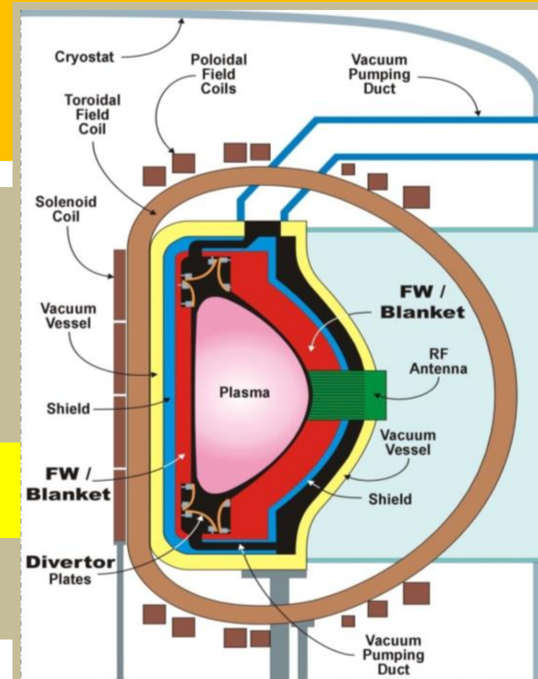
- Structural, breeding, multiplier, coolant, insulator, T barrier Exposed to steep gradients of heating, temperature, stresses
- Many material interfaces e.g. liquid/structure
- Many joints, welds where failures occur, irradiation

Reliability / Availability / Maintainability / Inspect. (RAMI)

- FNCs inside vacuum vessel in complex configuration lead to fault intolerance and complex lengthy remote maintenance
- Estimated MTBF << required MTBF
- Estimated MTTR >> required MTTR

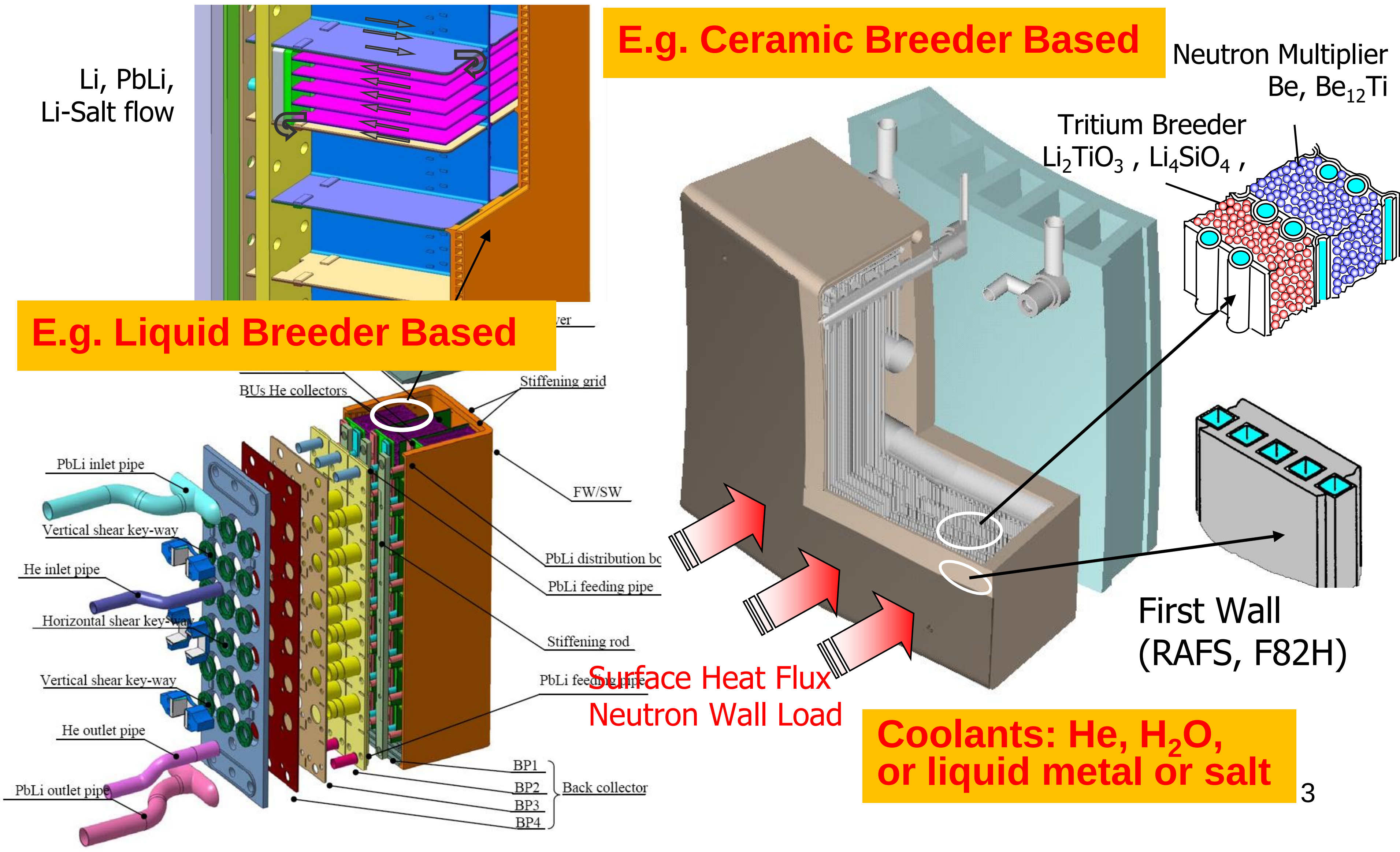
Low avail.

- No practical solutions yet
- How to do RAMI R&D?



- **Serious Challenges that require aggressive FNST R&D and a well thought out technically Credible Pathway to DEMO**

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



Fusion Nuclear Environment is Complex & Unique

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

- Bulk 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 Forces

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

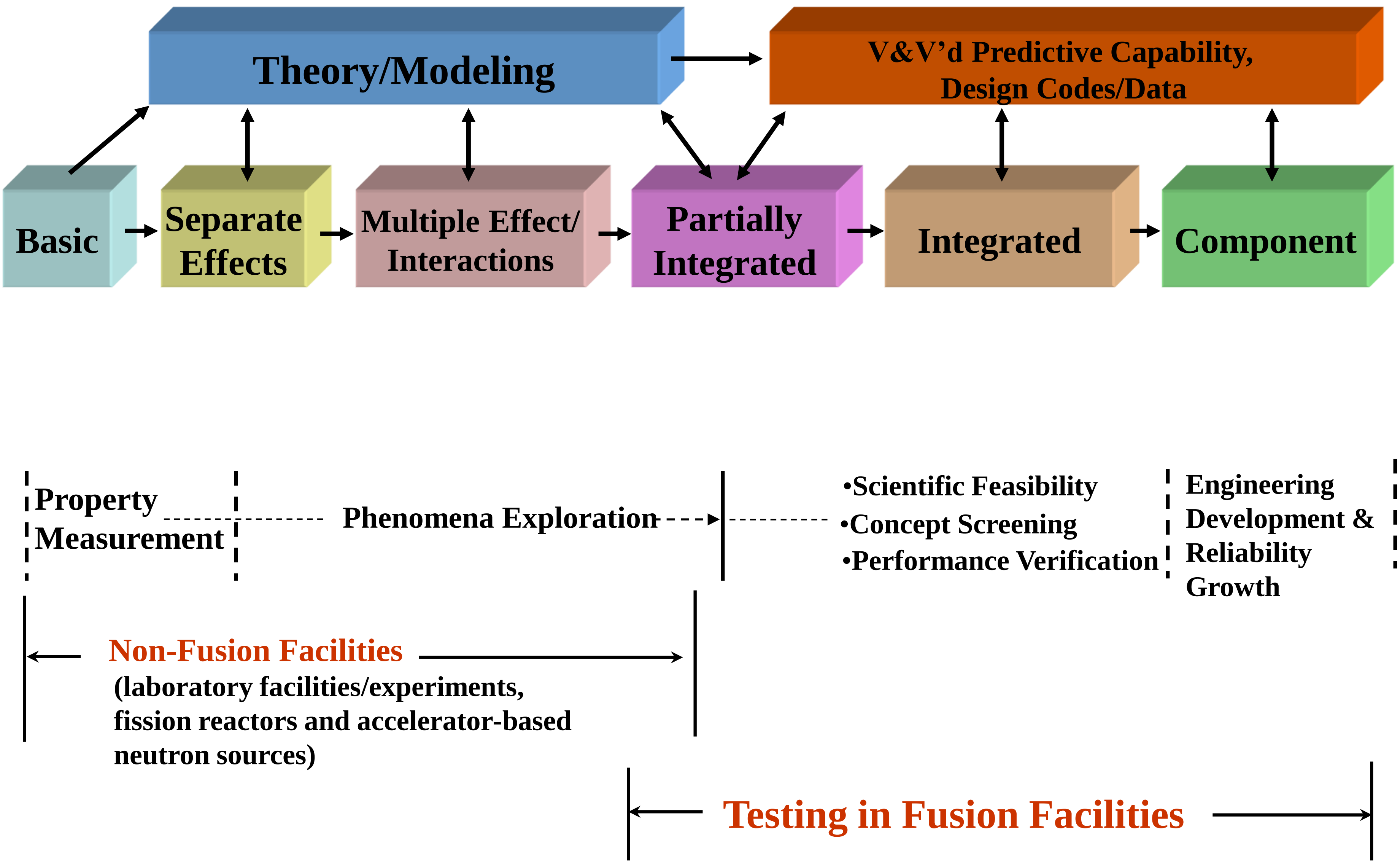
Multiple functions, materials, and many interfaces in highly constrained system

Combined Loads, Multiple Environmental Effects

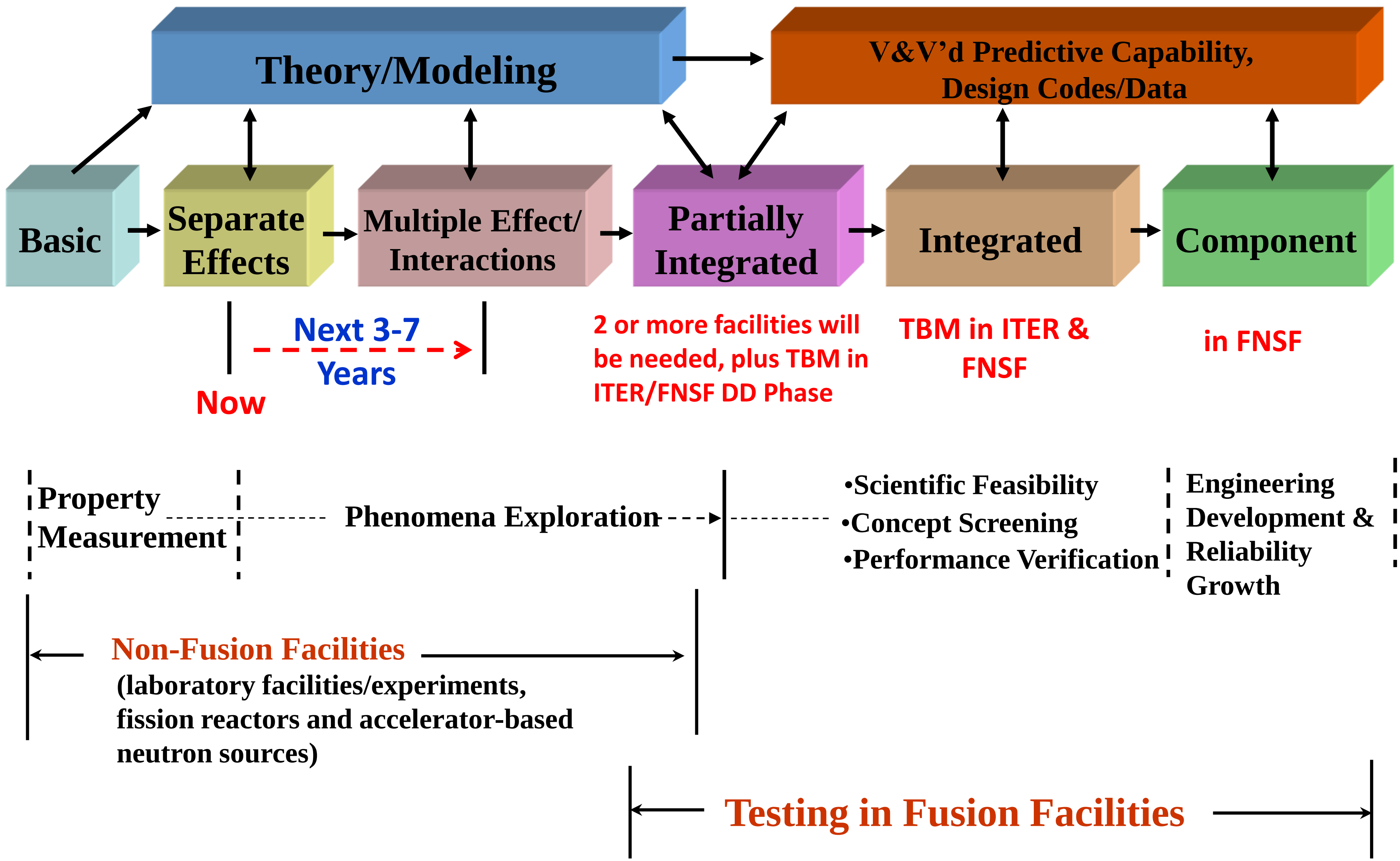
- Thermal-chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

- Many new phenomena YET to be discovered – Experiments are a MUST
- Simulating multiple effect/multiple interactions in Experiments & Models is necessary
- Laboratory experiments need to be substantial to simulate multi loads and interactions

Science-Based Framework for FNST R&D involves modeling & experiments in non-fusion and fusion facilities



We are now in mostly "Separate Effects" stage. We Need to move to "multiple effects/multiple interactions" to discover new phenomena and enable future integrated tests in ITER TBM and FNSF



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

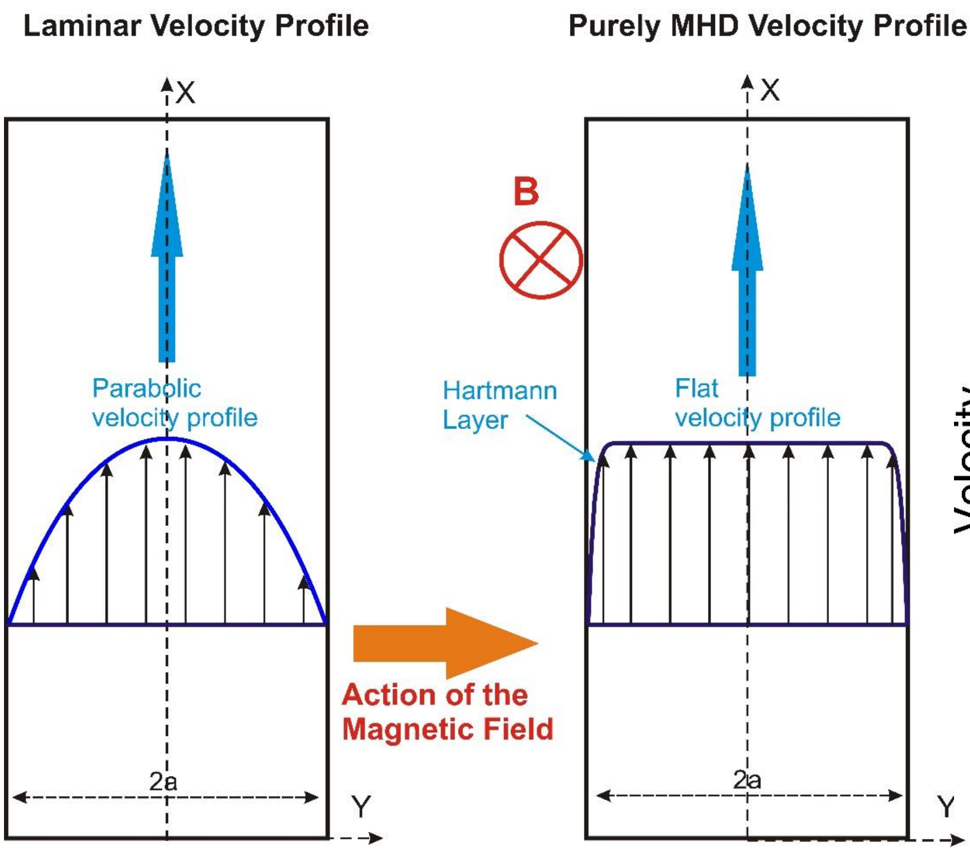
Example: MHD Thermofluids

In the next several slides, taking MHD thermofluids as an example, we will show:

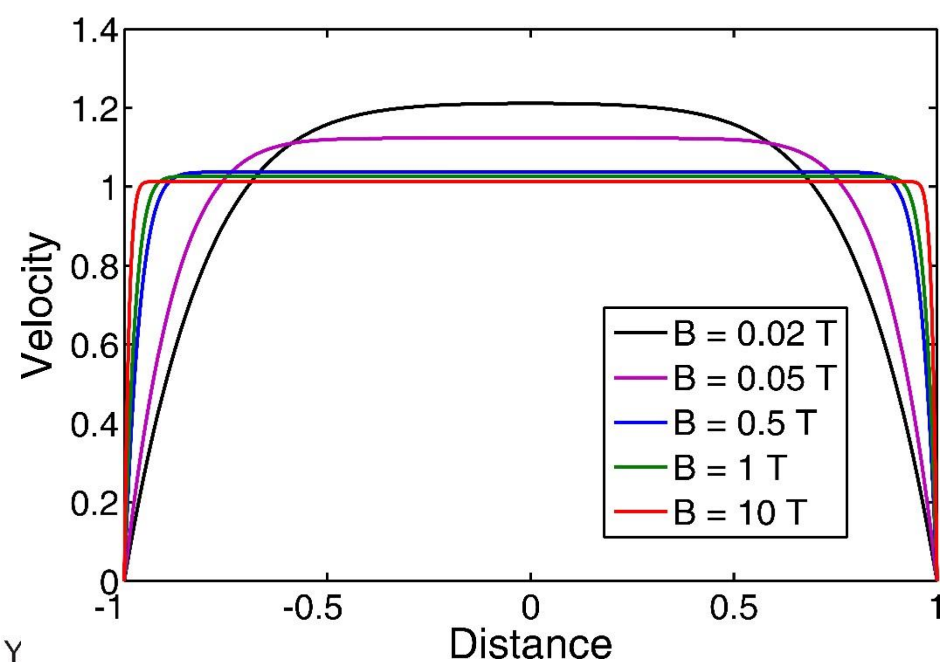
1) Why simulating multiple effects/multiple interactions is NECESSARY
2) Why planning and designing multiple effects laboratory facilities that can preserve the key phenomena of the fusion nuclear environment is a very challenging scientific task!

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*: Base laminar parabolic flow profile strongly altered by the action of the Lorentz force leading to **flat laminar core** and **very thin Hartmann and side layers**



Increasing the magnetic field strength reduces the thickness of the Hartmann layers and makes the velocity profile flatter. (pressure drop proportional to B if wall is electrically insulated or B^2 if wall is highly conducting)

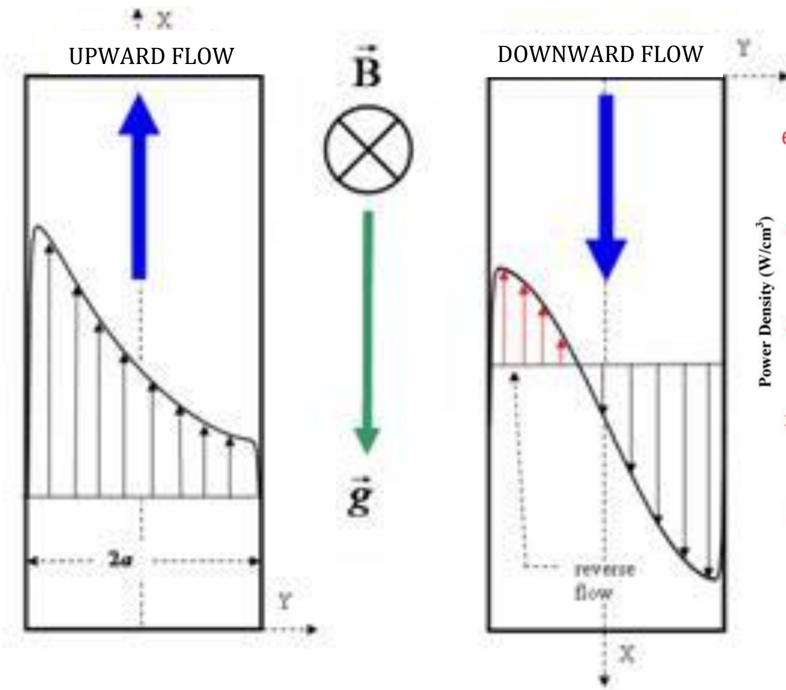


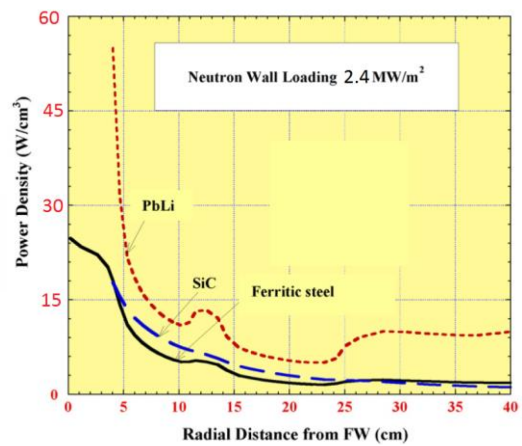
Discovery: Spatial gradients in nuclear heating & temperature in LM blanket combined with $\vec{g}$ and $\vec{B}$ lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior of the blanket in the fusion nuclear environment

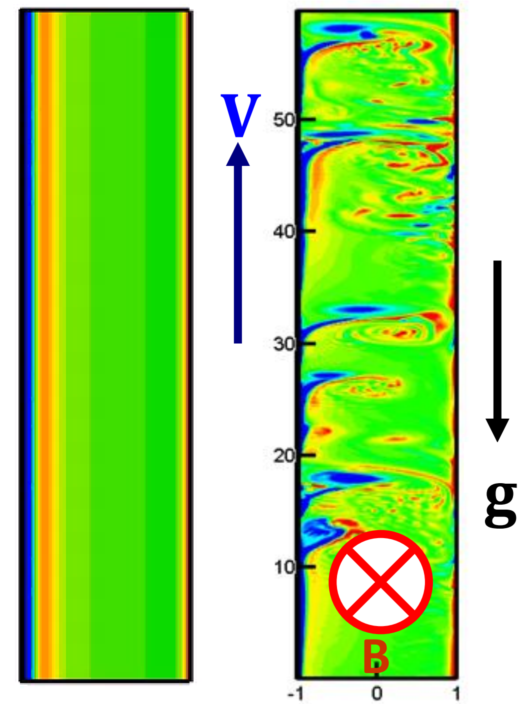
Buoyant MHD interactions result in an unstable "Mixed Convection" flow regime

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.

- **Blankets designed with current knowledge of phenomena and data will <u>not</u> work**
- **New: "Fusion Nuclear MHD" is very different from standard MHD in other fields**

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

- **We have been investigating how to satisfy the above requirements in upgrading the MaPLE facility at UCLA: Big challenges!!**

  Examples are highlighted in the next several slides

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

- In MHD Thermofluids, key conditions include electromagnetic, viscous, inertial and buoyancy forces. To essentially preserve phenomena, we should consider relevant non-dimensional parameters that express ratios between the forces:

Non-Dimensional Parameters
➢ Reynolds Number, $Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{\rho u L}{\mu}$
➢ Hartmann Number, $Ha = \left(\frac{Electromagnetic\ forces}{Viscous\ forces}\right) \hat{}0.5 = BL\sqrt{\frac{\sigma}{\mu}}$
➢ 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

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

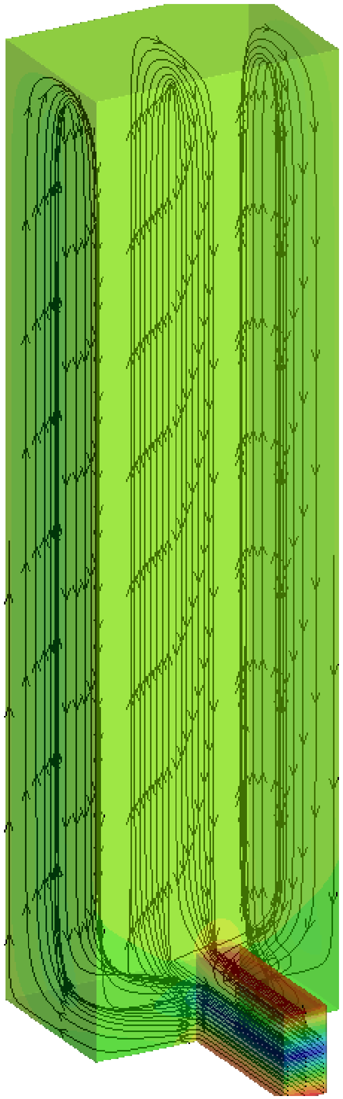
Grand Challenge

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?**

HyPerComp Incompressible MHD solver for Arbitrary Geometry

We advanced the 3-D MHD Modelling codes to play a major role in pre-experimental analysis and prediction of unstable mixed convection flows. An example is the HiMAG code.



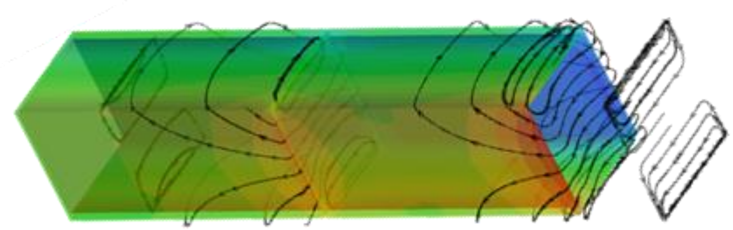
The HIMAG Code, developed jointly by HyPerCom and UCLA, was extended to model the MHD flow of liquid metals and heat transfer in the presence of strong electromagnetic fields, heat sources and temperature gradients.

<u>Summary of code capabilities:</u>

- 3D, parallel incompressible flow solver (2nd order accurate in space and time)
- Free surface capture using the level set technique
- Arbitrary mesh structure (hexahedral / tetrahedral / prismatic cells)
- Electric potential as well as induced magnetic field formulations for MHD
- Multi-material walls, multi-fluid flow
- Time dependent heat and mass transfer
- Lagrangian modeling of particulate flow

HIMAG has been favorably validated against test data at high Hartmann numbers, and verified against key analytical results

Pure MHD flow at Ha = 10^4 in a simple 3-channel DCLL geometry

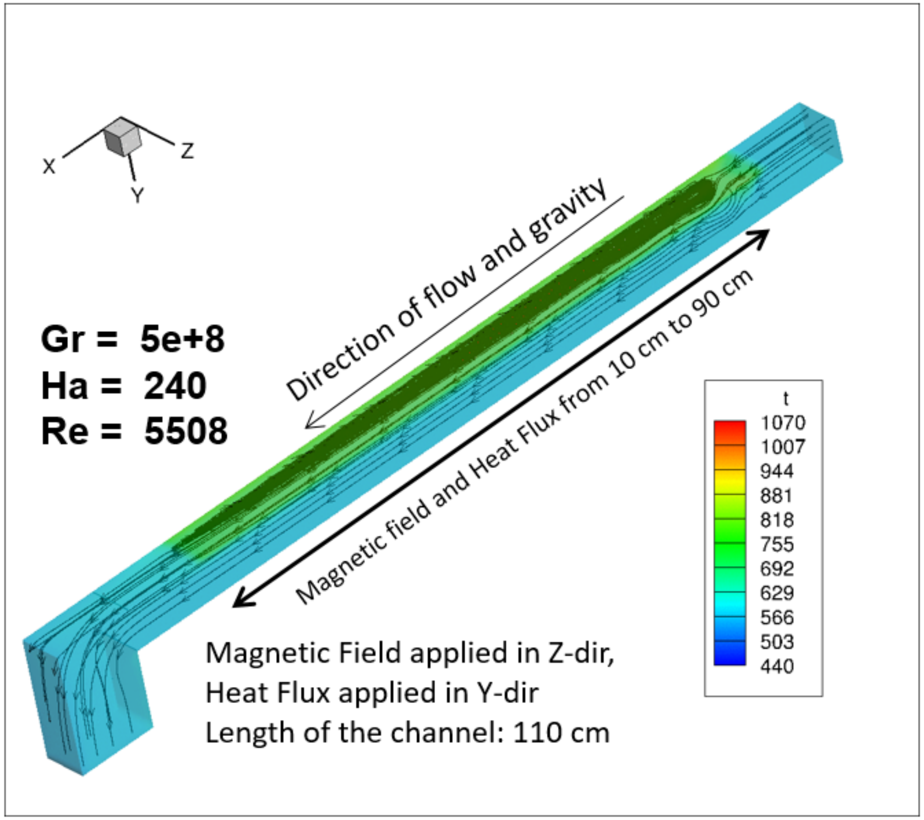


MHD channel flow with segmented insulating walls showing electric current lines, electric potential contours.

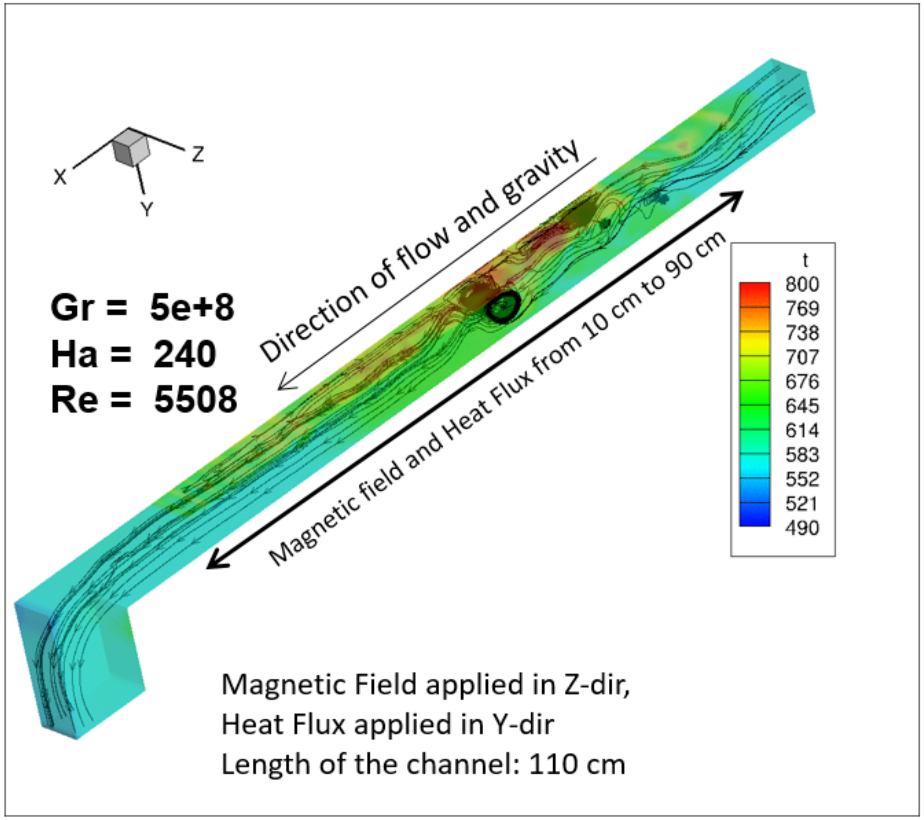
Recent HIMAG results for mixed convection "downward flows" with B, g, heating, and temperature gradient is illustration of advanced 3D computations

- 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 higher Joule dissipation.**

Conducting Walls



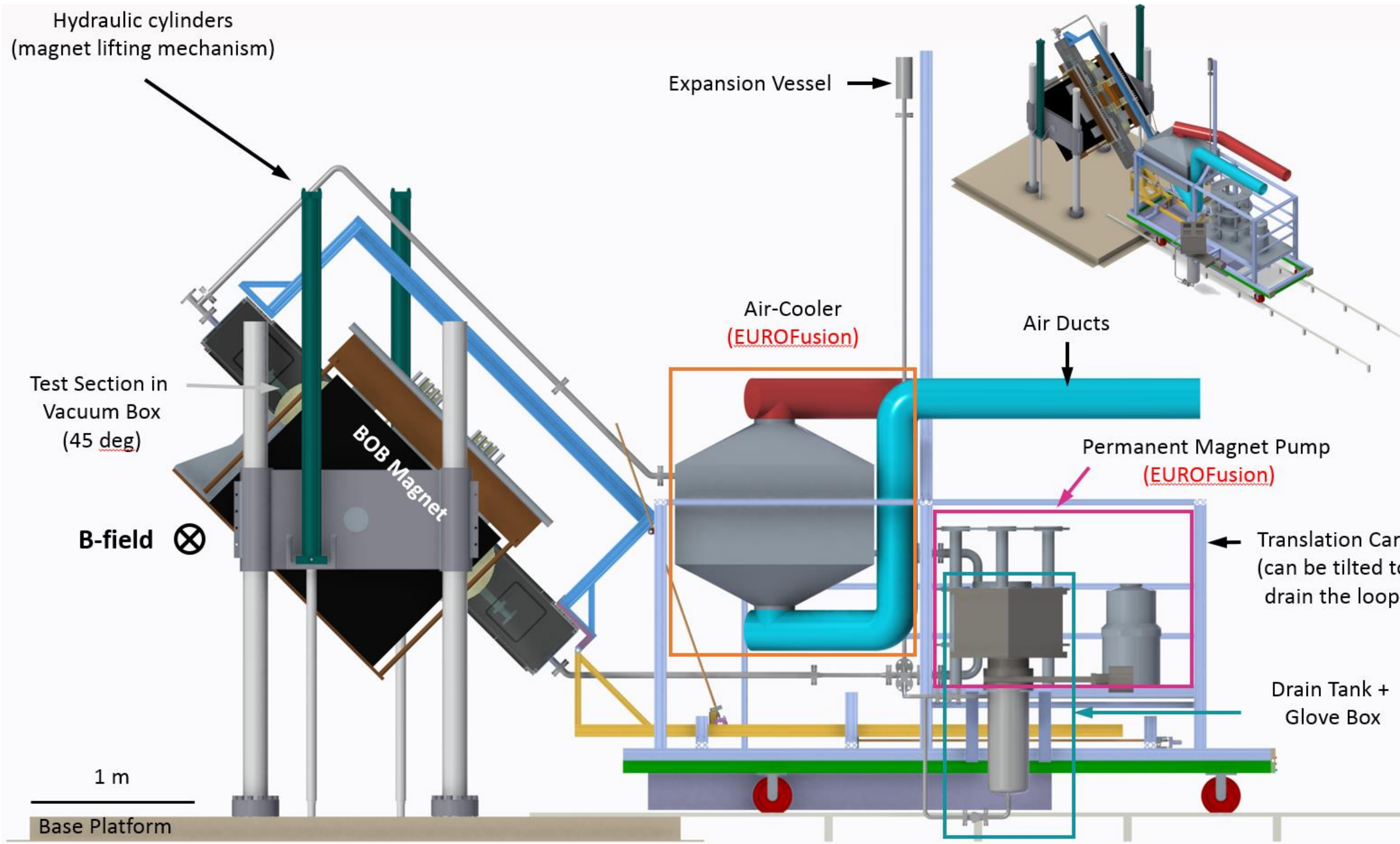
Insulating Walls



Upgrading the MaPLE facility at UCLA is in its final phase

The purpose of the upgrade is to provide capabilities to investigate MHD mixed convection (simulating Heating & Temperature Gradients combined with $\vec{g}$ and $\vec{B}$).

First experiments will be started soon by the UCLA-EUROfusion team



UCLA

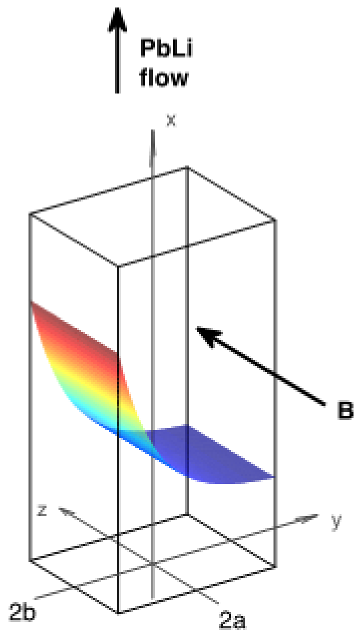
There is no practical method for simulating volumetric heating in LM laboratory experiments. So What should we do?

At UCLA, we investigated alternative methods to simulating the temperature gradients using approximations that result in correct direction of the slope. Our approach is to produce representative temperature variations using either flowing external hot fluids or one-sided surface heating, while aiming at higher Gr:

$$Grashof\ number = \frac{Buoyancy\ forces}{Viscous\ forces} = \frac{g\beta L^3 \Delta T}{v^2}$$

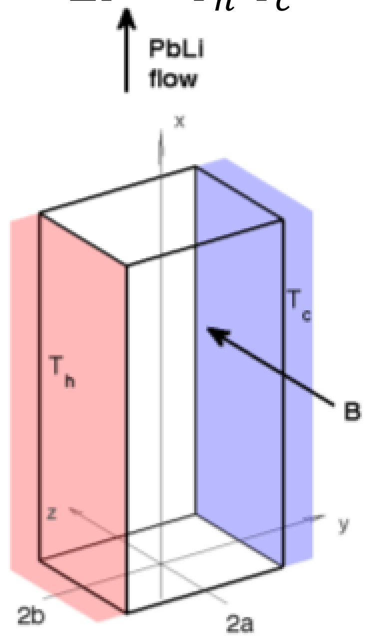
Reference Blanket:
volumetric Nuclear heating

$$\Delta T = NWL * L/k$$



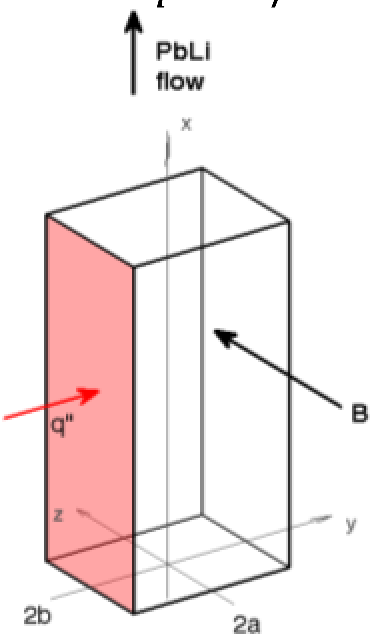
Experiment:
Flowing external hot fluids and constant T B.C.

$$\Delta T = T_h\text{-}T_c$$



Experiment:
surface heating/insulation

$$\Delta T = q'' * L/k$$



Pre-experimental numerical analysis for the mixed-convection experiments

- We have advanced Numerical simulation codes and utilized them for pre-experimental design of the mixed convection experiments that will be performed in upgraded MaPLE loop.
- In particular, We utilized 3D MHD mixed convection numerical simulations to help answer the following important questions:
  - ✓ **What is minimum surface heat flux needed to observe reasonably strong buoyancy effects in the MHD flow?**
  - ✓ **What is the maximum surface heat flux allowed to restrict the maximum temperature and thermal stress in the duct walls below a permissible value?**
  - ✓ **What is the optimal location of flow diagnostics (thermocouples, LEVI probes, electrical potential pins) in the test section?**

The answer to the above questions has provided an **"operational-window"** for the new experiments in the upgraded MaPLE loop!

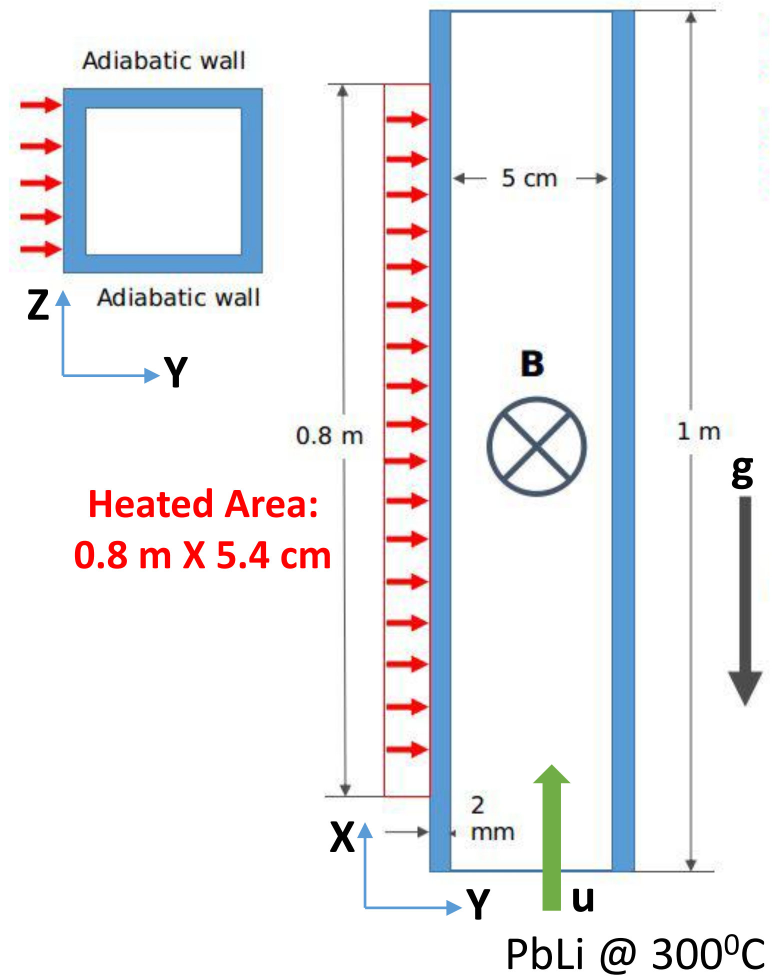
Numerical test matrix considered for the pre-experimental analysis

- HIMAG simulations for **MHD mixed convection upward flows** have been completed and analysis of **downward flows** is underway.
- The numerical results are evaluated for **flow development, velocity profile asymmetry, temperature distribution** and **flow instabilities including regions of flow reversal**.

Input Parameters

Values	0.1 MW/m2	0.5 MW/m2	1 MW/m2
5 cm/sec	Re = 5508 Gr = 10^8	Re = 5508 Gr = $5*10^8$	Re = 5508 Gr = 10^9
10 cm/sec	Re = 11016 Gr = 10^8	Re = 11016 Gr = $5*10^8$	Re = 11016 Gr = 10^9
15 cm/sec	Re = 16524 Gr = 10^8	Re = 16524 Gr = $5*10^8$	Re = 16524 Gr = 10^9

All cases are modelled at a magnetic field strength of 0.5 T corresponding to a Ha = 240. The magnetic field is maintained relatively low to preserve Gr/Ha and to observe instabilities.

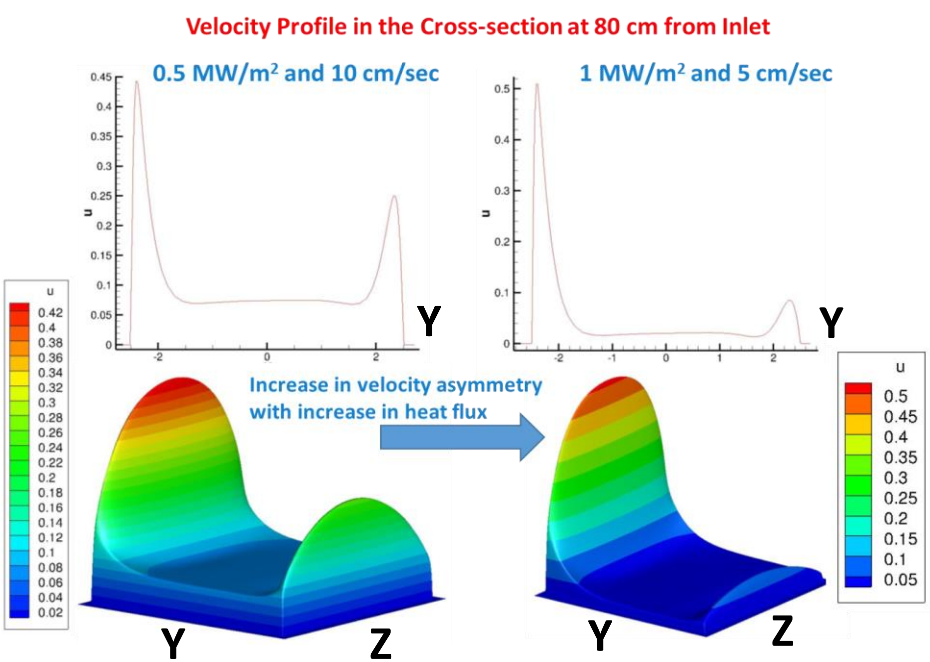


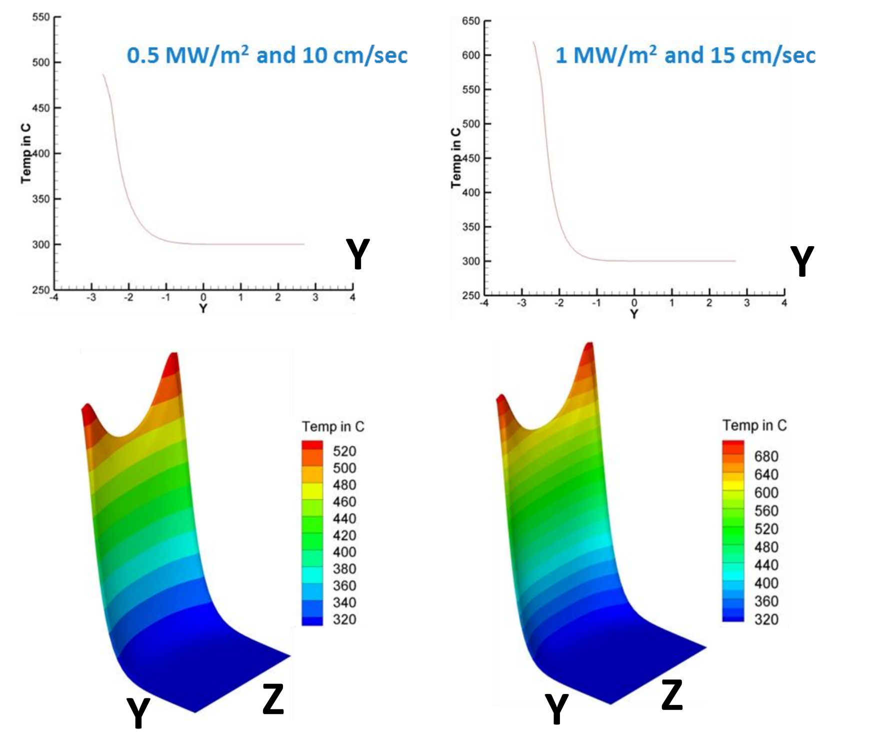
Spatial temperature gradients combined with *g* and *B* lead to a strongly altered flow distribution with velocity asymmetry

Mixed convection regime leads to strong alteration of the base MHD flow

Purely MHD M-shaped velocity profile in a conducting duct becomes **asymmetrical by the action of buoyancy forces close to the hot wall**.

Higher surface heat flux causes a high surface temperatures in the form of localized **“hot regions”** near the heated wall. Moreover, the temperature profile in the fluid shows strong gradients.





The pre-experimental analysis provided an operational "matrix" for the experiments that can be performed in the upgraded MaPLE loop

Values	0.1 MW/m2	0.5 MW/m2	1 MW/m2
5 cm/sec	• Strong Velocity Asymmetry ~ 41% • Maximum duct wall temp ~ 367 ^{0}C	• Strong Velocity Asymmetry ~ 60% • Maximum duct wall temp ~ 578 ^{0}C	• Strong Velocity Asymmetry ~ 82% • Maximum duct wall temp ~ 847 ^{0}C
10 cm/sec	• Strong Velocity Asymmetry ~ 24% • Maximum duct wall temp ~ 360^{0}C	• Strong Velocity Asymmetry ~ 45% • Maximum duct wall temp ~ 567 ^{0}C	• Strong Velocity Asymmetry ~ 65% • Maximum duct wall temp ~ 838 ^{0}C
15 cm/sec	• Weak Velocity Asymmetry ~ 9% • Maximum duct wall temp ~ 352 ^{0}C	• Strong Velocity Asymmetry ~ 26% • Maximum duct wall temp ~ 549 ^{0}C	• Strong Velocity Asymmetry ~ 48% • Maximum duct wall temp ~ 828 ^{0}C

- More simulations are currently underway for **buoyancy-opposed downward flows**. Such flows are expected to encounter **flow instabilities and flow reversals**.

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

Helium-Cooled Lead Lithium (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)**

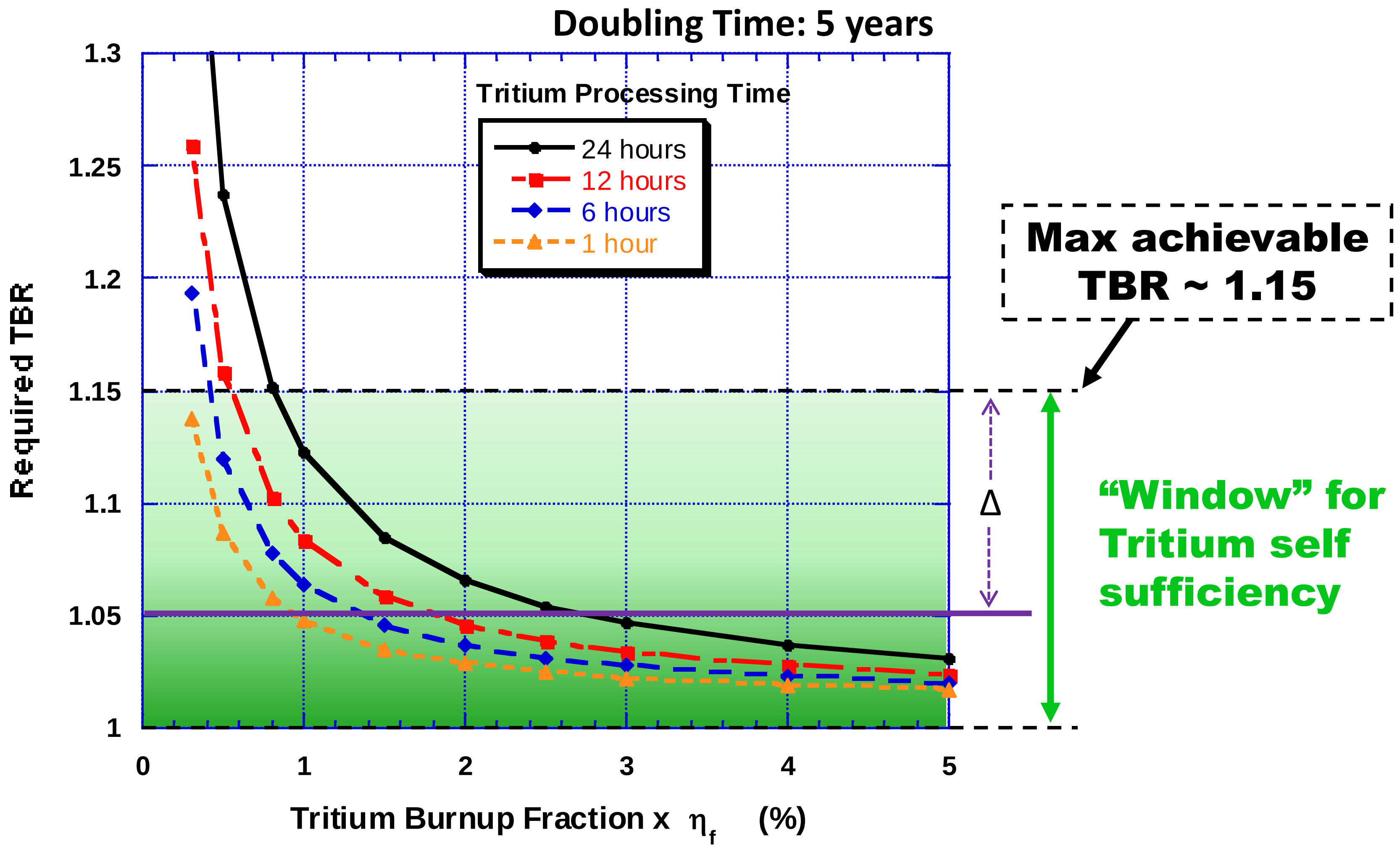
Self-Cooled LM

- **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?!)

The Issue of External Tritium Supply is Very Serious and Has Major Implications on Fusion Development Pathway

- The **"start-up" tritium inventory** required for any reactor or DEMO is a strong function of physics and technology parameters, particularly T burn fraction, fueling efficiency and tritium processing time.
  - This start-up inventory is ~15-30 kg with current state-of-the-art, and can be reduced to ~8-12 kg if a burn fraction x fueling efficiency of 5% can be achieved.
- There is no practical external source of tritium available for fusion development beyond ITER (definitely not for multiple DEMOs around the world)
  - Heavy water reactors in Canada, Argentina, China, India, Korea, and Romania may be able to supply part of the start up inventory for one DEMO (but not 2) if DEMO is built before 2060. But this is highly uncertain because heavy water reactors may all be shut down.
  - A fission reactor can only produce ~ 0.5 kg of T per year
  - Can not store tritium for very long because of radioactive decay
- Start-up with deuterium-rich fuel would delay power production by years and is not economically sensible
- A scheme to generate start-up inventory for DEMO using FNSF has been proposed - merits serious explorations (may be the only option left?)

Achieving T self-sufficiency imposes important requirements on R&D of plasma physics, blanket and tritium processing

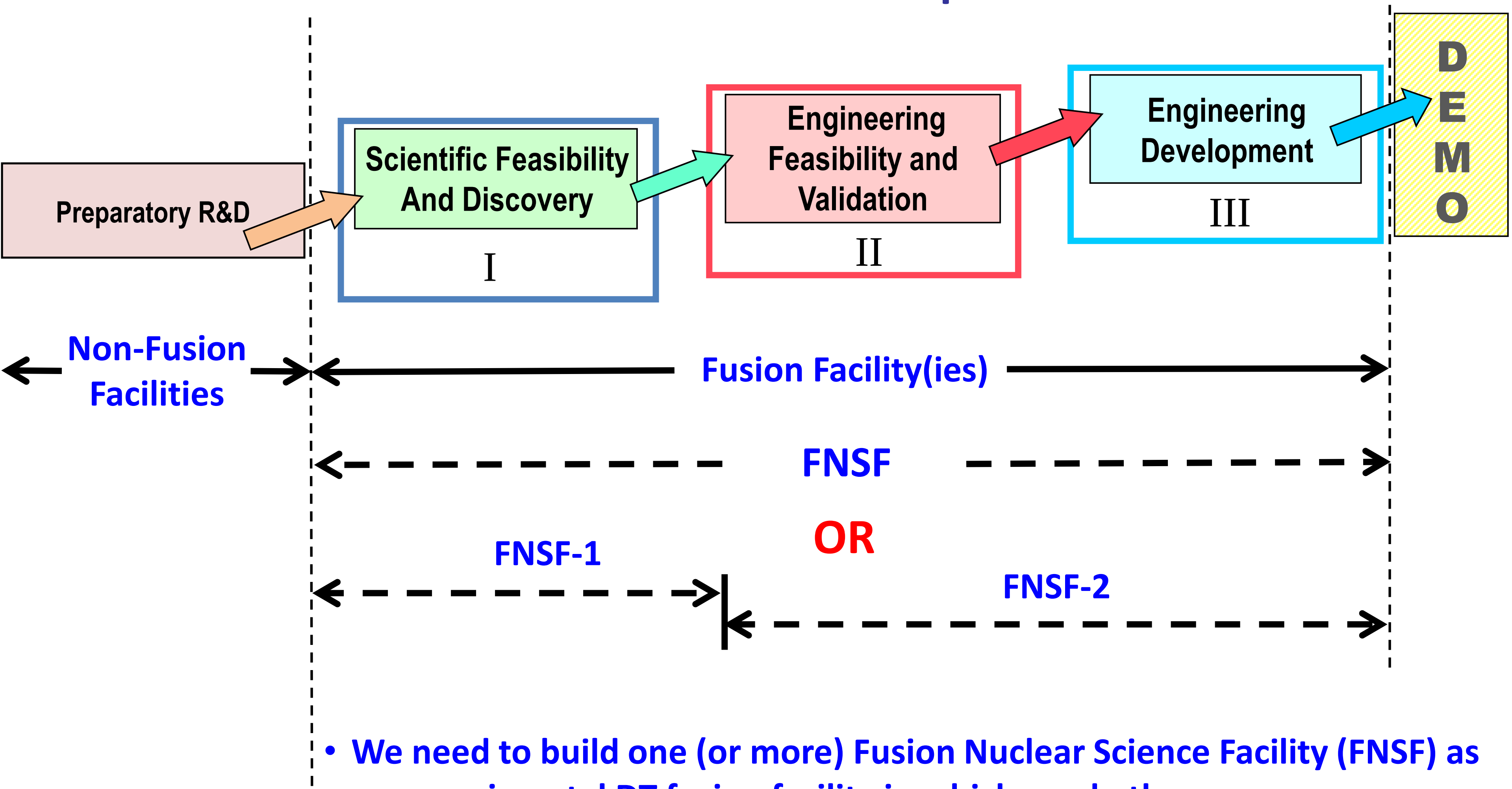


Attaining Tritium Self Sufficiency in DT Fusion Imposes Key Requirements on Physics and Technology. **The goal for R & D should be to achieve:**

T burnup fraction (f_b) x fueling efficiency (η_f) > 5% (not less than 2%)

T processing time (in Plasma exhaust/fueling cycle) < 6 hours

Necessary R&D Stages of Testing FNST components in the fusion nuclear environment prior to DEMO



- We need to build one (or more) Fusion Nuclear Science Facility (FNSF) as an experimental DT fusion facility in which we do the necessary experiments (Stages I, II, III) of FNST components development in the fusion nuclear environment prior to DEMO

Concluding Remarks (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 is 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

Concluding Remarks (2 of 2)

- **Even with the aggressive R&D of computational simulation and experiments in non-fusion facilities that we must do, we will still have serious uncertainties in predicting the blanket behavior in the fusion nuclear environment**

  Therefore, the primary goal of the next DT fusion facility, e.g. FNSF or CFETR (at least the 1st stage) is to perform FNST experiments to discover synergistic effects and learn about blanket/PFC/Materials integrated behavior in the fusion nuclear environment. The next DT fusion facility cannot be for validation or demonstration.

- **RAMI is the "Achilles heel" for fusion. RAMI will be the key issue in determining the feasibility of plasma confinement configurations and blanket concepts**
  - MTBF for Blanket/FW/PFC in any DT fusion Device is estimated to be very short while MTTR is predicted to be too long – leading to very low availability of only a few percent - **DANGER**
  - Very low Availability (a few percent) will be a dominant issue to be confronted by the next DT fusion device (regardless of its name FNSF, CFETR, DEMO, etc)
  - RAMI must be the most critical factor in any planning we do

- **External Tritium Supply is very limited and expensive AND achieving tritium self-sufficiency in fusion devices has many uncertainties.**

Thank you!