

The Role of Multiple Effects/Interactions in a Science Based Blanket/FW R&D pathway

Presented by Neil Morley

**Prepared by Mohamed Abdou, Sergey Smolentsev, Alice Ying,
Neil Morley, Gautam Pulugundla, Cyril Courtessole - UCLA**

More detailed description of blanket concepts, issues, R&D needs and strategies available in:
M. Abdou, N. B. Morley, S. Smolentsev, A. Ying, S. Malang, A. Rowcliffe, M. Ulrickson,
Blanket/first wall challenges and required R&D on the pathway to DEMO,
Fusion Eng. Des. 100 (2015) 2-43.

Fusion Materials Workshop, UT / ORNL

July 25-29, 2016

Outline

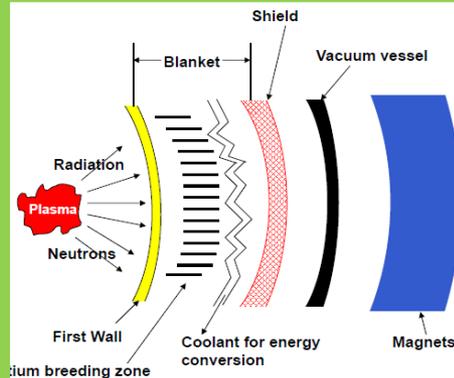
- Part 1 – Blanket/FW introduction and multiple effects R&D examples and pathway (monday)
- Part 2 – Conclusions on the need for multiple effects R&D and facilities (tuesday)

Key Technical Challenges beyond ITER for Fusion Nuclear Science

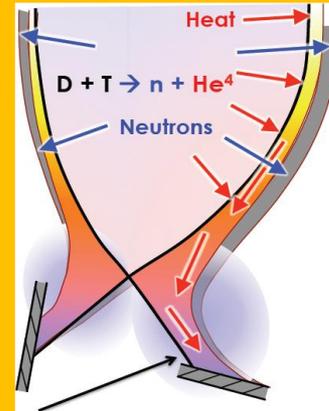
FNST: Fusion Nuclear Components (In-Vessel Components: Blanket/FW, Exhaust/Divertor) and associated technical disciplines (Materials, RAMI, Tritium)

Blanket / FW

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



Exhaust / Divertor



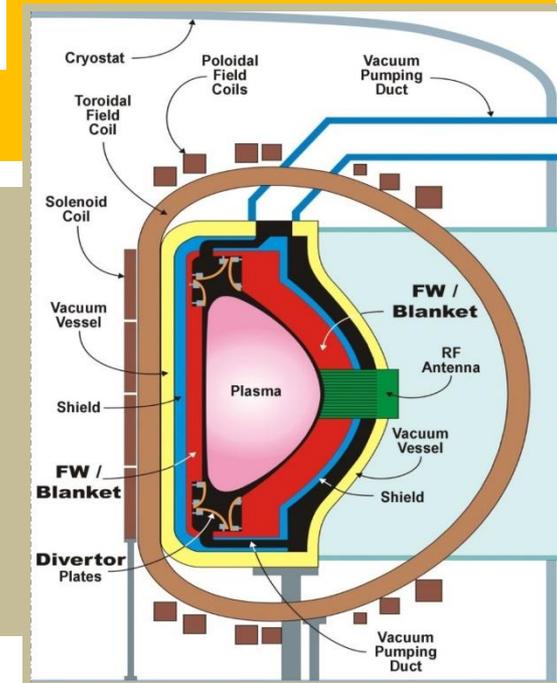
- High heat and particle fluxes and technological limits: challenge to define a practical solution
- Both solid and liquid walls have issues
- Huge T inventory in Exhaust for low T burn fraction

Materials

- Structural, breeding, multiplier, coolant, insulator, T barrier, FW
- 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
- No practical solutions yet
- How to do RAMI R&D?

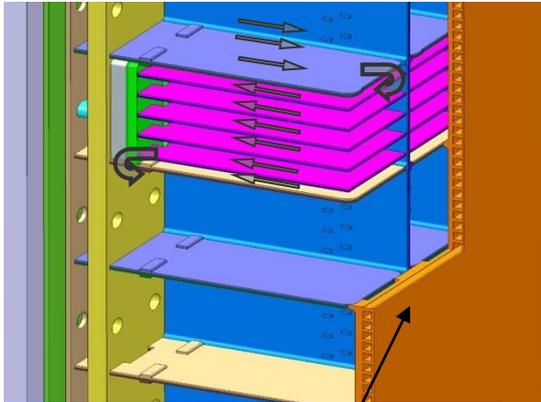


- What do we need to do going forward?

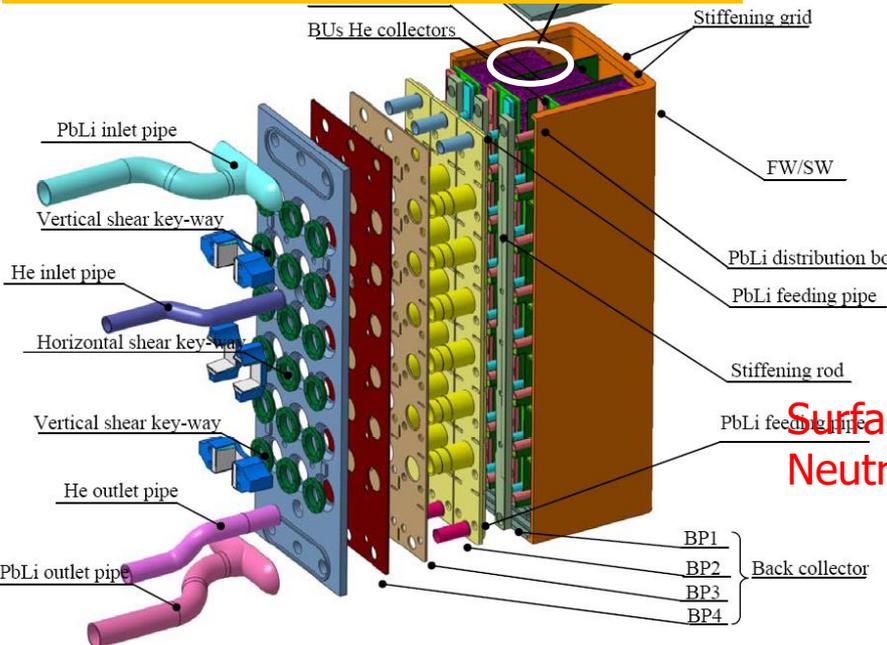
- We understand the issues but the problem is defining technically credible R&D pathway

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

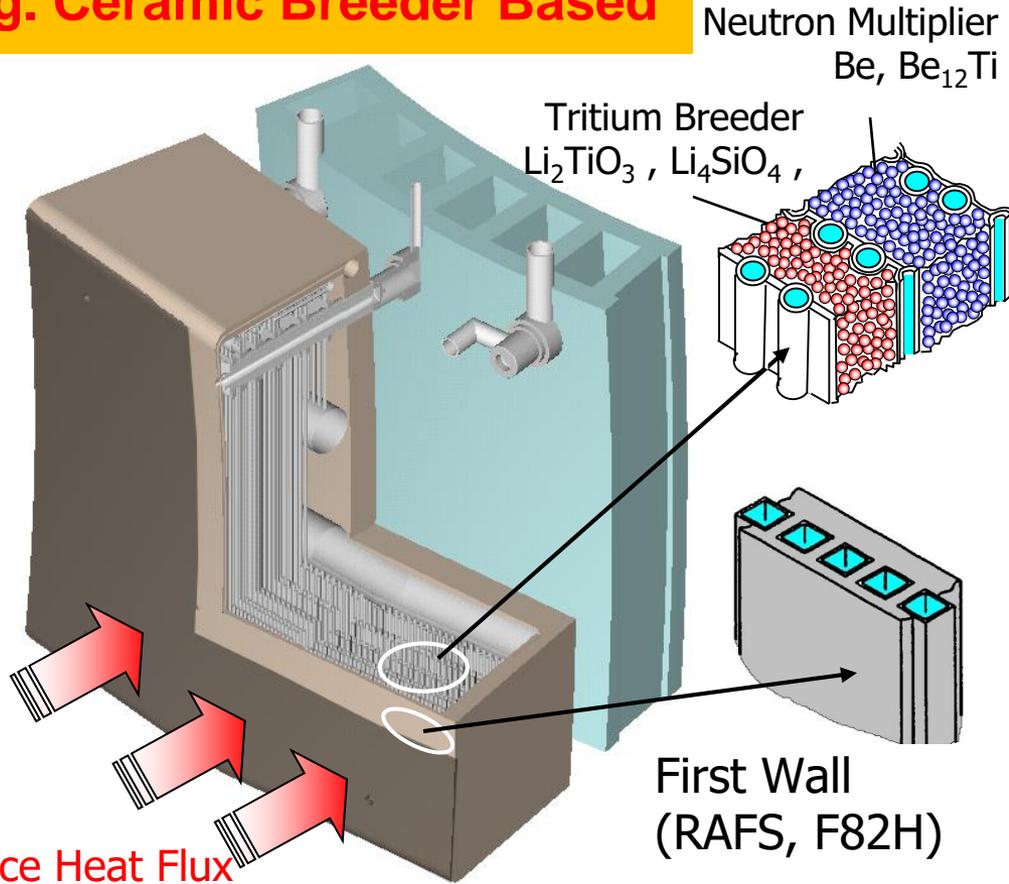
Li, PbLi,
Li-Salt flow



E.g. Liquid Breeder Based



E.g. Ceramic Breeder Based



Surface Heat Flux
Neutron Wall Load

Coolants: He, H₂O,
or liquid metal or salt

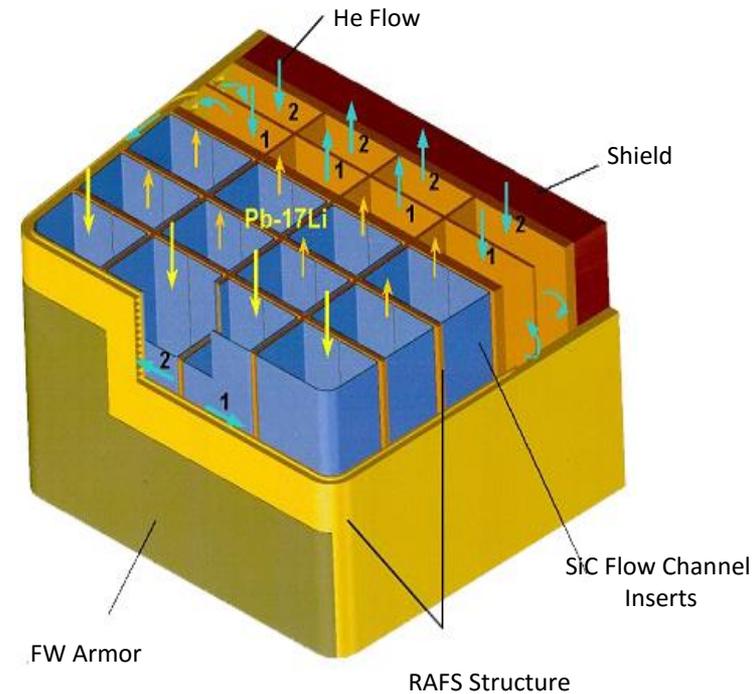
What are the US innovative blanket concepts?

- DCLL was down-selected as the lead US blanket concept after about three decades of blanket studies (most recently APEX/US-TBM, RENEW, FESAC, ARIES)

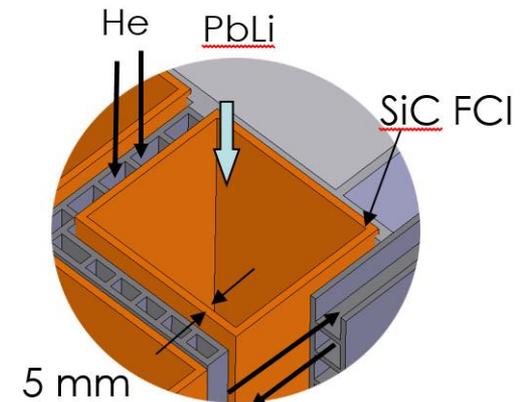
- *Pathway towards a high-temperature, high power density, high-efficiency, low tritium partial pressure blanket system, while using near term RAFM steel as structure*
- *PbLi operates at 600-700 °C (compared with 450 °C in other concepts). A Flow Channel Insert (FCI) is used to decouple the PbLi temperature from the RAFM structure and to reduce MHD pressure drop*
- *Has much common R&D with the broader family of PbLi/LM Concepts*

- High performance, helium cooled, ceramic breeder selected as a back up system

- *Has markedly different breeder feasibility issues, but common R&D on structure, fabrication, He cooling*
- *Supported by significant international research programs*
- *US focus on high power density, high reliability innovation*



Dual Coolant Lead Lithium Blanket/FW



Our vision to make progress on FNS and Materials Interactions/Blanket/FW/Tritium in the near future given a limited US budget

- Focus on R&D in **niche** areas of US scientific strength, capability, and leadership that we presented at community forums, discussed and agreed upon with FES in 2015, and that are consistent with the FES ten-year perspective
 - Address areas of high scientific content that enable the innovative features of US blanket/FW systems
 - Upgrade unique facility capabilities to perform targeted experiments
 - Develop and validate predictive capabilities required to extrapolate results and design blanket/FW and tritium systems for ITER TBM, FNSF, and DEMO
- Use these **niche** research areas to attract and enable effective **international collaboration opportunities**
 - Allows access to resources, materials, R&D results, and TBM and DEMO designs and experiments of the much larger international FNST programs at low cost and low level of commitment
 - Keeps US research and designs still grounded in the practical concerns of building and deploying real, safe, reliable nuclear components for when the US does commit to building an FNSF

US Niche Areas and Research Elements for FNS and Materials Interactions/Blanket/FW/Tritium

Niche scientific R&D areas

- Liquid Metal MHD Thermofluids and Materials Interactions (UCLA)
- Ceramic Breeder / Multiplier Material System Thermomechanics (UCLA)
- Tritium Transport and Permeation (UCLA, INL)
- Safety Codes and Analysis (INL)
- Selected Functional Materials Properties, Behavior, and Fabrication (UCLA, SBIR, International Partnerships, Structural Materials Program, INL)

Research Elements

Phenomenological and computational modeling

Experiments

Simulation, Analysis and Concept improvement

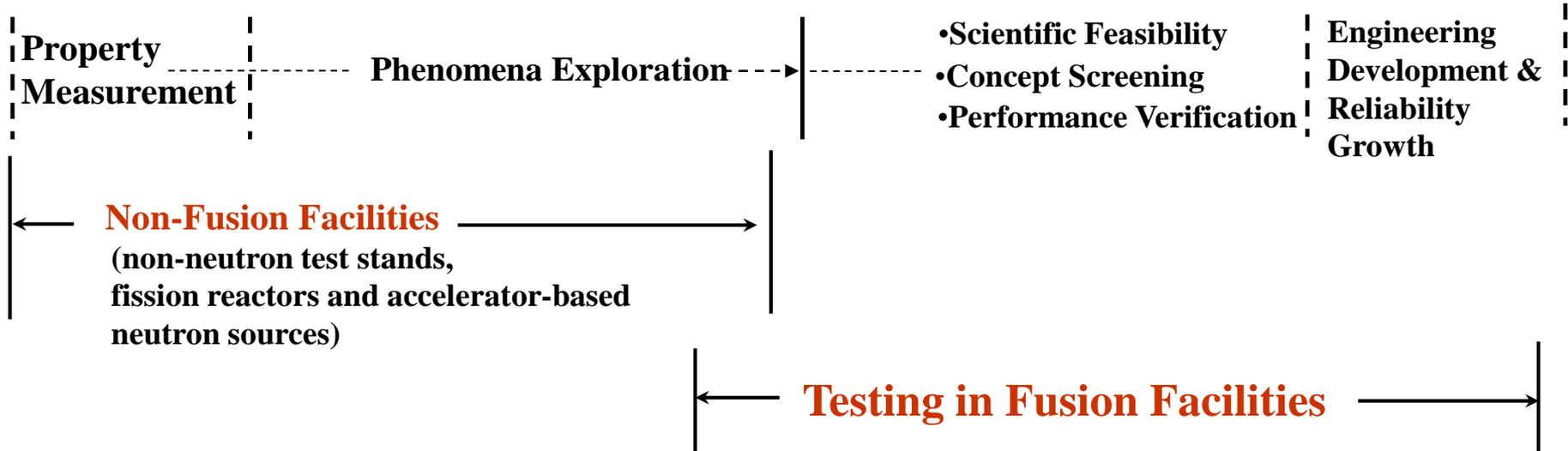
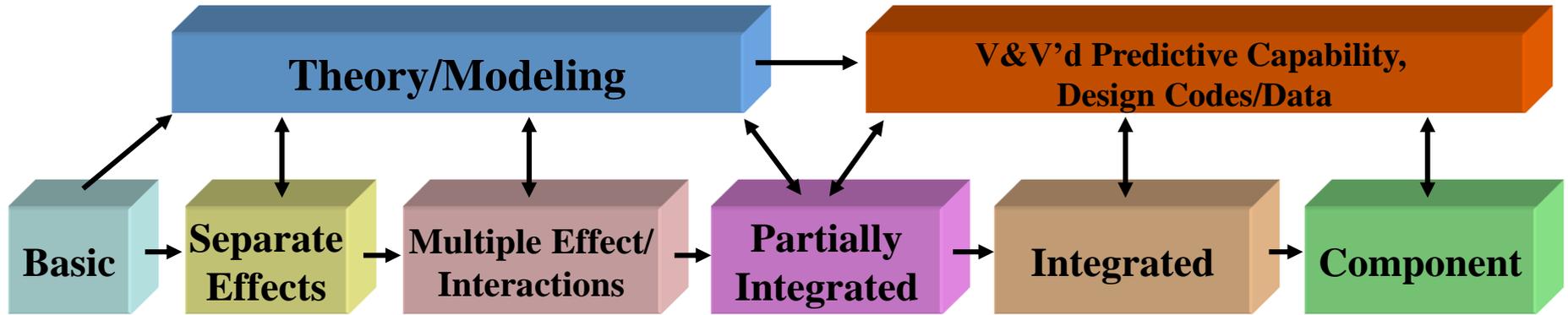
- **Phenomenological modeling is very challenging because of unknown synergistic phenomena**
- **Experiments are expensive, but essential to verify models as well as a tool to uncover synergistic phenomena**
- **Utilize codes and data for extrapolation to and improvement of blanket/FW concept**

Challenges in Developing the Blanket/FW and Implications for the R&D Pathway

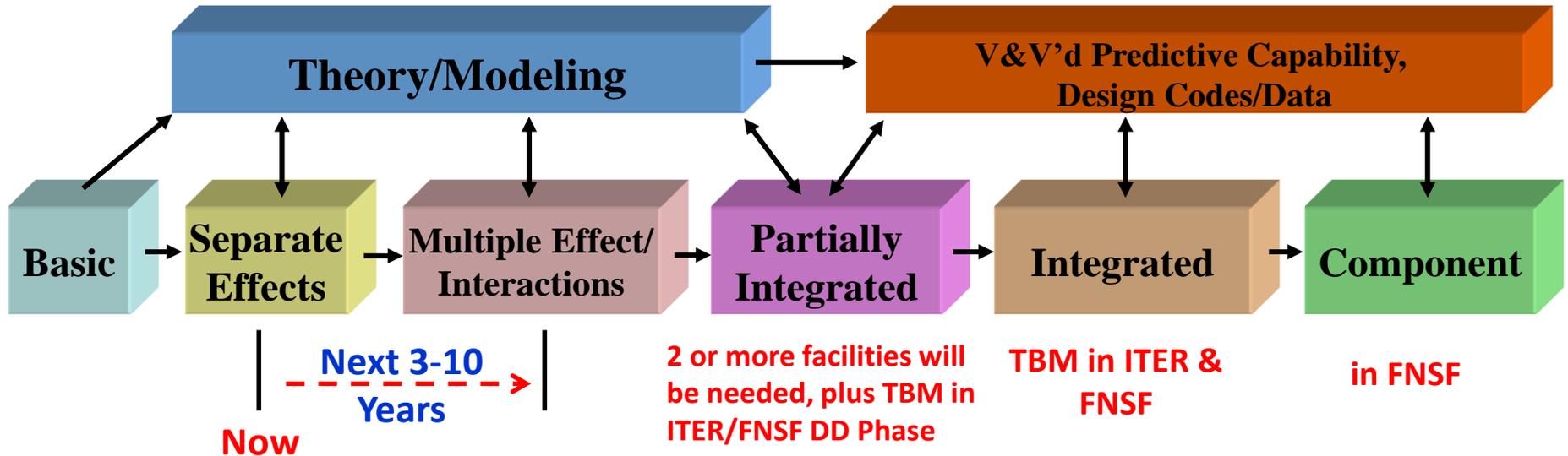
- The Fusion Nuclear Environment: Multiple field environment (neutrons, heat/particle fluxes, magnetic field, etc.) with high magnitude and steep gradients
 - Can't be recreated outside of a fusion device itself, only aspects of it can be simulated in the laboratory
- Nuclear heating in a large volume with steep gradients
 - A key aspect of the fusion nuclear environment that drives many blanket/FW phenomena, is also very difficult reproduce in the laboratory
- Complex configurations inside the vacuum vessel next to plasma
 - Difficult to make small representative tests in a small test volume
 - Failure tolerance, redundancy, and access very low
 - Failure potential and replacement time very high

Behavior of real blanket/FW components will be difficult to demonstrate and predict due to synergistic effects -- No Blanket has been built or tested

These Challenges require a Science-Based Framework for Blanket/FW R&D involving modeling & experiments in both 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



- Shifting from “Separate” to “Multiple” Effects Experiments is a MUST
- But there are many questions: e.g. how to simulate volumetric heating and temperature with gradients in laboratory facilities
- Limits on adequate simulation of blanket behavior in the fusion nuclear environment in modeling and non-fusion facilities
- Sequence and characteristics of multiple effects facilities required in the next 3-10 years

Recent Research Results at UCLA have shown clearly that LM thermofluid blanket behavior in the fusion environment cannot be predicted by synthesizing results of separate effects

Multiple Effects/Multiple Interactions — Laboratory experiments and modeling need to incorporate multiple effects to account for different components of the magnetic field, different flow orientations w.r.t. gravity, volumetric heating and gradients, temperature and temperature gradients that can drive new interacting and synergistic phenomena

Example: MHD Thermofluids

In the next several slides, taking MHD thermofluids as an example, we will provide details on:

- 1) Why simulating multiple effects / multiple interactions is absolutely **NECESSARY** to correctly observe synergistic effects in the fusion nuclear environment, and
- 2) Scientific analysis of how to plan and design multiple effects laboratory facilities that can preserve the key phenomena (very challenging task!)

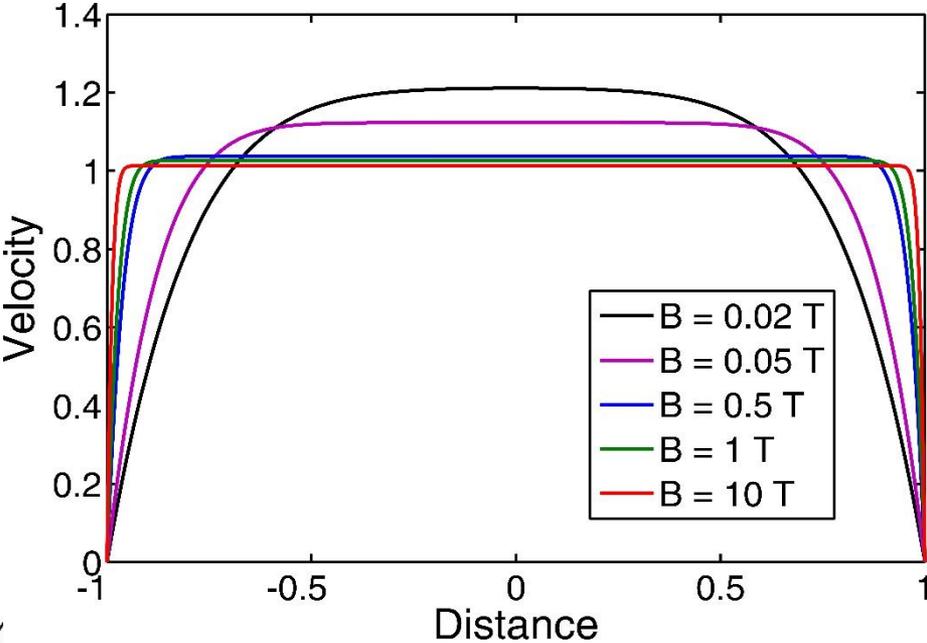
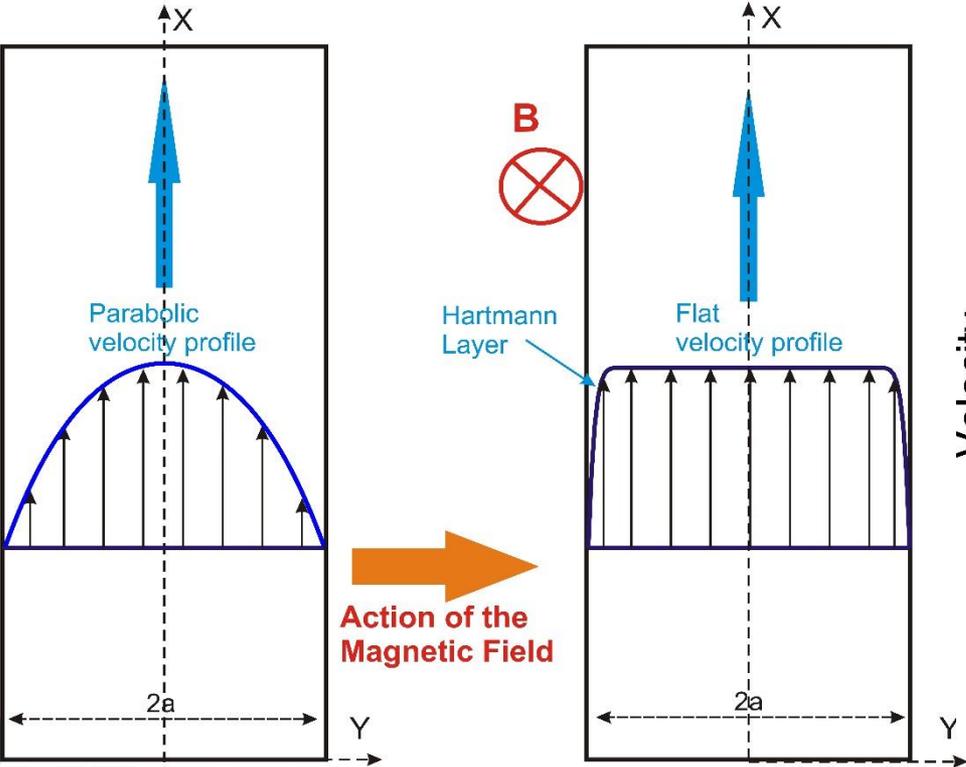
Liquid Metal MHD Flow Behavior PURELY in the Presence of a Magnetic Field

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 perfectly conducting

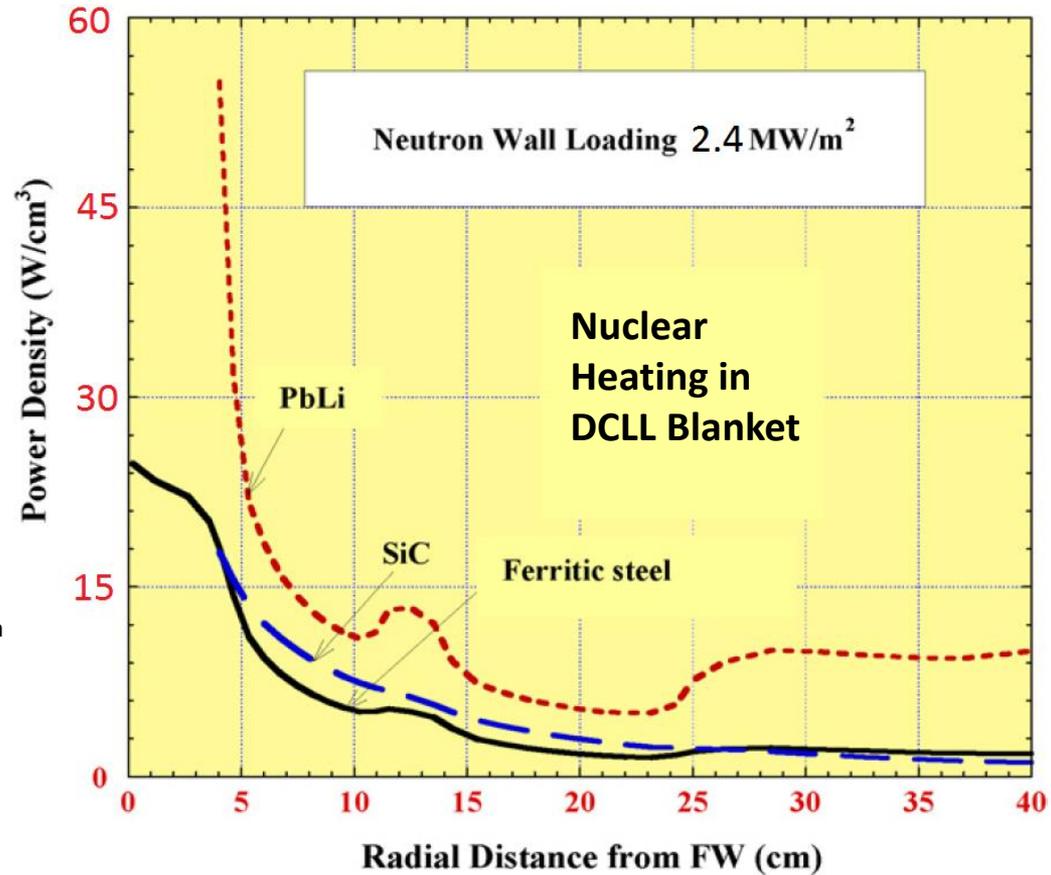
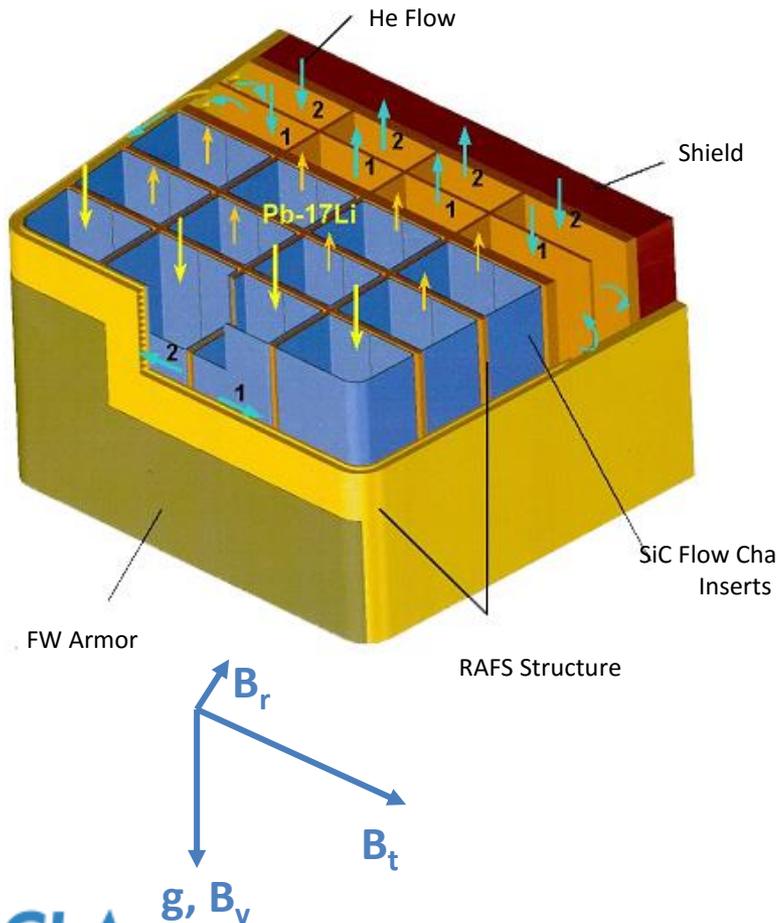
Laminar Velocity Profile

Purely MHD Velocity Profile



However, 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

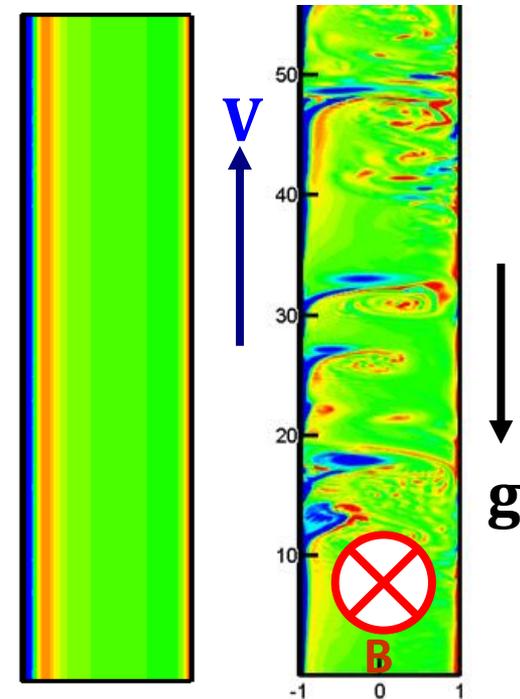
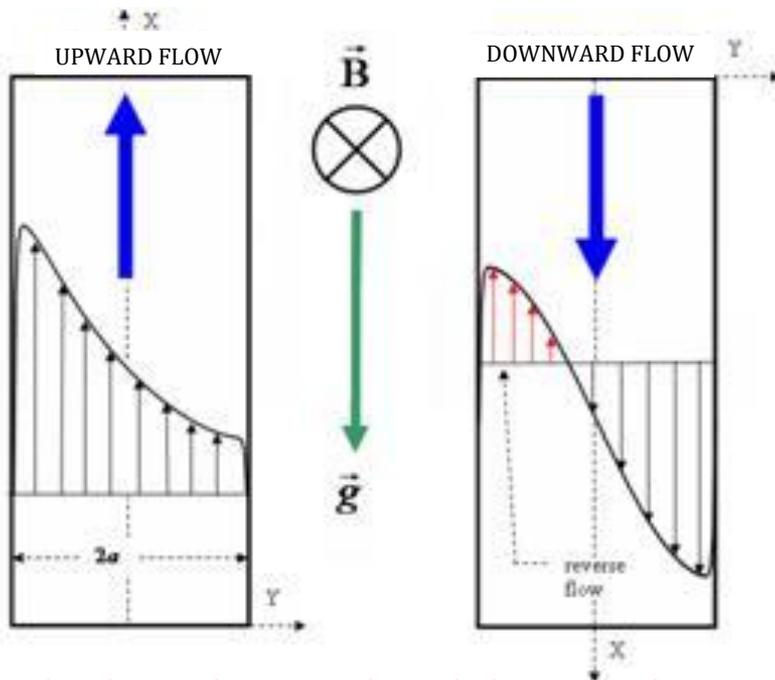
Midplane DCLL cross-section with downward flowing PbLi in channel near FW



These conditions, spatial gradients in nuclear heating & temperature in LM blanket combined with g and B , 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**” for downward flowing FW channels

Vorticity Field shows new **instabilities** that further affect all thermal, tritium and corrosion transport phenomena



- Blankets designed with knowledge only of separate effects phenomena and data will not work – e.g. downward FW channel flow
- This result is from modeling at limited parameters in idealized geometry.

What do we need to do to address “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 initiative 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 the above requirements in order to upgrade the MaPLE facility at UCLA: Big challenges in satisfying all these requirements.** Key details highlighted the next several slides

Multiple effects experiments will necessarily be at scaled down 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 Flow 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, $Gr = \frac{\text{Buoyancy forces}}{\text{Viscous forces}} = \frac{g\beta\Delta TL^3}{\nu^2} = \frac{g\beta\dot{q}L^4}{\nu^2\kappa}$

- 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
 - $r = \sqrt{\frac{Gr}{HaRe\left(\frac{a}{b}\right)^2}}$ - 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/FW does not experience just one set of conditions

- There are 60-100 modules, each will have its own conditions (e.g. different Ha, Gr) and hence there are large variations in MHD thermofluid flow phenomena.
- For example, due to different magnetic field, neutron wall loads and different gravity orientations (see figure) for each blanket module, we have a wide range of parameter values, such as,

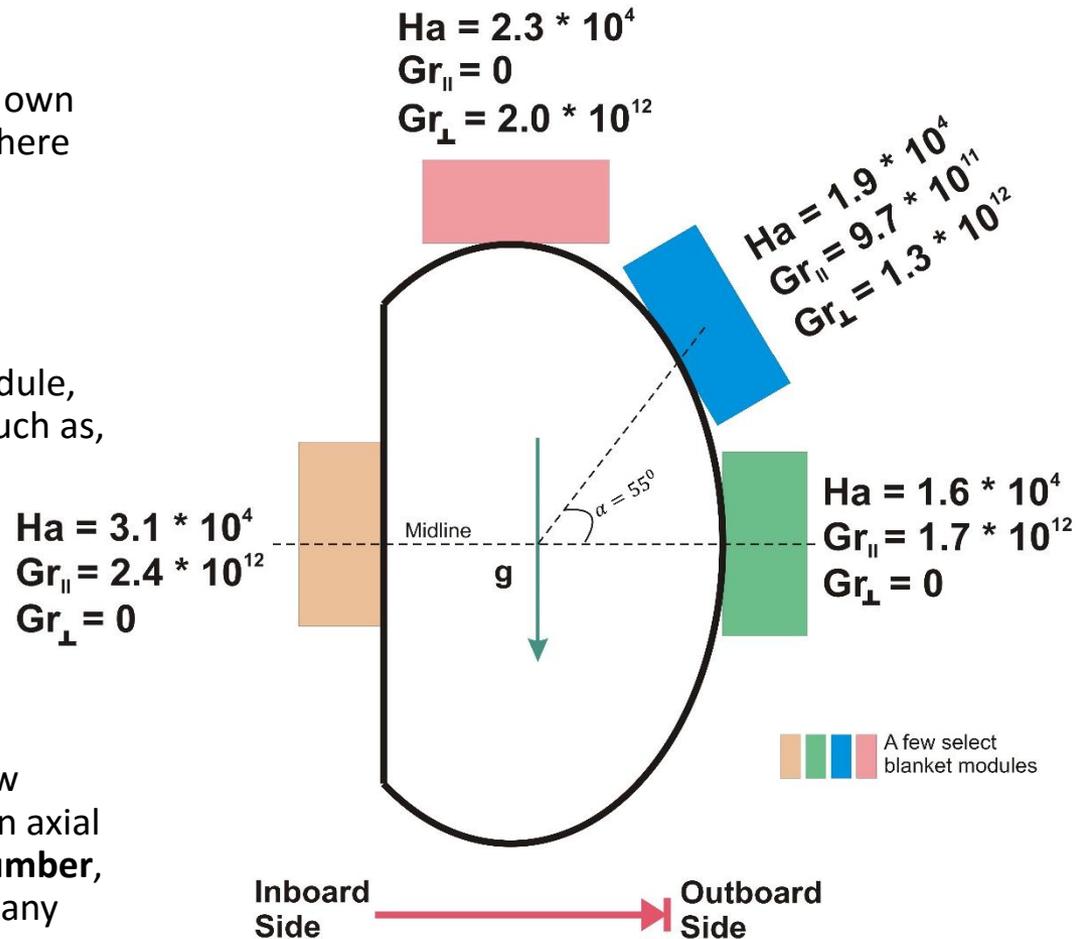
- **Parallel** radial Grashof Number

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

- **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.**

Options are limited for simulating volumetric nuclear heating in lab facilities

- **Embedded resistive heaters** - only in “discrete” spatial locations
 - Heaters will alter the behavior in regions where they are embedded – changing packing density (CB) or obstructing the flow (LM, He)
 - For LMs they provide additional current closing pathways, altering the MHD behavior
- **RF/Microwaves** - Heating “skin depth” too small in metal walls or liquid metals
 - Skin depth in good conductors is very small, all the power deposited near the surface
 - Heating in poor conductors (CB) will depend on dielectric constant rather than conductivity, e.g. for typical Li_4SiO_4 which has a high dielectric constant, the skin depth is too large indicating poor absorption
- **Induction heating** - Will strongly stir liquid metals, changing flow behavior
 - Induction currents can penetrate some metal walls or LM flows a sufficient distance to generate volumetric heating (poorer conductors have deeper penetration)
 - But these currents will induce forces in LM flow causing stirring and mixing that change the behavior of the experiment under study
- **γ -ray sources** - No practical source can safely provide enough heating
 - A γ -ray source (Co-60 with 1.17 MeV, 1.33 MeV) can produce enough γ -rays with sufficient penetration to simulate volumetric heating with gradient; and with no residual radioactivity in the exposed experimental components
 - However, the radioactivity required to produce enough heating (~ 2 MCi, 1.8 Kg of pure Co-60 for 10 KW heating) has safety issues (loss of the required cooling even when not in use, can cause melting) with consequences not acceptable/ not feasible

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

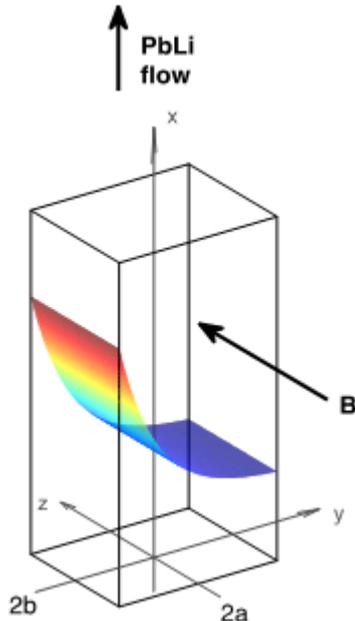
At UCLA, we investigated alternative methods to simulating the temperature gradients using approximations that result in correct direction of the slope. Our approach is to produce representative temperature variations using either flowing external hot fluids keeping constant T B.C. or one-sided surface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

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

Reference Blanket:

volumetric Nuclear heating

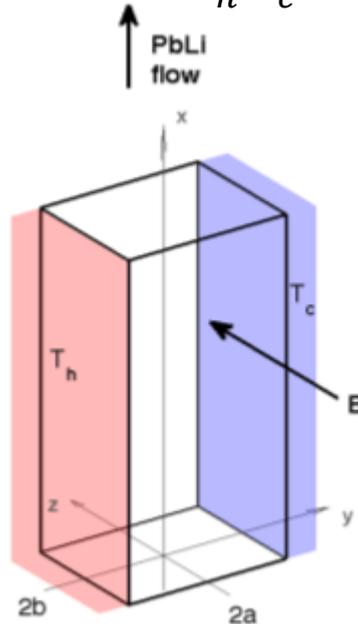
$$\Delta T = NWL * L/k$$



Experiment:

Flowing external hot fluids and constant T B.C.

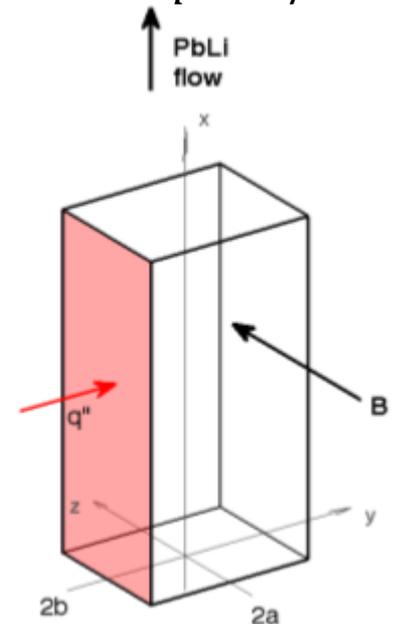
$$\Delta T = T_h - T_c$$



Experiment:

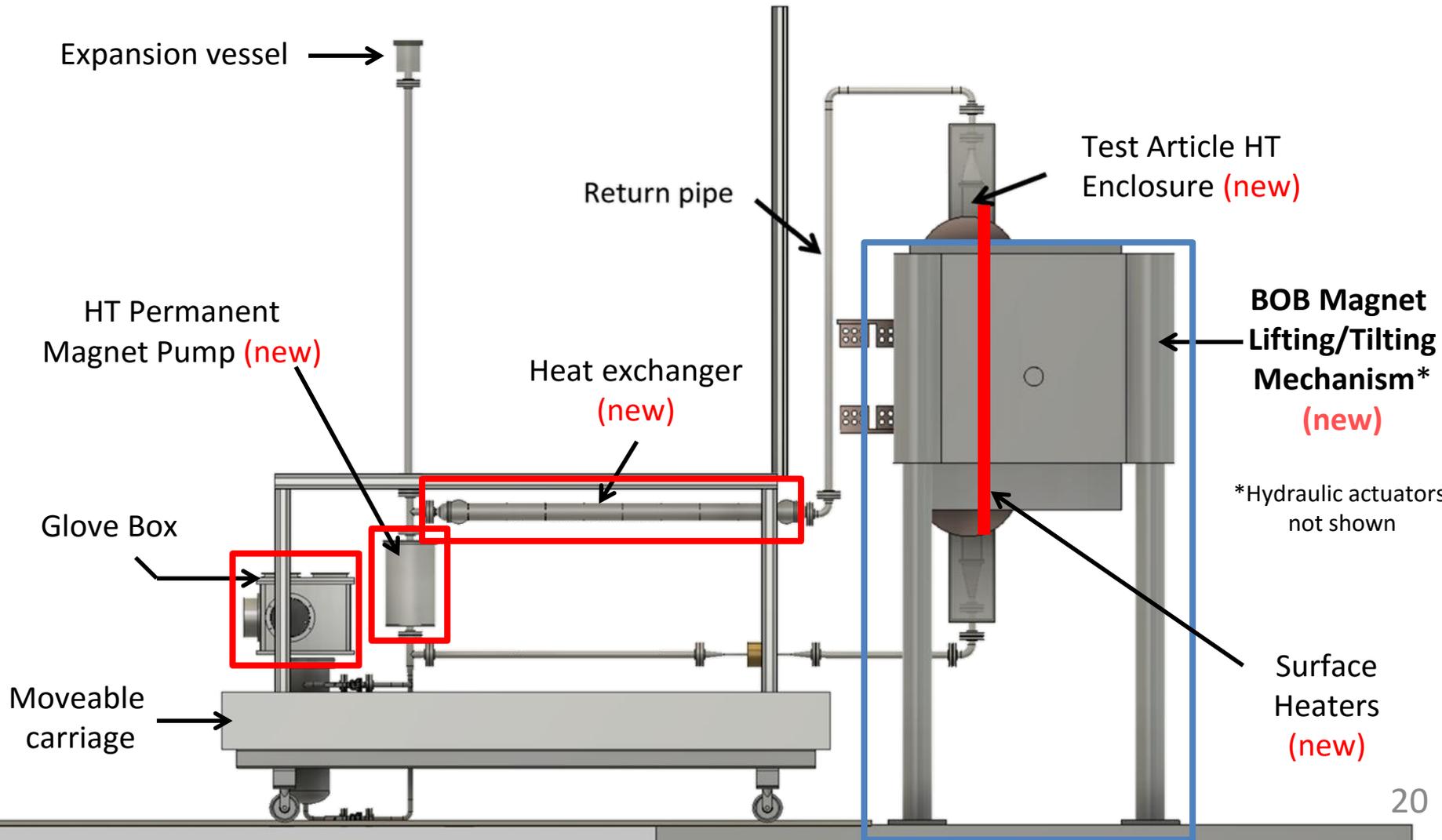
surface heating/insulation

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



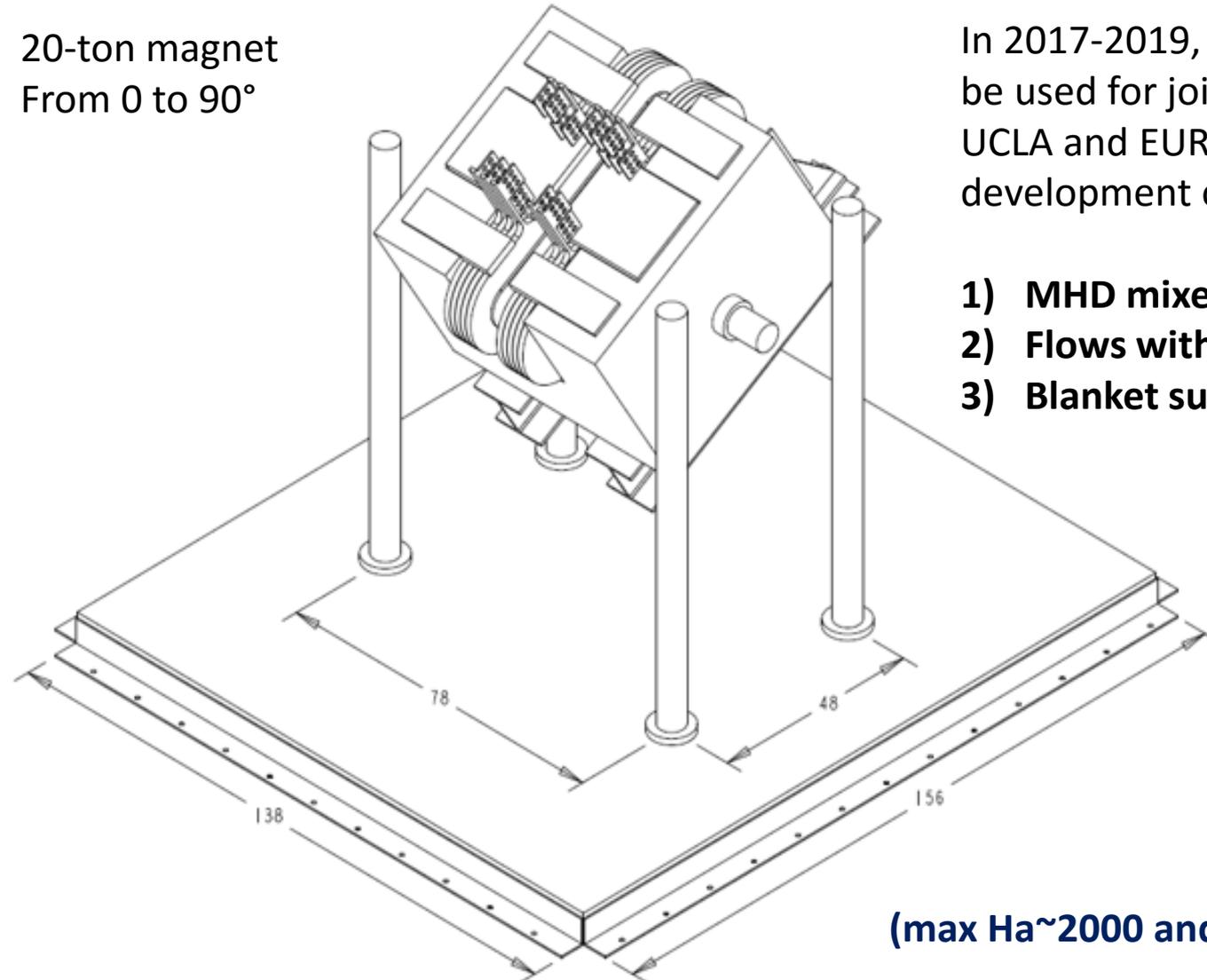
Upgrading the MaPLE facility is underway at UCLA

Exemplary Partnership between UCLA/FES and EUROfusion



MaPLE will be significantly upgraded to enable new effects: flexible orientation to gravity and simulated volumetric heating

20-ton magnet
From 0 to 90°

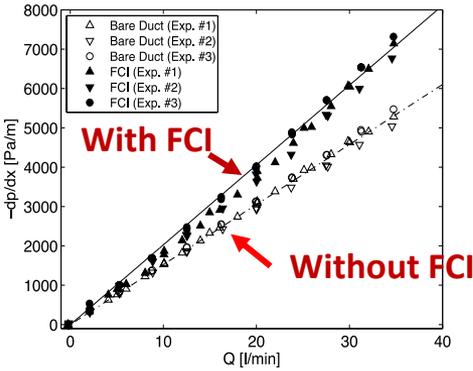


In 2017-2019, the upgraded MaPLE will be used for joint experiments between UCLA and EUROfusion to support development of DCLL:

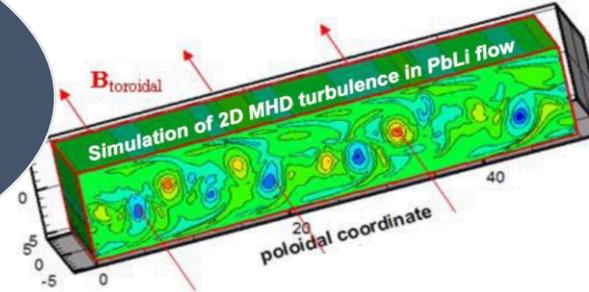
- 1) MHD mixed-convection flows
- 2) Flows with FCI
- 3) Blanket subcomponent testing

(max $Ha \sim 2000$ and $Gr \sim 10^{12}$ with PbLi)

Multiple effects include fluid-material interactions too



PbLi flow is strongly influenced by MHD interaction with all magnetic field components and buoyancy-driven convection driven by spatially non-uniform volumetric nuclear heating

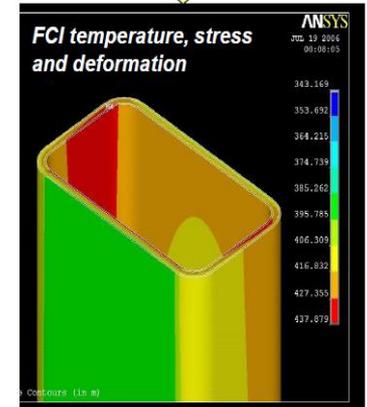


Cracking and movement of the FCIs will strongly influence MHD flow behavior by changing conduction paths that change electric current profiles

Temperature and thermal stress of SiC FCI are determined by this MHD flow and convective heat transport processes



Deformation, movement and cracking of the FCI depend on FCI temperature and thermal stress coupled



Experimental testing of foam-based CVD coated SiC FCI in flowing PbLi and magnetic field – FCI didn't survive, more work is needed on improving FCI materials and fabrication

GOAL 1: Demonstrate reduction of MHD pressure drop by FCI

GOAL 2: Address chemical/physical compatibility between the FCI and PbLi in a long run

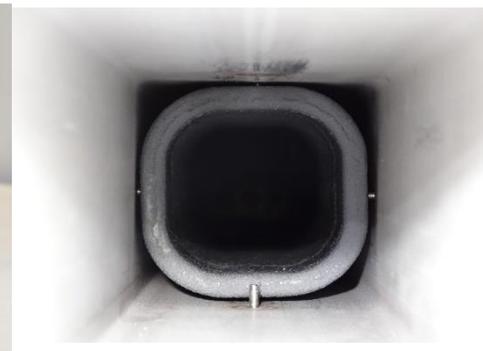
- FCI fabrication using foam core, and sealed with aerogel and CVD outer layer
- Prototypes survived 1000 h separate effects tests with 700C PbLi exposure and applied temperature gradient
- But infiltration occurred during the course of this 6500 h flowing PbLi experiment and MHD insulation properties were comprised



30 cm foam-based SiC FCI manufactured by Ultramed, USA



Picture of the FCI in the test section and after extracted from the duct.



Outline

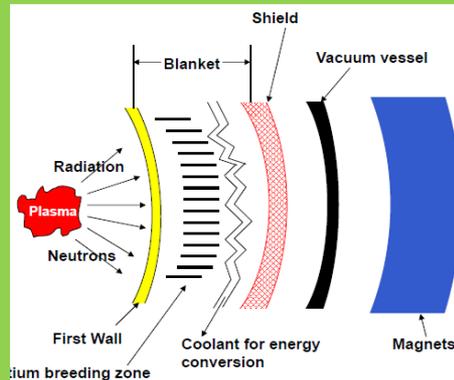
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Key Technical Challenges beyond ITER for Fusion Nuclear Science

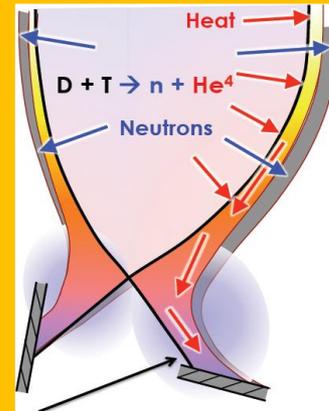
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Exhaust / Divertor



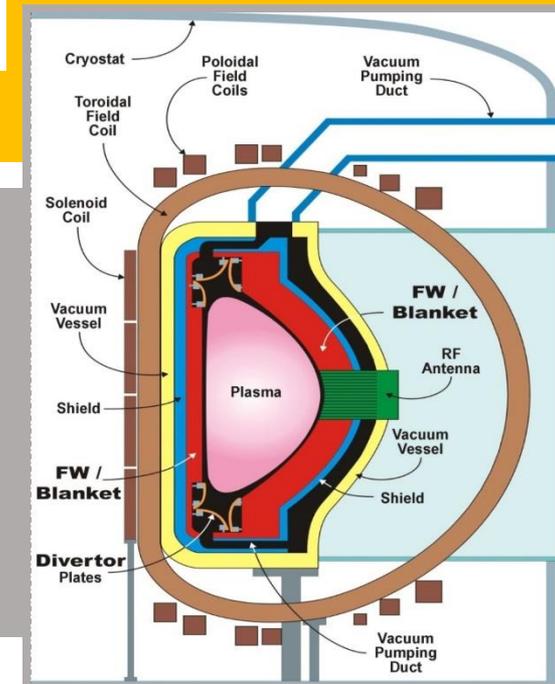
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Materials

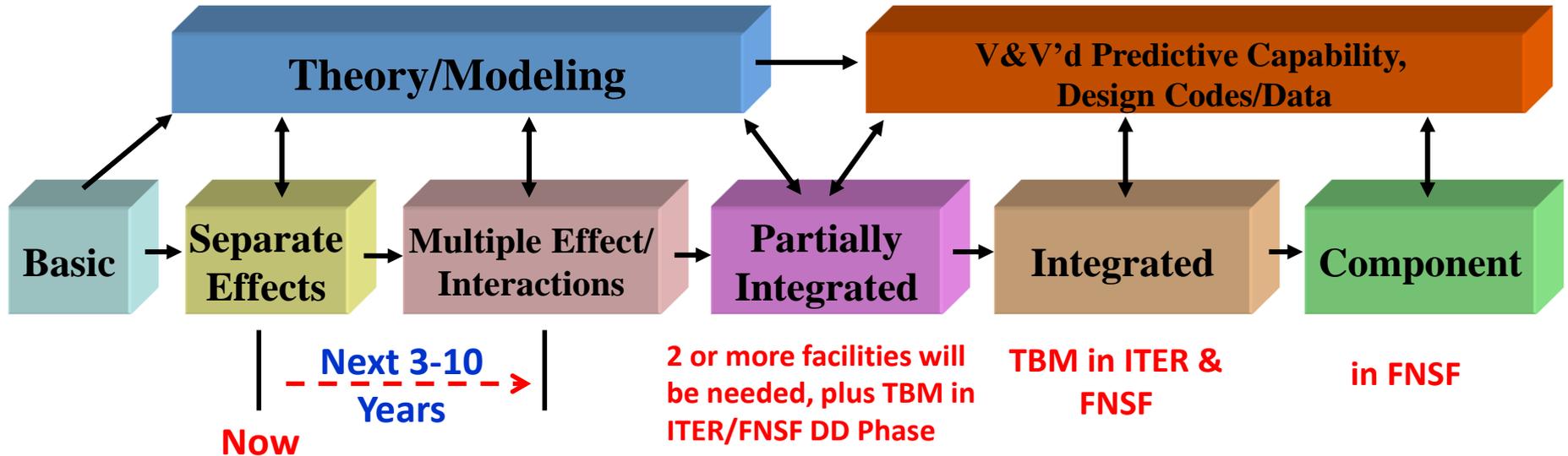
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- Shifting from “Separate” to “Multiple” Effects Experiments is a MUST
- But there are many questions: e.g. how to simulate volumetric heating and temperature with gradients in laboratory facilities
- Limits on adequate simulation of blanket behavior in the fusion nuclear environment in modeling and non-fusion facilities
- Sequence and characteristics of multiple effects facilities required in the next 3-10 years

RAMI issue will be the most serious challenge for fusion nuclear components from beginning to end

MTBF/MTTR requirements for Blanket & Divertor are driven by the location *inside* the vacuum vessel:

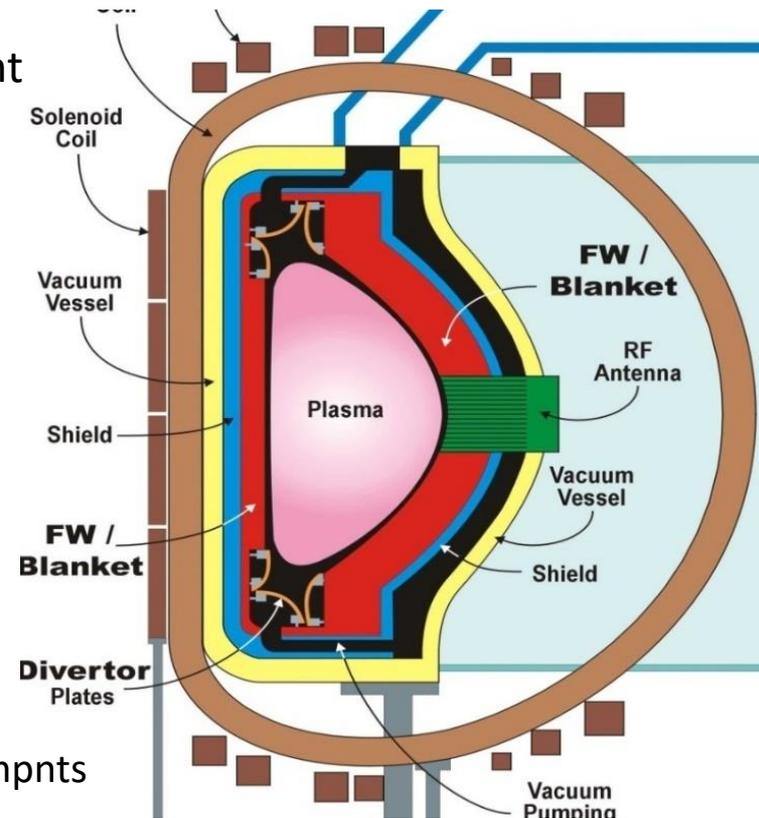
- severe and unsimulatable fusion nuclear environment
high failure potential
- many failures (e.g. coolant leak) require immediate shutdown, no redundancy possible,
low fault tolerance – short MTBF
- limited access, repair/replacement difficult
long MTTR

Conclusion: Understanding performance, design margin, failure modes/rates should be the priority of FNST R&D - Not a long dpa life

R&D should focus on:

- scientific understanding of early life multiple effects, performance and failures of Blanket/FW materials/compts
- unit cell mockups and subcomponent tests including non-nuclear tests to uncover synergistic effects
- fabrication and properties of structural and functional materials that can be used in these tests

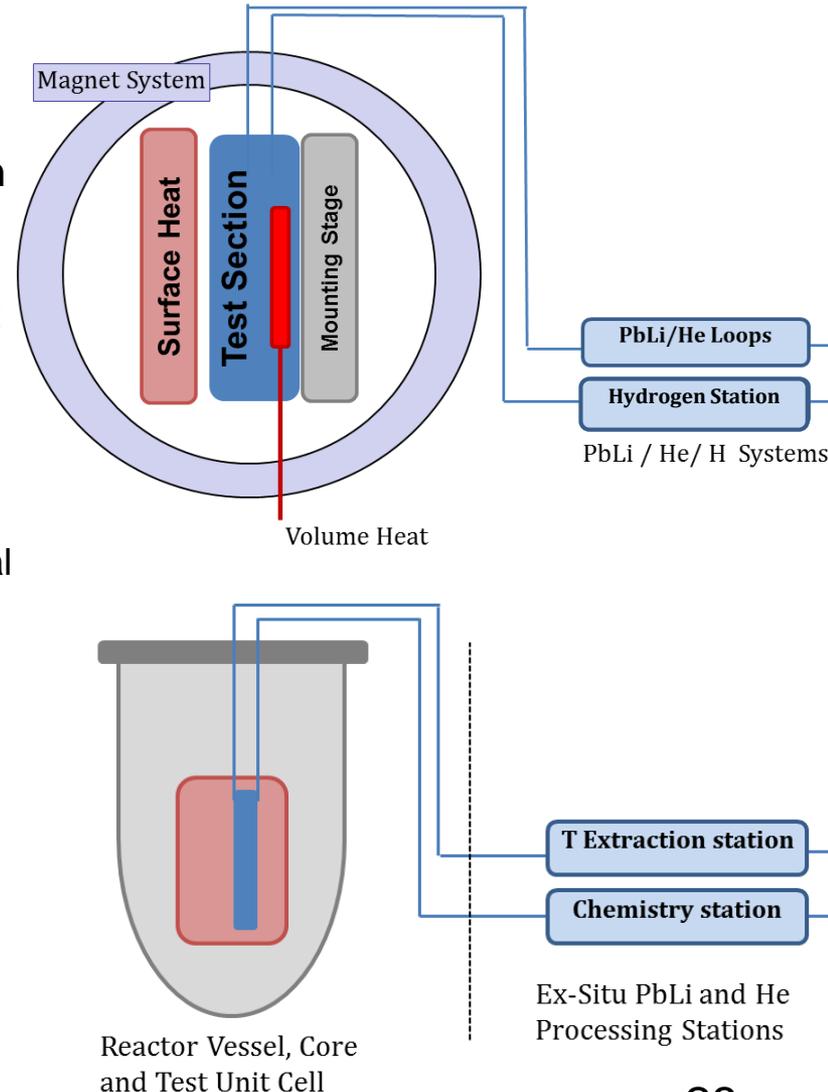
so that Blanket/FW functions, requirements and safety margins can be achieved and designs simplified & improved – and materials requirements refined



Doing blanket/FW multiple effects research will require several significant facilities

These facilities must simulate conditions in a manner to preserve synergistic phenomena – this requires careful analysis of the balance of forces and it is very challenging. Examples we proposed in recent studies:

- **Blanket Thermomechanics Thermofluid Test Facility**
 - simulated surface and volumetric heating, temperature gradients, orientation to gravity, and other environmental conditions
 - test mockups and ancillary systems of prototypical size, scale, materials
- **Tritium Extraction and Processing Facility**
 - unit cell mockups exposed to fission neutrons
 - PbLi loop coupled to ex-situ tritium processing and chemistry systems
- **Blanket/FW tests in long pulse tokamaks (ITER-DD, FNSF-DD, Divertor test tokamak...)**
 - study FW heat flux and time-varying reactor-like magnetic fields and disruption



R&D Initiative proposed by UCLA for a national study on defining blanket/FW Multiple Effects facilities

National Study on Blanket / FW Multiple Effect / Multiple Interaction and Partially Integrated Test Facilities

- **Issue:** The US fusion program must build the capabilities for performing multiple effect / multiple interactions experiments and simulations prior to any testing of a blanket/FW in a fusion environment.
- But building such facilities is very complex and the cost of the facility for full simulation can be very expensive
- **Initiative:** Lead a study of needs and tradeoffs between the capabilities of simulation incorporated in the facility and cost
- The experts on Blanket/FW thermofluid/mechanical R&D are at UCLA and other institutions in the FNS program. The mechanical engineers, material fabrication specialists, magnet designers and cost professionals reside in labs and industry.
 - **Several labs have** indicated their support for this study
 - **EUROfusion** has also indicated a strong interest participating in the study. Other international interest is likely

Summary Points about Multiple Effects/Multiple Interactions and experiments in laboratory facilities

- **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

Summary Points about Multiple Effects/Multiple Interactions and experiments in laboratory facilities (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/material behavior in the fusion nuclear environment**

Therefore, the primary goal of the next DT fusion facility (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
 - 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 critical factor in any planning we do