

Scientific Framework for Advancing Blanket/FW/Tritium Fuel Cycle Systems towards FNSF & DEMO Readiness

**Input to FESAC Strategic Plan Panel
Gaithersburg, Washington, June 3, 2014**

(Greenwald Gaps G11, G12 as well as G13, G14)

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Right now, we do not know and cannot predict how the blanket/FW will work in the fusion nuclear environment

- There are many yet undiscovered phenomena caused by multiple effects/multiple interactions and synergetic effects in the blanket/FW
Compelling examples from recent discoveries show that blankets designed with current knowledge of phenomena and data **will not work**
 - The source of this problem is that the fusion nuclear environment has many fields with steep gradients (magnetic, neutrons, nuclear heating), and the blanket has many functions and materials.
- MTBF for Blanket/FW in any FNSF is estimated to be very short while MTTR is predicted to be months – leading to low availability of only a few percent
 - MTBF/MTTR will be the key issue in determining the feasibility of plasma confinement configurations and the feasibility of blanket concepts
 - **Therefore, predicting prompt response and behavior of systems in the fusion nuclear environment in the very early life must be the highest priority**

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**

-T prod, PEX, Shielding, FW

- PbLi, CB, Be, FS, SiC, Refractories

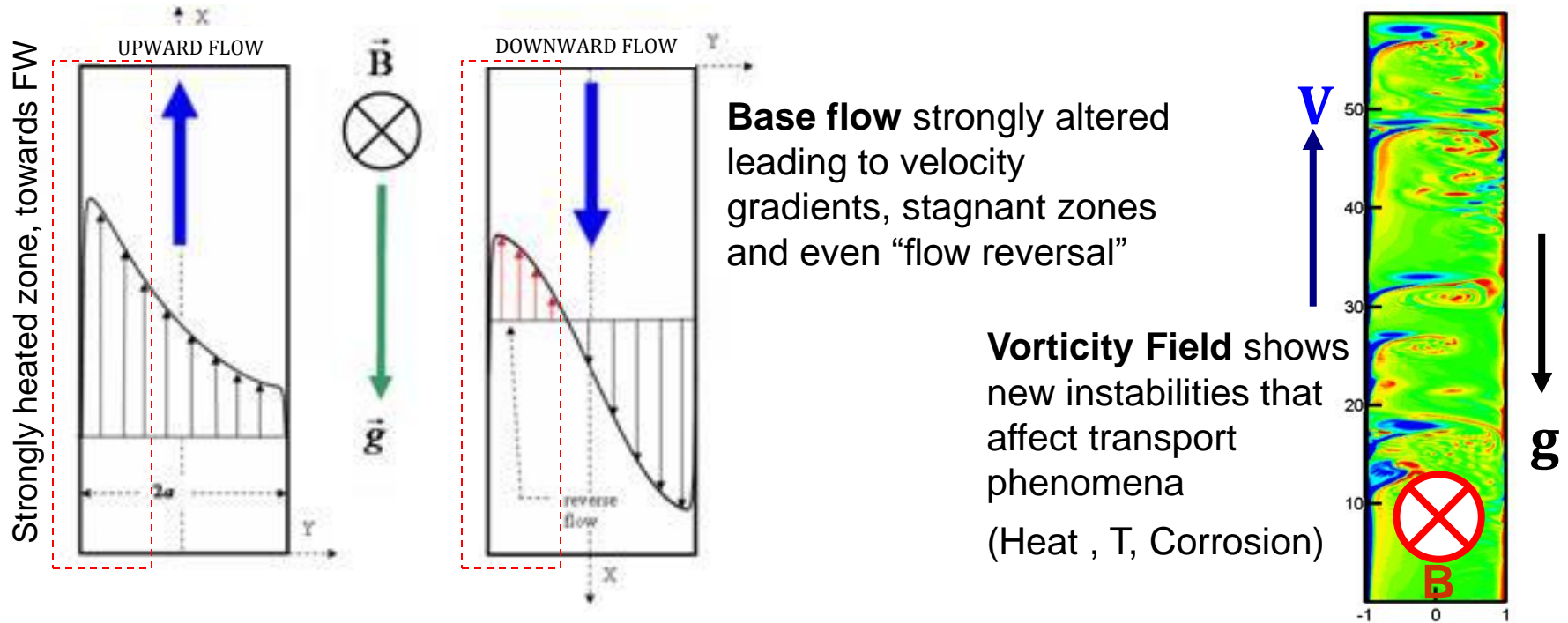
Combined Loads, Multiple Environmental Effects

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

- Many new behaviors and phenomena YET to be discovered – Experiments are a MUST
- Laboratory experiments need to be substantial to simulate multi loads and interactions
- Theory and simulation essential to move beyond limited experimental parameters

Example: Spatial Gradients in Nuclear Heating and Temperature in LM Blanket Lead to New Phenomena that fundamentally alter our understanding of the behavior of the blanket in the fusion nuclear environment

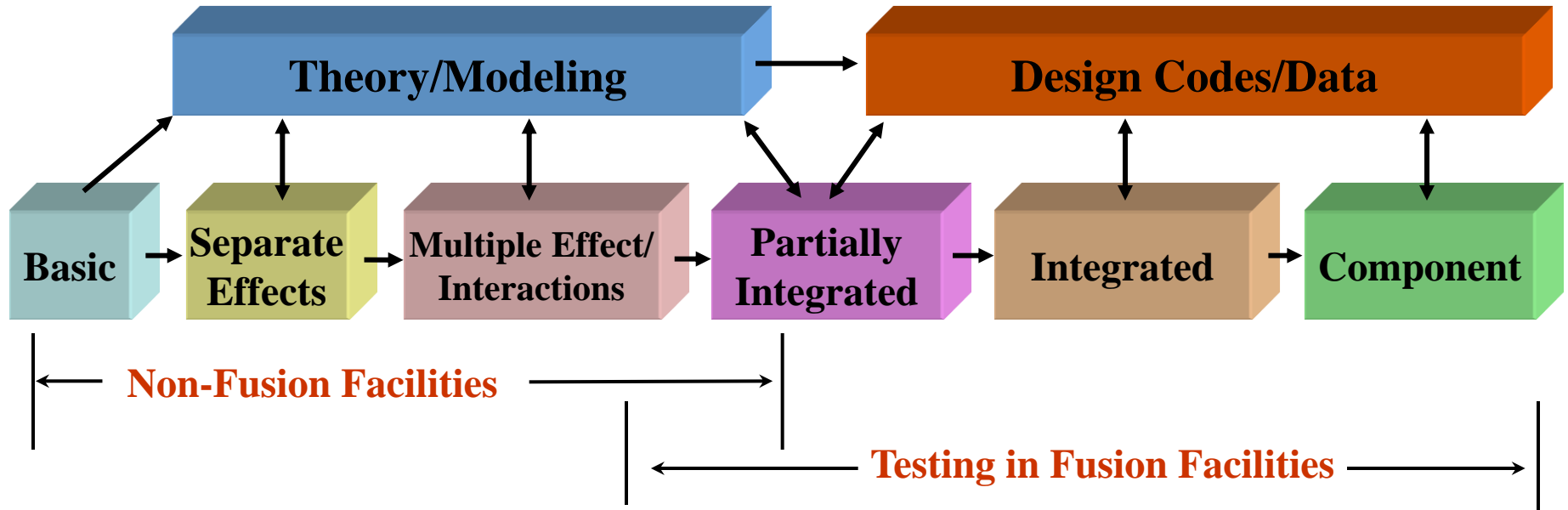
Buoyant MHD interactions result in “Mixed Convection” flow regime



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

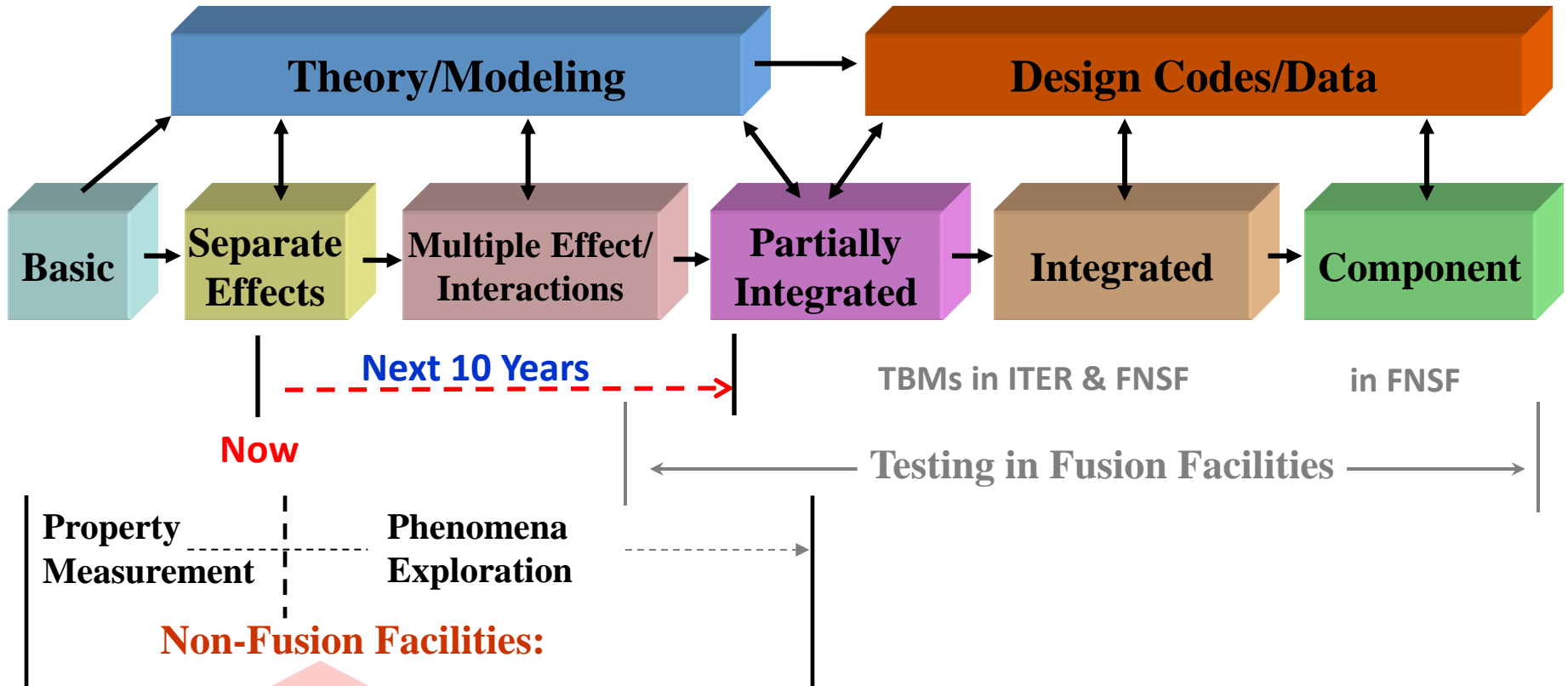
- We need to go to higher parameters but there are computational challenges that must be overcome
- We need also to perform experiments that can include multiple effects including high magnetic field and bulk heating with gradients and flexibility in orientation to **g**

The Strategic Plan must utilize a Science-Based Framework that includes experiments AND theory/modeling and uses BOTH non-fusion and fusion facilities



1. The framework follows a logical progression of increasing loads, interactions, and configuration complexity in both experiments & modeling
2. For each step, define detailed performance parameters to quantify requirements of experiments & modeling and measure progress
3. Recognize also the role, need, and challenge of theory and validated modeling to extend understanding beyond the parameter ranges and conditions achievable in test facilities to enable next steps

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

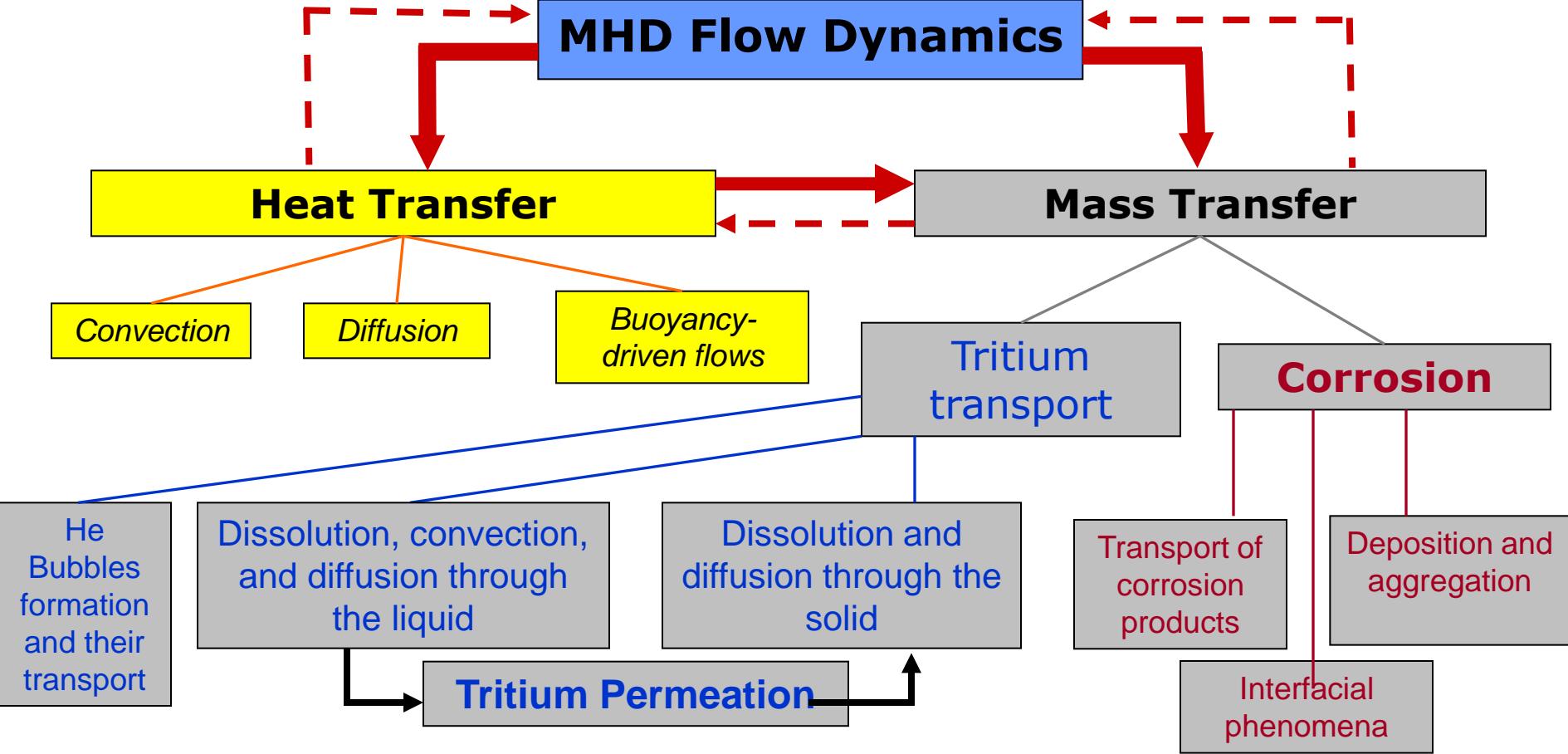


A number of upgraded/new experimental facilities are needed that:

- Use real materials, prototypic temperatures
- Simulate surface and bulk heating and gradients
- Provide large volume and use multiple channels
- E.g. for LM blanket: higher Ha , Gr and multi-component B and $gradB$

Predicting blanket behavior requires calculating many responses having strong coupling & complex dependence on many interacting phenomena

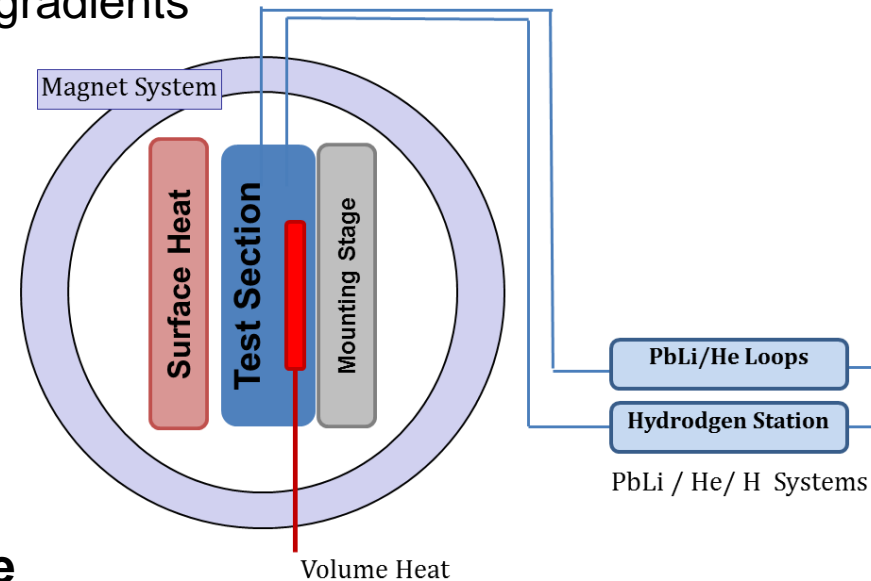
Example: tritium permeation requires modeling & experiments that integrate Momentum, Heat, and Mass Transfer with bulk & interfacial material phenomena



Modeling, computation, and experimental challenges to enable predicting blanket behavior are enormous -- strong computational and experimental initiatives are required

Required Facility: Example -- Multiple Effect / Multiple Interaction test environment for Blanket/FW MHD thermofluids and thermomechanics

- **Provide test environment that simulates fusion environment conditions other than neutrons and plasma**
 - Large volume magnetic field with prototypic gradients
 - Simulated surface, volume heating with gradients
 - Steady and transient mechanical loads
- **Capability to reach prototypical Temp, Flow, Pressure over extended periods**
 - PbLi and He high temperature coolant flow and processing loops
 - Chemistry control & vacuum systems
- **Accommodate complex configuration, prototypic materials with failure tolerance**
 - From simple geometries to prototypical size, configuration, and materials
 - Both LM Blankets and CB Blankets



Laboratory Facilities will be more **expensive** than current separate effects facilities. But their cost is a **small fraction of costs of tests in ITER or FNSF** where a single failed TBM can result in months of lost operation time **costing ~\$300-\$500 million/yr**

Strategy to make progress on needed Blanket/FW R&D in the next decade given a limited US budget environment

- Support niche scientific R&D areas of US core competency and recognized leadership critical to US blanket concepts
 - Recommended niche areas include: (1) Liquid Metal Magnetohydrodynamics and Transport Phenomena, (2) Ceramic Breeder Materials Interactions, (3) Tritium Transport, Extraction and Permeation, (4) Large Area Helium High Heat Flux Removal, (5) Safety and Failure Effects Codes and Analysis, (6) Functional Materials Properties and Fabrication
 - Each niche area initially supported at the 1-3M/year level, then increased in future years
- Use these niche research areas to attract and enable international collaboration opportunities
 - Provide the US with access to the R&D and test facilities of other world programs including ITER-TBM R&D and results
 - Need formal supporting ITER-TBM partnership with 2 or more parties to get such access
- Prepare and construct substantial multiple effect/multiple interactions Blanket/FW test facilities.

Set specific 10 Year Key Task and Goals in the US Niche Research Areas

(Examples where other countries expressed strong interest to collaborate with US)

Basic and Separate Effect

- Understand FCI impact on **MHD pressure drop and flow control** in PbLi
- Model **corrosion and tritium extraction** from PbLi with prototypic material systems and temperatures
- Establish basic tritium and helium **solubility and transport properties** in PbLi with typical impurity control
- Measure ceramic breeder pebble and foam material **mechanical, creep and fracture properties**
- Determine **He-cooling heat transfer** limits for large area FW and blanket surfaces

Multiple-Effect/Multiple-Interaction

- Extend Ha/Re/Gr parameter range in understanding the impact of **MHD mixed convection and turbulence** on transport & corrosion
- Determine long term cyclic loading and geometric effects **on CB unit cell heat transfer** and tritium release
- Complete construction of substantial **test facility for blanket/FW MHD**, thermofluids, and thermomechanics that approaches blanket scales
- Create numerical methodology and basic **platform for integrated simulations** of blanket unit cell and mockup and components

There is a serious problem for the strategic plan that must receive attention from this panel

Talking only about “Materials” in FES and FESAC documents is confusing and leads to missing the very serious technical issues for Blanket/FW/Tritium that must be addressed in the next 10 years

- “Materials” can indeed be used a catch-all category that includes the full research portfolio
- But the problem is that that FES has a very specific program called “Materials” which focuses on structural materials and mostly irradiation
- All the major technical disciplines discussed in this presentation are explicitly missing in this classification:
 - MHD thermofluids, ceramic breeder thermomechanics interactions, neutronics, tritium transport / breeding / extraction / permeation, failure mode and effects
- **Recommendation:** Add “Fusion Nuclear Science” or “Material Interactions” to the classification to include these disciplines currently addressed under other programs called Blanket, PFC, Safety, Tritium, etc.

Possible backup slides

Fusion Nuclear Science & Technology (FNST)

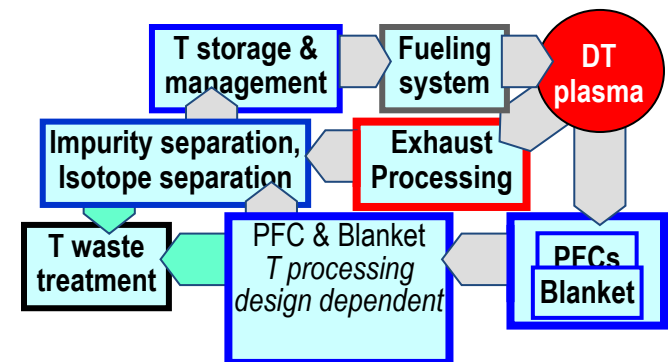
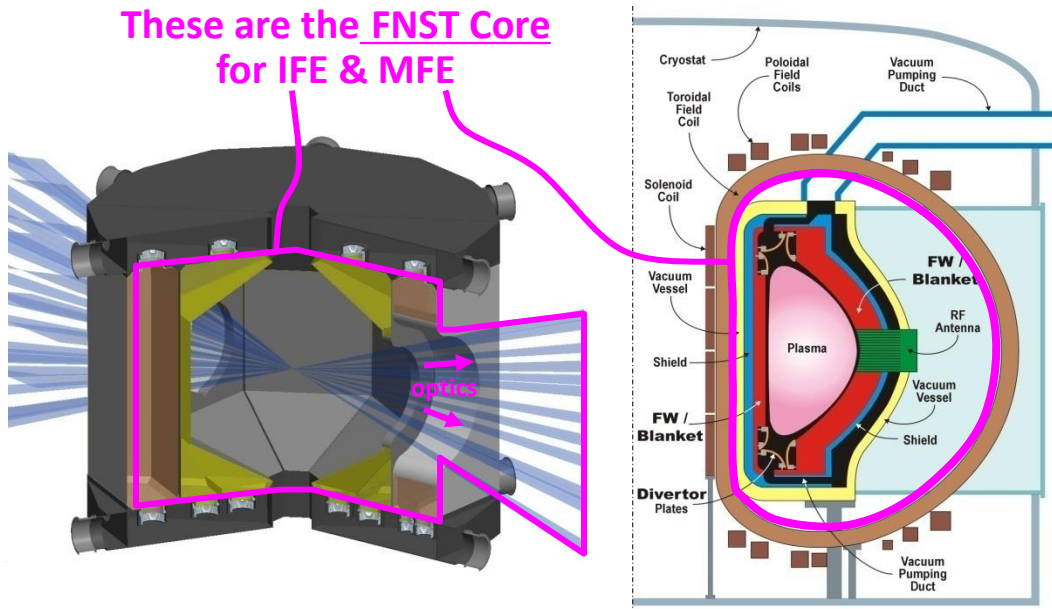
FNST is the science, engineering, technology and materials for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

In-vessel Components

- Divertor/PFC
- Blanket and Integral First Wall
- Vacuum Vessel and Shield

Key Supporting Systems

- Tritium Fuel Cycle
- Instrumentation & Control Systems
- Remote Maintenance Components
- Heat Transport & Power Conversion Systems



Tritium Fuel Cycle pervades entire fusion system

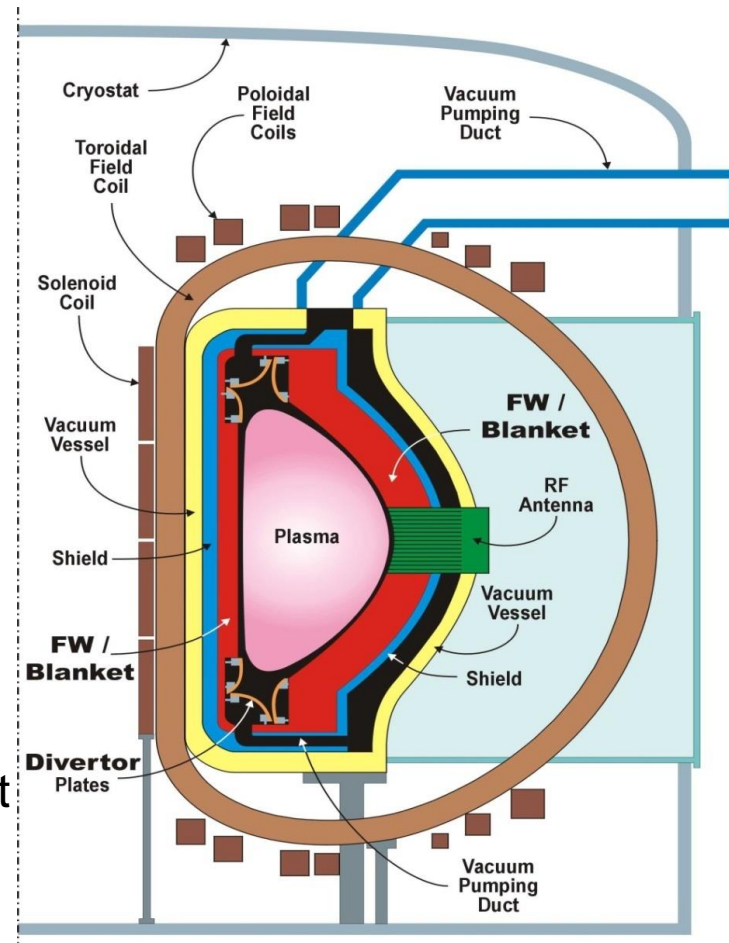
This short MTBF / long MTTR issue will be the most serious challenge in Fusion Development from beginning to end

In addition to the severe nuclear environment, MTBF/MTTR requirements for Blanket & Divertor are driven by **the location inside the vacuum vessel**:

- ❑ 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: Performance, Design Margin, Failure Modes/Rates should now be the focus of Blanket R&D, Not a long dpa life

1. Setting goals for MTBF/MTTR is more important NOW than dpa goals for lifetime of materials
2. Current R&D now should focus on:
 - scientific understanding of multiple effects, performance and failures so that functions, requirements and safety margins can be achieved and designs simplified & improved
 - subcomponent tests including non-nuclear tests
(current irradiation data for RAFS is more than sufficient for now)



Reliability/Availability/Maintainability/Inspectability (RAMI) is a serious challenge that has major impact on priorities and strategy for fusion R&D

Availability required for each component needs to be high								
Component	#	failure rate (1/hr)	MTBF (yrs)	MTTR/type		Fraction Failures Major	Outage Risk	Component Availability
				Major (hrs)	Minor (hrs)			
Toroidal	16	5×10^{-6}	23	10^4	240	0.1	0.098	0.91
Two key parameters:				MTBF – Mean time between failures MTTR – Mean time to repair				
Magnet supplies	4	1×10^{-4}	1.14	72	10	0.1	0.007	0.99
Cryogenics	2	2×10^{-4}	0.57	300	24	0.1	0.022	0.978
Blanket	100	1×10^{-5}	11.4	800	100	0.05	0.135	0.881
Divertor	32	2×10^{-5}	5.7	500	200	0.1	0.147	0.871
Htg/CD	4							0.884
Fueling	1							0.998
Tritium System	1							0.995
Vacuum	3							0.998
Conventional equipment – instrumentation, cooling, turbines, electrical plant							0.05	0.952
TOTAL SYSTEM							0.624	0.615
							(Due to unscheduled maintenances)	

DEMO availability of 50% requires:

- Blanket/Divertor Availability ~ 87%
- Blanket MTBF >11 years
- MTTR < 2 weeks

Extrapolation from other technologies shows expected MTBF for fusion blankets/divertor is as short as ~hours/days, and MTTR ~months
GRAND Challenge: Huge difference between Required and Expected!!

Summary of research priorities and facility needs for blanket/FW power extraction and tritium production

**Operational in
10-20 years**

Testing in the Integrated Fusion Environment (100M-1000M's)

Scientific Feasibility Testing: ITER TBM Experiments/PIE
Engineering Feasibility and Development Testing in FNSF

**Construction
and operation
over next
10 years**

Multi-Effect / Multiple Interactions (~20-30M class)

Blanket Mockup Thermomechanical/Thermofluid Testing
Blanket Unit Cells in Fission Reactors → Tritium Extraction Test Facility
Virtual Component and System Predictive Capability Initiative

**Needs
increased
support NOW**

Separate Effects Materials Interactions and Modeling (each ~1-3M /year)

PbLi Based Blanket Flow, Heat Transfer, and Tritium Transport Processes
Blanket Tritium Extraction from Breeder
Helium Cooling and Reliability of High Heat Flux Surfaces/Blanket/FW
Ceramic Breeder Thermomechanics and Tritium Release
Structural and Functional Materials Properties and Fabrication

International Collaboration Opportunities on FNST R&D

- US should establish two “supporting partnership” agreements for TBM. The preferred two are 1- with EU on their He-cooled Lead Lithium, and 2- with Korea on their He-cooled Ceramic Breeder.
 - These “supporting partner agreements” avoid the financial commitments and the “political sensitivities” associated with leading a TBM concept, but provides the US with access to the R&D from other major world programs (which is now the primary focus of all countries). **Note that this R&D for ITER TBM is the same as that required for FNSF and for DEMO.**
 - Each of these agreements requires \$2-3 millions per year of R&D in the US (it can start smaller and increased gradually). These can be based on the “niche” areas above. Details need to be negotiated and will involve requests from the US to incorporate some of the features of our concepts into their TBS. **This must occur soon, within 1 year, to be included in IO PDR.**
 - Note that a TBM hardware itself costs less than 1 million dollars. The ancillary equipment costs about 10 to 15 millions. The Lead Party will pay for this, but the US may have to contribute to a portion.
- The US should also negotiate a collaborative research agreement with EUROfusion
 - The EU is starting a huge new program on Blanket Design and R&D for DEMO under an EU Consortium “EUROfusion” (replaces EFDA). The project will spend 60 man-year for 4 years for blanket R&D (This is in addition to >\$20M for TBM under F4E)
 - The US contribution can be based on the “niche” area above
- There are other opportunities for international collaboration e.g. China, Japan

Temperature control and hysteretic morphology study for ceramic breeder pebble beds

Objectives: Assess causes of packing disruption, consequent morphology evolution, and temperature control for optimized tritium release and removal

Approach: Multi-scale numerical and phenomenological modeling coupled with experimental investigations on critical data needs and benchmark tests

Current state

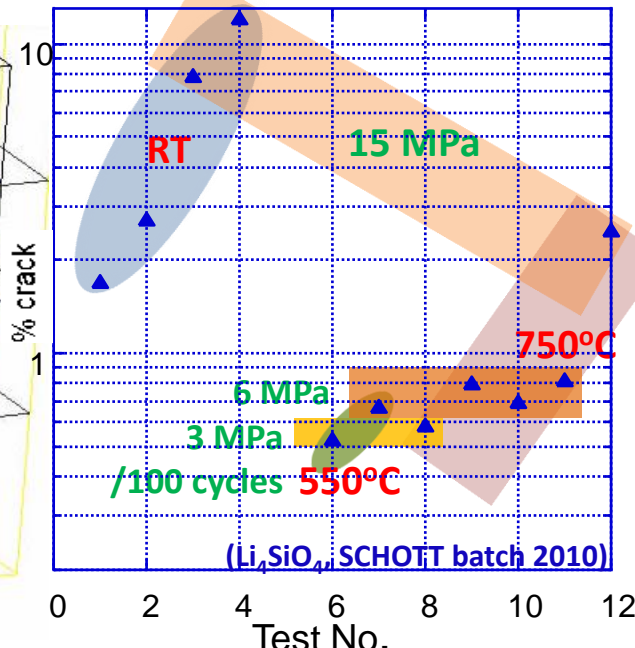
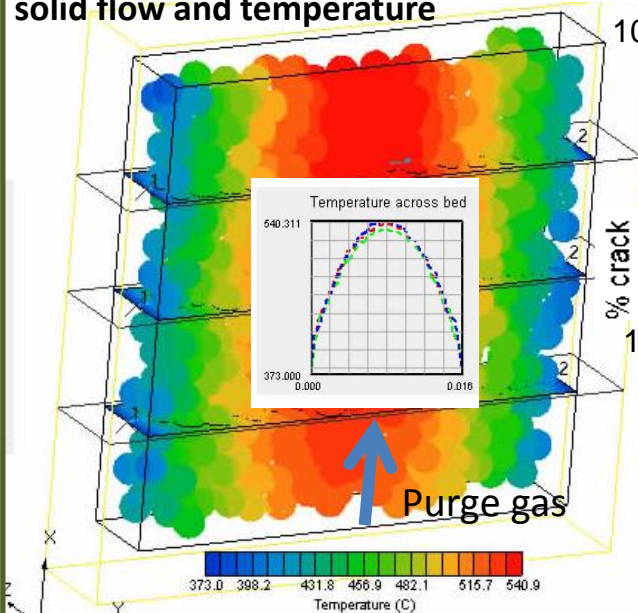
Transient DEM determines packing morphology evolution

10550 pebbles modeled

6.6% crack from both walls

Import DEM ensemble geometry for direct simulation of conjugate fluid/solid flow and temperature

Experimental investigation of at what loads will cracking occur and to what extent



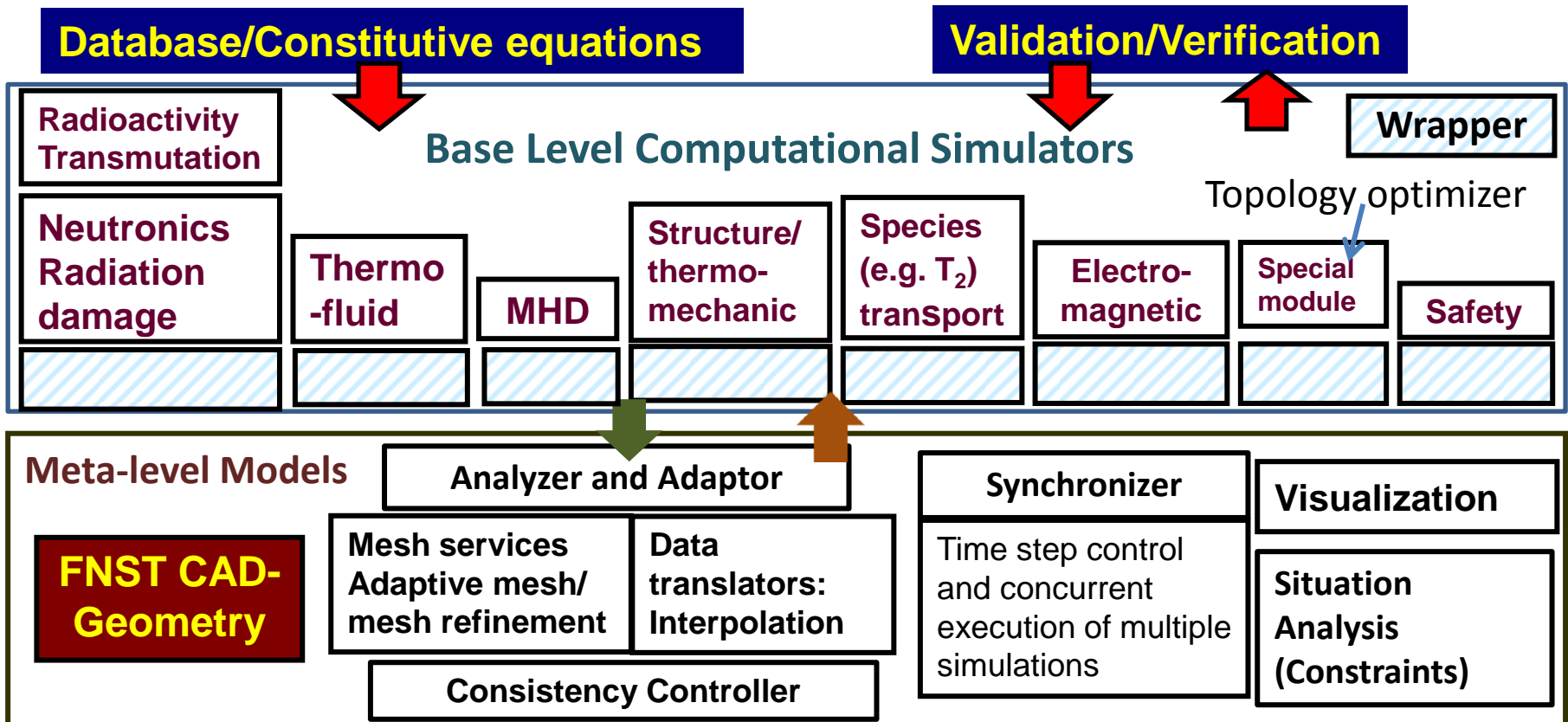
Moving Forward

- Necessity to have new out-of-pile, experimental facilities specifically designed to allow measurements of macroscopic manifestations of 'microscopic' phenomena and validate temperature control predictions
 - Pebble beds with **volumetric heating** can not be faithfully recreated by experiments with **contact heating**
 - Representative heating techniques on large-scale experiments are critical!
- Realistic phenomenological creep and sintering deformation models need to be developed and incorporated into transient DEM code

Extreme geometric complexity and inter-related scientific disciplines in fusion plasma chamber systems make the development of V-ISPC respected

- Virtual Integrated Simulation Predictive Capability (V-ISPC) addresses 3-D fusion nuclear science (FNS) physical phenomena in a virtual fusion plasma chamber system
- As a numerical experimental tool to visualize, comprehend, and discover FNS phenomena & for design exploration/optimization and performance evaluation

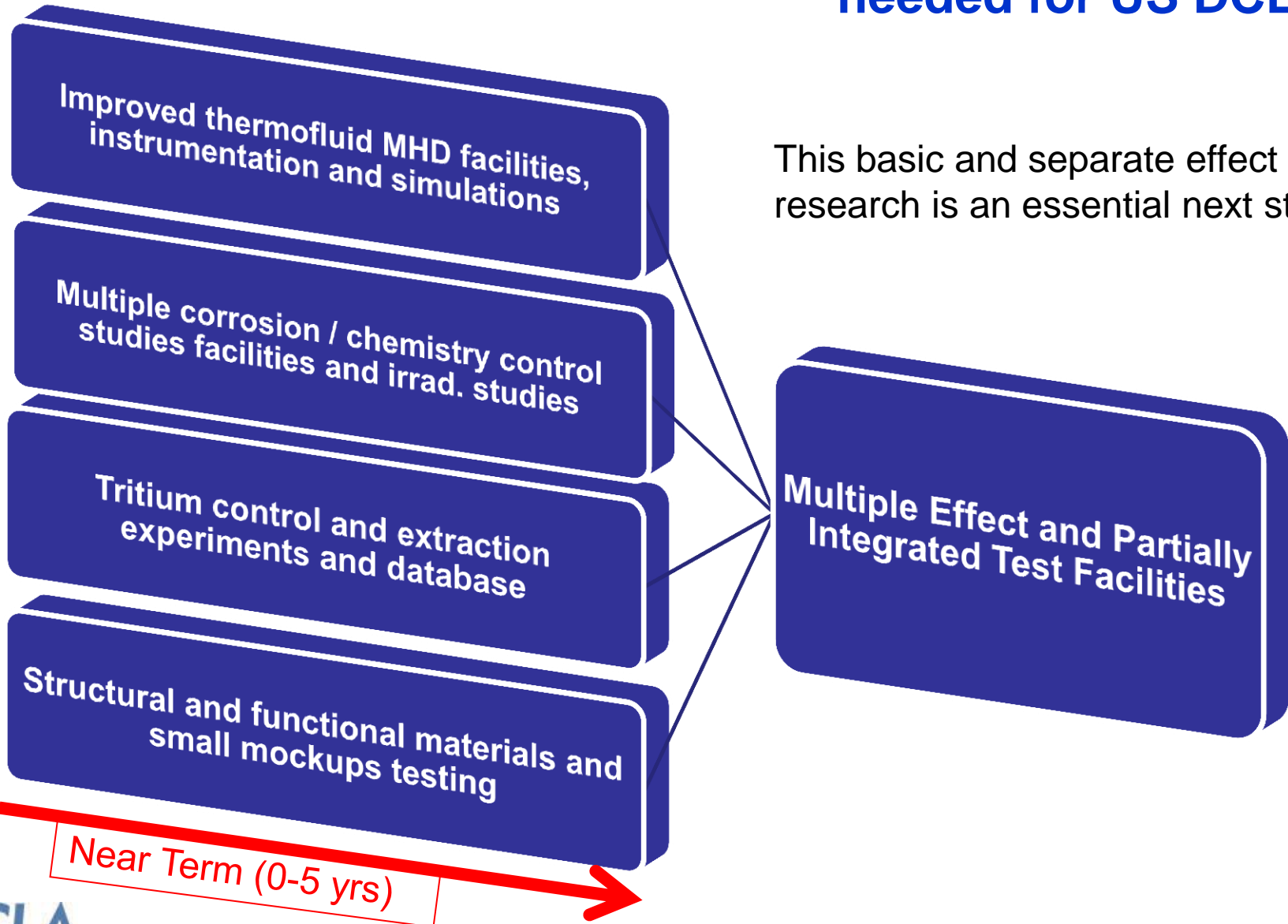
Data from Multiple-effect testing facility, TBM, FNSF



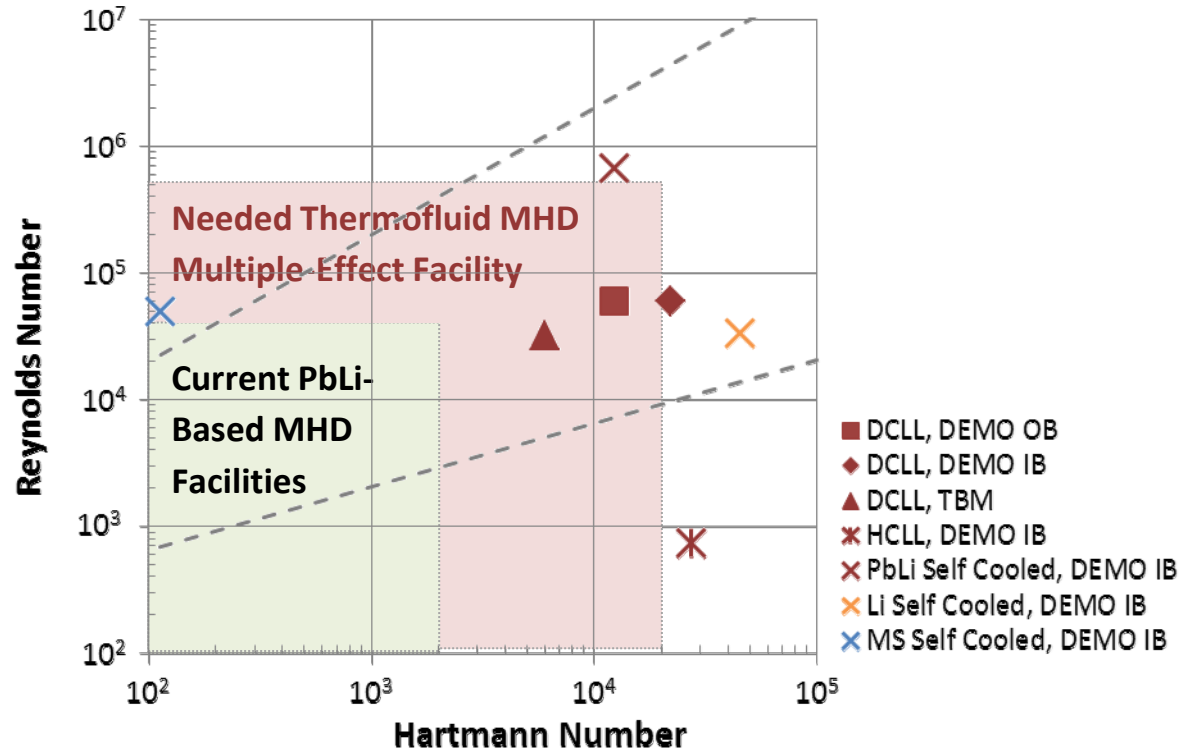
Goal: Validated Predictive Capability for Fusion Chamber In-vessel Components

Basic and Separate Effects Research Thrusts/Facilities needed for US DCLL

This basic and separate effect research is an essential next step



Simple Re-Ha Illustration of Where we are and where we need to go in Pb-Li MHD research



- Use Real Materials, Real Temperatures
- Simulate Surface and bulk heating and gradients
- Provide large volume and use multiple channels
- Have Higher B, Ha, and Gr

Enhancing Research in the US Niche Areas

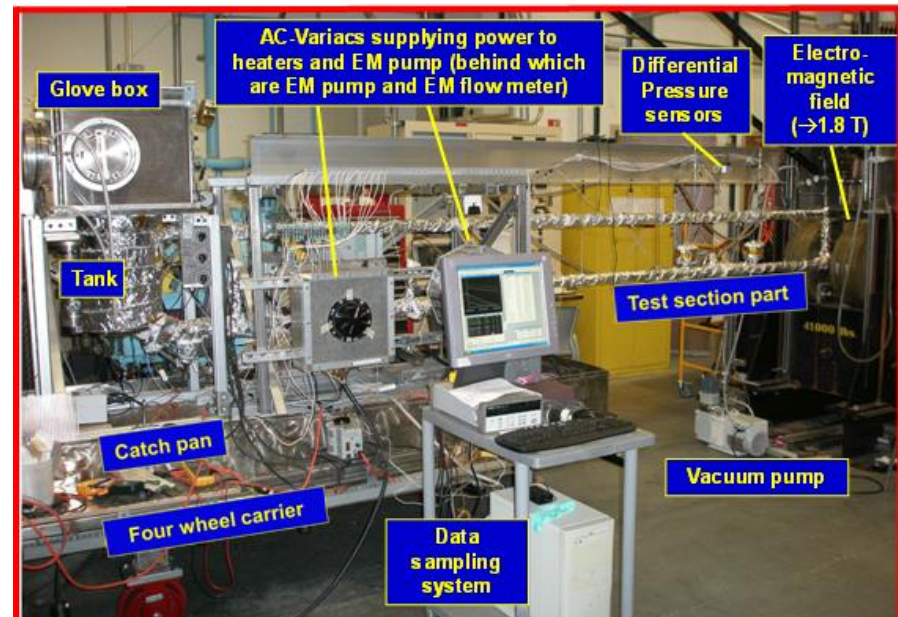
Example: MHD Thermofluids for Liquid Metal Blankets at UCLA

- **Codes/Modeling: \$1M/yr**

- HIMAG and several UCLA research codes are unique MHD Thermofluid computational tools with cumulative investment ~\$8M
- Need continued improvements to the level of real blanket design/analysis tools
- Achieve higher Ha/Re/Gr, code acceleration, multiple effects, V&V, etc.
- Dedicated development team of ~5 people

- **Facility/Experiments: \$1M/yr**

- A key capability in the MTOR lab is the MaPLE MHD PbLi Experiment: a 400C PbLi loop coupled to a 1.8T gap magnet
- Upgrade hot leg to more prototypic 550C
- Implement magnet tilting to allow simulation of different poloidal positions relative to
- Secondary He coolant loop to simulate dual coolant unit cells (shared with ceramic breeder thermomechanics test stand)
- Stronger, larger volume magnet system

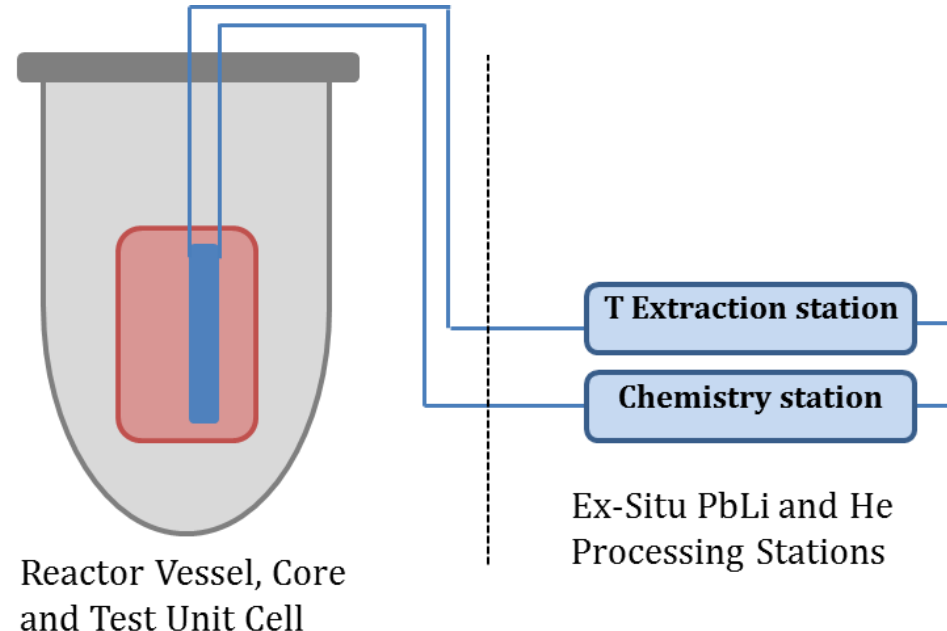


Only US PbLi loop (MaPLE loop) in the UCLA MTOR Laboratory

Breeding Unit Cell and Extraction Facility – simulate nuclear and thermal conditions

Simulate nuclear and thermal conditions in breeder unit cell and processing stream

- In-Pile breeder unit cell mockups
- PbLi/He coolant/breeder flow loops
- Ex-vessel tritium extraction and chemistry control



ATR Largest flux traps are 12.5 cm diameter

Key Blanket/FW Recommendations of Recent Studies

(RENEW, FNS-PA, FESAC-Materials)

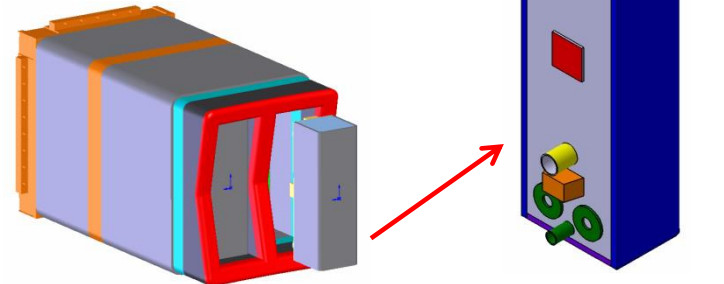
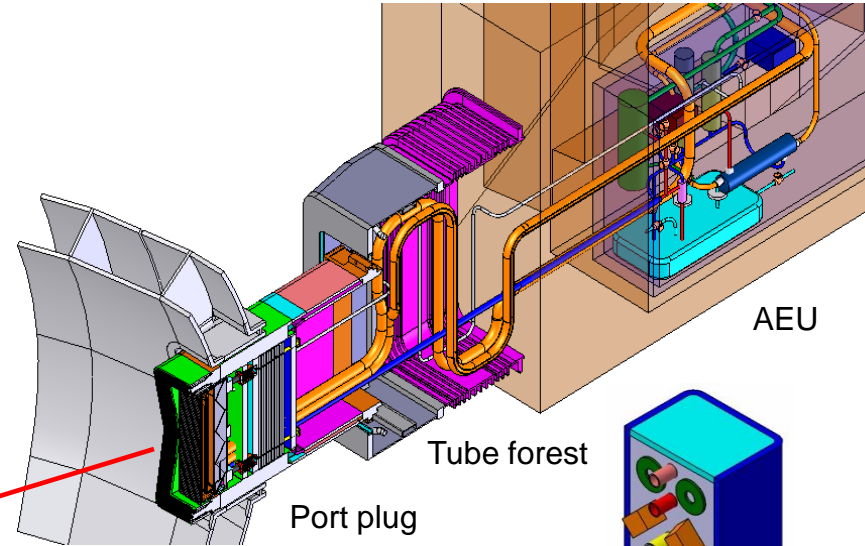
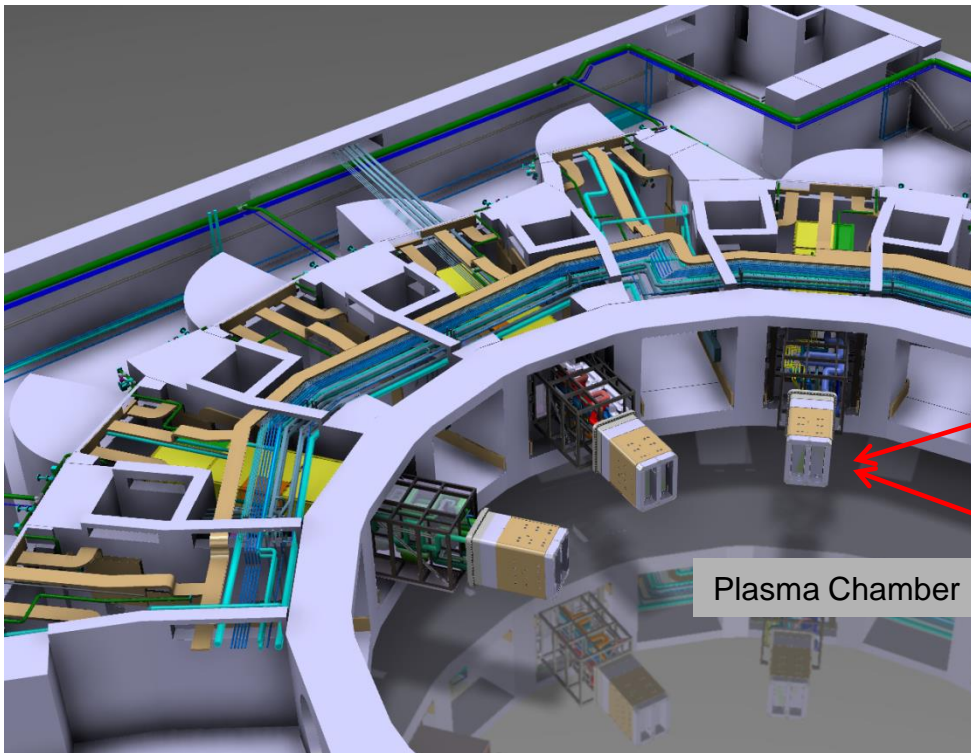
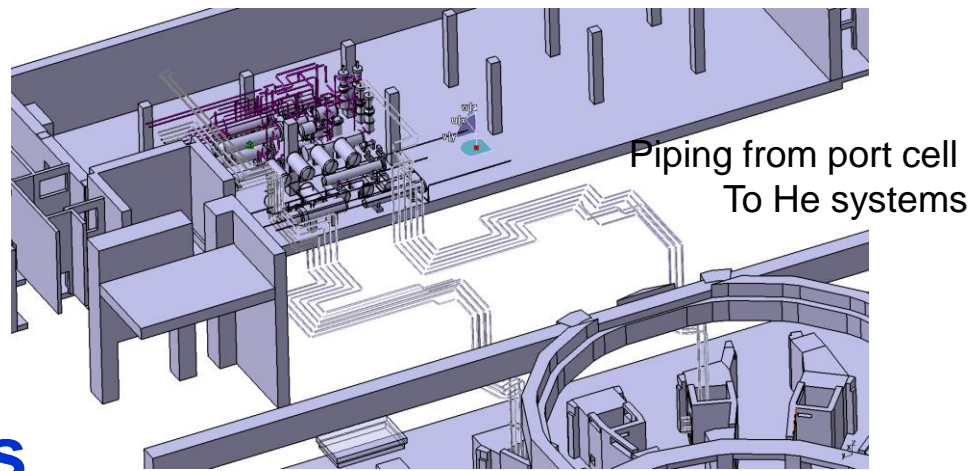
- Examine key feasibility issues for Pb-Li based blanket concepts as soon as possible
- Retain ceramic breeder blankets at a lower level as a backup option having different breeder feasibility issues
- Develop predictive capabilities that can simulate time-varying temperature, mass transport, and mechanical response of blanket components and systems
- Near-term research should be initiated on blanket and tritium extraction systems performance and reliability with prototypic geometry and loads
 - Explore possibility of unanticipated synergistic effects
 - Calibrate predictions of behavior/performance derived from separate effect experiments and modeling
 - Ameliorate early-life failure modes before fusion environment testing
 - Provide much more reliable understanding Blanket/FW experiments and components in fusion environment testing

What are the principal challenges in simulating the fusion nuclear environment?

- **Nuclear heating in a large volume with sharp gradients, not possible to reproduce in simulation facility. Use various techniques**
 - Embedded heaters in LM, on walls or in flow channel inserts.
 - Inlet temperature control (flow in hot, let cool)
- **Complex magnetic field with toroidal field / poloidal field fidelity or transient fields during disruptions**
 - Requires complex magnet systems, very important for LM systems
 - Or integration with long pulse confinement devices
- **Complex mockup configuration with prototypic size and scale**
 - Not possible in fission reactors

Can not bring together all conditions in one test or fully simulate nuclear heating

ITER-TBM can be used for Stage I Fusion Tests: prompt response and break-in to fusion environment experiments



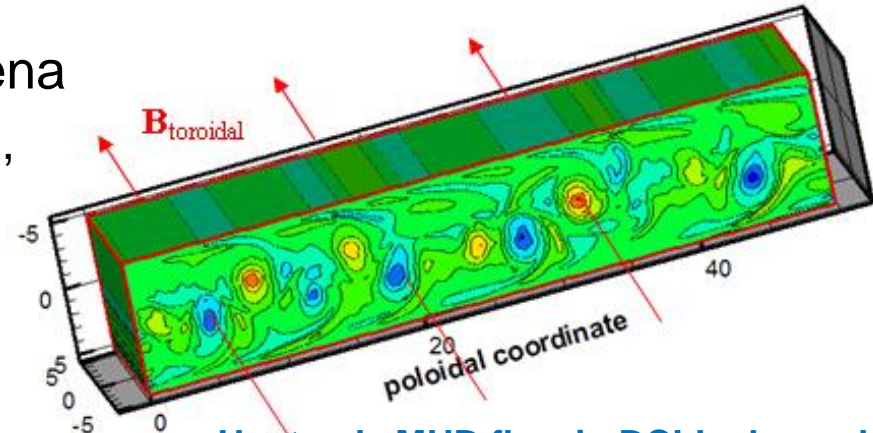
Three port plugs with 6 TBMs

Port plug with 2 TBMs

DCLL TBM

Coupled effect of nuclear heating, thermal expansion and irradiation damage (in DT phase)

- DT Phase will drive important phenomena
 - Temperature dependent fluid properties, Buoyancy and natural convection (Gr)
 - Thermomechanical load on FCIs
 - Tritium buildup and transport (cyclic equilibrium over many pulses)
- Loads gradually increasing over time
 - gradually more volumetric nuclear heating that may drive mixed convection, thermal expansion and thermal stress in FCI
 - Increasing number of thermal cycles
 - Increase in radiation damage (swelling) in FCI, saturates ~ 1 dpa in ceramic
- Measurements in TBM and AEU
 - channel flow rates and temperature inside FCI
 - Flow rates, temp, concentrations at AEU
 - PIE after multi-year operations



Unsteady MHD flow in DCLL channel (Smolentsev, UCLA)



Thermomechanical response of heated FCI in PbLi (Hypertherm)

ITER and FNSF Tradeoffs

- ITER-TBM will most likely represent the first opportunity to do integrated fusion environment
 - Conditions are sufficient for Stage I testing, Use extended HH/DD phases for partially integrated testing (e.g. DCLL MHD)
 - Significant infrastructure and strong collaboration,
- A moderate-fluence Fusion Nuclear Science Facility or similar facility will be still required
 - ITER conditions are not sufficient to establish engineering feasibility or explore middle-of-life irradiation damage effects
 - ITER-TBM is not a full sector nor steady state and won't be able to fully demonstrate tritium production, transport and recovery
 - Confidence level and reliability will not have been established to justify a DEMO decision
 - Timing of ITER is too long, $Q=10$ in 2027?

Environmental conditions for ITER-TBM

- The testing conditions of ITER include:
 - large test ports typical of blanket modules in power plants;
 - plasma discharges with typical neutron and surface heat loads and startup/termination/off-normal scenarios;
 - fusion neutron energy spectrum, volumetric heating, tritium production, and beginning of life radiation damage with spatial gradients;
 - strong and spatially complex magnetic field (~ 5 T);
 - strong confinement of radioactivity, allowing realistic tritium concentrations.
- Each TBM has an integrated plasma-facing first wall
 - but currently recessed 12 cm (is this negotiable after initial operations prove successful?)
- Each TBM is linked to tritium recovery and heat-extraction systems reproducing the fusion power/fuel cycle systems
 - Capabilities to control temperatures and other inlet conditions
 - Capabilities to deploy instrumentation

Performance Parameters and Characteristics

	ITER-TBM	DEMO	
Neutron Wall Loading (average)	0.78	2-3	MW/m ²
Surface Heat Flux*	0.1	0.5*	MW/m ²
Plasma Pulse Length	100-200 (HH/DD) 400 (DT typical I) 3000 (DT NI)	steady state	s
Magnetic Field	4	4 (OB), 11 (IB)	T
Plasma Current	15	20	MA
Blanket Fluence*	0.1	5	MW.y/m ²
Blanket Size	1.6 x 0.48	~2	m
Spectra	Fusion-like, moderated by SS and H2O	Fusion	

*Estimate per TBM or blanket module

Should we do both FNSF and ITER-TBM?

Answer: Yes

- Get results from two different machines that have different size, field, plasma conditions, attachments
- Take advantage of ITER-TBM international collaboration on blanket concepts, materials, fabrication, tritium, etc.
- Incremental cost of ITER TBM is not large given all R&D and test facilities are common between TBM/FNSF
- Multiple ITER pulses will be interesting from the perspective of accelerated cyclic aging
 - Augmenting the FNSF results that have fewer cycles but higher fluence