

An integrated program strategy of modelling and experiments in laboratory facilities and in a DT Fusion Nuclear Science Facility to develop Fusion Nuclear Technology and Materials for DEMO

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Outline

- World Energy Situation and Why Fusion is Needed
- Current World Fusion Program Goals
- Fusion Nuclear Science and Technology (FNST) : Introduction

- FNST/Blanket Major Issues/Challenges
- **Innovative Concepts** to Improve Fusion Attractiveness
 - High Power Density
 - High Temperature
 - Progress on DCLL, Liquid Walls, EVOLVE

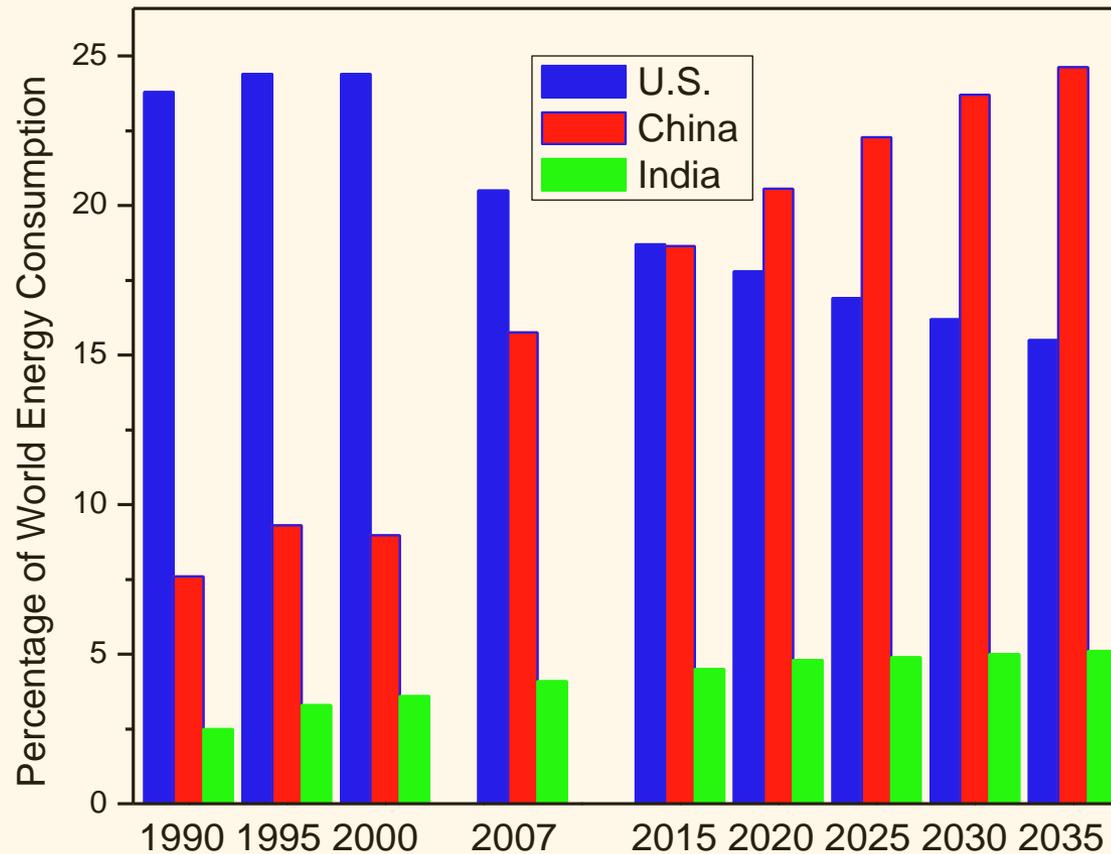
- Integrated Strategy for FNST R&D
- Modelling & Laboratory Facilities for Blanket R&D the next 10 yr
- FNST R&D in DT Fusion Testing Facilities, FNSF
- Concluding Remarks

World Energy Situation

- **The world uses a lot of energy**
 - Average power consumption = 17 TW (2.5 KW per person)
 - World energy market ~ \$3 trillion / yr (electricity ~ \$1 trillion / yr)
- **The world energy use is growing**
 - To lift people out of poverty, to improve standard of living, and to meet population growth
- **Climate change and debilitating pollution concerns are on the rise**
 - 80% of energy is generated by fossil fuels
 - CO₂ emission is increasing at an alarming rate
- **Oil supplies are dwindling**
 - Special problem for transportation sector (need alternative fuel)

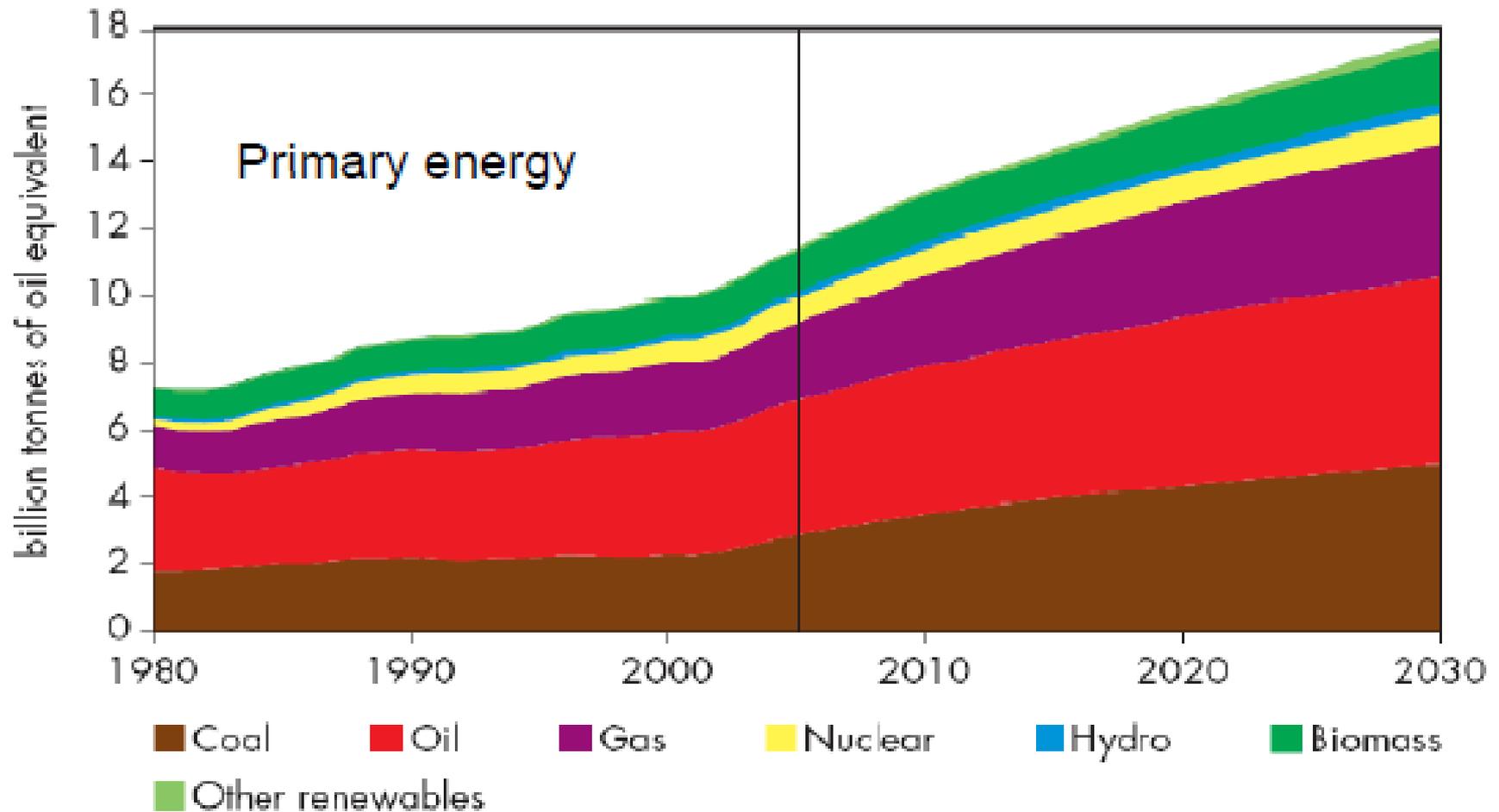
Total Projected Energy Use for Selected Countries

China energy use is rising faster than we anticipated.



Source: Energy Information Administration, International Energy Outlook 2010

Where we're headed under BAU: by 2030, energy +60%, electricity +75%, continued fossil dominance



WEO 2007

**What is problematic
about this future ?**

The problem is not “running out” of energy

Some mid-range estimates of world energy resources. Units are terawatt-years (TWy). Current world energy use is ~17 TWy/year.

OIL & GAS, CONVENTIONAL	1,000	
UNCONVENTIONAL OIL & GAS (excluding clathrates)	2,000	
COAL		5,000
METHANE CLATHRATES		20,000
OIL SHALE	30,000	
URANIUM in conventional reactors		2,000
...in breeder reactors		2,000,000
FUSION (if the technology succeeds)	250,000,000,000	
RENEWABLE ENERGY (available energy <u>per year</u>)		
Sunlight on land		30,000
Energy in the wind		2,000
Energy captured by photosynthesis		120

Real problems: the economic, environmental, and security risks of fossil-fuel dependence

- Coal burning for electricity & industry and oil burning in vehicles are main sources of severe urban and regional air pollution – SO_x , NO_x , hydrocarbons, soot – with big impacts on public health, acid precipitation.
- Emissions of CO_2 from all fossil-fuel burning are largest driver of global climate disruption, already associated with increasing harm to human well-being and rapidly becoming more severe.
- Increasing dependence on imported oil & natural gas means economic vulnerability, as well as international tensions and potential for conflict over access & terms.

Real problems: Alternatives to conventional fossil fuels all have liabilities & limitations

- Traditional biofuels (fuelwood, charcoal, crop wastes, dung) create huge indoor air-pollution hazard
- Industrial biofuels (ethanol, biodiesel) can take land from forests & food production, increase food prices
- Hydropower and wind are limited by availability of suitable locations, conflicts over siting
- Solar energy is costly and intermittent
- Nuclear fission has large requirements for capital & highly trained personnel, currently lacks agreed solutions for radioactive waste & links to nuclear weaponry
- Nuclear fusion doesn't work yet
- Coal-to-gas and coal-to-liquids to reduce oil & gas imports doubles CO₂ emissions per GJ of delivered fuel
- Increasing end-use efficiency needs consumer education

Solving the Energy Problem and Reducing Greenhouse Gas Emission Requires Pursuing a **Diversified Portfolio Approach**

- Improve energy **efficiency**
- Expand use of **existing** “clean” energy sources (e.g. **nuclear and renewable sources – solar, wind, etc.**)
- Develop technologies to **reduce impact of fossil fuels** use (e.g. carbon capture and sequestration)
- Develop major **new** (clean) energy sources (e.g. **fusion**)
- Develop **alternate (synthetic) fuels** and electrical energy storage for transportation

CREATING a Star on Earth

Fusion: The Ultimate Energy Source for Humanity

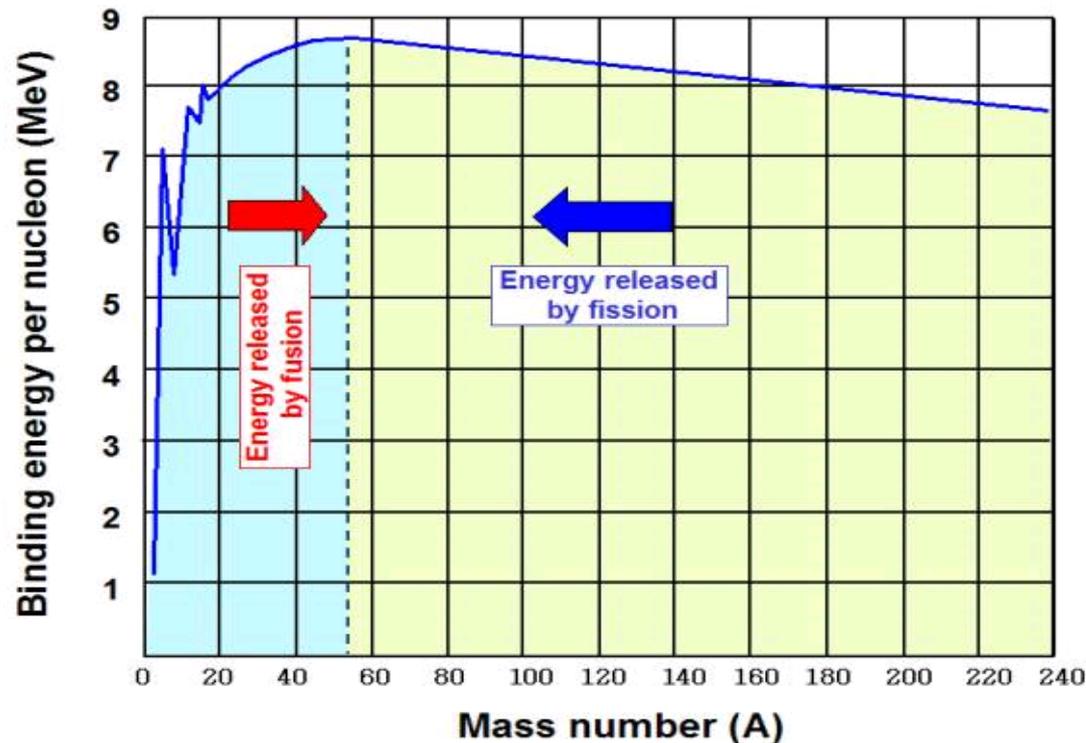
What is nuclear fusion?

- **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 combining 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

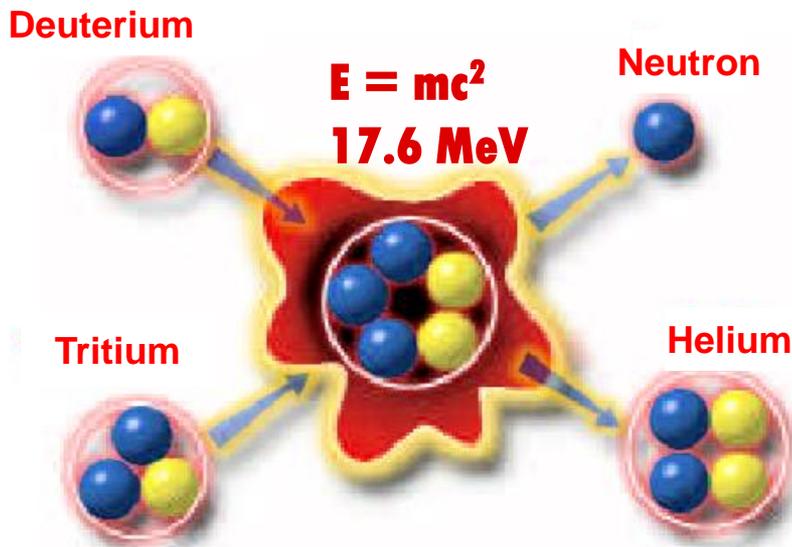
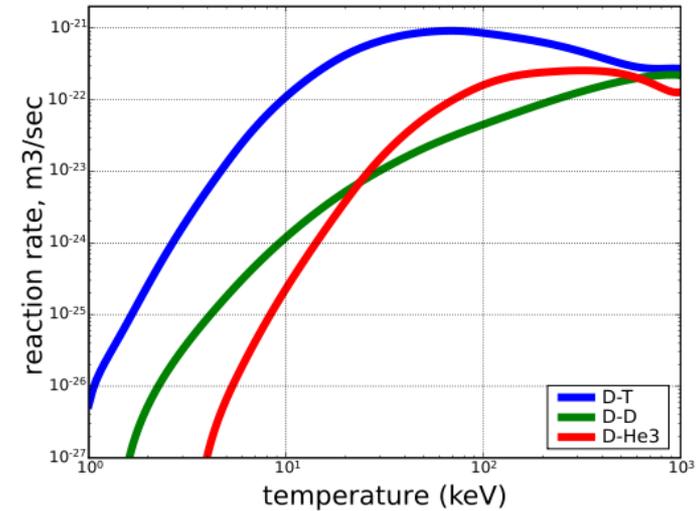
In contrast to fossil fuels (oil, gas, coal) where chemical energy is stored, and huge mass needed to “store” energy



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

$\text{Li} + \text{n} \rightarrow \text{T} + \text{He}$
Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)

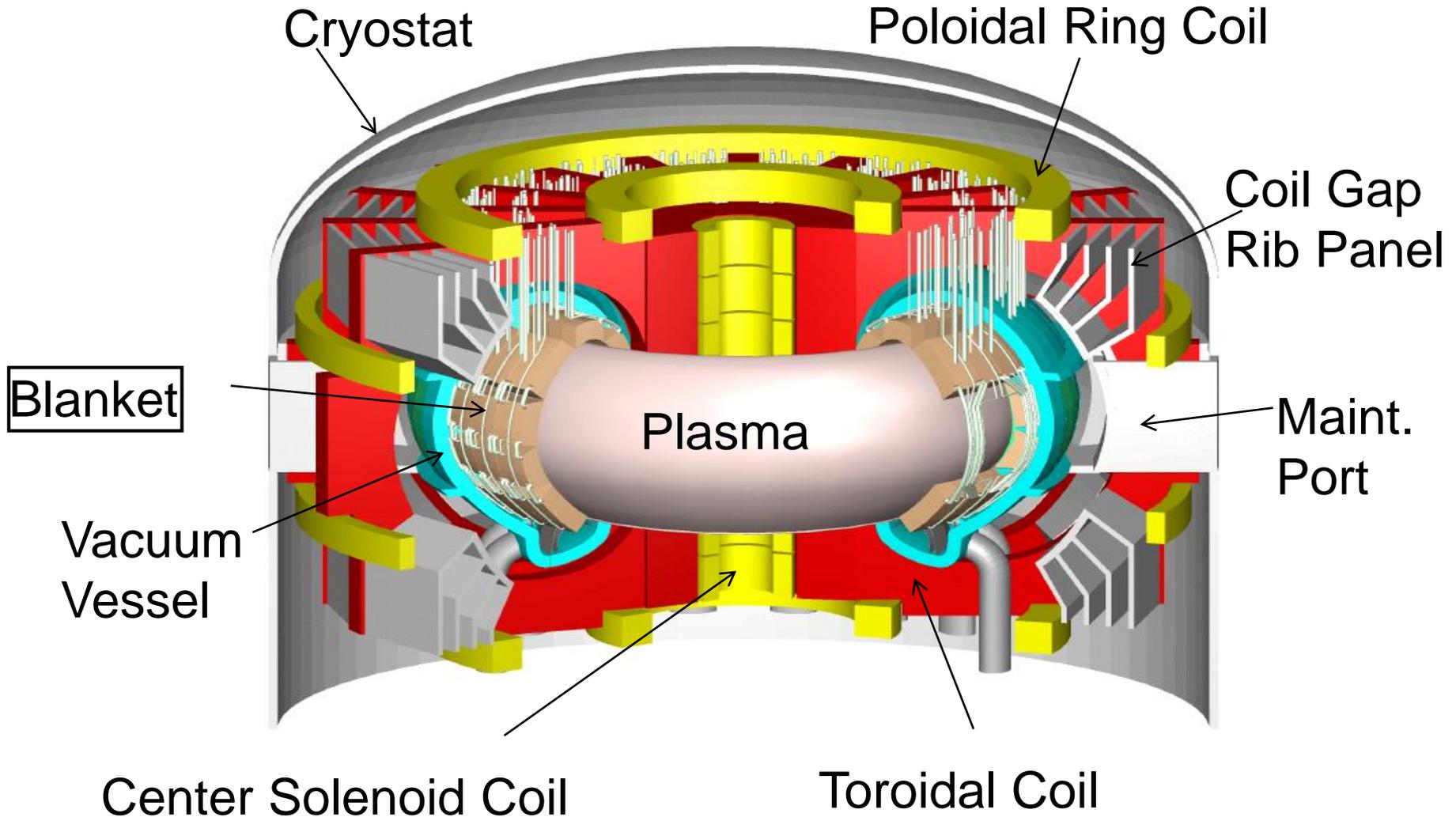
Incentives for Developing Fusion

- Sustainable energy source
(for DT cycle: provided that Breeding Blankets are successfully developed and tritium self-sufficiency conditions are satisfied)
- No emission of Greenhouse or other polluting gases
- No risk of a severe accident
- 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 ~2040(?)

Plans for DEMO are based on Tokamaks



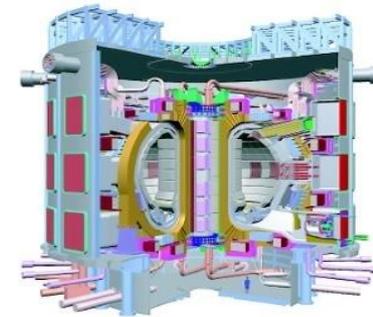
(Illustration is from JAEA DEMO Design)

Fusion Research is about to transition from Plasma Physics to Fusion Nuclear Science and Engineering

- 1950-2010
 - The Physics of Plasmas
- 2010-2035
 - The Physics of Fusion
 - Fusion Plasmas-heated and sustained
 - $Q = (E_f / E_{input}) \sim 10$
 - ITER (MFE) and NIF (inertial fusion)



National Ignition Facility



ITER

- ITER is a major step forward for fusion research. It will demonstrate:
 1. Reactor-grade plasma
 2. Plasma-support systems (S.C. magnets, fueling, heating)

**But the most challenging phase of fusion development still lies ahead:
The Development of Fusion Nuclear Science and Technology**

The cost of R&D and the time to DEMO and commercialization of fusion energy will be determined largely by FNST.

Fusion Nuclear Science and Technology

***Grand Challenges
with Exciting Opportunities
for Young Researchers***

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.

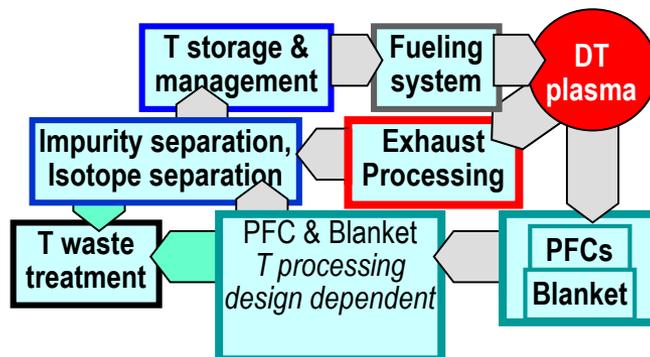
In-vessel Components (Core)

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

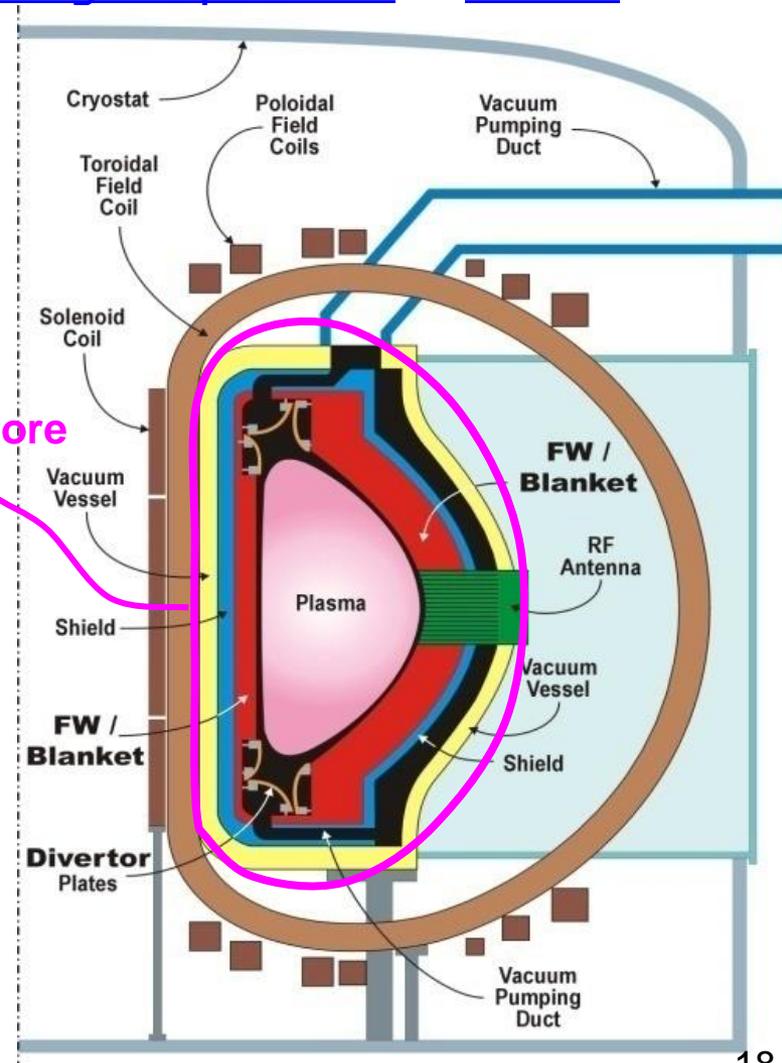
Key Supporting Systems

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

Tritium Fuel Cycle pervades entire fusion system

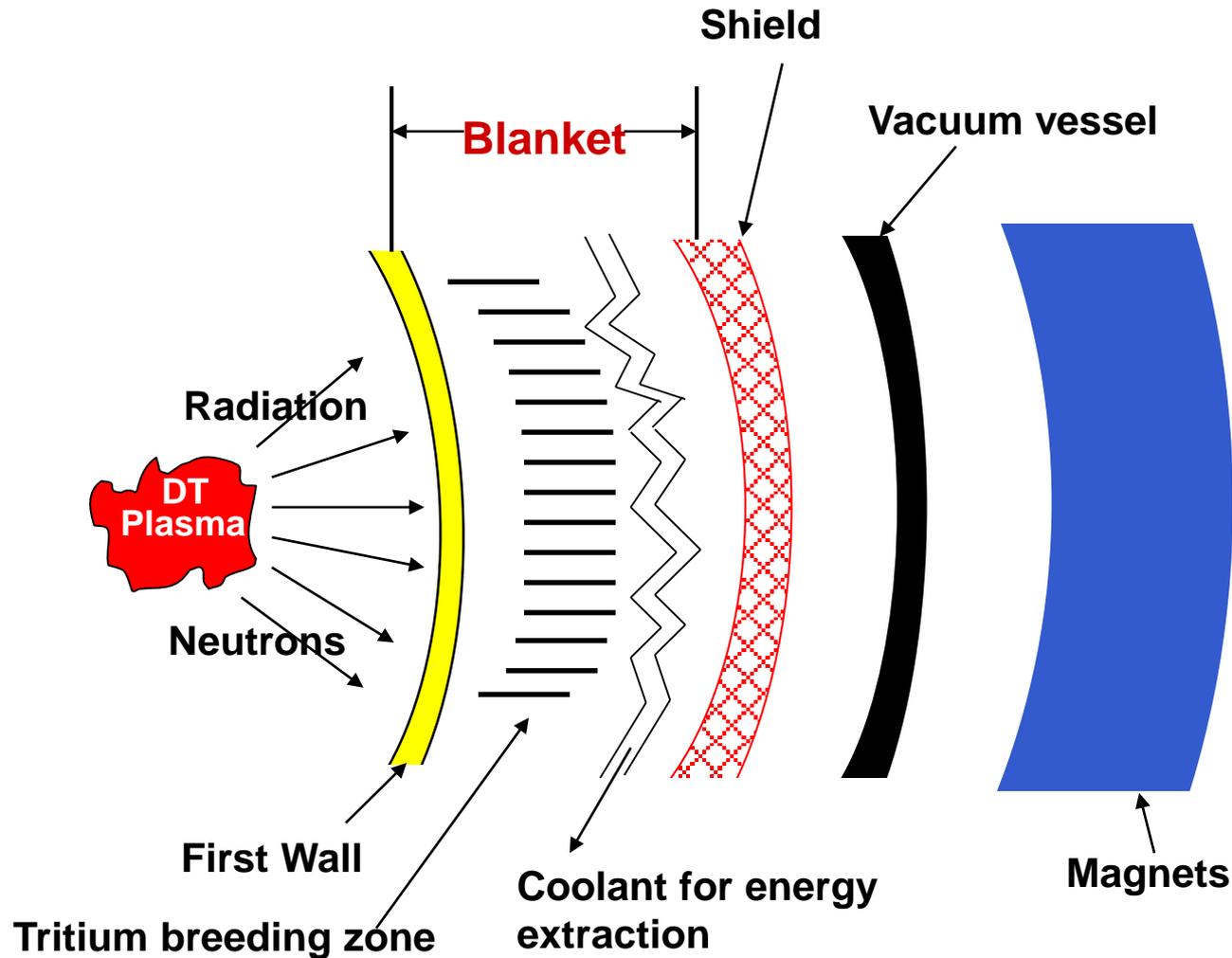


FNST Core



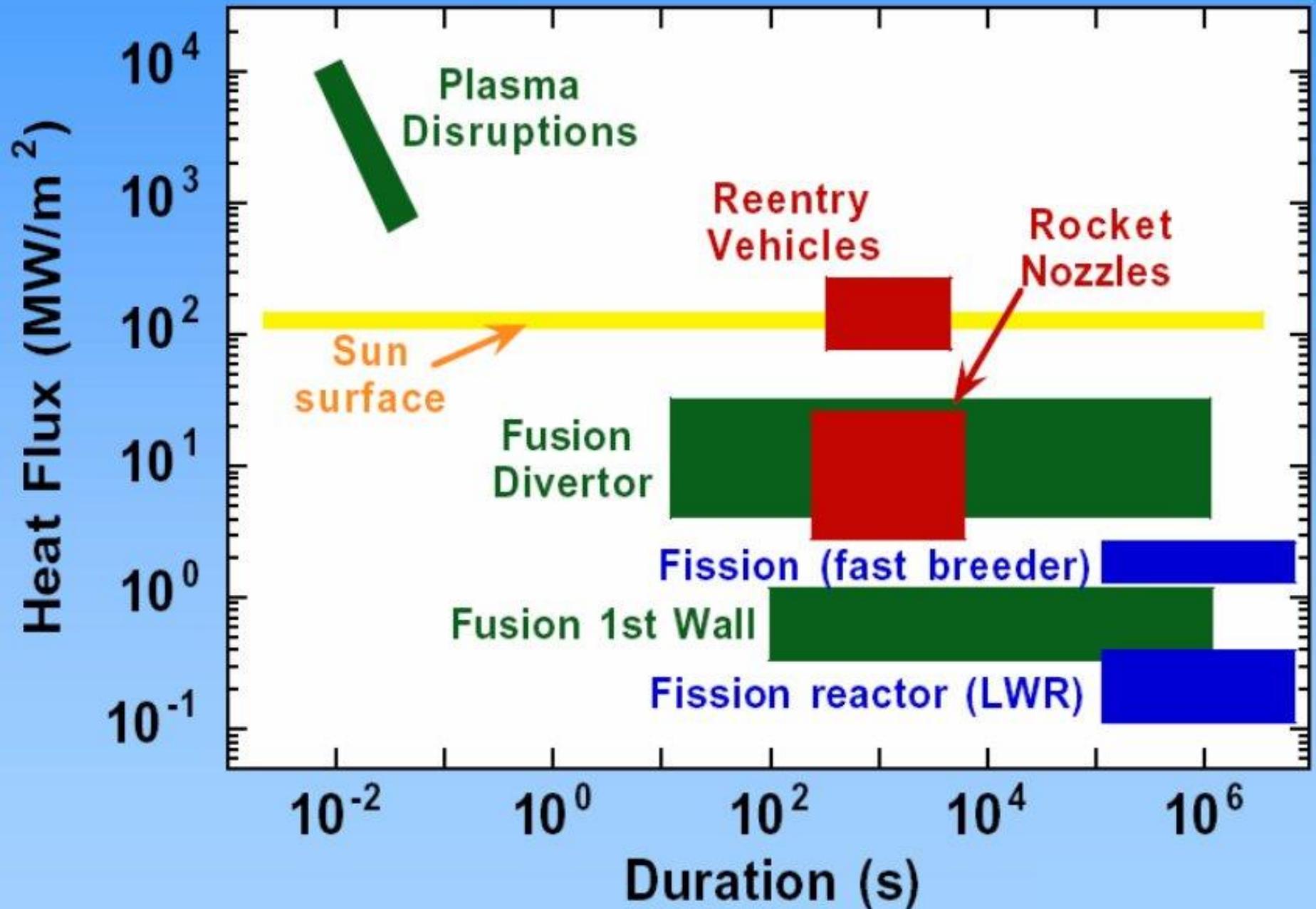
A Key FNST Component is the Blanket

The primary functions of the blanket 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.

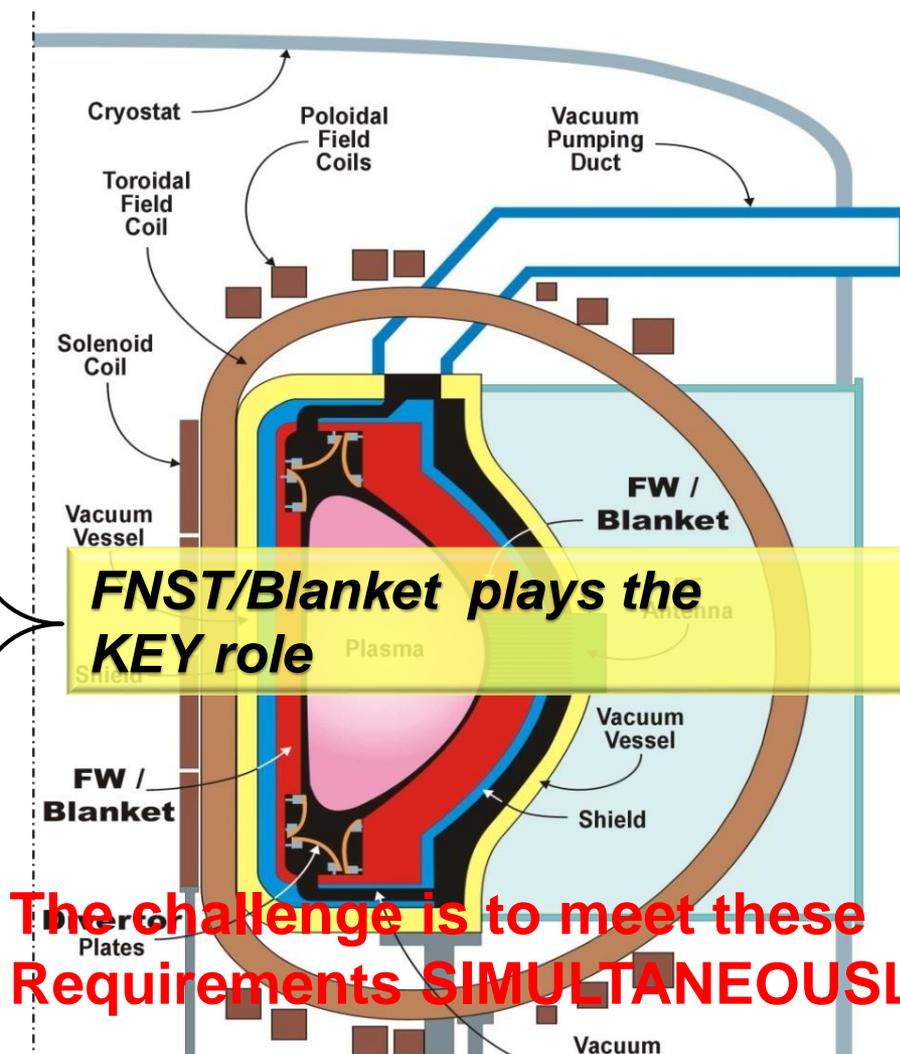
Comparison of Heat Fluxes



Fusion Goal: Demonstrate that fusion energy can be produced, extracted, and converted under practical and attractive conditions

Requirements

1. Confined and Controlled Burning Plasma (feasibility)
2. Tritium Fuel Self-Sufficiency (feasibility)
3. Efficient Heat Extraction and Conversion (feasibility)
4. Reliable System Operation (feasibility/attractiveness)
5. Safe and Environmentally Advantageous (feasibility/attractiveness)



**Yet, FNST has not received the priority and resources needed.
E.g. No fusion blanket has ever been built or tested.**

FNST embodies most of the remaining Feasibility and Attractiveness Issues in Fusion Energy Development.

FNST R&D is essential to confront Grand Challenges

Need High Power Density/Physics-Technology Partnership

- High-Performance Plasma
- Blanket/FW/divertor Technology Capabilities

Need Low Failure Rate

$$COE = \frac{C \cdot i + \text{replacement cost}}{P_{fusion} \cdot \text{Availability} \cdot M \cdot \eta_{th}} + O \ \& \ M$$

Energy Multiplication

Need High Temp. Energy Extraction

Need High Availability / Simpler Technological and Material Constraints

$$\frac{(1 / \text{failure rate})}{1 / \text{failure rate} + \text{replacement time}}$$

- **Need Low Failure Rate:**
 - Innovative Chamber Technology
- **Need Short Maintenance Time:**
 - Simple Configuration Confinement
 - Easier to Maintain Chamber Technology

Challenging Fusion Nuclear Science and Technology Issues

1. Tritium Supply & Tritium Self-Sufficiency
2. High Power Density
3. High Temperature
4. MHD for Liquid Breeders / Coolants
5. Tritium Control (Permeation)
6. Reliability / Availability/ Maint./ Inspect.(RAMI)
7. **R&D in non-fusion facilities:** How to simulate the complex FNST environment?
8. **R&D in Fusion Facilities:** How to build small DT plasma-based devices to test and develop FNST?

Need for High Power Density Capability

A. To improve potential attractiveness of fusion power compared to other energy sources (e.g., fission)

	PWR	BWR	LMFBR	ITER-Type
Average core power density (MW/m ³)	96	56	240	0.4

B. The larger challenge is to develop concepts that can simultaneously achieve high power density AND high temperature

- FW/Blanket/Divertor concepts developed in the 1970s and '80s have limitations on power density capability (wall load and surface heat flux)
- Some **PROGRESS** has been made in this area over the past decade, but we still need more “innovation”, more “ingenuity”

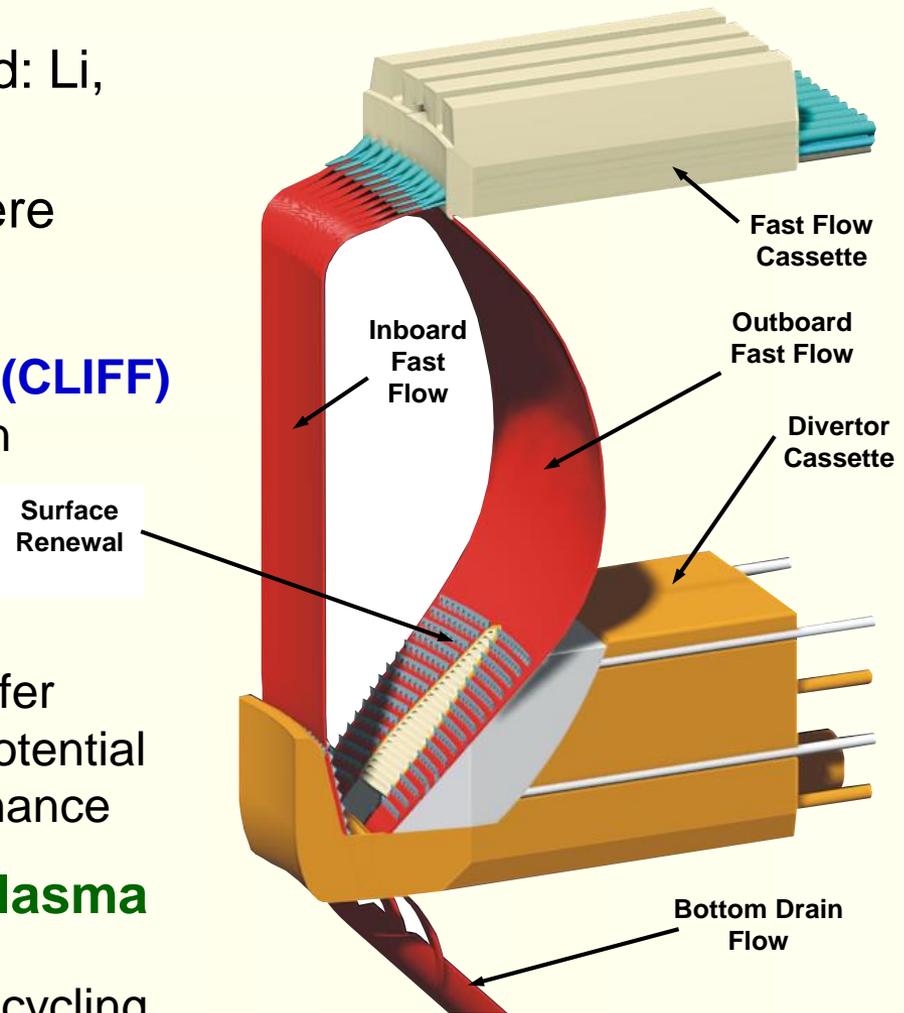
Concepts considered for High Power Density

Some progress has been made over the past several years in exploring first wall / blanket / divertor concepts with high power density capability:

- a) **Liquid walls**/liquid surfaces (mostly in the APEX and ALPS studies)
- b) Advanced **solid first wall** concepts (e.g., EVOLVE and DCLL)
- c) Advanced **solid divertor** concepts (especially in EU)

Many liquid wall reactor concepts for high power density were conceived & analyzed in APEX

- ❑ Many candidate liquids were studied: Li, Sn-Li, Sn, Flibe and Flinabe
- ❑ Several liquid wall flow schemes were conceived:
 - Thick liquid walls
 - **Thin fast flowing protection layer (CLIFF)**
 - Inertial or EM assisted wall adhesion
 - Integrated or stand-alone divertors
- ❑ Concept performance was analyzed from many perspectives
 - Liquid wall flow MHD and heat transfer
 - Breeding, shielding and activation potential
 - Simplicity of system design, maintenance
- ❑ **Interactions of liquid walls with plasma operation were emphasized**
 - Plasma edge effects, impurities & recycling
 - Liquid metal motion coupling to plasma modes



Thin liquid wall concept (blanket region behind LW not shown)

Some Key Points From Liquid Wall Studies

- ❑ **Thin fast flowing layers** protecting more conventional closed channel blankets appear to be the most feasible and attractive concept
 - ❖ high power density capability
 - ❖ disruption survivability
 - ❖ improved plasma performance

(Thick liquid walls for tokamaks appear very difficult to implement for a number of reasons, especially MHD and flow control)

- ❑ Based on comprehensive plasma edge modeling studying impurity vapor intrusion into core plasma, Liquid **Sn and Sn-Li have the highest surface temperature** capability ($> 630^{\circ}\text{C}$)
 - ❖ Flinabe salt with low melting point ($\sim 300^{\circ}\text{C}$) is a promising alternative to LMs
- ❑ Liquid walls have strong possibilities to **improve plasma performance**
 - ❖ Close fitting conducting shell effects
 - ❖ Hydrogen gettering leading to low recycling
 - ❖ Impurity gettering
 - ❖ Helium trapping and pumping in nano-bubbles

(but “Rotating shell” effects on Resistive Wall Modes due to fast LM motion do not appear to aid stabilization)

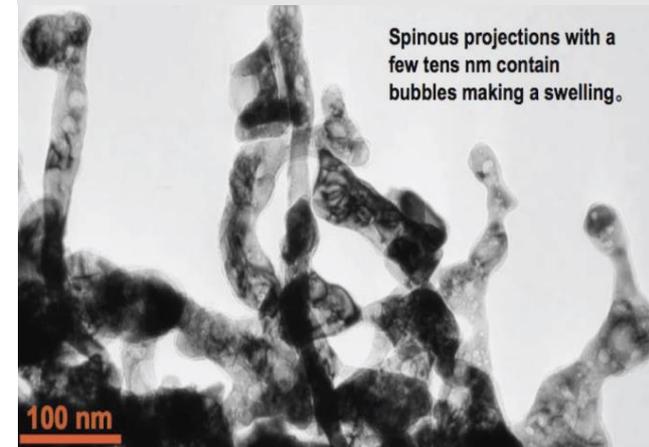
Why Consider Liquid Walls for Divertors?

- ◆ Tungsten (W) is currently considered the only reactor relevant PFC material, but it has issues
 - embrittlement below 700C,
 - surface damage in DT+He plasmas (see right)**Can W be the only option we pursue? Risky!**

- ◆ **Liquid walls** have a completely different set of advantages and issues
 - Continuously renewed surface: **immune** to erosion, particle and neutron damage
 - Can potentially do two functions: **pump particles & remove heat**
 - Much thinner mechanical construction of the plasma-coolant interface possible
 - Disruptive forces on LW not structural issue
 - **PMI issues include effect of sputtering + evaporation on plasma and LW Op. Temp.**
 - **Liquid surface can move and interact electromagnetically with plasma/field**

Tungsten surface after long-term plasma exposure

- Structures a few tens of nm wide
- Structures contain nano bubbles



100 nm (VPS W on C) (TEM)

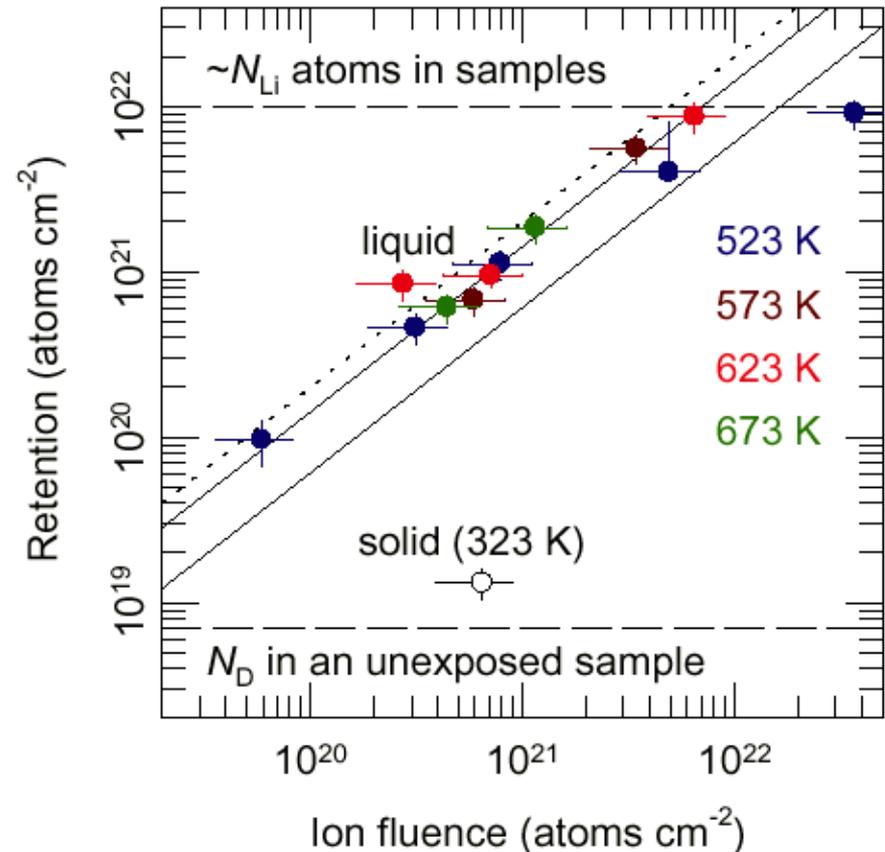
NAGDIS-II: pure He plasma
N. Ohno et al., in IAEA-TM, Vienna, 2006,
TEM - Kyushu Univ., $T_s = 1250$ K, $t = 36,000$ s, 3.5×10^{27} He⁺/m², $E_{ion} = 11$ eV

Properties of candidate liquid metals

- ◆ Gallium – low melting point & vapor pressure
 - $Z=31$, atomic weight =69.7
 - MP= 29.8 °C, BP = 2204 °C
 - $\rho = 6.1\text{g/cm}^3$, $c_p = 0.37\text{ J/g }^\circ\text{C}$
 - $k: 40.6\text{ W/m}^\circ\text{C}$, $\eta = 140\text{ n}\Omega\text{ m}$
 - Vapor pressure = 10^{-7} Torr at 900 °C
- ◆ Tin – lowest overall vapor pressure and good thermal conductivity
 - $Z=50$, atomic weight=118.7
 - MP = 232 °C, BP = 2602 °C
 - $\rho = 7.0\text{ g/cm}^3$, $c_p = 0.23\text{ J/g }^\circ\text{C}$
 - $k: 66.8\text{ W/m}^\circ\text{C}$, $\eta = 115\text{ n}\Omega\text{ m}$
 - Vapor pressure = 10^{-7} Torr at 1000 °C
- ◆ Lithium – low Z and hydrogen retention, interesting for pumping the edge (see right)
 - $Z=3$, atomic weight =6.9
 - MP = 180.5 °C, BP = 1342 °C
 - $\rho = 0.5\text{ g/cm}^3$, $c_p = 3.58\text{ J/g }^\circ\text{C}$
 - $k: 84.8\text{ W/m}^\circ\text{C}$, $\eta = 93\text{ n}\Omega\text{ m}$
 - Vapor pressure = 10^{-7} Torr at 400 °C

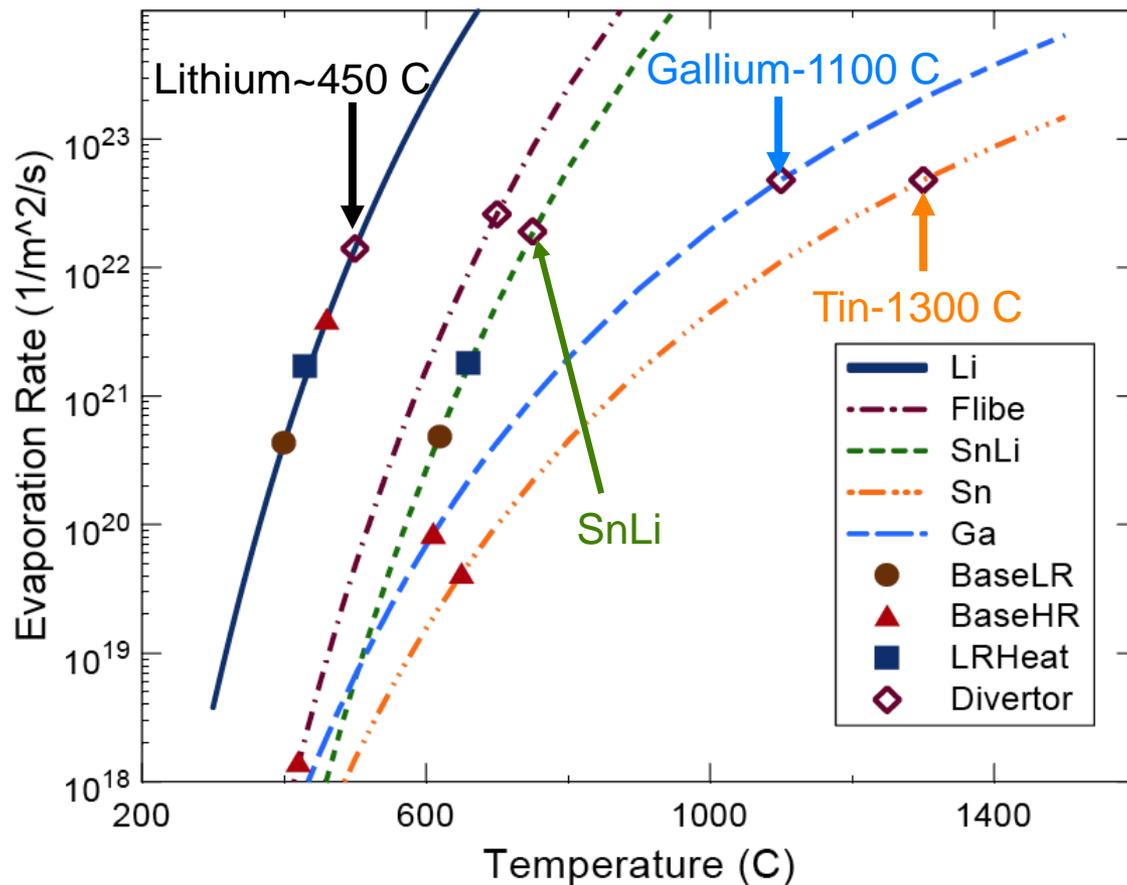
Li can hold nearly a 1:1 ratio of D:Li

M. J. Baldwin et al., Nucl Fusion **42** (2002) 1318



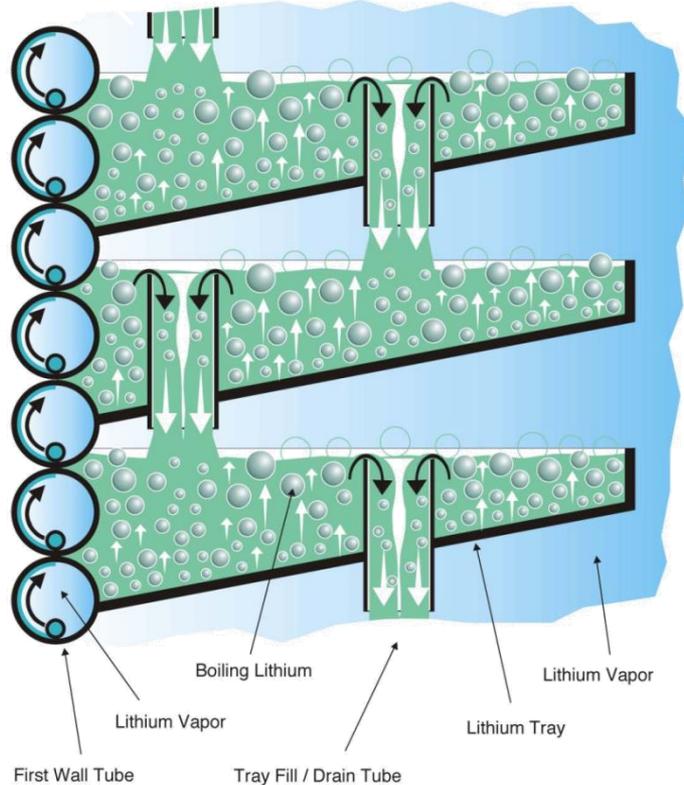
Strong effects on plasma operation such as improved confinement and ELM suppression

Temperature limits for liquid metal PFCs set by the evaporation rate (allowable influx to the plasma)



- ◆ Tin and Gallium surface temperature limits in the divertor are ~1300C and 1100C
- ◆ Lithium has a low temperature limit (450C) in comparison to gallium and tin
 - ⇒ Lithium would not be a candidate for a LM PFC *except* for its recycling properties and high k and c_p
 - ⇒ reduced recycling alternative is **SnLi eutectic ; tin(~80%)-lithium(~20%)**

Innovative Solid First Wall Concepts



EVOLVE (APEX)

- Novel concept based on use of high temperature refractory alloy (e.g. tungsten) with innovative heat transfer/transport scheme for vaporization of lithium
- Low pressure, low stresses
- Low velocity, MHD insulator not required
- High power density / temperature / efficiency
- Key issues relate to tungsten

- Attempts to extend the capabilities and attractiveness of solid walls have required very advanced structural materials
- EVOLVE requires **W alloy** for high power density, high temperature
But the Material Community wasn't enthusiastic 10 yrs ago (risky, costly, very long-term)
- But since W is being seriously considered now for the Divertor, we should reconsider EVOLVE

Lessons learned:

The most challenging problems in FNST are at the ***INTERFACES***

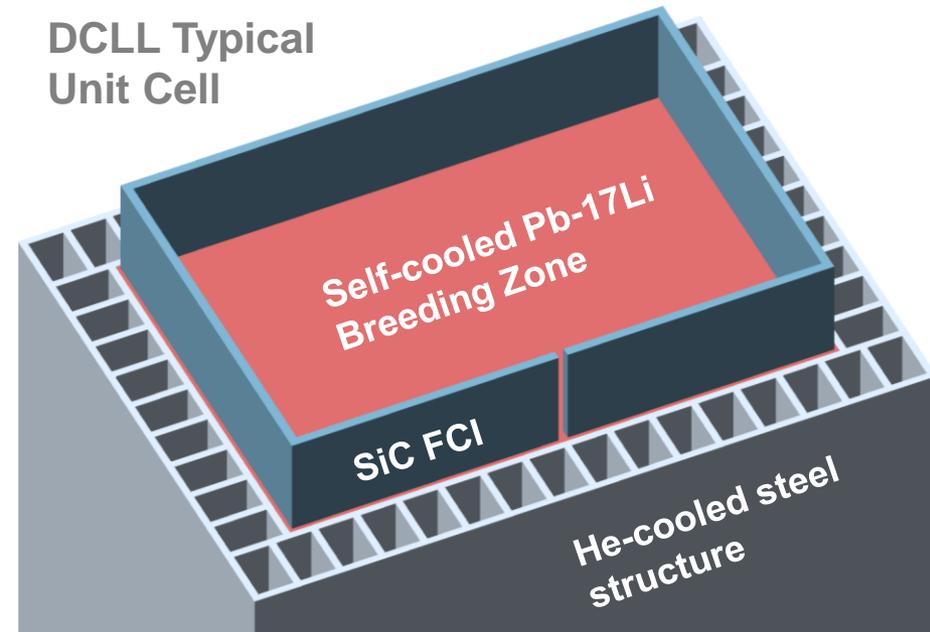
- Examples:
 - MHD insulators
 - Thermal insulators
 - **Corrosion** (liquid/structure interface temperature limit)
 - Tritium permeation
- Research on these interfaces **must be done jointly by blanket and materials researchers**

Pathway Toward Higher Temperature Through Innovative Designs with Current Structural Material (RAFM Steel):

Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept

How can high outlet temperature be reached?

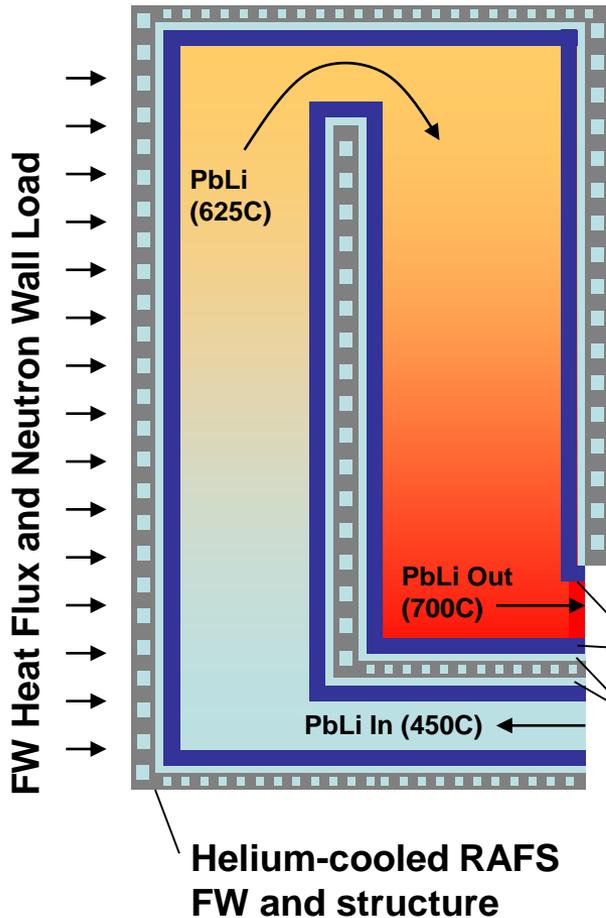
- **Cool all RAFM steel structures with He** ($T_{in}/T_{out} \sim 350/450\text{C}$, carries 40-50% of the total energy)
- **Have a PbLi breeding zone that is flowing and self-cooled** ($T_{in}/T_{out} \sim 450/700\text{C}$, carries other 50-60% of the total energy)
- **Isolate the hot PbLi from the cooler structure by use of a non-structural liner called a Flow Channel Insert (FCI) that:**
 - ❖ **Prevents leakage of volumetric nuclear heat** deposited in the PbLi from entering the (lower efficiency) He coolant stream
 - ❖ **Provides nominal electrical insulation** to keep MHD pressure drop manageable
 - ❖ **Is compatible with PbLi** at elevated temperatures $\sim 800\text{C}$.



MAJOR IMPROVEMENTS OF THE DCLL BLANKET CONCEPT (In the US during the last 10 years)

- A. Design Evolution
 - B. Tritium Extraction from the PbLi
 - C. Improvement of the SiC flow channel Inserts (concept, design, and materials)
 - D. Detailed modeling analysis of the MHD impact on the liquid metal flow in the DCLL blanket
 - Fluid flow mixed convection
 - Tritium permeation
 - Corrosion of FS in PbLi
-
- **China is working on similar concept:** Need more close collaboration on modeling, experiments, design, and analyses
 - **Eurofusion and UCLA** are initiating strong collaboration program on DCLL

Simplified DCLL Blanket Module Flow Scheme



- All structural walls are RAFS actively cooled by He
- Cold PbLi flows up the FW (where volumetric heating is strongest), turns, and flows back down the back of the blanket module
- SiC FCIs separates and insulates the flowing PbLi from the RAFS walls
- FCIs are loosely slip-fit together, and GAPS between FCIs and structure is filled in by nearly stagnant PbLi

SiC FCIs
Gap between FCI and Structure
(Filled with nearly stagnant PbLi)

- The interface temperature between the RAFS structure and gap PbLi is controlled by the He cooling, and kept $< 500\text{C}$.

Design of the SiC flow channel Inserts (FCI)

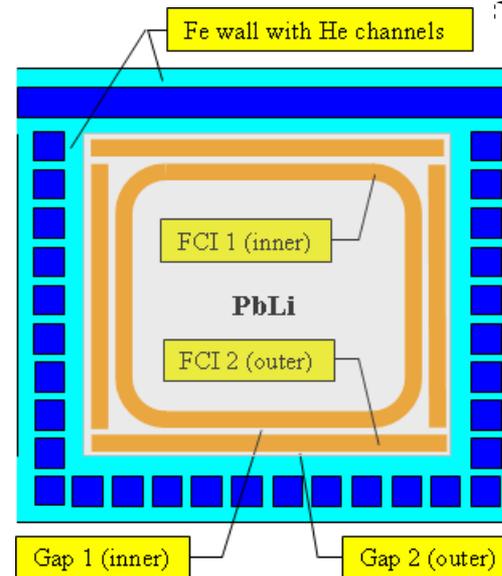
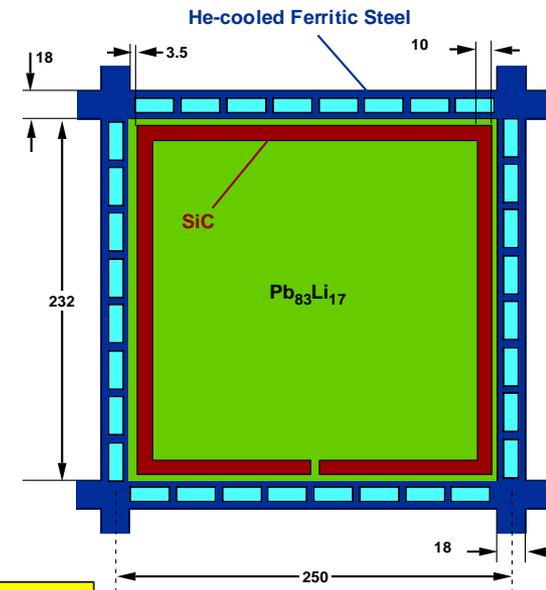
Initial FCI design:

- The flow channel inserts made of a SiC-composite serve as electrical and thermal insulator.
- The **large temperature difference** between the flowing LM on one side of the insert-wall ($\sim 700^\circ\text{C}$) and the steel wall at the other side ($< 470^\circ\text{C}$) can result in **large thermal stresses**, leading to **cracks** with a negative impact on electrical insulation.

Proposed improvement/solution:

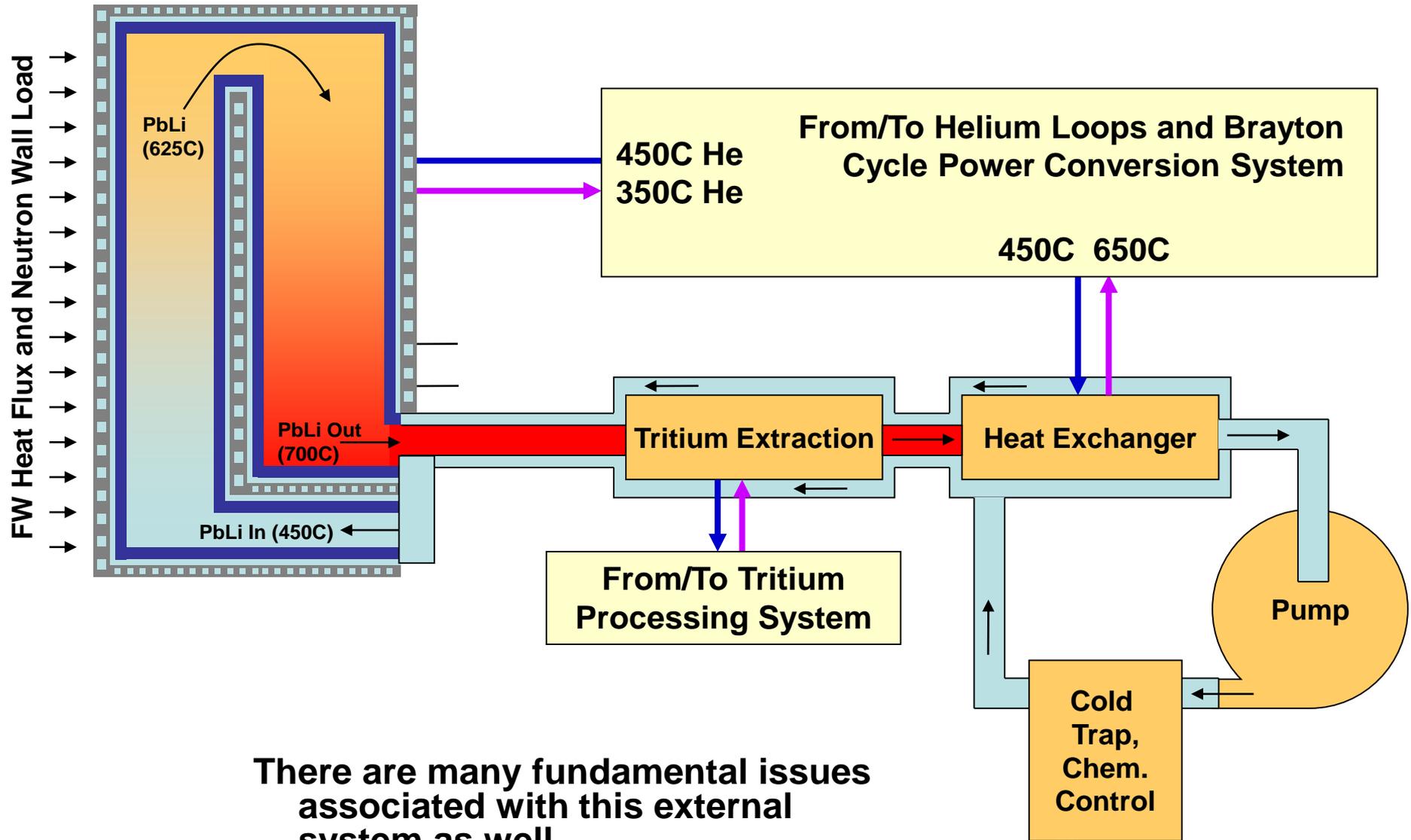
- Split the function of the insert into two elements:
 - Outer FCI provides thermal insulation
 - Inner FCI provides reliable electrical insulation

“Single FCI”



“Nested FCI”

A Simplified DCLL System



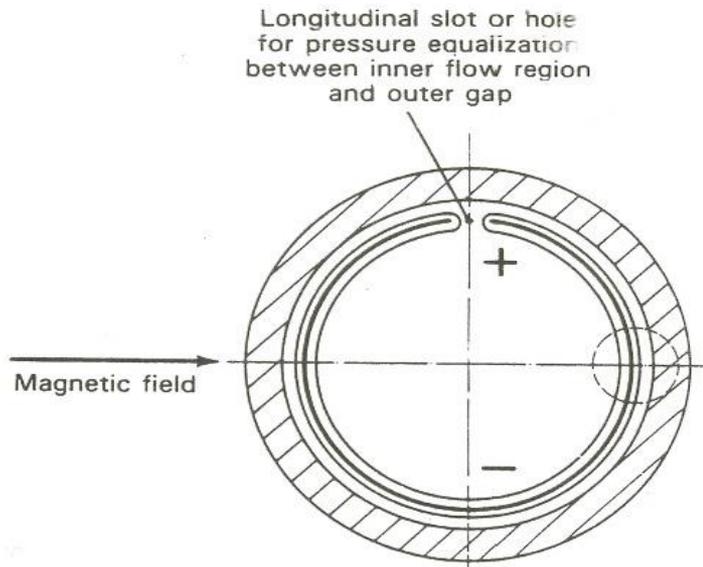
There are many fundamental issues associated with this external system as well.

Low Temperatures DCLL blanket Near-Term Option being evaluated by US and EU

Characteristics:

- Intended for the use in an early FNSF and DEMO for the case SiC FCI's can't be qualified in time (high fluence irradiation tests in fusion typical neutron field required),
- FW and entire blanket structure cooled with Helium
- **Sandwich FCI's** in all poloidal ducts are used for electrical and thermal insulation,
- PbLi inlet/outlet temperatures ~ 350 C/470 C
- He inlet/outlet temperatures ~ 350 C/500 C
- Achievable efficiency in the power conversion system ~ 36 %

Principle of Sandwich Flow Channel Insert

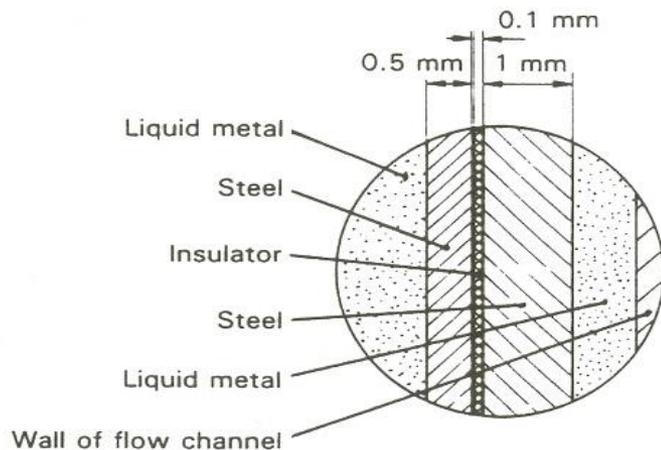


Goal:

De-couple electrically the flowing liquid metal from the load-carrying steel walls for Low-temperature PbLi Concept (PbLi temperature $<470\text{C}$)

Technical Approach:

Flow channel inserts made of a sandwich steel-alumina-steel



Tritium Transport, Permeation, and Recovery

- Tritium transport is affected by the tritium concentration profile and temperature
 - Tritium generated inside the breeder moves via diffusion due to concentration gradient, convection due to the bulk motion of the fluid, soret effect due to temperature gradient, etc .
- Tritium solubility in PbLi is low and still not that well characterized. Tritium tends to permeate into He coolant
 - How much tritium is permeated into helium coolant, and how can it be controlled?
- Tritium removal from PbLi, what are the methods, the extractor materials and tritium transport behavior
 - Tritium extraction with high efficiency can help control unwanted permeation
 - But tritium extraction must be compatible with high temperature PbLi in direct contact, as well as impurities
- It is critical to be able to predict tritium transport, tritium inventory, and tritium permeation in lead-lithium liquid metal (LM) blankets with great accuracy to provide information for fusion reactor safety. Therefore, developing sophisticated and comprehensive phenomenological and computational models and performing experiments are necessary

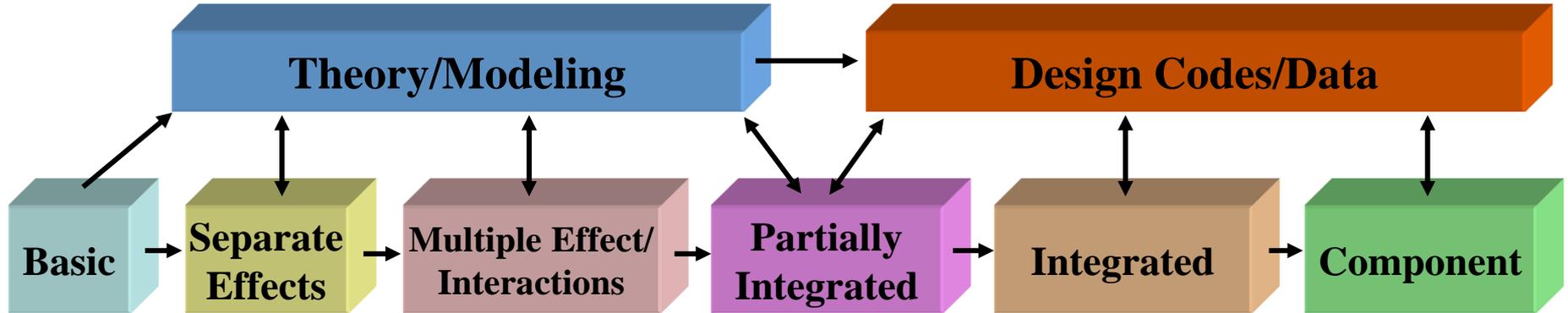
Moving Forward: Need for an Integrated R&D Program Strategy

- **During the period 1970 – 2000, the world spent much effort on exploring options and ideas for blanket concepts, structural materials, liquid and ceramic breeders, coolants, configurations, etc.**
 - Invested considerable resources on design and evaluation studies and exploratory R&D
- **During the past decade, the world programs decided on their preferred concepts and selected primary and backup concepts, materials, and designs**
 - Larger investment was made in real experiments, more complex modeling, and more detailed analysis and designs
 - But the experiments have been mostly limited to single-effects
- **Going Forward We will need to build much more sophisticated facilities, perform multiple effect/ multiple interaction experiments and we need to do much more complex modeling**

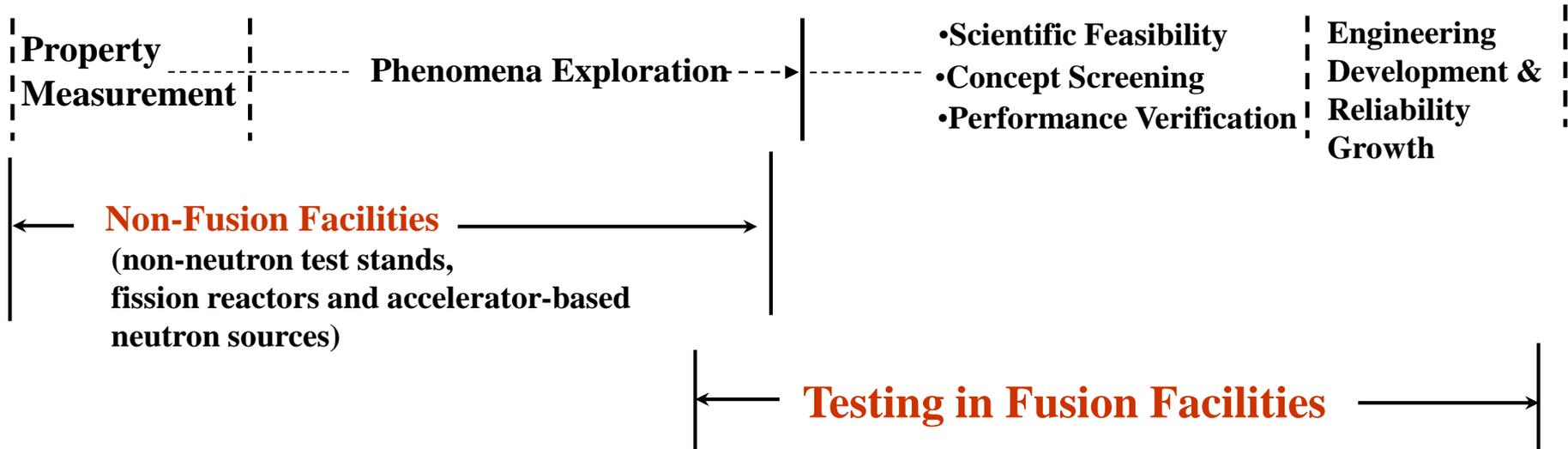
We need an integrated program strategy of modelling and experiments in laboratory facilities and in a DT Fusion Nuclear Science Facility to develop Fusion Nuclear Technology and Materials for DEMO

An Integrated Program Strategy for Blanket/FW R&D involves modeling & experiments in non-fusion and fusion facilities.

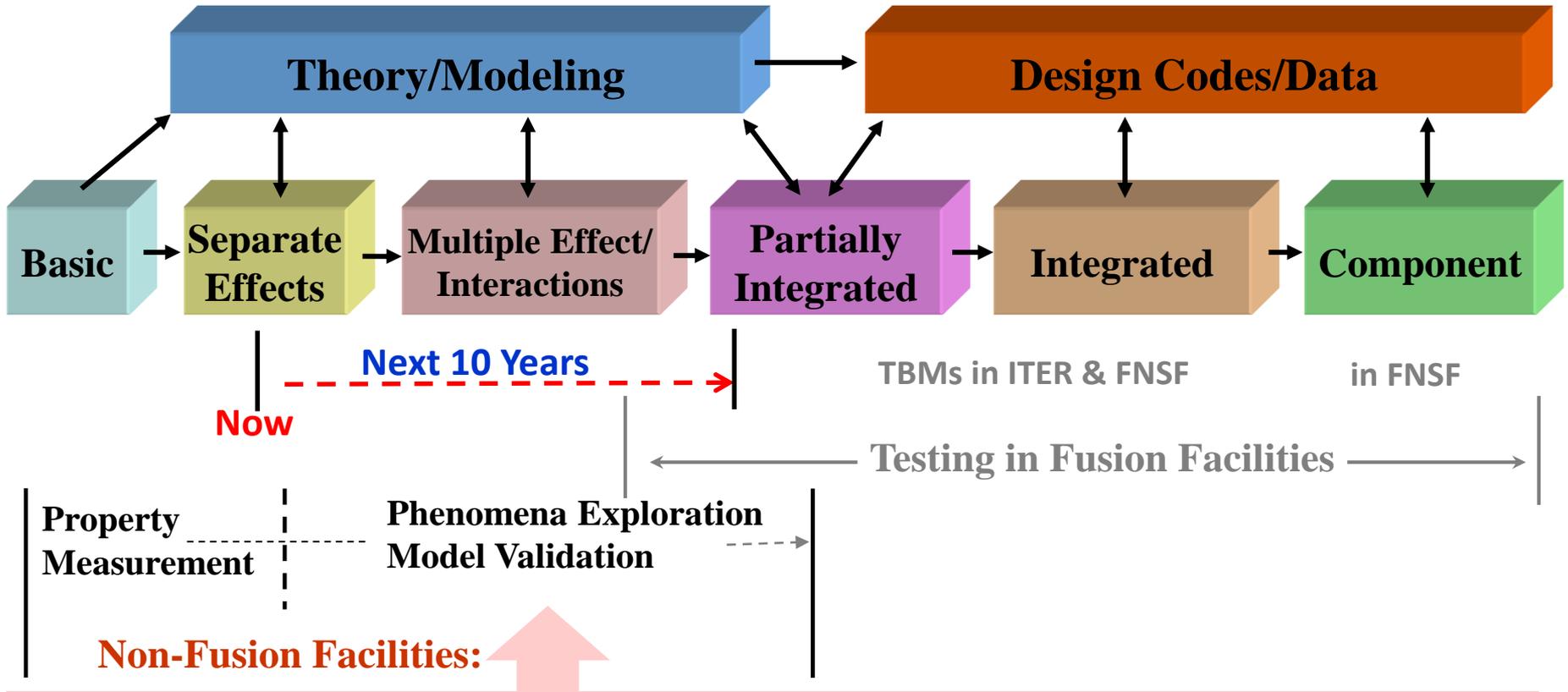
It should be utilized to identify and prioritize R&D Tasks



For each step, detailed performance parameters can be defined to quantify requirements of experiments and modeling and measure progress



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



Multiple Effects / Multiple Interactions – bringing together different combinations of multiple physical loads, multiple materials and complex configurations that can drive new interacting and synergistic phenomena

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**

What are the Principal Challenges in the development of FNST/Blanket/FW

- The Fusion Nuclear Environment: Multiple field environment (neutrons, heat/particle fluxes, magnetic field, etc.) with high magnitude and steep gradients.
- Nuclear heating in a large volume with steep gradients
 - *drives temperatures and most FNST phenomena.*
 - *very difficult to simulate in laboratory facilities*
- Complex configuration with FW/Blanket/Divertor inside the vacuum vessel.

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*)

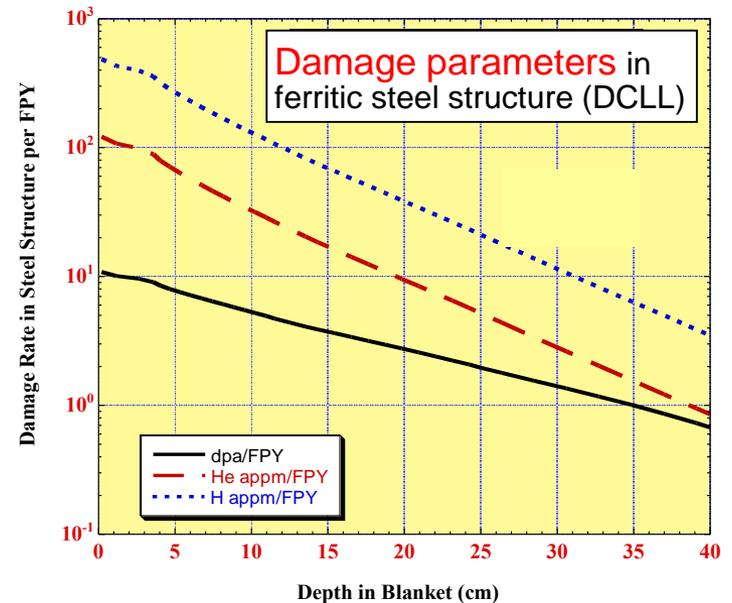
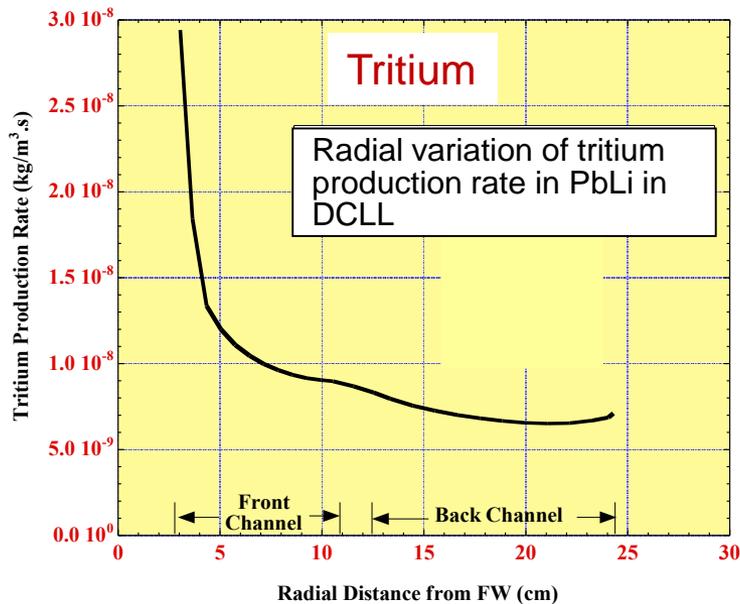
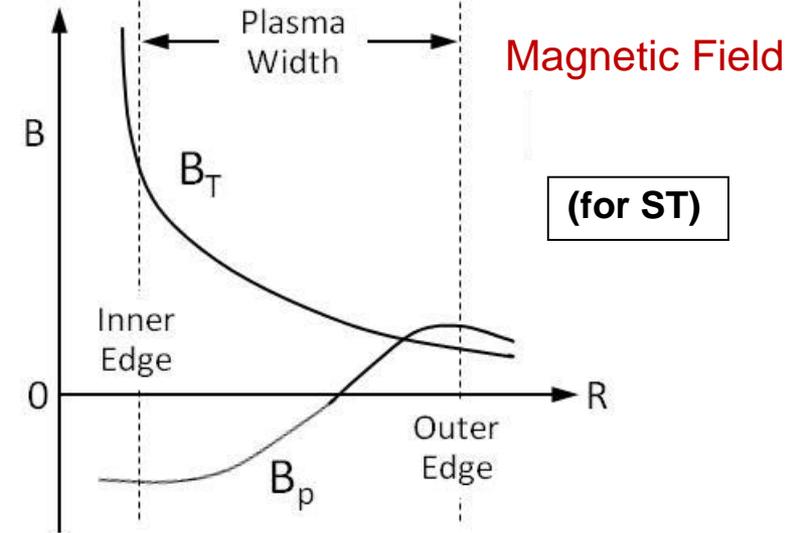
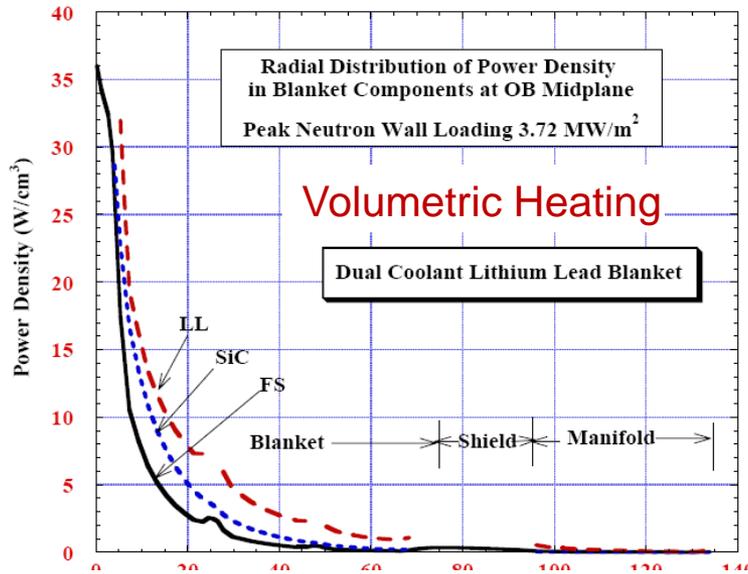
**Multiple functions, materials,
and many interfaces in highly
constrained system**

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

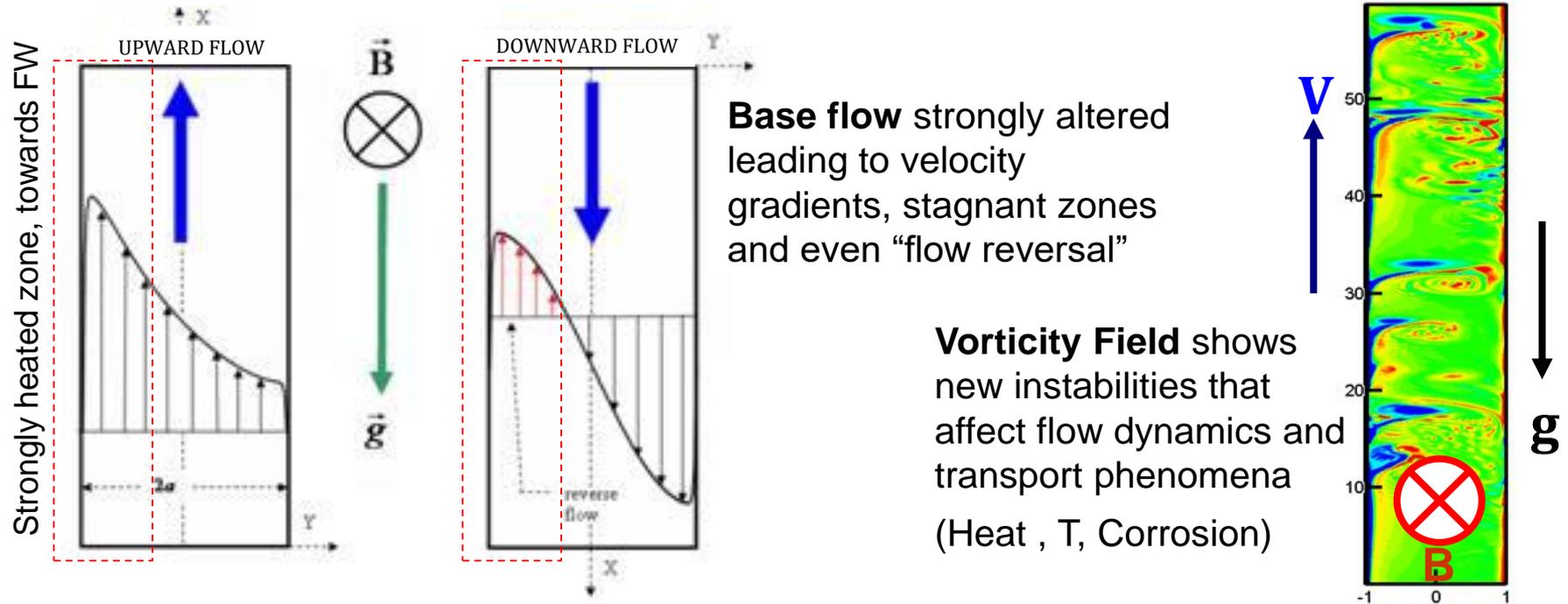
There are strong GRADIENTS in the multi-component fields of the fusion environment



These gradients play a major role in the behavior of fusion nuclear components. Simulating these gradients in experiments is challenging but Essential.

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



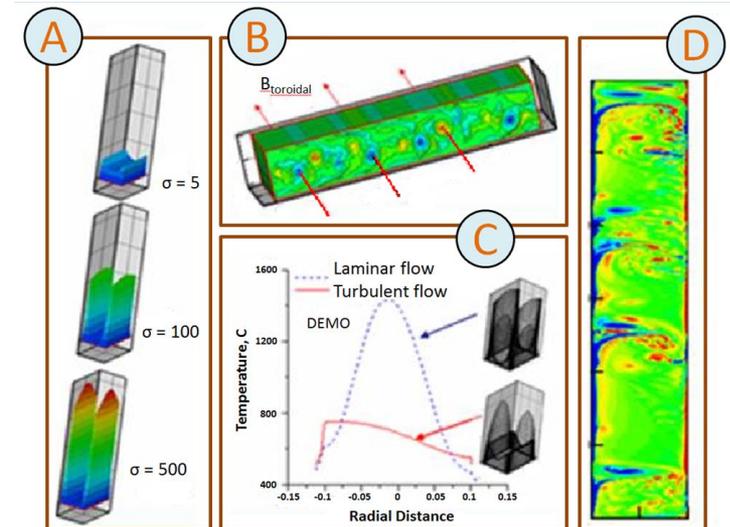
This result is from modeling at limited parameters in idealized geometry,

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

The Issues of mixed convection, flow instability and MHD turbulence drastically change our understanding of LM blankets

Characteristic values of the dimensionless MHD flow parameters for LM blanket concepts under different conditions.

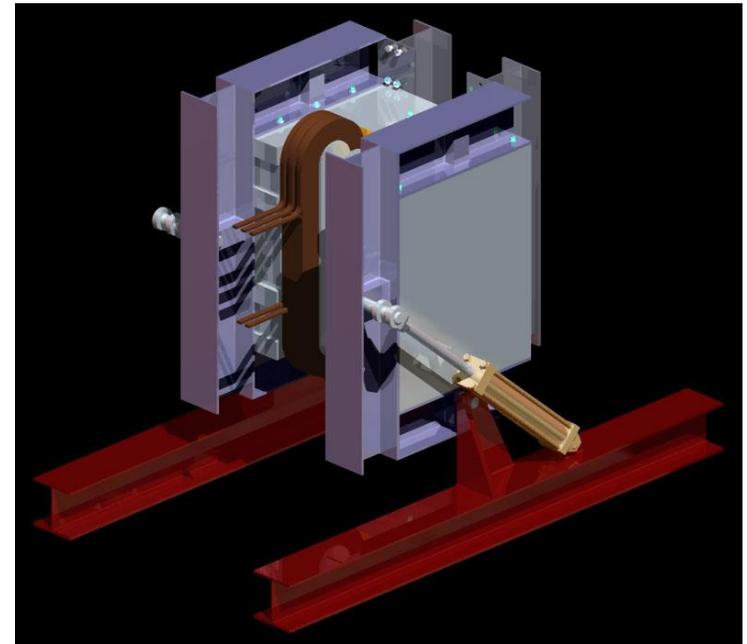
	DCLL	DCLL	DCLL	HCLL	Li/V Self-cooled
<i>Machine</i>	ITER TBM	DEMO	DEMO	ITER TBM	DEMO
<i>Location</i>	Outboard	Outboard	Inboard	Outboard	Inboard
B_0 , T	4	4	10	4	10
L , m	0.1	0.1	0.1	0.07	0.05
U_0 , m/s	0.04	0.07	0.15	0.001	0.5
NWL, MW/m ² (average)	0.78	2.13	1.33	0.78	2.0
Ha	6.5×10^3	1.2×10^4	3.0×10^4	1.1×10^4	4.5×10^4
Re	3.0×10^4	6.0×10^4	1.2×10^5	670	3.2×10^4
N	1.4×10^3	2.4×10^3	7.5×10^3	1.8×10^3	6.0×10^4
R	4.6	5.0	4.0	0.06	0.7
Gr	7.0×10^9	2.0×10^{12}	1.6×10^{12}	1.0×10^9	6.0×10^8



- Gr (and Ha) will be different at outboard, top/bottom and inboard
- Therefore, experiments, modelling and analysis will have to address ALL regions
- There will be many different types of blanket module designs in the same device

Next non-fusion facilities should be capable of simulating ALL variety of MHD flow conditions in LM blankets

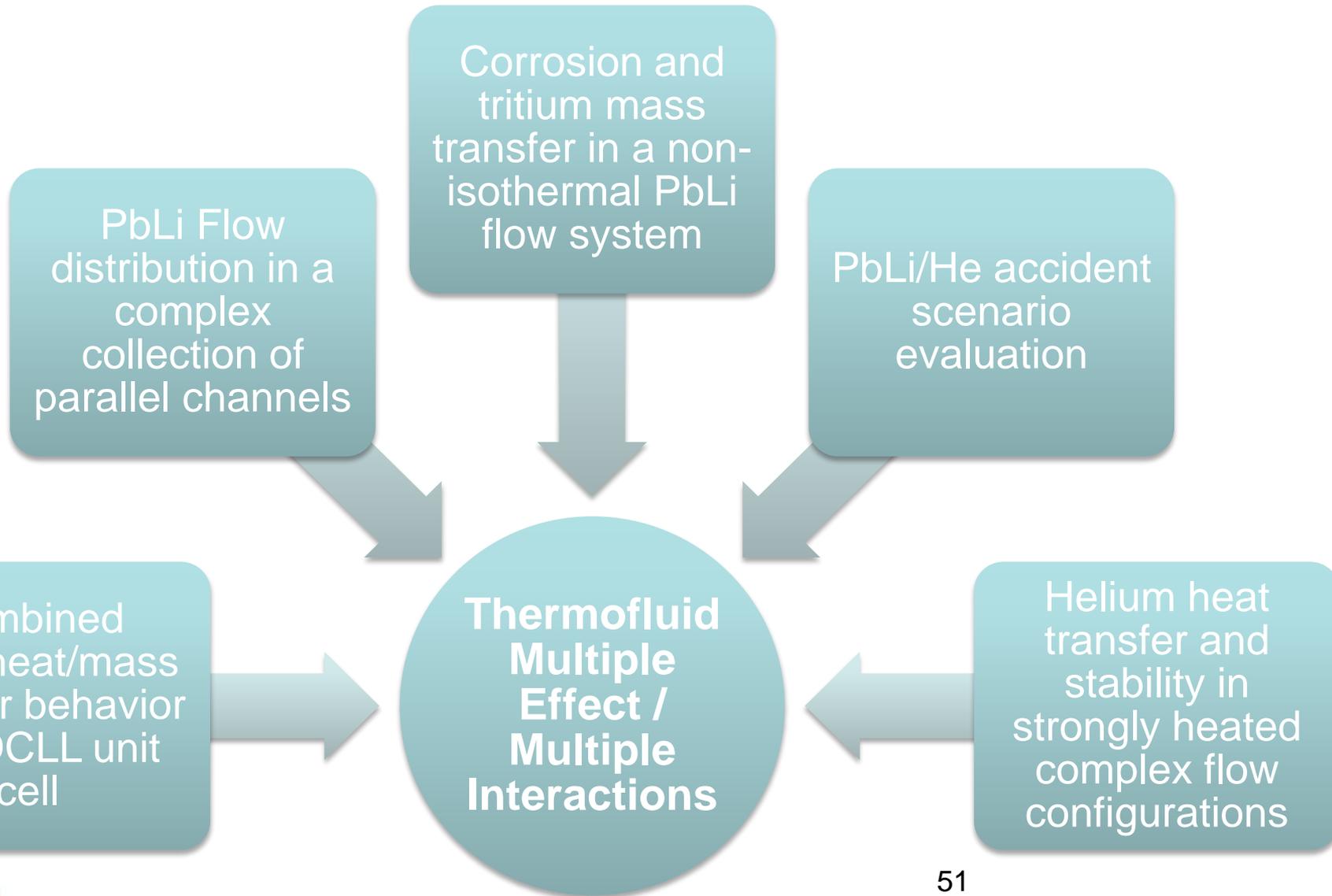
- Right balancing among gravity, MHD, inertia and viscose forces – Ha/Re , Ha/Gr , Gr/Re
- Prototypic magnetic fields from moderate to strong with gradients
- Large magnet workspace
- Arbitrary orientation of a magnet from horizontal to vertical
- Prototypic volumetric heating with sharp gradients
- Multiple channels
- MHD flow + Heat transfer + Mass transfer



Construction of tilting system for the BOB magnet is ongoing project at UCLA

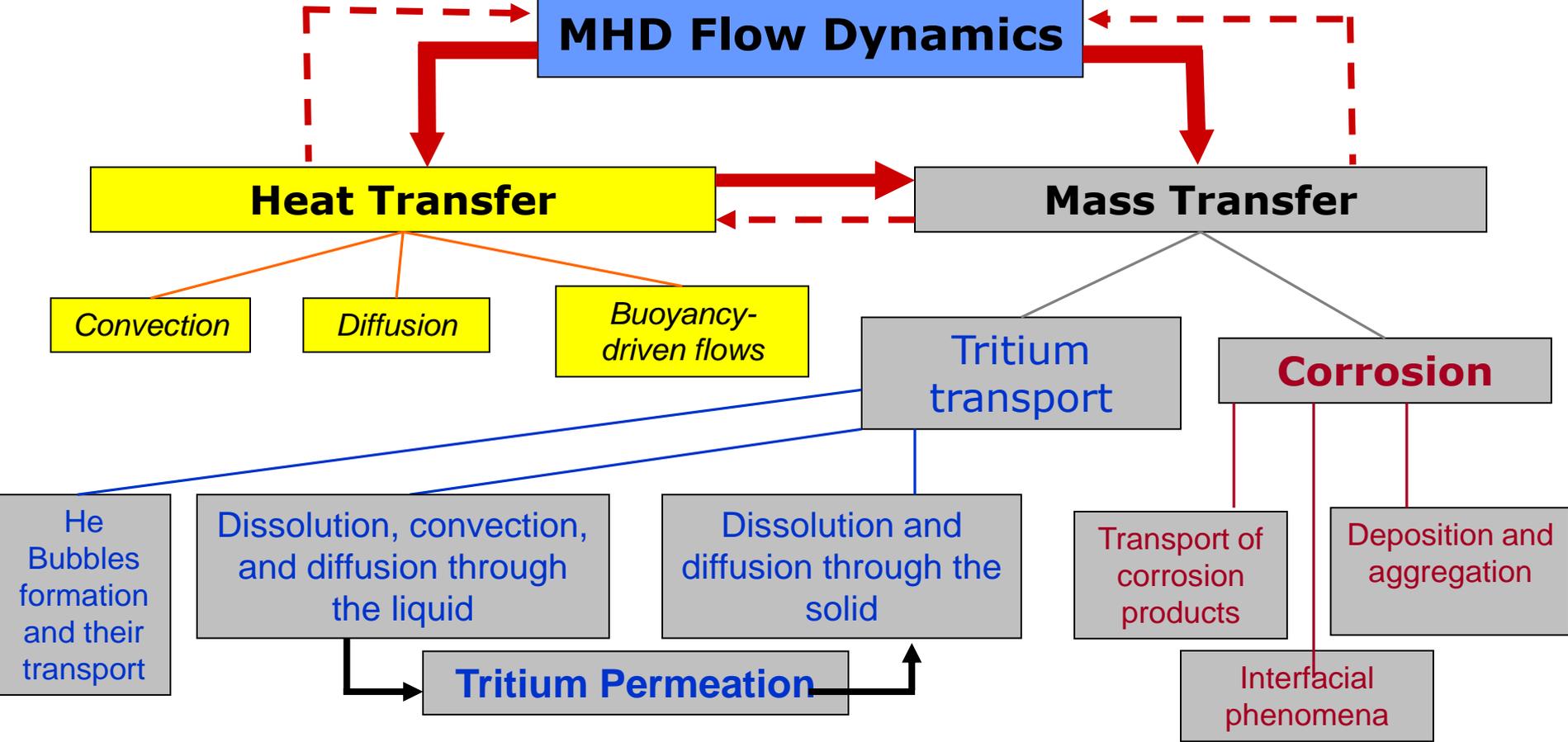
- Reproducing all these features in experiments is very challenging
- Strong large-workspace air-gap magnets are available but expensive
- Reproducing volumetric heating is challenging. IR or resistive heating is not relevant. The idea of the Gamma-Ray source (A. Ibarra, CIEMAT) deserves to be explored

What do we think we need to know about DCLL MHD thermofluid multiple effects / multiple interactions



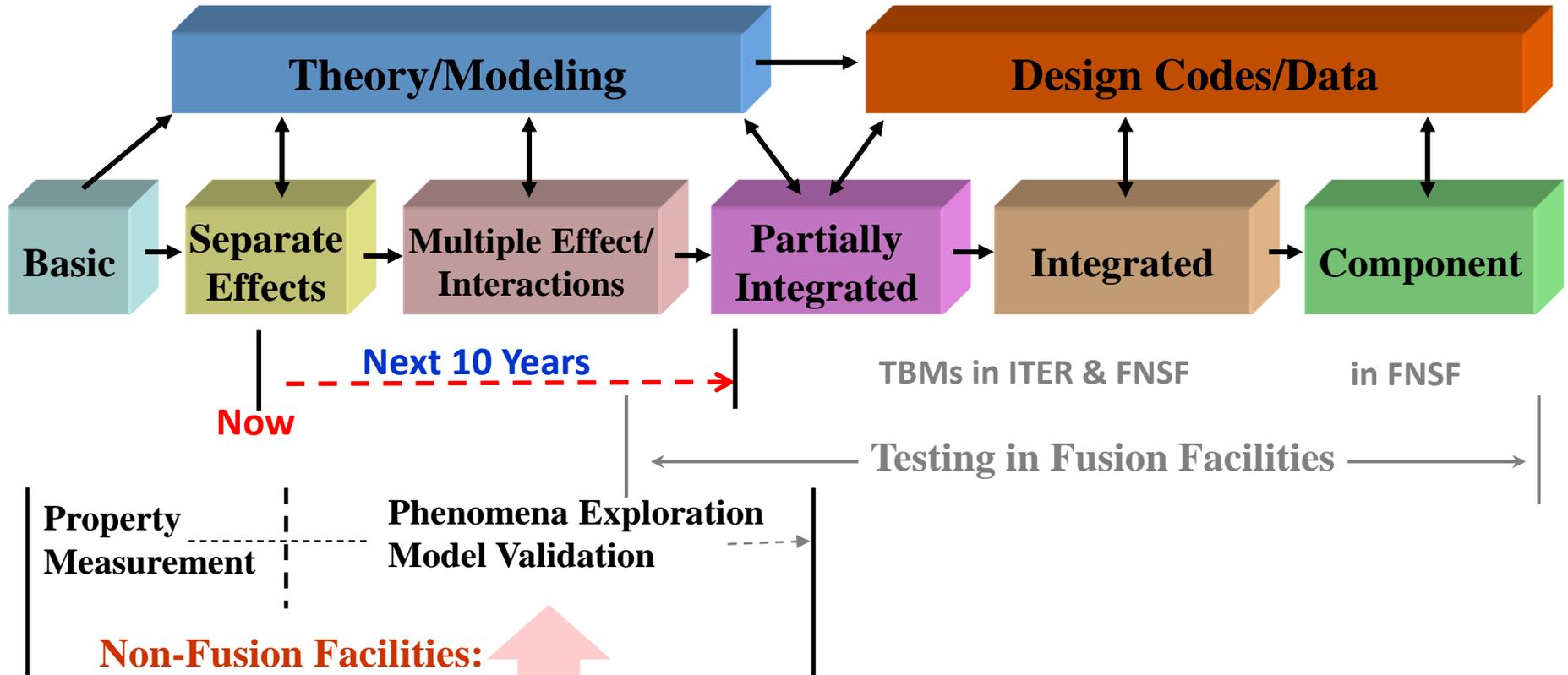
Predicting blanket behavior requires calculating many responses having strong coupling & complex dependence on many interacting phenomena

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

So how do we explore, discover, understand and accurately model multiple effect multiple interactions phenomena?



A handful of upgraded/new experimental facilities will be needed that:

- Use real materials, prototypic temperatures
- Simulate surface and bulk heating and gradients
- Provide large volume and use multiple channels
- Have more prototypic Ha , Gr , N , Re , etc.

The World Programs need to Move more toward “multiple effects/multiple interactions” experiments and modeling

- To discover new phenomena that will arise due to multiple fields/multiple interactions
- To attempt to understand the likely true behavior (currently unknown) of materials, fluids, and subcomponents of the Blanket/FW in the fusion nuclear environment
- To calibrate results of experimentally observed “**synergistic**” effects against “**synthesis**” of separate effect experiments and modeling
- Provide much more reliable input to Blanket/FW designs

The World needs to construct a number of new facilities:

- With capabilities to **simulate combined loads** (thermal, mechanical, chemical, nuclear, and EM load conditions); particularly surface and volumetric heating, temperature and gradients
- With capabilities for experiments with **prototypic geometry, multi-material unit cells and mockups**

We envision two **thermofluid MHD** facilities beyond near term upgrades of existing facilities

- **Multiple Effect/Multiple Interactions Blanket Facility**

Role: Address near full size DCLL unit cell thermofluid flow and transport issues and reduced scale multi-channel flow control

- **Partially Integrated Blanket Facility**

Role: bring together all simulated conditions affecting thermofluid/thermomechanical blanket/FW performance to the maximal practical degree prior to FNSF

These are both non-nuclear facilities that can be flexibly operated and instrumented to investigate both prompt and long time scale DCLL blanket phenomena in a controlled and well characterized fashion

Blanket MHD thermofluid test facilities

Multiple Effect/Multiple Interactions Blanket Facility.

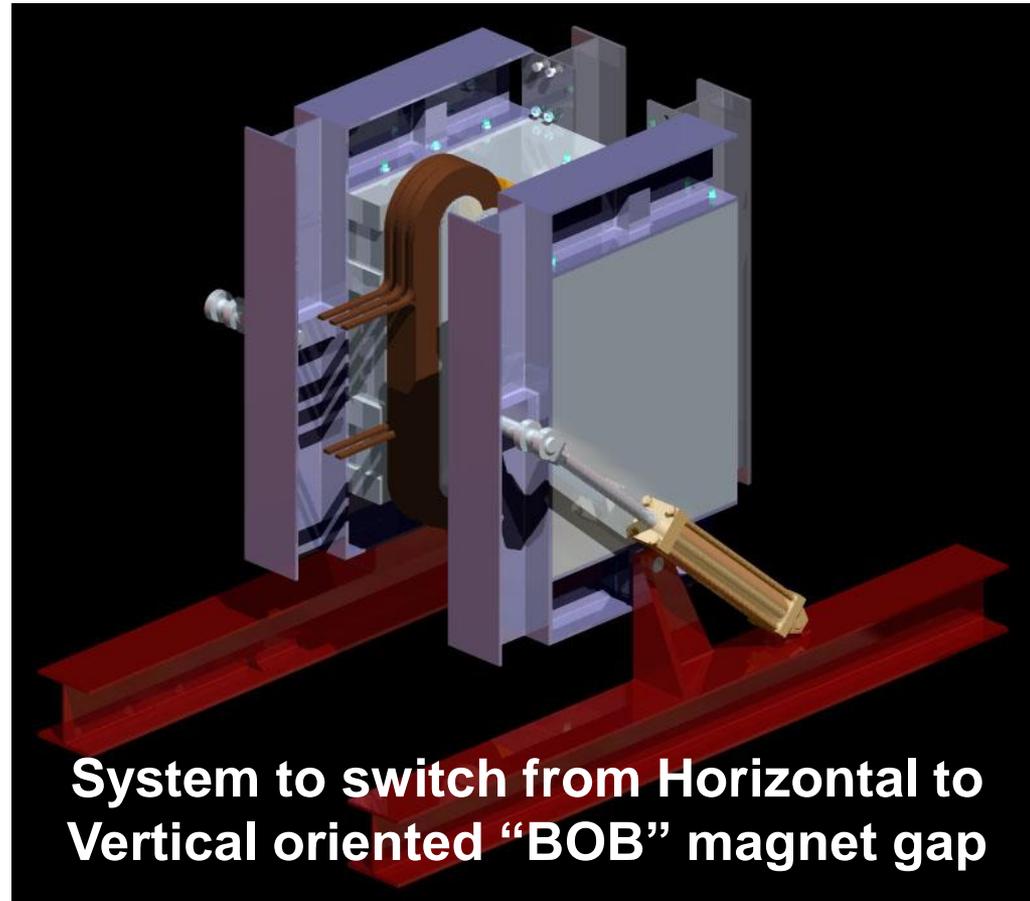
Role: Address near full size DCLL unit cell thermofluid flow and transport issues and reduced scale multi-channel flow control

- strong magnetic field, ~5T
- Magnetic volume capable to accommodate full single channel size, ~0.3 x 1.5 m)
- controlled orientation with respect to gravity and channel walls
- simulated volumetric heating and gradients, temperature & grad.
- PbLi and He flow loops at prototypic temperatures (~1/2 TBM scale)

\$20M class facility, can be a gradual extension of MTOR/MaPLE facilities at UCLA

Possible upgrades for MaPLE and BOB magnet

- Flexible B orientation
- Higher flowrate and temperature PbLi
- Simulated volumetric heating
- Online PbLi purification
- Instrumentation
- Secondary He coolant
- Higher magnetic field
- Larger magnetic volume



Evolve into the Multiple Effect Multiple Interaction facility just described
Collaboration with China/INEST?

Blanket MHD thermofluid test facilities

Partially Integrated Blanket Facility.

Role: bring together all simulated conditions affecting thermofluid/thermomechanical blanket/FW performance to the maximal practical degree prior to FNSF

- Simulated toroidal and poloidal magnetic field
- Up to full size FW/blanket test modules in multiple poloidal orientations with respect to gravity
- Simulated surface and volumetric heating and gradients
- PbLi and He flow loop of ~full DEMO module size
- Prototypic temperatures, pressures, materials

\$50-80M class National Laboratory facility to really prepare for FNSF – requires significant design and construction effort

INEST? (needed to do R&D for CFTR)

Multiple Effect / Multiple Interaction

Discussion Topics

- How do we really simulate volumetric heating in LMs without distorting the experiment? Simulate the temperature gradients?
 - Exploring ways to producing temperature gradients with only surface heating (H lamp, graphite, radiative)
 - Ideas beyond embedded heaters, in wall, FCI or flow
 - Do we need to do MHD simulations with immersion heaters to look at flow and transport distortion
 - An Idea was proposed that a **gamma-ray source** could do this. What kind of power is typical? Short attenuation in Pb
 - Induction heating, skin depth and unintentional stirring
 - Microwaves for ceramic breeder, in resonant cavity

Study on Blanket/FW

Multiple Effect/Multiple Interaction and Partially Integrated Test Strategy and Facilities

Why the Study is Needed

- The subject of multiple effect/multiple interactions is very complex and requires experienced blanket R&D experts
- But the cost of the facility for full simulation can be very expensive
- Therefore, tradeoffs between the capabilities incorporated in the facility and COST are needed. Developing cost estimates require mechanical design for a given set of specified parameters
- Requires Blanket R&D experts as well as mechanical engineers and magnet designers and cost professionals. There are several US institutions interested in developing proposals to construct blanket facilities

The study could be “international” and a good mechanism for collaboration

Establish the base of the pyramid **Before** proceeding to the top

We need substantial NEW Laboratory-scale facilities NOW

We must start NOW Blanket R&D for FNSF/CFETR

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

Functional tests: ITER **TBM** Experiments and PIE

Engineering Feasibility Testing in a **Fusion Nuclear Science Facility**

Multi-Effect Test Facilities (each ~5-20M and 50M class)

Blanket Mockup Thermomechanical/ Thermofluid Testing Facility

Tritium Fuel Cycle Development Facility

Bred Tritium Extraction Testing Facility

Fission Irradiation Effects Testing on Blanket Mockups and Unit Cells

Fundamental Research Thrusts (each ~1-3M per year)

PbLi Based Blanket Flow, Heat Transfer, and Transport Processes

Plasma Exhaust and Blanket Effluent Tritium Processing

Helium Cooling and Reliability of High Heat Flux Surfaces /Blanket/FW

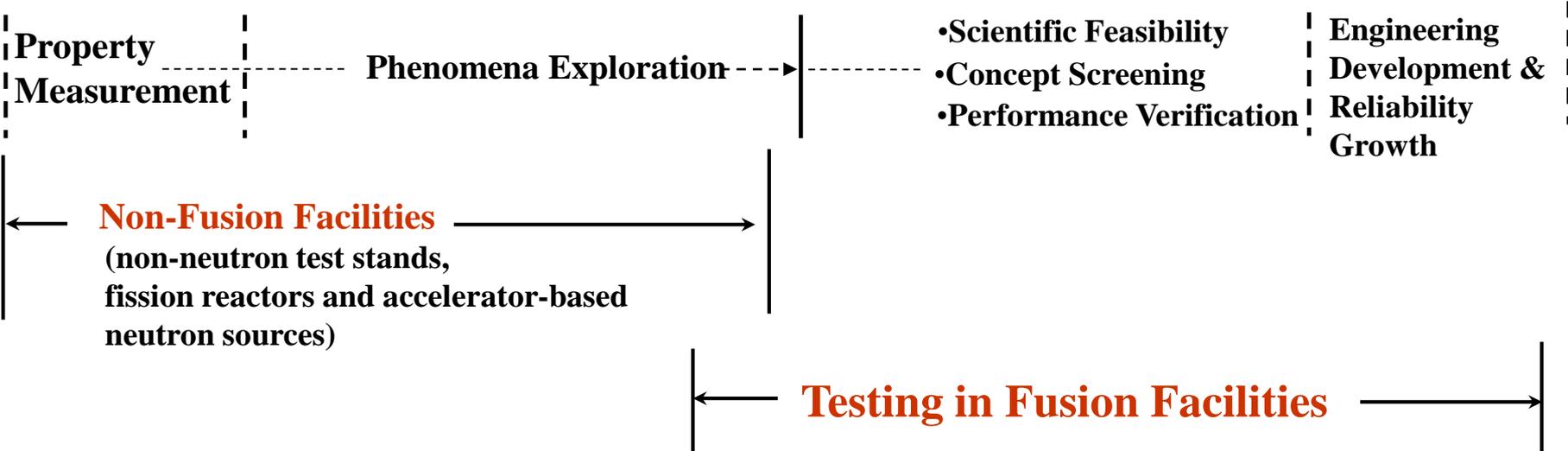
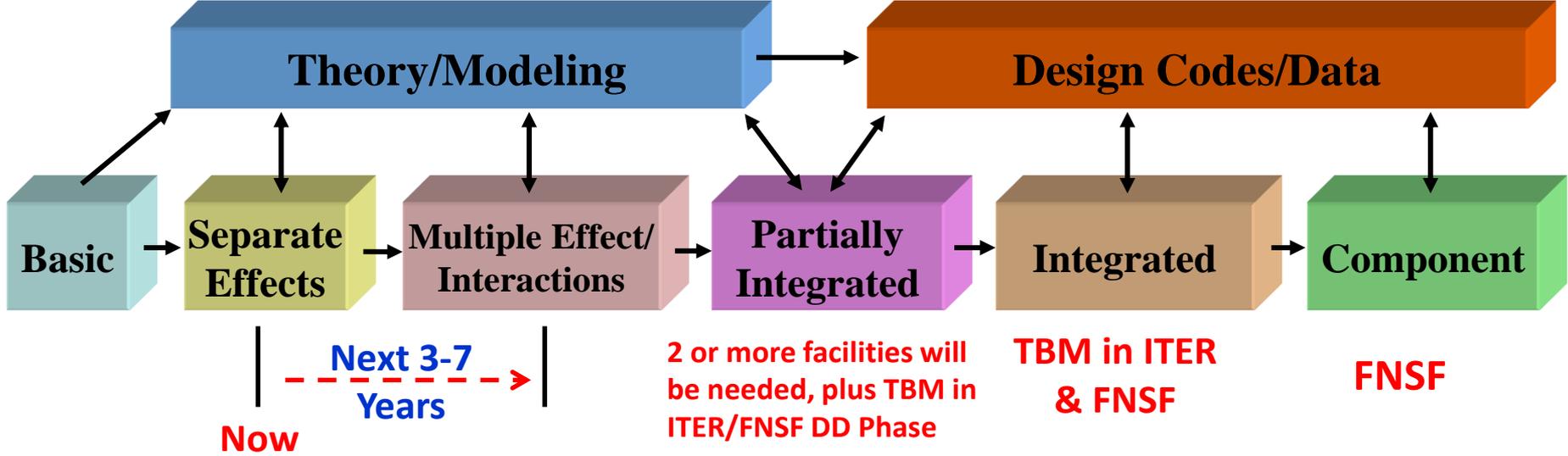
Ceramic Breeder Thermomechanics and Tritium Release

Structural and Functional Materials Fabrication

FNST Pyramid

Testing in DT Fusion Facilities is a Major and Essential element of the Integrated Program Strategy for Blanket/FW R&D

ITER TBM limited But FNSF is for integrated and Component R&D



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!!

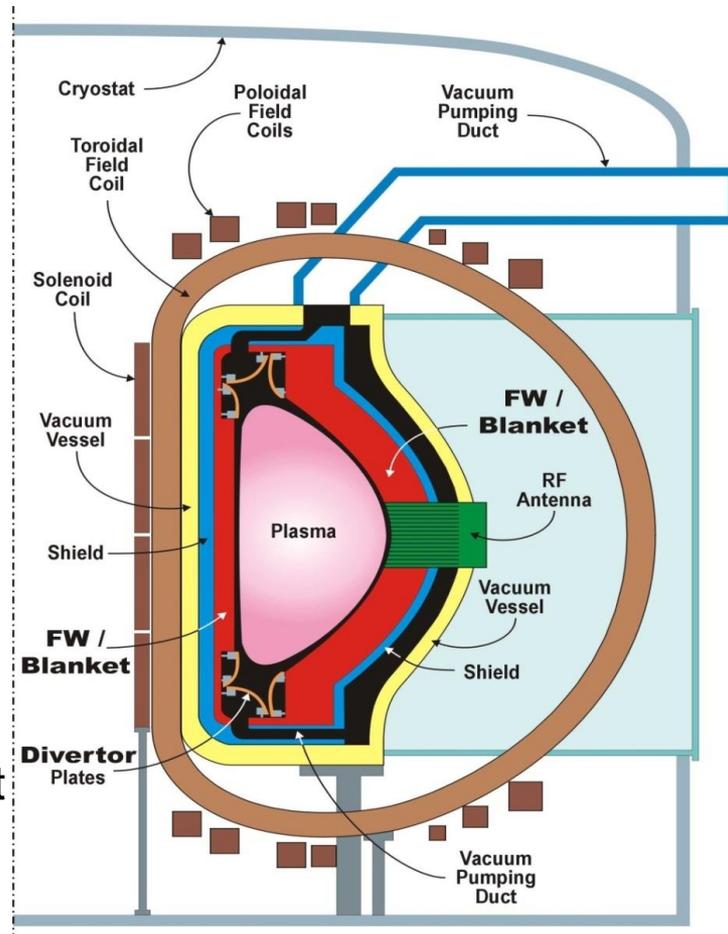
This short MTBF / long MTTR issue will be the most serious challenge in Fusion Development from beginning to end

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)



Fusion Nuclear Science Facility (FNSF)

- The idea of FNSF (also called VNS, CTF) is to build a small size, low fusion power DT plasma-based device in which Fusion Nuclear Science and Technology (FNST) experiments can be performed and tritium self sufficiency can be demonstrated in the relevant fusion environment:

1- at the smallest possible scale, cost, and risk, and

2- with practical strategy for solving the tritium consumption and supply issues for FNST development.

In MFE: small-size, low fusion power can be obtained in a low-Q (driven) plasma device, with normal conducting Cu magnets.

The DD Phase of FNSF also has a key role in providing integrated testing without neutrons prior to the DT Phase.

Why FNSF should be low fusion power, small size

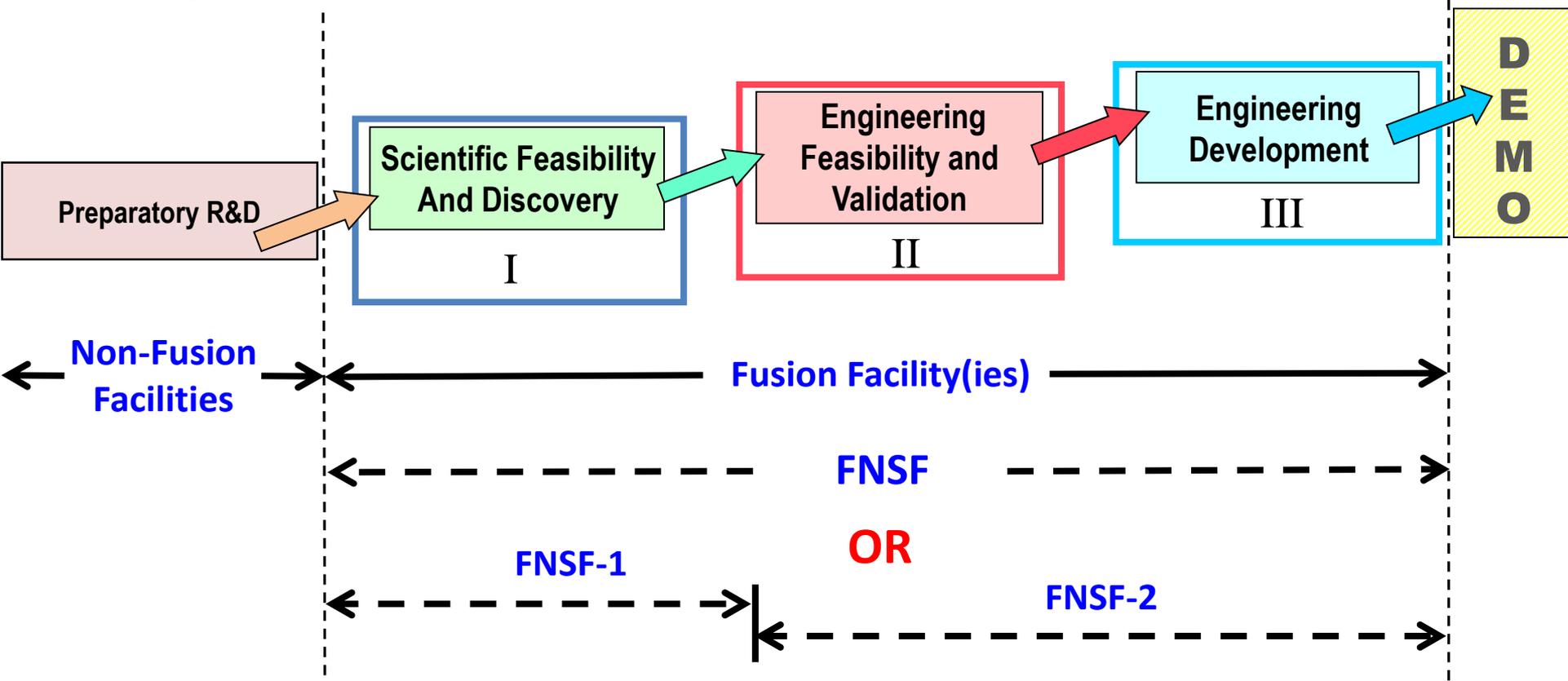
- To reduce risks associated with external T supply and internal breeding shortfall
- Reduce cost (note Blanket/FW/ Divertor will fail and get replaced many times)
- FNST key requirement 1-2 MW/m² on 10-30 m² test area
- Cost/risk/benefit analysis lead to the conclusion that FNSF fusion power <150 MW
- For Tokamak (standard A & ST) this led to recommendation of:
 - Low Q plasma (2-3) - and encourage minimum extrapolation in physics
 - Normal conducting TF coil (to reduce inboard B/S thickness, also increase maintainability e.g. demountable coils).

Scope FNSF so that we can build it the soonest.

Planning facilities to be very ambitious leads to ever rising costs

And very lengthy schedule delays (learn the lesson of ITER)

Science-Based Pathway to DEMO Must Account for Unexpected Challenges in Current Blanket/FW/Divertor and Confinement Concepts



- Today, we do not know whether **one** facility will be sufficient to show scientific feasibility, engineering feasibility, and carry out engineering development **OR** if we will need **two or more** consecutive facilities.

May be multiple FNSF in parallel?!

We will not know until we build one!!

- Only Laws of nature will tell us regardless of how creative we are. We may even find we must change “direction” (e.g. New Confinement Scheme)

Base Breeding Blanket and Testing Strategy in FNSF

- **A Breeding Blanket should be installed as the “Base” Blanket on FNSF from the beginning**
 - Needed to breed tritium.
 - Switching from non-breeding to breeding blanket involves complexity and long downtime. There is no non-breeding blanket for which there is more confidence than a breeding blanket.
 - Using base breeding blanket will provide the large area essential to “reliability growth”. This makes full utilization of the “expensive” neutrons.
- **The primary concepts for DEMO should be used for both “testing ports” and “Base” Breeding Blanket in FNSF**
- **Both “port-based” and “base” blanket will have “testing missions”**
 - Base blanket operating in a more conservative mode (run initially at reduced parameters/performance)
 - Port-based blankets are more highly instrumented, specialized for experimental missions, and are operated near their high performance levels; and more readily replaceable

Reduced activation Ferritic/Martensitic Steel (FS) is the reference structural material option for DEMO

- FS is used for TBMs in ITER and for mockup tests prior to ITER
- FS should be the structural materials for both base and testing breeding blankets on FNSF.
- FS irradiation data base from fission reactors extends to ~80 dpa, but it generally lacks He (only limited simulation of He in some experiments).
 - ✓ There is confidence in He data in fusion typical neutron energy spectrum up to at least 100 appm He (~10 dpa).
 - Note: Many material experts state confidence that FS will work fine up to at least 300 appm He at irradiation temperature > 350°C.

FNSF Strategy/Design for Breeding Blankets, Structural Materials, PFC & Vacuum Vessel

- DD phase role : All in-vessel components, e.g. divertor, FW/Blanket performance verification without neutrons before proceeding to the DT Phase

Day 1 Design

- Vacuum vessel – low dose environment, proven materials and technology
- Inside the VV – **all is “experimental.”** Understanding failure modes, rates, effects and component maintainability is a crucial FNSF mission.
- Structural material - reduced activation ferritic steel for in-vessel components
- Base breeding blankets - conservative operating parameters, ferritic steel, 10 dpa design life (acceptable projection, obtain confirming data ~10 dpa & 100 ppm He)
- Testing ports - **well instrumented, higher performance blanket experiments**
(also special test module for testing of materials specimens)

Upgrade Blanket (and PFC) Design, Bootstrap approach

- Extrapolate a factor of 2 (standard in fission, other development), 20 dpa, 200 appm He.
Then extrapolate next stage of 40 dpa...
- Conclusive results from FNSF (real environment) for testing structural materials,
 - no uncertainty in spectrum or other environmental effects
 - prototypical response, e.g., gradients, materials interactions, joints, ...

**The problem with fusion is that it is not being developed fast enough (taking too long!)
“The Time to Fusion seems to be always 40 years away”**

The World Needs Fusion.

To accelerate the development of fusion energy requires a change in Governments Policies and in the Fusion Community strategy/focus:

- **Need More Substantial Funding : Governments must invest in long-term solutions for the future**
- **Problems are challenging: Need More Ingenuity**
- **Fusion Community strategy/focus need to change: Need to Focus on the Major Remaining Challenge: Launch an aggressive FNST Program NOW**

This is essential to realizing fusion in the 21st Century

Concluding Remarks

- Progress in Blanket/FW R&D will pace our realization of DEMO
- A **Science-Based Framework** for Blanket R&D with modeling and experiments in non-fusion and fusion facilities has been proposed
 - It should be utilized to identify and prioritize R&D Tasks
- Blanket R&D is **now in “separate effect” stage**. The World Programs **need to move rapidly toward “multiple effects/multiple interactions” experiments and modeling**
 - This requires a number of new laboratory facilities: relatively expensive but a small fraction of the cost of tests in DT fusion facilities
- **Principal Challenge in development** of blanket/FW is multiple-field unique fusion nuclear environment to be experienced by a blanket with multiple materials, multiple functions and complex configuration. **Primary Challenges in simulating the Blanket in this environment are:**
 - Nuclear heating in a large volume with steep gradients (not reproducible in laboratory experiment)
 - Complex magnetic field 3-component with transients
 - Complex mockup configuration with prototypic size and scale (not possible in fission reactors)
- **RAMI** is a serious challenge that has major impact on priorities and strategy for fusion R&D and is likely to determine the ultimate feasibility and attractiveness of fusion power
- **Fusion Nuclear Science Facility (FNSF)** is needed parallel to ITER. It is a small size, low fusion power with driven DT plasma. FNSF is necessary to perform experiments on fusion nuclear components: Blanket/FW/Divertor and Tritium fuel cycle
 - DD Phase for “Partially Integrated” experiments
 - First DT Phase is for “scientific discovery,” not for validation

Thank you!



Backup slides