Blanket/First Wall Challenges and Required R&D on the pathway to DEMO

for the near-term in laboratory experiments and medium-term in FNSF/CFETR

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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.

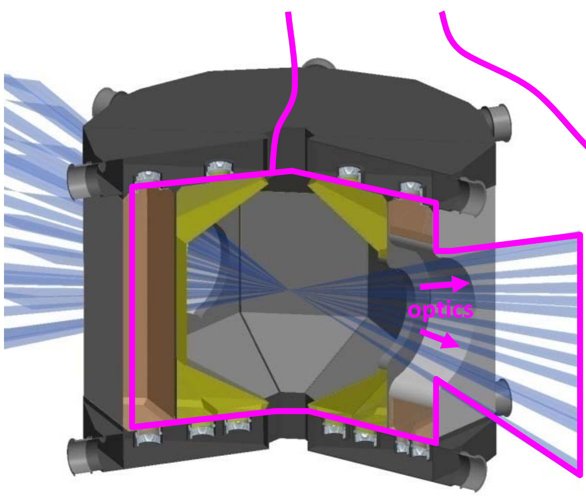
In-vessel Components

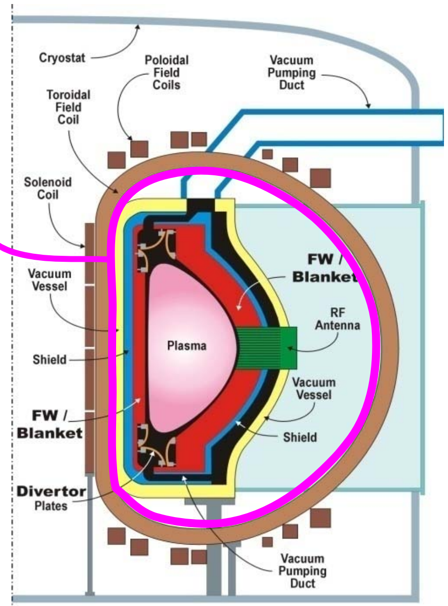
- **Plasma Facing Components**
  divertor, limiter, heating/fueling and final optics, etc.
- **Blanket** and **Integral First Wall**
- **Vacuum Vessel** and **Shield**

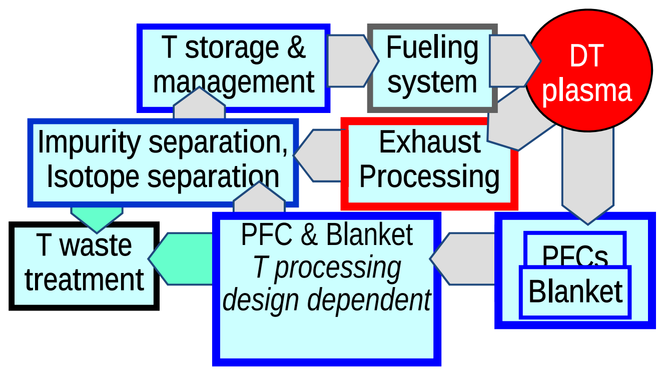
The nuclear environment also affects

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

These are the FNST Core
for IFE & MFE







Fusion Nuclear Science and Technology (FNST) must be the Central element of any Roadmapping for fusion

ITER (and KSTAR, EAST, JT-60SU, etc) will show the Scientific and Engineering Feasibility of:

- **Plasma (**Confinement/Burn, CD/Steady State, Disruption control, edge control)
- **Plasma Support Systems** (e.g. Superconducting Magnets)

- **ITER does not address FNST (all components inside the vacuum vessel are NOT DEMO relevant - not materials, not design, not temperature)**

  (TBM provides very important information, but limited scope)

- **FNST is the major missing Pillar of Fusion Development**

FNST will Pace Fusion Development Toward a DEMO.

In particular, the Blanket/First wall has complex multiple effects/multiple interactions that represent major challenges and have huge impact on the R&D in non-fusion and fusion facilities on the pathway to DEMO

Introductory Remarks

- The importance of blanket was recognized from Day 1 of fusion energy research.
- In the 1970's: Blanket issues and design were a dominant part of fusion reactor studies. **Major R&D accomplishments in the 1970's:** can breed tritium with Li and with Be in CB, can extract tritium from Li, fast tritium release from CB
- In the 1980's:
  - Many blanket concepts (>50) were proposed. BCSS-type studies were performed to narrow concepts to 4
  - Extensive Technical Planning Studies (e.g. FINESSE) were carried out to identify issues and define modeling, experiments and facilities required for Blanket R&D
  - **Major R&D Tasks were defined, far-sighted Roadmap was identified. Asked for implementation and funds**
- **Serious "Detour" in the 1990's and 2000's**
  - Fusion research was set back by serious cuts in funding and debates about programmatic issues
  - **Blanket research suffered the most:** Funds did not come and the well-thought-out R&D plans of the 1980's were not fully implemented
  - While the blanket program broadened to other countries (positive), the major blanket programs were seriously limited in funding, and hence in R&D capabilities
  - **Major Concern**: Blanket researchers, many are new and young, may think that just continuation of current programs is sufficient to develop blankets for DEMO
- **The objective of this presentation is to illuminate the blanket R&D required on the path to DEMO, with emphasis on the near- to mid-term (next 3-7 yrs)**

Blanket/First Wall Challenges and Required R&D on the pathway to DEMO

Outline

1. Science-Based Framework
2. Summary of Blanket/FW Issues
3. Challenges in Blanket/FW R&D
4. Where are we today? Where do we need to go the next 3-7 years?
5. Blanket R&D in non-fusion facilities
6. Blanket R&D in fusion facilities
7. Concluding Remarks

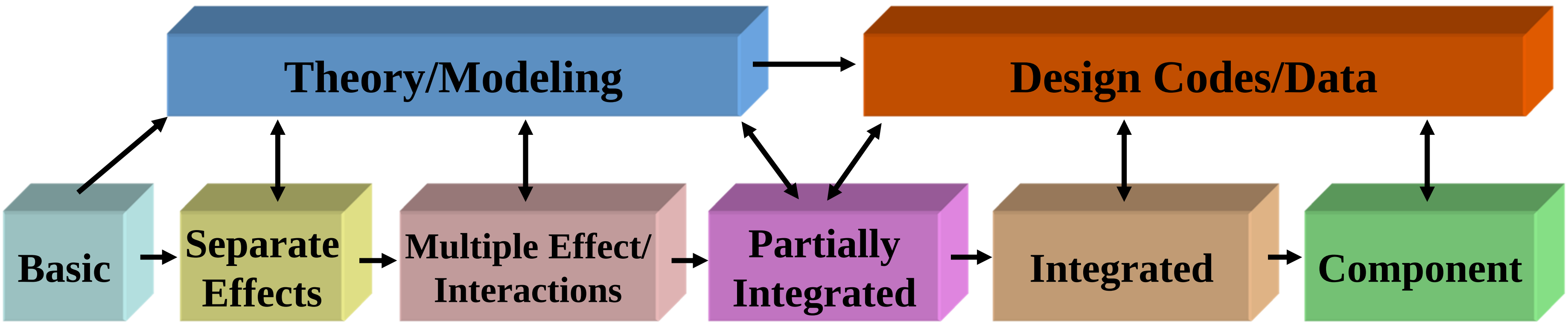
Status of Blanket Research

The state-of-the art and ongoing R&D is presented in many papers particularly the ISFNT series of conferences. See for example, papers from ISFNT-11 (September 2013), which will appear in Fusion Engineering and Design soon (expected July 2014)

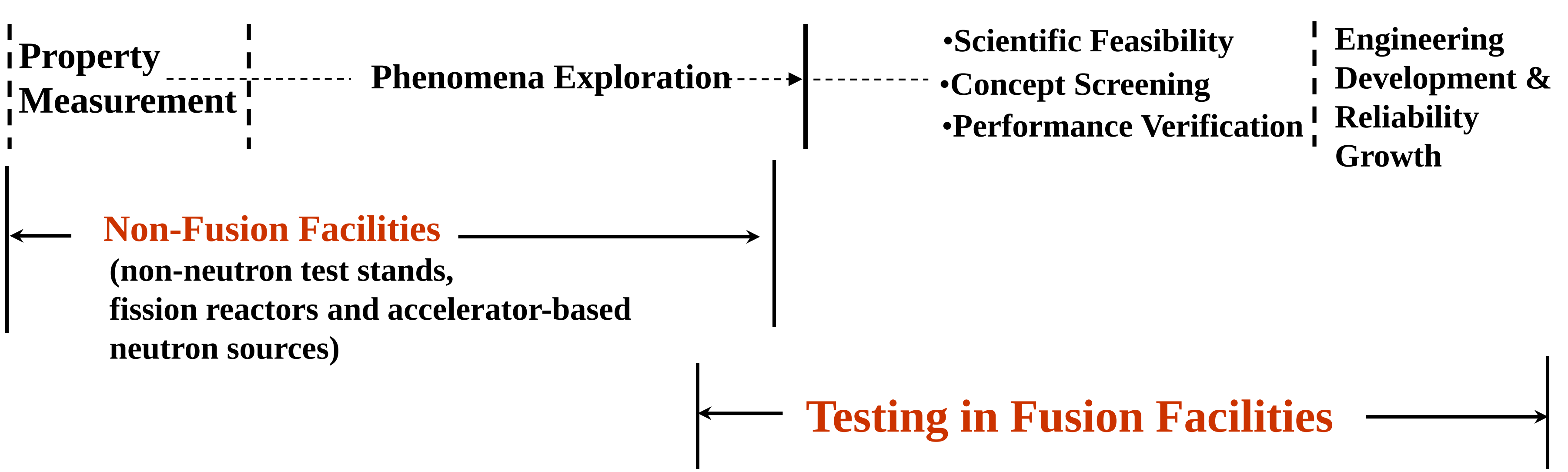
In this presentation we will not attempt to summarize the ongoing R&D, but we will make general observations about the current deficiencies in ongoing R&D. Our focus in this presentation is on future (near- and mid-term) R&D

Science-Based Framework for Blanket/FW R&D involves modeling & experiments in non-fusion and fusion facilities.

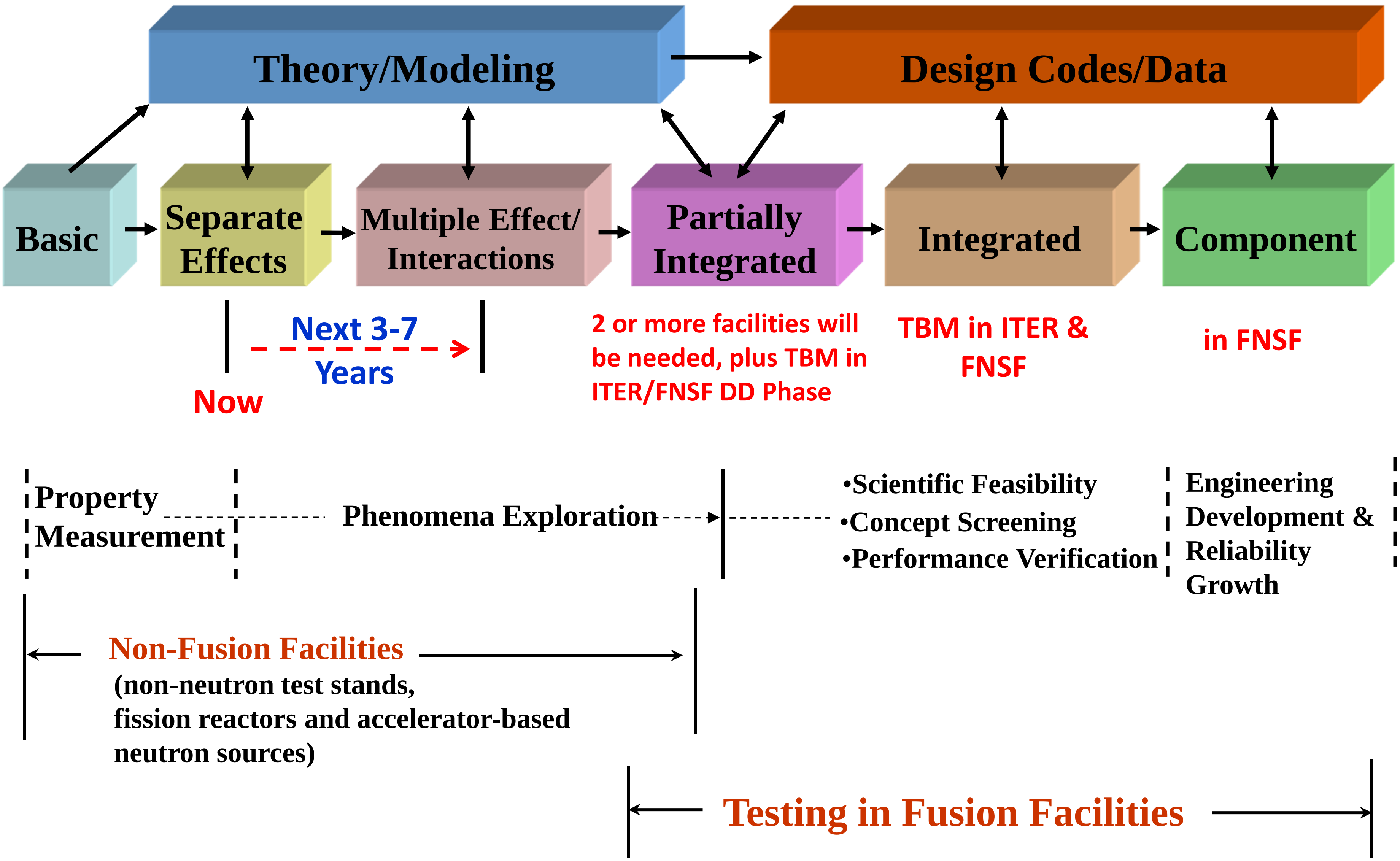
It should be utilized to identify and prioritize R&D Tasks



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



Top-Level Technical Issues for FNST/Blanket (set 1 of 2)

(Details of these issues published in many papers)

Tritium

1. "Phase Space" of practical plasma, nuclear, material, and technological conditions in which tritium self-sufficiency can be achieved
2. Tritium extraction, inventory, and control in solid/liquid breeders and blanket, PFC, fuel injection and processing, and heat extraction systems

Fluid-Material Interactions

3. MHD Thermofluid phenomena and impact on transport processes in electrically-conducting liquid coolants/breeders in both electrically conducting and insulated ducts
4. Interfacial phenomena, chemistry, compatibility, surface erosion & corrosion

Materials Interactions and Response

5. Structural materials performance and mechanical integrity under the effect of radiation and thermo-mechanical loadings in blanket/PFC
6. Functional materials property changes and performance under irradiation and high temperature and stress gradients (including HHF armor, ceramic breeders, beryllium multipliers, flow channel inserts, electric and thermal insulators, tritium permeation and corrosion barriers, etc.)
7. Fabrication and joining of structural and functional materials

Top-Level Technical Issues for FNST/Blanket

(set 2 of 2)

Plasma-Material Interactions

8. Plasma-surface interactions, recycling, erosion/redeposition, vacuum pumping
9. Bulk interactions between plasma operation and blanket and PFC systems, electromagnetic coupling, and off-normal events

Reliability, Availability, Maintainability, Inspectability (RAMI)

10. Failure modes, effects, and rates in blankets and PFC's in the integrated fusion environment
11. System configuration and remote maintenance with acceptable machine down time

All issues are strongly interconnected:

- they span requirements
- they span components
- they span many technical disciplines of science & engineering

What are the Principal Challenges in the development of 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)*

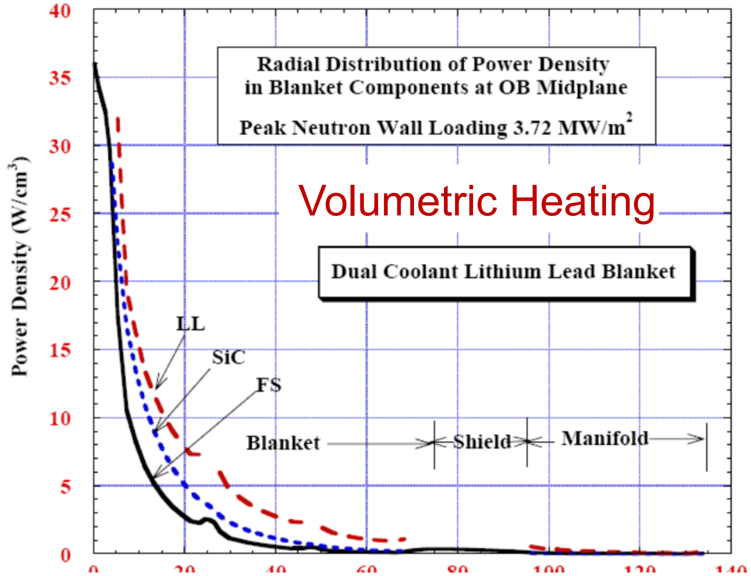
Multiple functions, materials, and many interfaces in highly constrained system

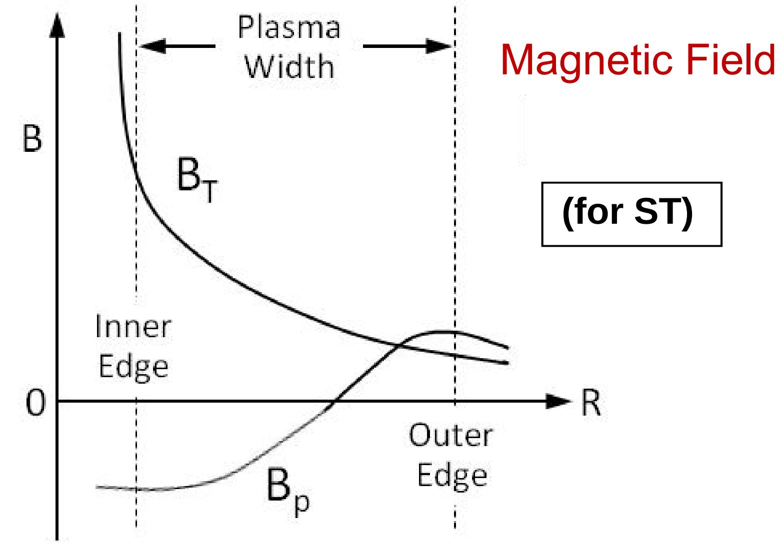
Combined Loads, Multiple Environmental Effects

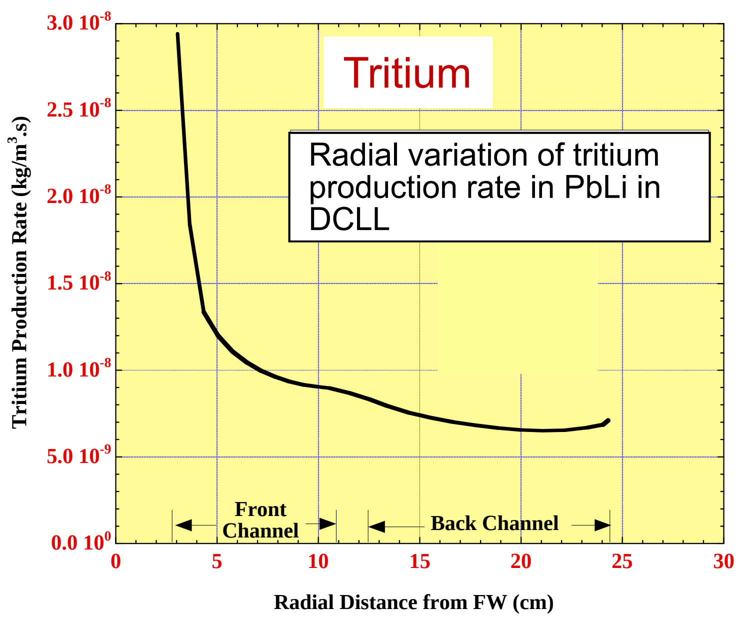
- Thermal-chemical-mechanical-electrical-magnetic-nuclear interactions and synergistic effects
- Interactions among physical elements of components

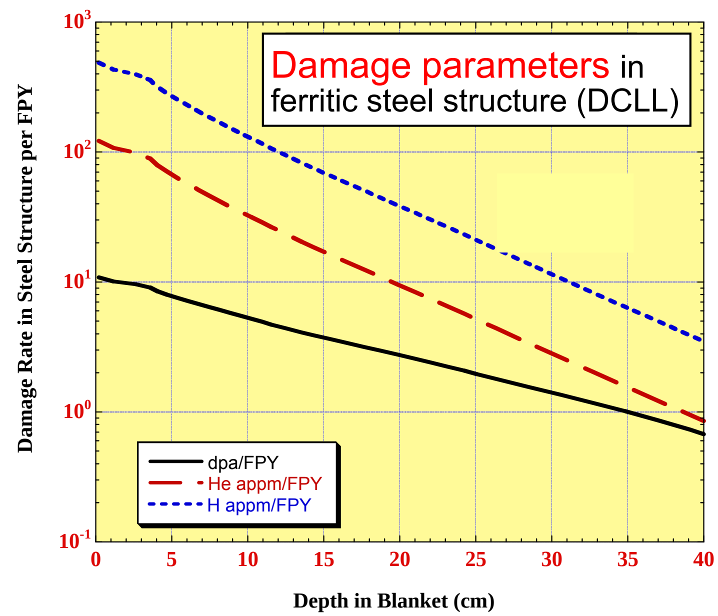
- Many new phenomena YET to be discovered – Experiments are a MUST
- Simulating multiple effect/multiple interactions in Experiments & Models is necessary
- Laboratory experiments need to be substantial to simulate multi loads and interactions

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.

Simulating Bulk Heating and Gradients Is Important but Challenging

Simulating nuclear **bulk heating in a large volume with gradients** is necessary to:

1. Simulate the temperature and temperature gradients
   * Most phenomena are temperature dependent
   * Gradients play a key role, e.g. :
     – Temperature gradient, stress gradient, differential swelling impact on behavior of component, failure modes
2. Observe key phenomena (and "discover" new phenomena)
   – E.g. nuclear heating and magnetic fields with gradients result in complex mixed convection with Buoyancy forces playing a key role in MHD momentum, heat, and mass transfer
   – For liquid surface divertor the gradient in the normal field has large impact on fluid flow behavior

Accurately simulating nuclear **bulk heating (magnitude and gradient) in a large volume requires a neutron field – achievable ONLY in DT-plasma-based facility**

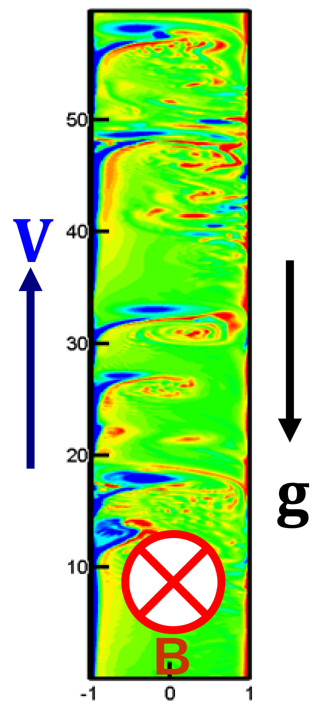
– not possible in laboratory
– not possible with accelerator-based neutron sources
– not possible in fission reactors (very limited testing volume, wrong spectrum, wrong gradient)

Conclusions:

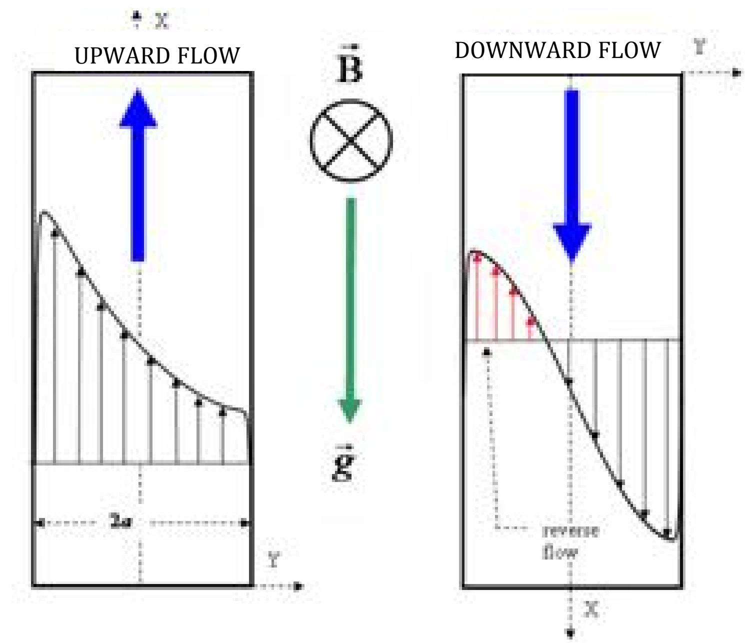
– We must devote major effort to produce bulk heating with the correct gradients in blanket laboratory experiments
– Ultimately, Blanket development requires a DT-plasma based facility (FNSF) to provide the environment for <u>fusion nuclear science experiments</u>.
– The "first phase" of FNSF must be focused on "Scientific Feasibility and Discovery" – it cannot be for "validation."

Example

Spatial Gradients in Volumetric Nuclear Heating and Temperature in LM Blanket Lead to New Phenomena: "Mixed Convection" Flows with buoyant MHD Phenomena.



Vorticity Field with buoyancy forces playing a key role



Combined effects of B and gradients in volumetric heating can lead to "flow reversal."

Magneto-convection may be higher than the forced flow.

Such new phenomena have substantial impact on fluid MHD flow dynamics, heat transfer, corrosion/mass Transfer

Required Blanket/FW R&D in the near-term (3-7 yr)

- The world is working on two classes of concepts
  - **Liquid Metal Blankets**
    - All use ferritic steels, PbLi breeder (research on other material combinations is small)
    - All use He for cooling of FW and Blanket Structure
    - HCLL uses He coolant in the blanket; but DCLL uses PbLi self-cooling in the breeder region and has FCI
  - **Ceramic Breeder Blankets**
    - All use ferritic steels
    - All use pebble bed ceramics (Li_2TiO_3, Li_4SiO_4) and pebble bed Be
    - All use He cooling (except Japan water cooling)

- **Specific R&D Tasks required for liquid metal and ceramic breeder Blankets and tritium fuel cycle are identified in the paper**
  - **In this presentation, only some important considerations will be highlighted**

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

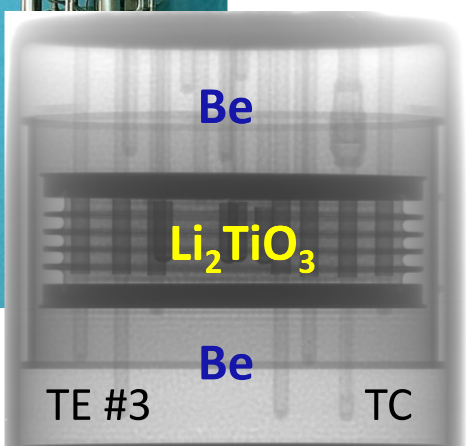
- To discover new phenomena that will arise due to multiple fields/multiple interactions
- To attempt to understand the likely true behavior (currently unknown) of materials, fluids, and subcomponents of the Blanket/FW in the fusion nuclear environment
- To calibrate results of experimentally observed "**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:

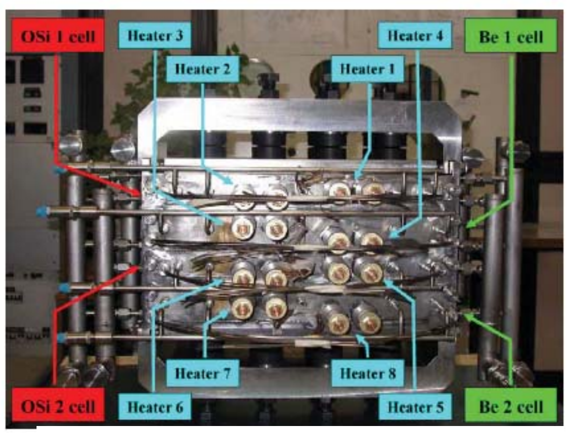
- With capabilities to simulate combined loads (thermal, mechanical, chemical, nuclear, and EM load conditions); particularly surface and volumetric heating, temperature and gradients
- With capabilities for experiments with prototypic geometry, multi-material unit cells and mockups

Multiple effects/multiple interactions experiments and modeling for solid breeder blanket concepts

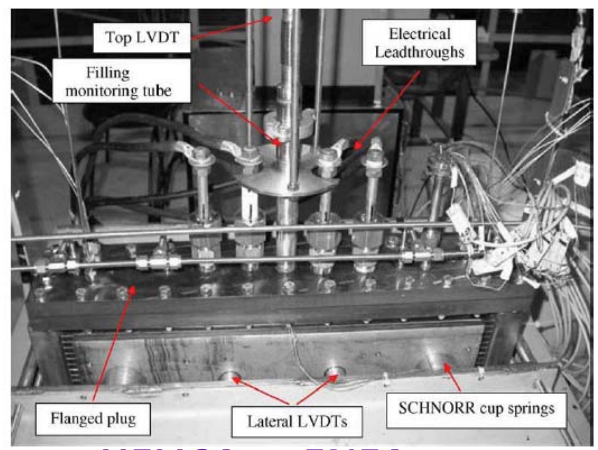
- Interestingly, ceramic breeder blanket R&D has already done and has ongoing multiple effects/multiple interactions (far ahead of liquid metal blankets in this regard)
- This was motivated by the **necessity to study "in-situ" tritium release** with real materials and prototypical temperatures which required **unit cell experiments in fission reactors**. Such experiments were then extended to study **pebble bed thermomechanics with prototypical conditions (including temperature gradient) and material interactions among breeder, Be, and structure, as well as tritium permeation** (test article size 6.75 cm diameter x 12.5c m height; Li-6 burnup ~3 cm; 2 dpa FS)
  - Data from in-pile experiments were encouraging, but showed **pebble bed breakage or sintering**. Such discoveries led to exploring new fabrication techniques, mixing of Li_2TiO_3 and Li_4SiO_4, etc.
- Laboratory facilities were also constructed at ENEA/KIT that utilize electric heaters
  - But data was not conclusive due to problems with electric heaters



In-pile PBA at NRG



HEXCALIBER at ENEA



HELICA at ENEA

Moving Forward with

Multiple effects/multiple interactions experiments and modeling for solid breeder blanket concepts REQUIRES:

- Continue in-pile experiments: extend conditions, improve instrumentation, better simulation of geometric effects and multiple interactions, more study on failure modes and consequences including sintering and pebble breakage; also test new materials/configurations

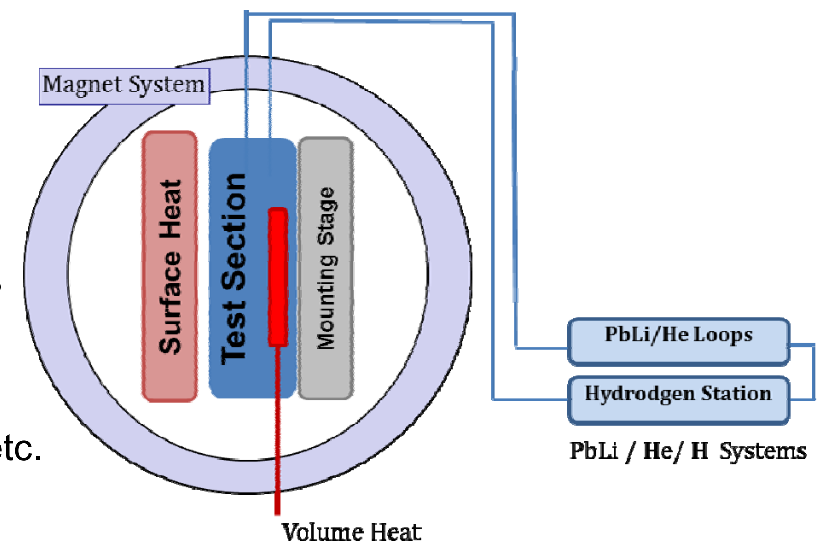
- Build new out-of pile facilities and more experiments with more reliable heating techniques and simulation of accurate temperature gradients, multiple materials, geometry, and thermomechanical loading conditions

- Some experiments should investigate the mechanisms and the impact of pebble relocations/packing rearrangements when pebble cracking/sintering occurs

$20-30M facility for competitive solicitation

Multiple-effect, multiple-interaction test facility for Blanket/FW thermofluids and thermomechanics

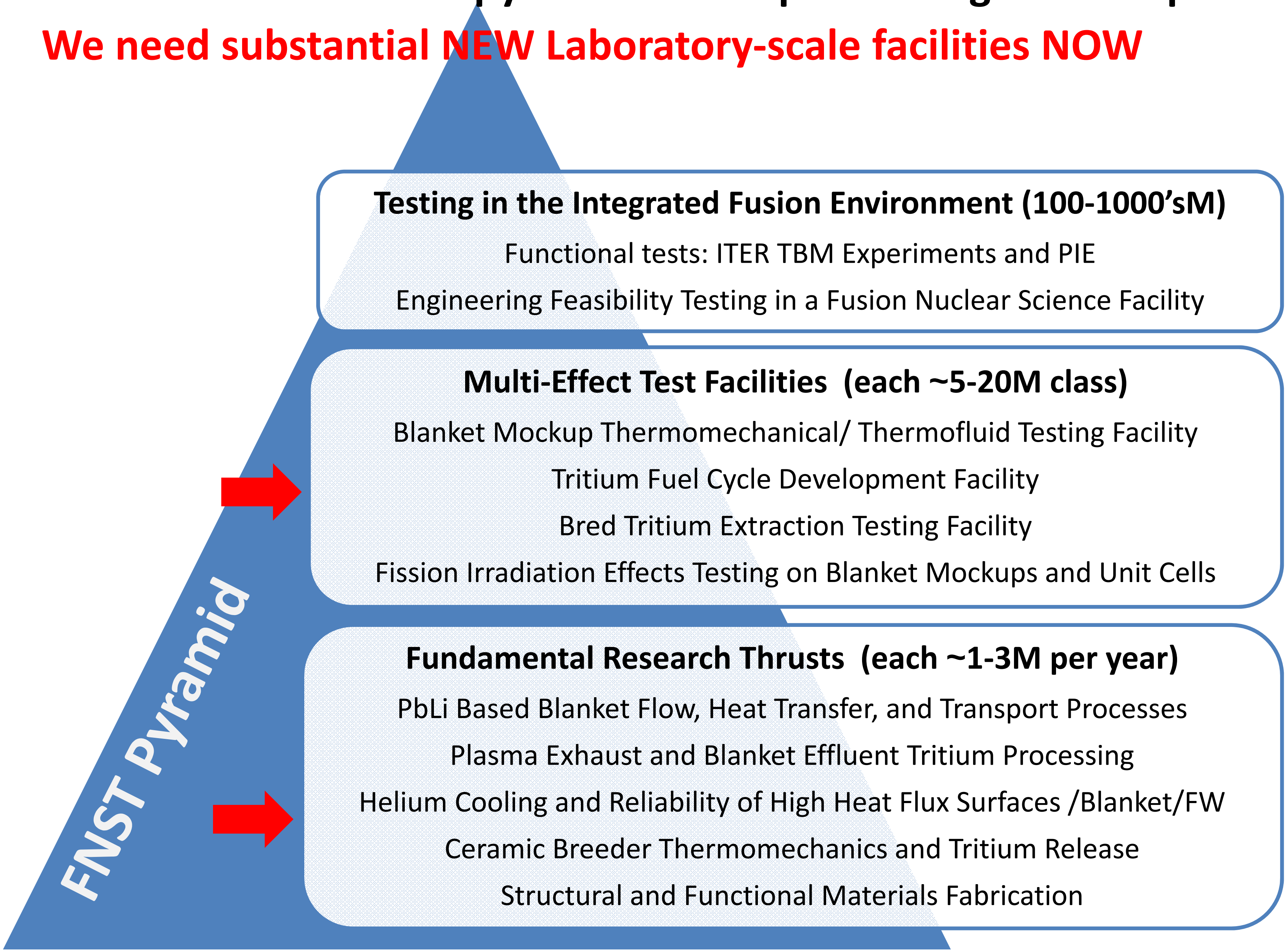
- **Provide test environment that simulates fusion environment conditions other than nuclear**
  - Large volume magnetic field with prototypic gradients
  - Simulated surface and volume heating
  - Other steady and transient loads
- **Capability to reach prototypical temperatures, flow, and pressure with gradients over extended periods**
  - Prototypic Ceramic Breeder, multiplier and He high temperature coolant and purge flow loops; Chemistry control systems, vacuum, etc.



- **Accommodate complex geometry and prototypic materials**
  - Test mockups and ancillary systems from simple geometries, up to prototypical size, complexity, and materials

Establish the base of the pyramid Before proceeding to the top

We need substantial NEW Laboratory-scale facilities 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 Major (hrs)	MTTR/type Minor (hrs)	Fraction Failures Major	Outage Risk	Component Availability
Toroidal C[illegible]	16	5×10^{-6}	23	10^4	240	0.1	0.098	0.91
P[illegible] C[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.884
Fueling	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.998
Tritium System	1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.995
Vacuum	3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.998
Conventional equipment- instrumentation, cooling, turbines, electrical plant							[illegible]	0.952
TOTAL SYSTEM	(Due to unscheduled maintenances)						0.624	0.615

Two key parameters:

MTBF – Mean time between failures

MTTR – Mean time to repair

DEMO availability of 50% requires:

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

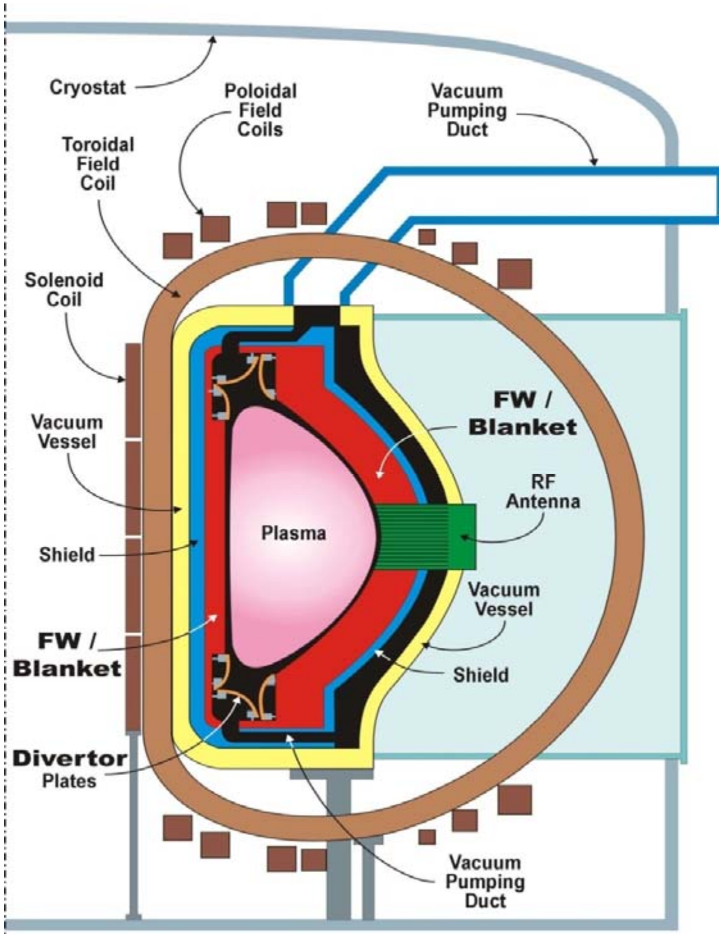
Extrapolation from other technologies shows expected MTBF for fusion blankets/divertor is as short as ~hours/days, and MTTR ~months
GRAND Challenge: Huge difference between Required and Expected!!

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)

Stages of Blanket R&D

Classification is in analogy with other technologies. Used extensively in technically-based planning studies, e.g. FINESSE. Used almost always in external high-level review panels.

- **Stage 0 : Exploratory R&D**
  - Understand issues through basic modeling and experiments
- **Stage I : Scientific Feasibility and Discovery**
  - Discover and Understand new phenomena
  - Establish scientific feasibility of basic functions (e.g. tritium breeding/extraction/control) under prompt responses (e.g. temperature, stress, flow distribution) and under the impact of rapid property changes in early life
- **Stage II : Engineering Feasibility and Validation**
  - Establish engineering feasibility: satisfy basic functions & performance, up to 10 to 20% of MTBF and 10 to 20% of lifetime
  - Show Maintainability with MTBF > MTTR
  - Validate models, codes, and data
- **Stage III: Engineering Development and Reliability Growth**
  - Investigate RAMI: Failure modes, effects, and rates and mean time to replace/fix components and reliability growth.
  - Show MTBF >> MTTR
  - Verify design and predict availability of components in DEMO

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/m^2 on 10-30 m^2 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

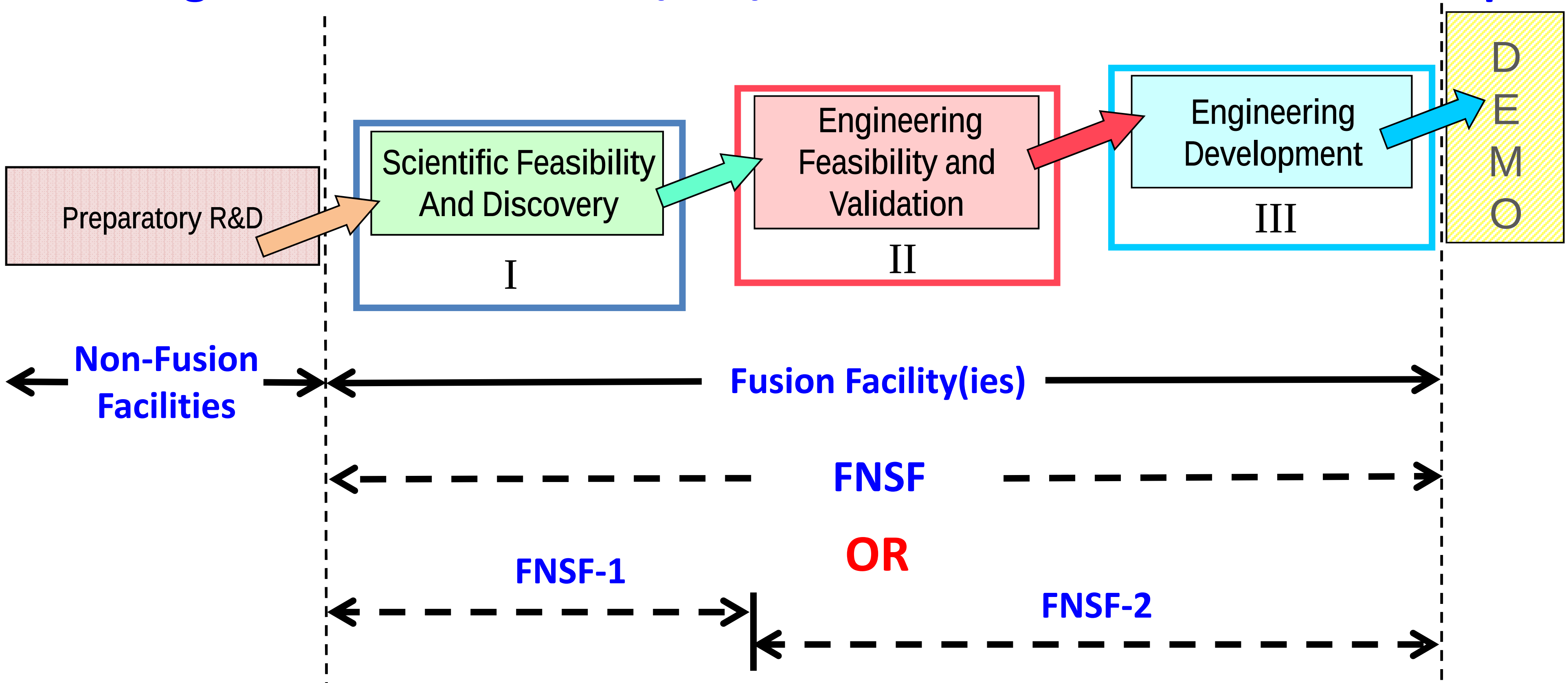
  - Normal conducting TF coil (to reduce inboard B/S thickness, also increase maintainability e.g. demountable coils).

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)

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, …

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!