

# Technologies Needed for Fusion DEMO and the Role of International Collaboration

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*Related publications can be found at [www.fusion.ucla.edu](http://www.fusion.ucla.edu)*

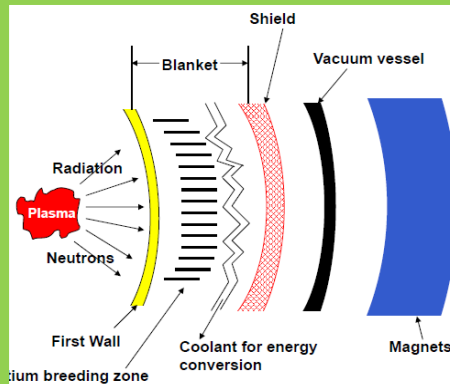
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# Key Technical Challenges beyond ITER

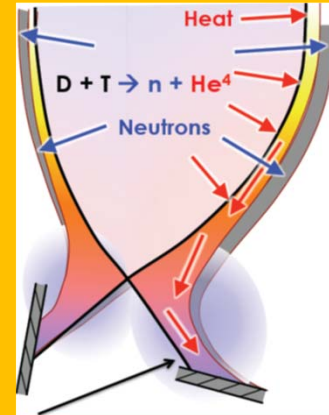
## FNST: Fusion Nuclear Components (In-Vessel Components: Blanket/FW, Exhaust/Divertor) and associated technical disciplines (Materials, RAMI, Tritium)

### Blanket / FW

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



### Exhaust / Divertor



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

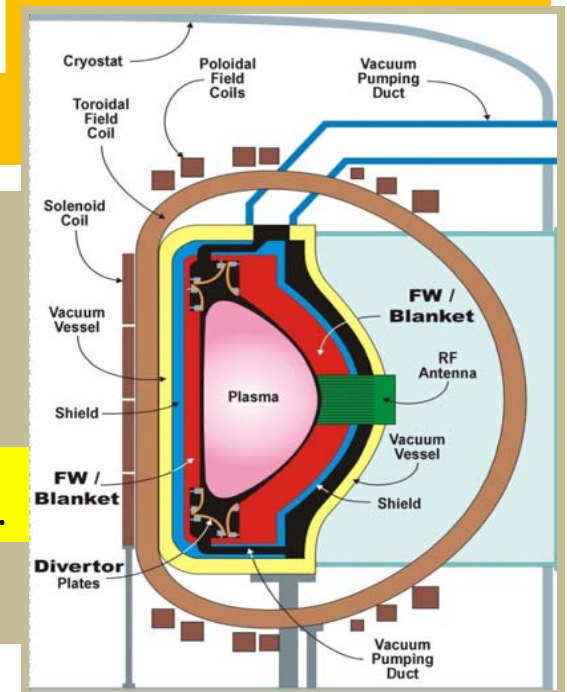
### Materials

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

### Reliability / Availability / Maintainability / Inspect. (RAMI)

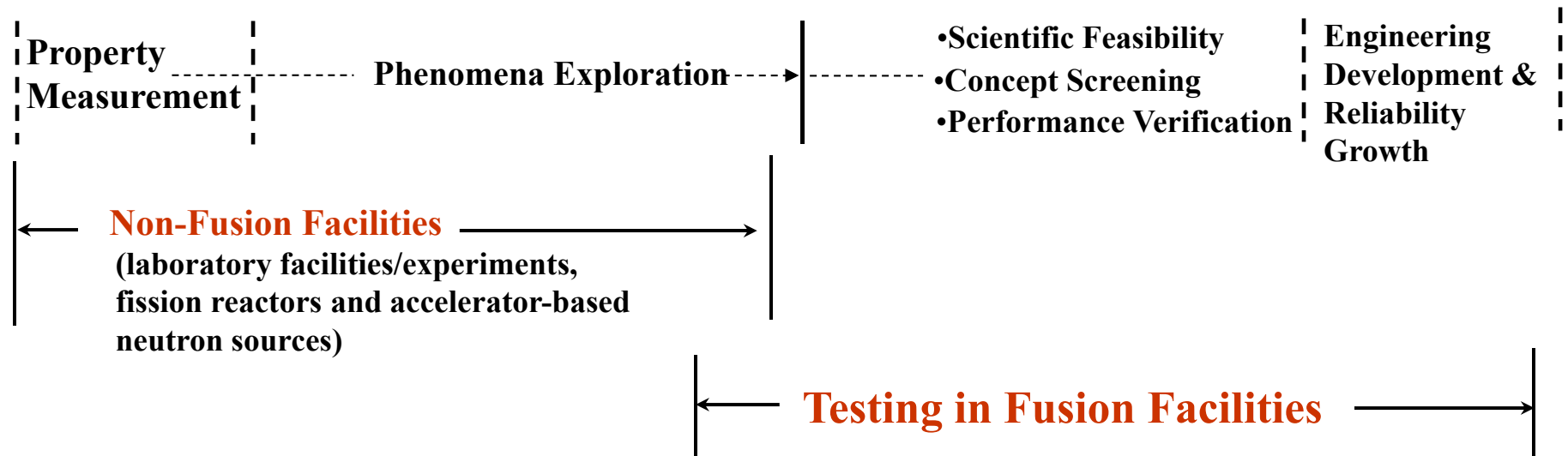
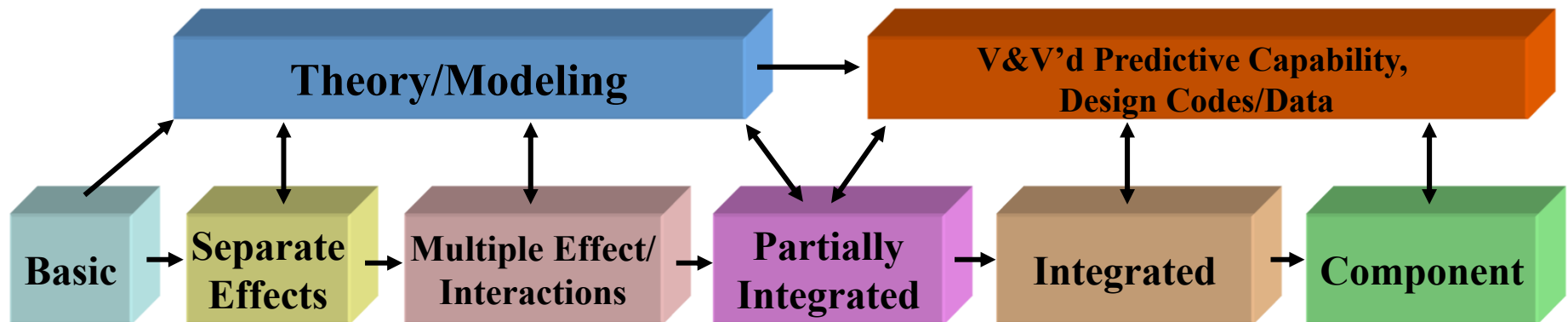
- FNCs inside vacuum vessel in complex configuration lead to fault intolerance and complex lengthy remote maintenance
- Estimated MTBF << required MTBF
- Estimated MTTR >> required MTTR
- No practical solutions yet
- How to do RAMI R&D?

**Low avail.**

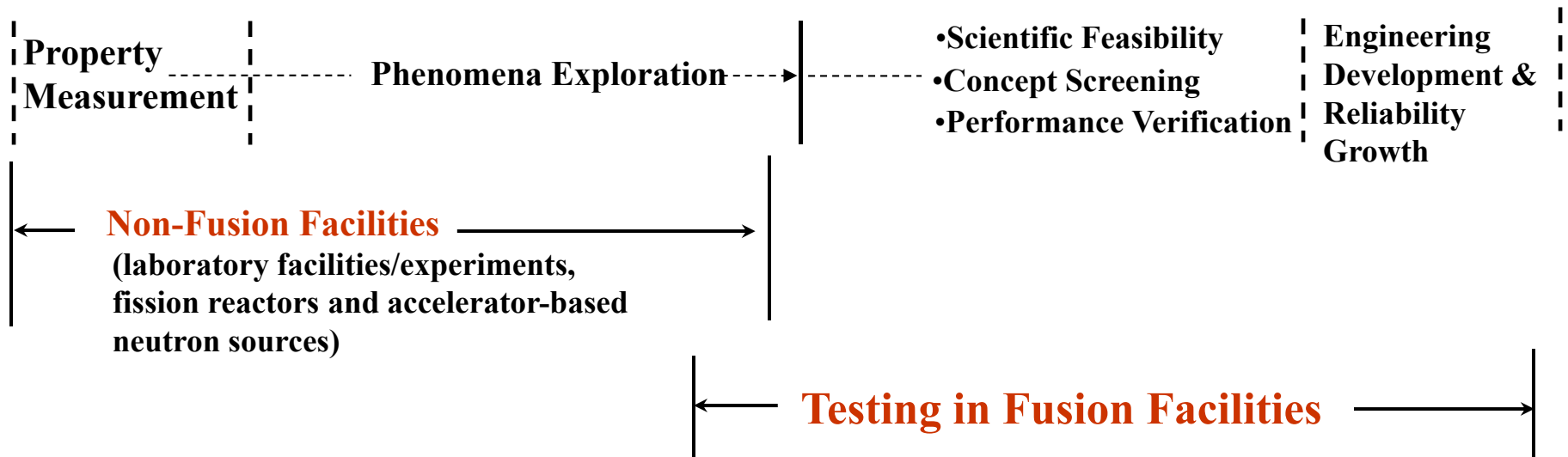
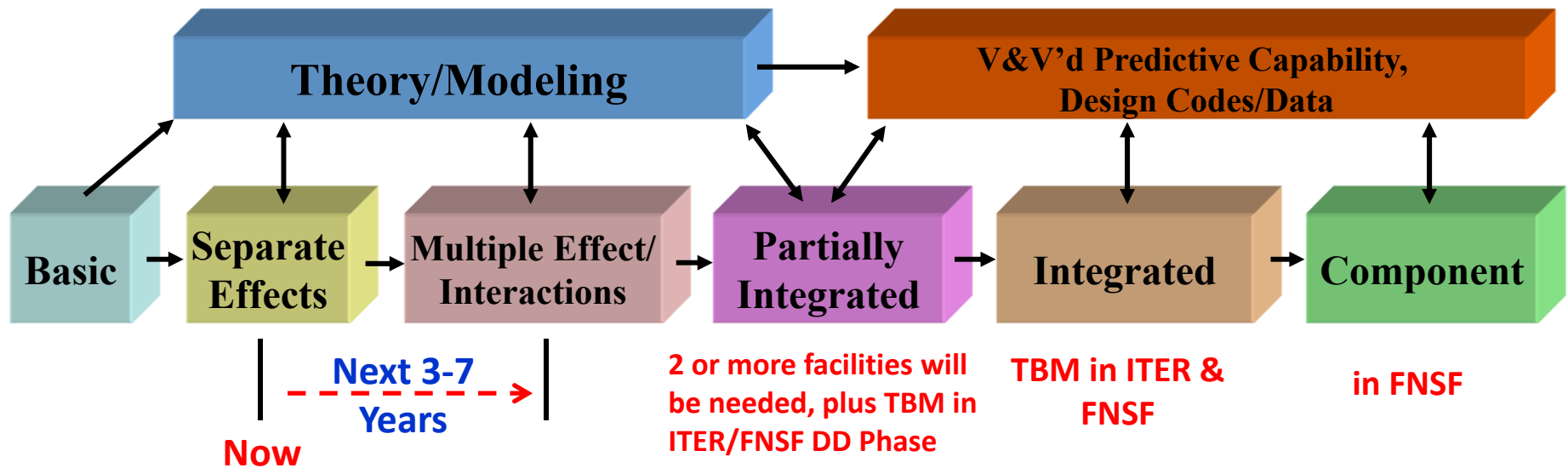


- **Serious Challenges that require aggressive FNST R&D and a well thought out technically Credible Pathway to DEMO**

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



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



**Recent research results (at UCLA) have shown clearly that the blanket/FW behavior in the fusion nuclear environment **cannot be predicted by synthesizing** results of separate effects**

**Moving forward with Multiple Effects/Multiple Interactions Experiments and Modelling is NECESSARY to understand and learn the behavior of blankets in the fusion environment**

### **Example: MHD Thermofluids**

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

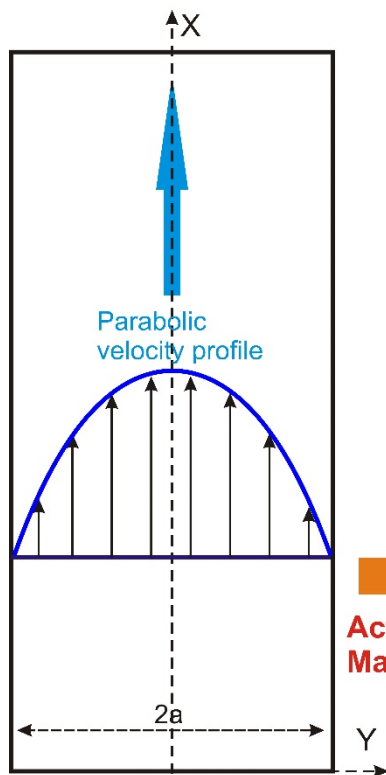
- 1) Why simulating multiple effects/multiple interactions is **NECESSARY**
- 2) Why planning and designing multiple effects laboratory facilities that can preserve the key phenomena of the fusion nuclear environment is a **very challenging scientific task!**

# Fusion Researchers for 30 years studied Liquid Metal MHD Flow Behavior in Blankets as if it were **PURELY** in the Presence of Magnetic Field (i.e. separate effect). So, the common assumption has been:

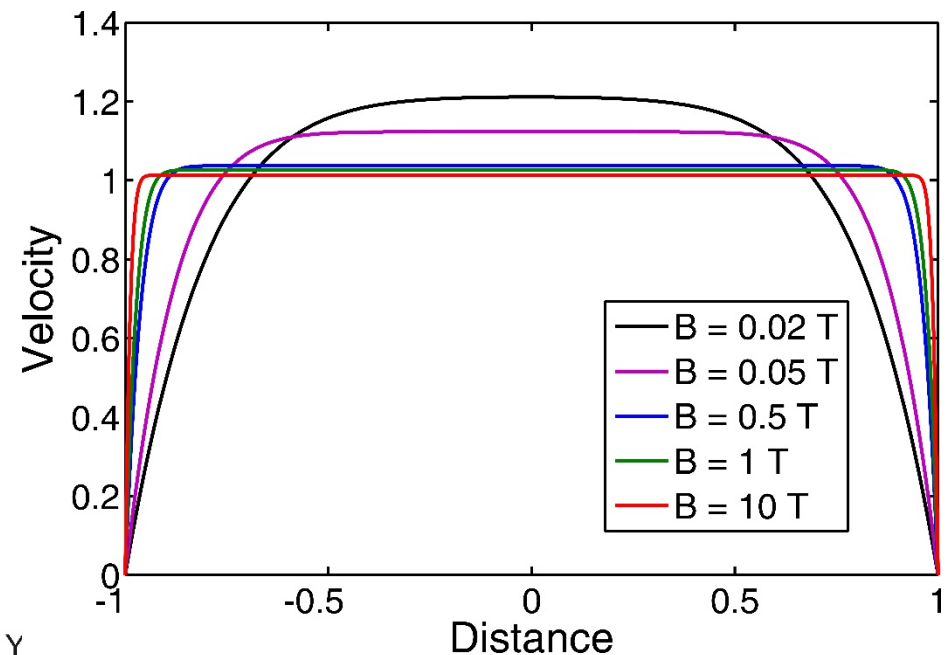
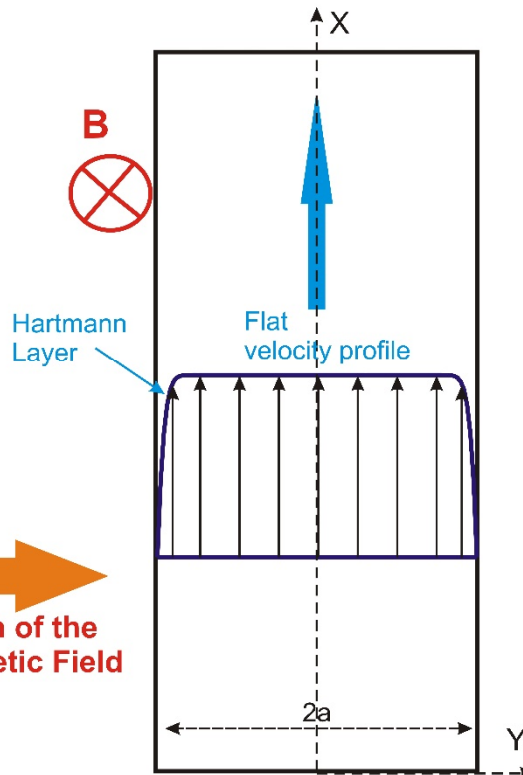
**Flow is Laminar:** Base laminar parabolic flow profile strongly altered by the action of the Lorentz force leading to **flat laminar core** and **very thin Hartmann and side layers**

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

Laminar Velocity Profile



Purely MHD Velocity Profile

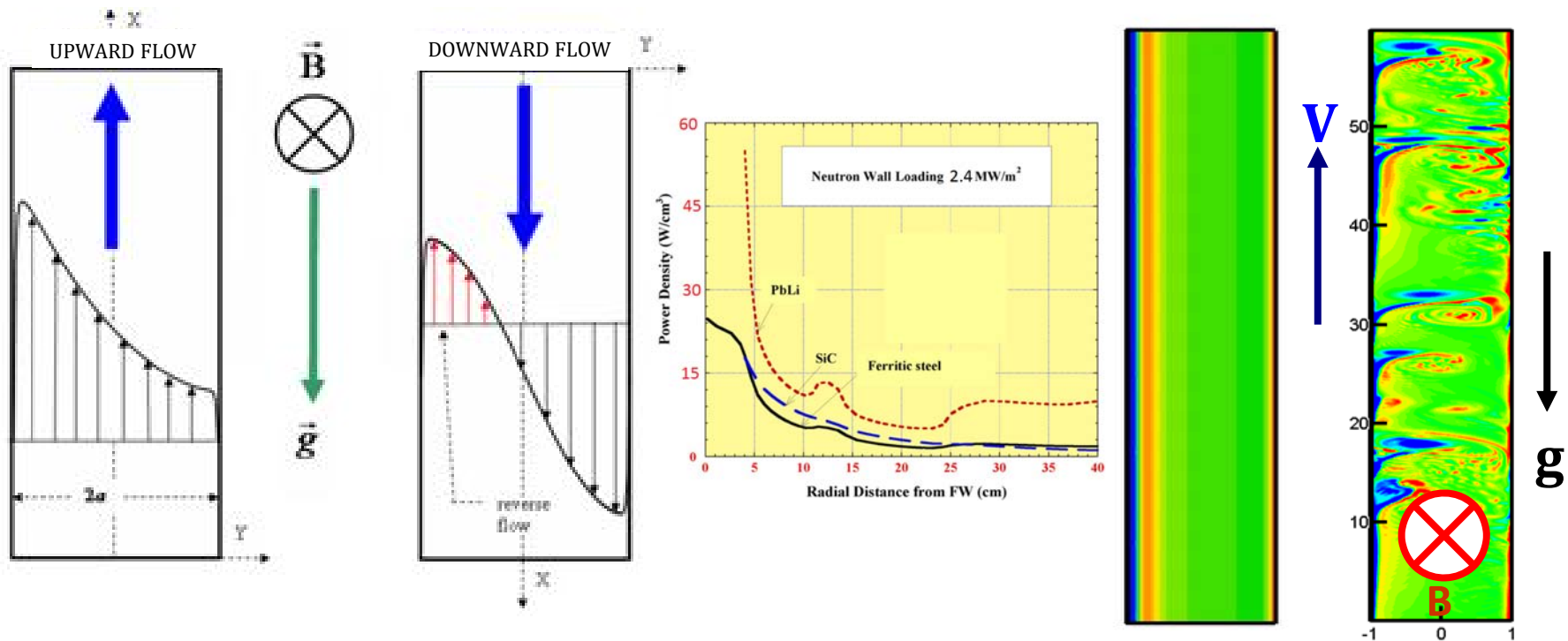


**Discovery:** Spatial gradients in nuclear heating & temperature in LM blanket combined with  $\vec{g}$  and  $\vec{B}$  lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior of the blanket in the fusion nuclear environment

lead to **Buoyant MHD interactions resulting in an unstable “Mixed Convection” flow regime**

**Base flow** strongly altered leading to velocity gradients, stagnant zones and even “**flow reversal**”

**Vorticity Field** shows new **instabilities** that affect transport phenomena (Heat, T, Corrosion)



*This result is from modeling at limited parameters in idealized geometry.*

- Blankets designed with current knowledge of phenomena and data will not work
- New: “Fusion Nuclear MHD” is very different from standard MHD in other fields

## What do we need to do to investigate “MHD Buoyant interactions/mixed convection flow” and other phenomena?

- Need to perform **multiple effects experiments** in which we can observe & characterize MHD mixed convection phenomena & discover new phenomena
- Need major initiatives to perform more integrated **phenomenological and computational modeling** using high speed computation (e.g. solve simultaneously Energy, Maxwell, and Navier-Stokes equations in a coupled manner, push for high performance parameters e.g. Ha, Gr, Re)

### Requirements in Experiments:

- 1) Simulation of volumetric heating and high temperature with steep gradients
  - 2) Provide flexible orientation of the channel flow w.r.t. gravity
  - 3) Provide sufficient volume inside the magnets to realistically simulate multi-channel flows with multi-material and geometry representation
  - 4) Include representative 3-component magnetic fields with gradients
  - 5) Use Prototypic Materials (e.g. PbLi, RAFM, SiC) and operating conditions (e.g. high T )
  - 6) Develop instrumentation techniques compatible with high-temperature liquid metals
- **We have been investigating how to satisfy the above requirements in upgrading the MaPLE facility at UCLA: Big challenges!!**  
Examples are highlighted in the next 2 slides



## Multiple effects experiments will necessarily be at scaled down conditions from blankets in DEMO. **How do we preserve phenomena?**

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

### Non-Dimensional Parameters

- Reynolds Number,  $Re = \frac{\text{Inertial forces}}{\text{Viscous forces}} = \frac{\rho u L}{\mu}$
- Hartmann Number,  $Ha = \left( \frac{\text{Electromagnetic forces}}{\text{Viscous forces}} \right)^{0.5} = BL \sqrt{\frac{\sigma}{\mu}}$
- Grashof Number,  $Gr = \frac{\text{Buoyancy forces}}{\text{Viscous forces}} = \frac{g \beta \Delta T L^3}{\nu^2} = \frac{g \beta \dot{q} L^4}{\nu^2 \kappa}$

- Need to consider these parameters in a coupled manner
- What is the “right combinations” of these Dimensionless Parameters to preserve phenomena? **Discovery of the right combinations is R&D by itself.****
- Examples of coupled parameters we should attempt to preserve in the experiments:
  - $Ha/Re$  – determines transition to turbulence in Hartmann layers
  - $r = \sqrt{Gr/Ha Re \left(\frac{a}{b}\right)^2}$  - responsible for the shape of velocity and temperature profile in steady mixed-convection flows
  - $Ha/\sqrt{Gr}$  – determines transition from 3D to Q2D in MHD mixed-convection flows

# Non-Linear LM MHD Phenomena is difficult to scale from experiment to DEMO (Blanket scaling problem similar to plasma physics!)

**DEMO BLANKET:**  $Ha \sim 10^4$ ,  $Gr \sim 10^{12}$ ,  $Re \sim 10^5$

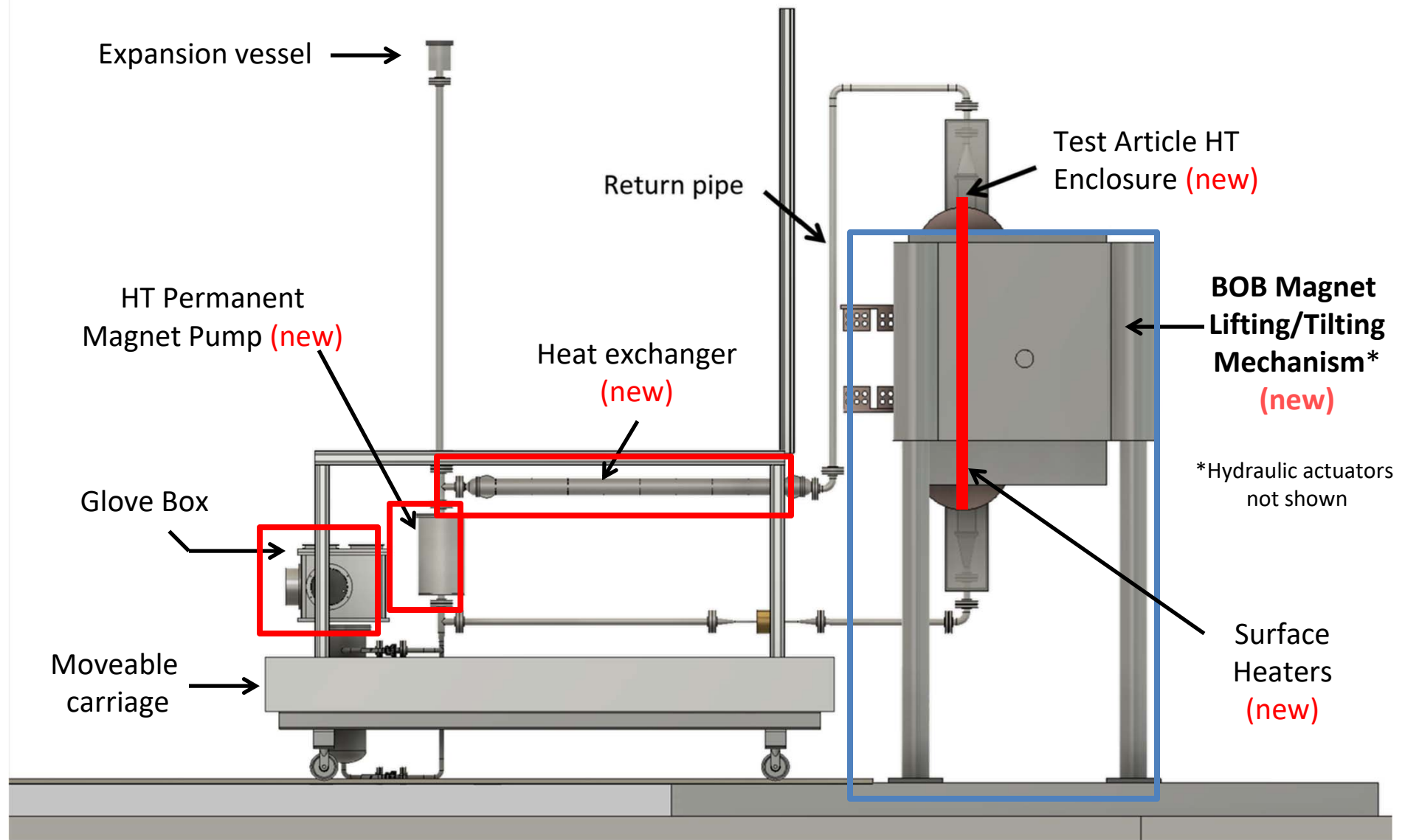
**EXPERIMENT:**  $Ha \sim 10^3$ ,  $Gr \sim 10^9$ ,  $Re \sim 10^5$

## Grand Challenge

Since blankets in DEMO/Power Reactors have very high parameters (e.g.  $Ha$ ,  $Gr$ ) that cannot be reached in laboratory, **how do we scale results from experiments to predicting Blanket behavior in DEMO?**

- Non-linear phenomena (difficult to scale)
- Higher  $Ha$  will suppress turbulence/instabilities
- Higher  $Gr$  will enhance buoyancy/instabilities
- **So, what will be the real behavior in the real blanket where both  $Ha$  and  $Gr$  are high?**

**Upgrading the MaPLE facility is underway at UCLA to investigate  
LM MHD behavior in multiple effect environment: Heating & Temperature  
Gradients combined with  $\vec{g}$  and  $\vec{B}$ , prototypical materials and conditions**  
**Exemplary Partnership between UCLA and EUROfusion**



# International collaboration, if utilized effectively, can play a major role in advancing FNST and Fusion development

## Example: USA/UCLA Experience

- Several years ago, we realized that the US FNST/Blanket program suffers from
  1. Limited budget
  2. Not having its own ITER TBM or equivalent project
- Given this situation, we developed a **vision** to make progress on FNST and Material Interactions/Blanket/FW/Tritium:
  1. Focus on R&D in **niche** areas of US scientific strength, capability, and leadership that we presented at community forums, discussed and agreed upon with FES, and that are consistent with the FES ten-year perspective
  2. Use these **niche** research areas to attract and enable effective **international collaboration opportunities**
    - Allows access to resources, materials, R&D results, and TBM and DEMO designs and experiments of the much larger international FNST programs at low cost and low level of commitment
    - Keeps US research and designs still grounded in the practical concerns of building and deploying real, safe, reliable nuclear components for when the US does commit to building an FNSF

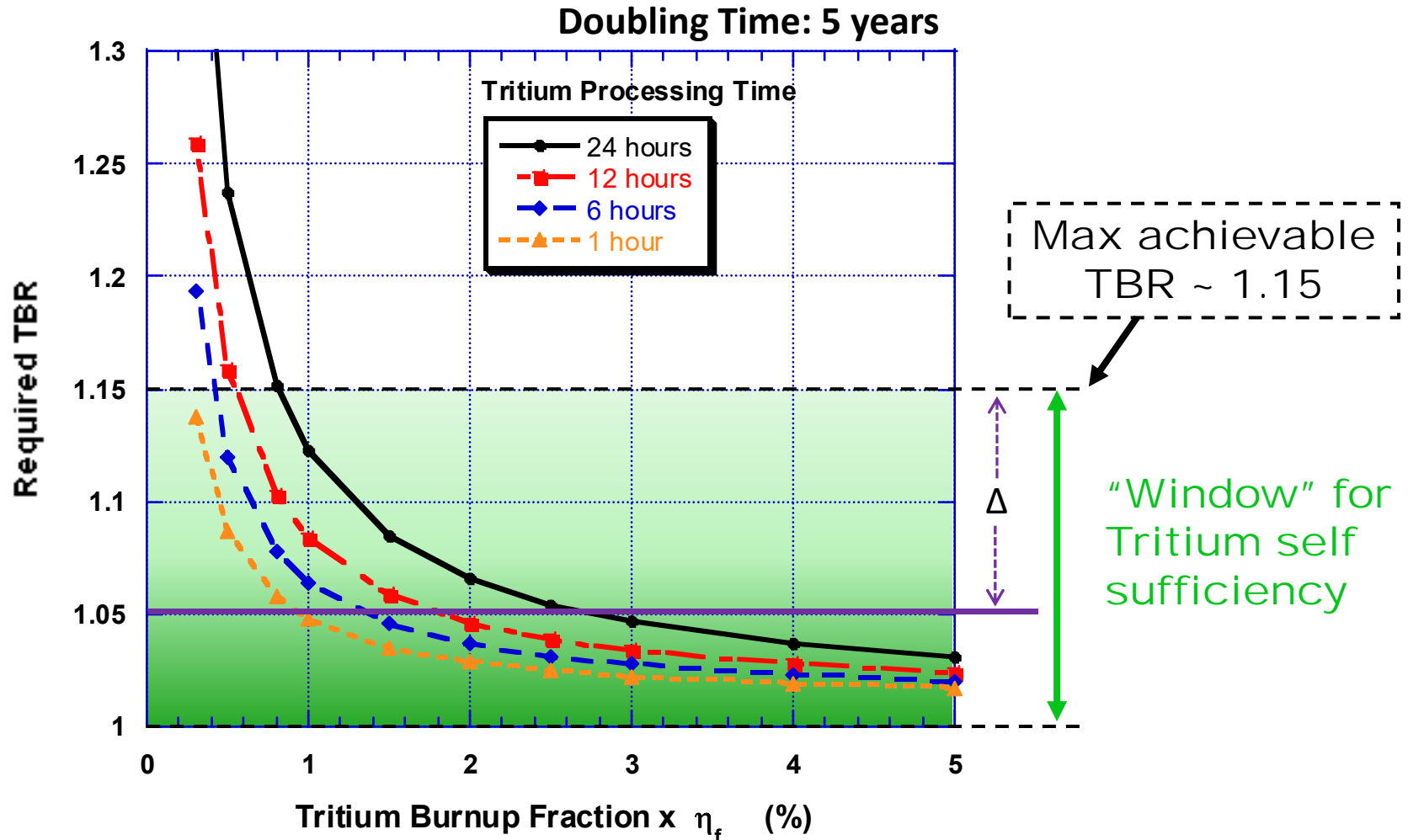
# **UCLA International collaboration Agreements are based on Mutual Benefits**

- **UCLA –EUROfusion agreement** to explore multiple effects/interactions in liquid metal blankets
  - *Co-share cost of Upgrading the unique MaPLE Facility at UCLA to provide variable  $B$  w.r.t. gravity, simulated nuclear heating and temperature gradients, prototypical materials and conditions (e.g. high temperature PbLi)*
  - *Joint 3-year experiments with EU scientists coming to UCLA*
- **UCLA-Korea (NFRI) agreement** to address key issues in ceramic breeder blankets
  - *Korea provides funds, fabricated materials, and access to Korean TBM*
  - *UCLA provides experience and performs experiments and modelling*
- **UCLA-India (IPR) agreement** to address key issues for LMs and ceramic breeders
  - *India provided funds, fabricated materials, and access to Indian TBM*
  - *UCLA provided experience, trained Indian scientists and performed experiments and modelling*

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

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

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



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

- T burnup fraction ( $f_b$ )  $\times$  fueling efficiency ( $\eta_f$ )  $> 5\%$  (not less than 2%)
- T processing time (in Plasma exhaust/fueling cycle)  $< 6$  hours

## Summary (1 of 2)

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

Blankets designed with current knowledge of separate effects phenomena and data **will not work**. The sources of this problem are:

1. The fusion nuclear environment has many fields with steep gradients (magnetic, neutrons, nuclear heating), and the blanket has many functions and materials – resulting in many yet undiscovered phenomena caused by multiple and synergistic effects/interactions
  2. Simulation of the full fusion nuclear environment in non-fusion facilities is impossible
  3. Accurate simulations of volumetric nuclear heating and temperature gradients is not possible
  4. The fusion conditions result in very high parameters (e.g. Ha, Gr) not achievable in the lab
  5. Phenomena such as MHD thermofluids is non-linear – so we do not know the scaling laws
- **We must build a number of laboratory facilities with strong capabilities to do the best possible simulation of the combined effects of the fusion nuclear environment and representative blanket mockups. A sequence of progressively more powerful facilities is needed (\$5M, \$20M, \$50M).** We also need a multiple of such facilities with different approaches to simulation to be constructed around the world.
  - We will also need to do much more serious modeling with high speed computation initiatives



## Summary (2 of 2)

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

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

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

For more details about topics in this presentation and other related technical areas, please see the following comprehensive recent article:

**Mohamed Abdou, Neil B. Morley, Sergey Smolentsev, Alice Ying, Siegfried Malang, Arthur Rowcliffe, Mike Ulrickson**

**“Blanket/first wall challenges and required R&D on the pathway to DEMO”**

**Fusion Engineering and Design, 100:2-43 (2015)**