Challenges and Pathways for Fusion Nuclear Science and Technology toward DEMO

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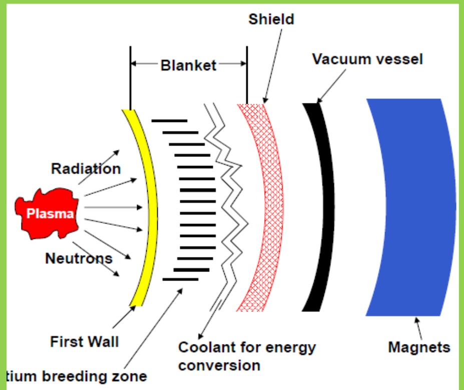
Key Technical Challenges beyond ITER

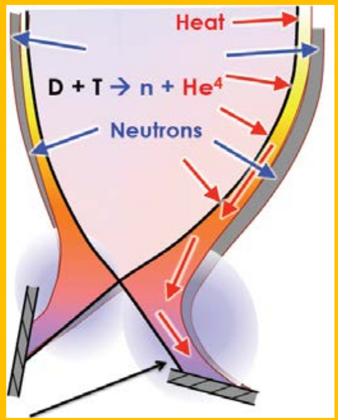
FNST: Fusion Nuclear Components (In-Vessel Components: Blanket/FW, Exhaust/Divertor) and associated technical disciplines (Materials, RAMI, Tritium)

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



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

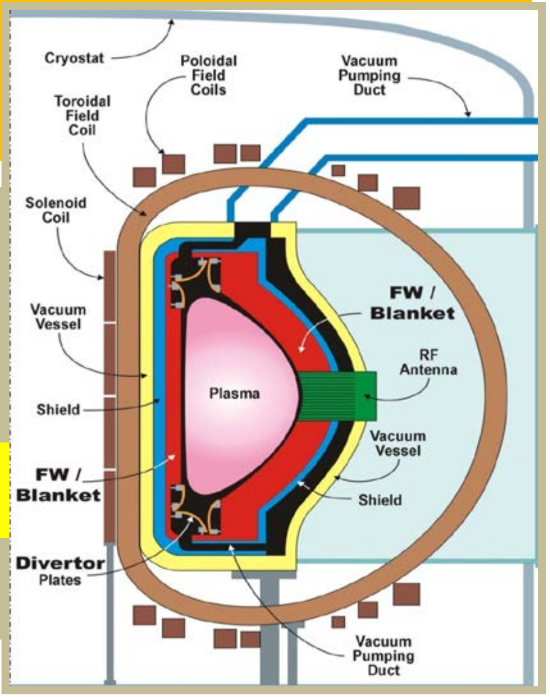
Materials

- 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**

Outline: presentation organized around Two Major FNST Topics that embody Key Challenges to developing Credible Pathway to DEMO

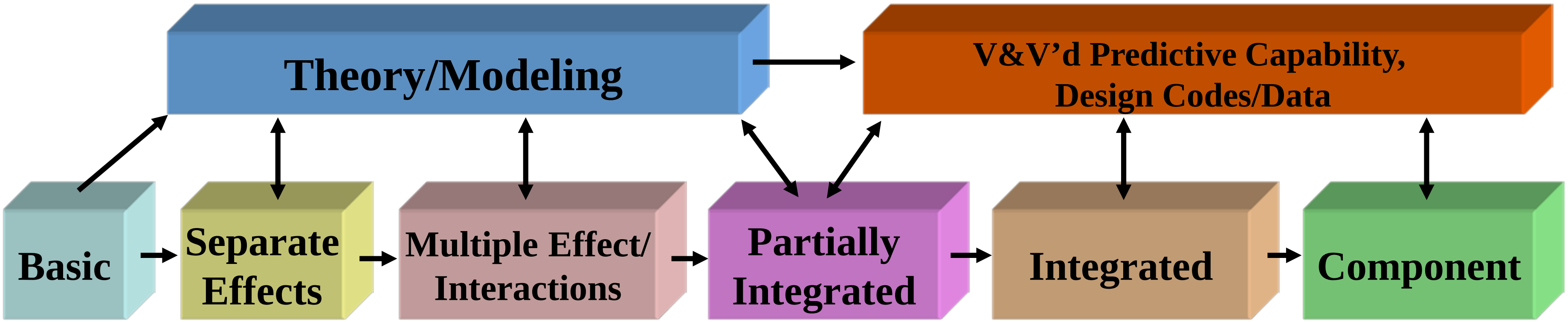
1) **FNST R&D in non-fusion facilities: Focus on "Multiple" Effects and Interactions in laboratory facilities**
   - Shifting from "Separate" to "Multiple" Effects Experiments is a MUST
   - Key questions: e.g. how to simulate volumetric heating and temperature with gradients in laboratory facilities
   - Limits on adequate simulation of blanket behavior in the fusion nuclear environment in modeling and non-fusion facilities
   - Sequence and characteristics of multiple effects facilities required in the next 3-10 years
2) **How do we do FNST R&D in the fusion nuclear environment before DEMO: FNSF Role, Issues, Features**
   a) **Fusion Nuclear Science Facility (FNSF) needed to perform FNST experiments**
      - Confronting the issue of RAMI
      - Tritium Self-Sufficiency Requirements and uncertainties
      - Staged approach to testing and development of blankets, PFC, Materials
      - How many FNSFs are needed, in each country and in the world

   b) **What is the optimum size and power for FNSF?**

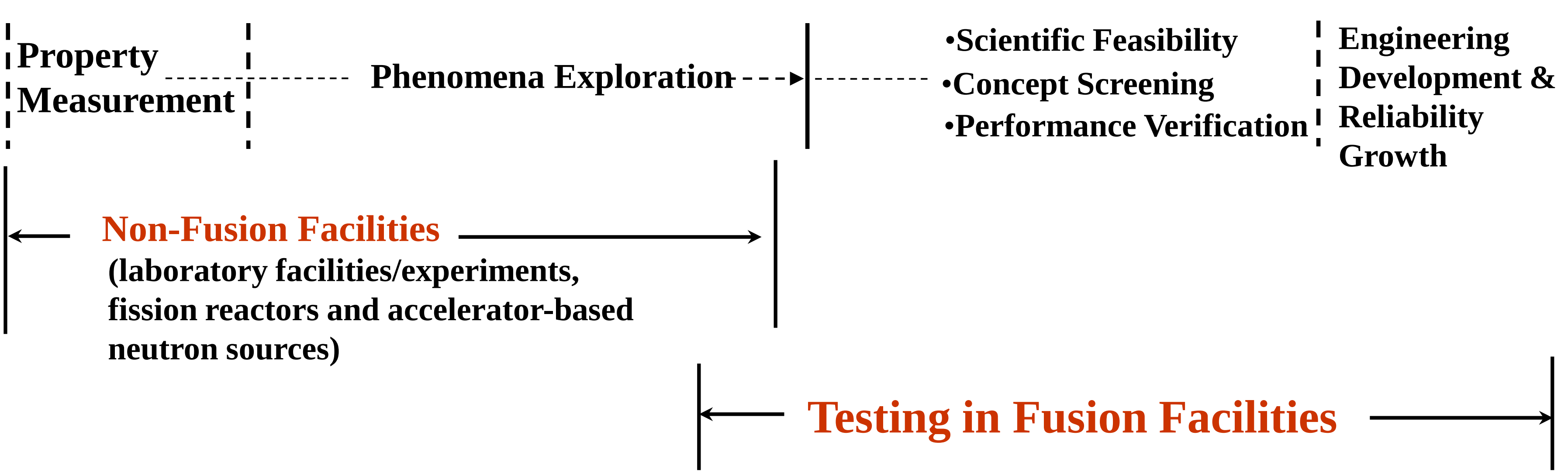
   c) **Can we skip FNSF and go directly to DEMO?**

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

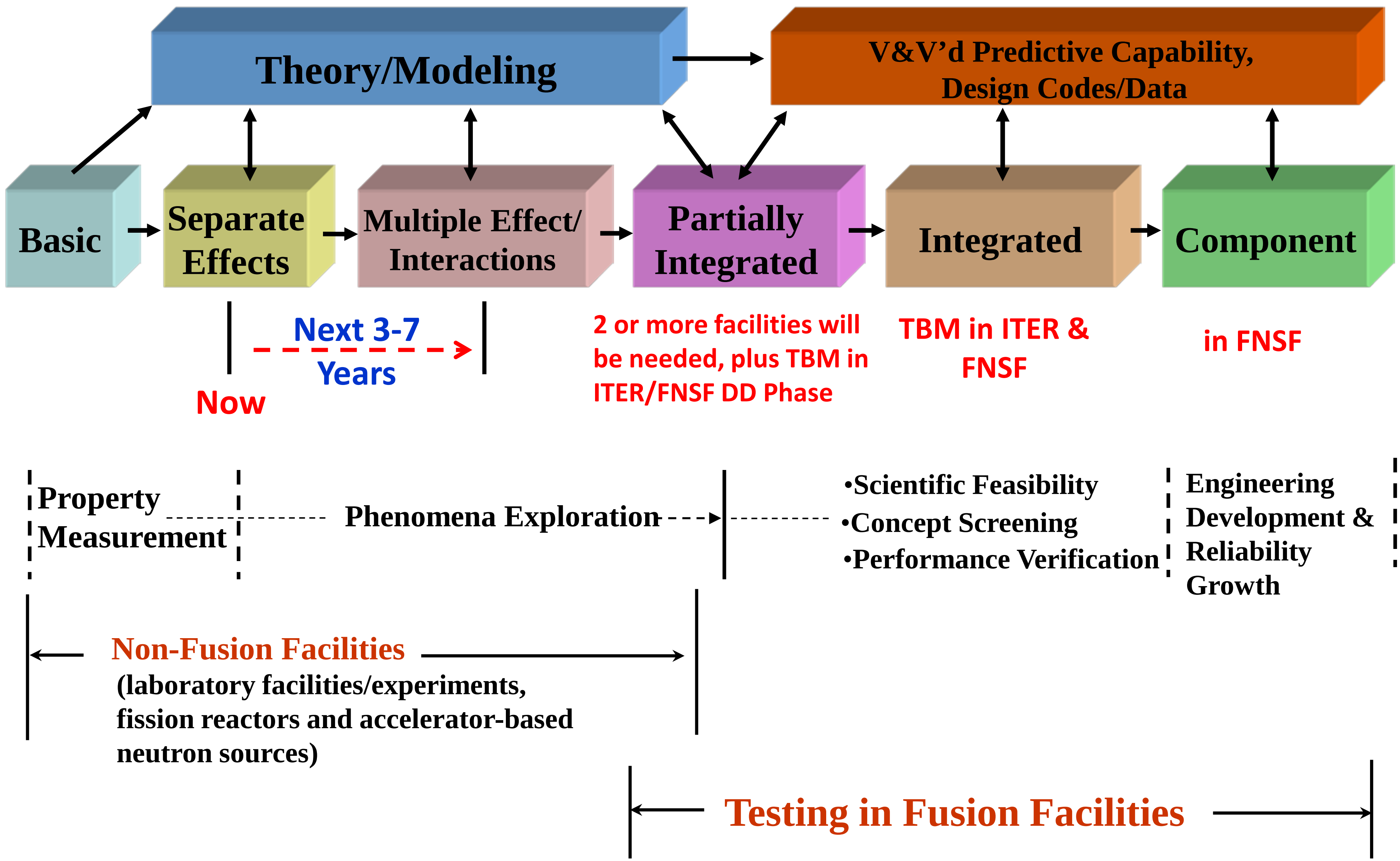
It should be utilized to identify and prioritize R&D Tasks



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



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

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

Example: MHD Thermofluids

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

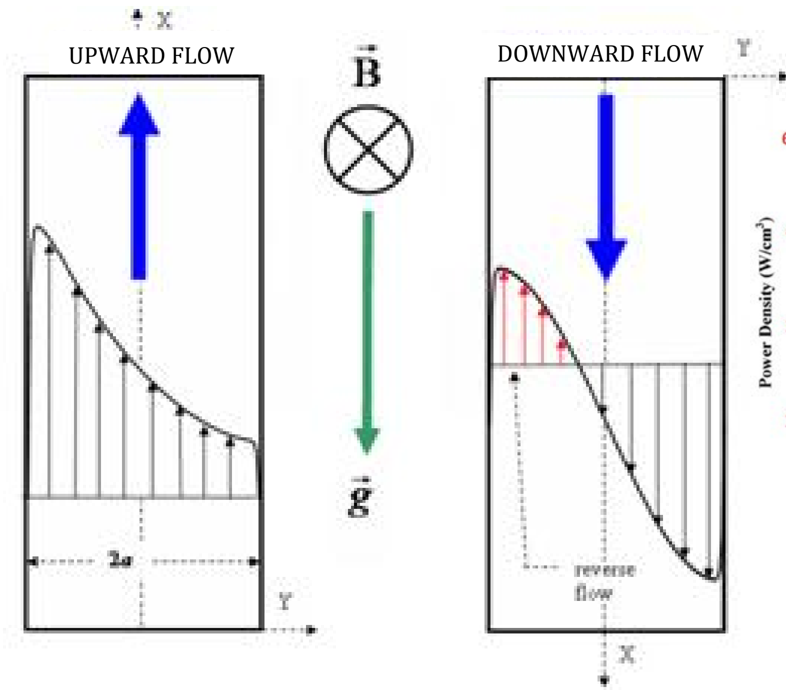
1) Why simulating multiple effects / multiple interactions is NECESSARY to correctly observe synergistic effects in the fusion nuclear environment, and
2) Scientific analysis of how to plan and design multiple effects laboratory facilities that can preserve the key phenomena (very challenging task!)

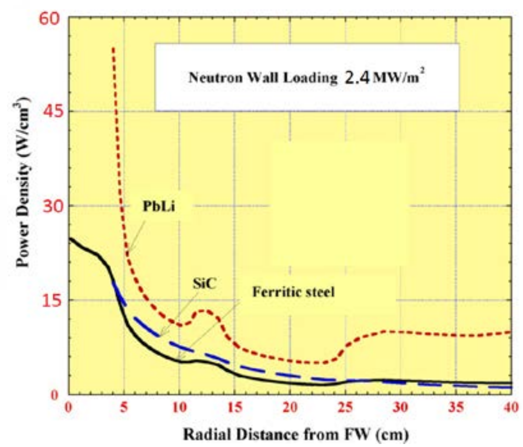
Example: Spatial gradients in nuclear heating & temperature in LM blanket combined with $\vec{g}$ and $\vec{B}$ lead to New Phenomena that fundamentally alter our understanding of the MHD Thermofluid behavior of the blanket in the fusion nuclear environment

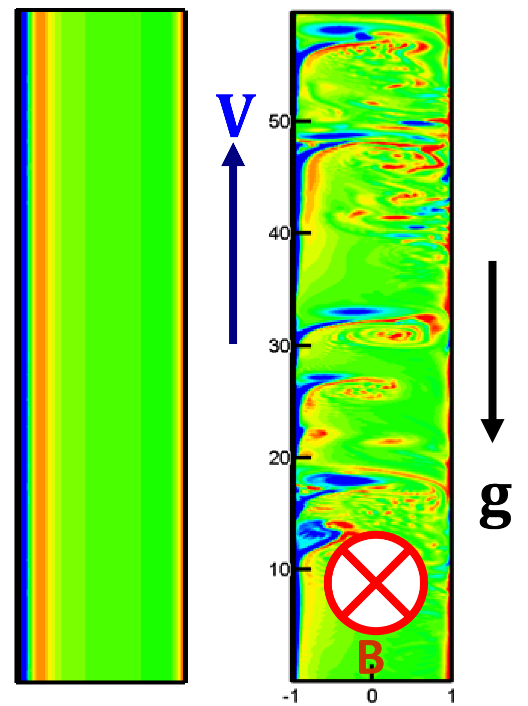
Buoyant MHD interactions result in "Mixed Convection" flow regime

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 <u>not</u> 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)

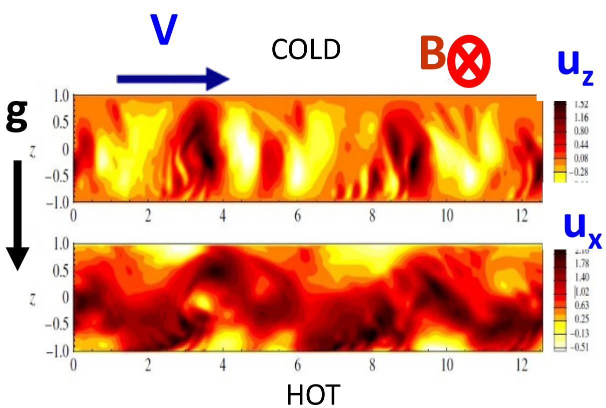
Requirements in Experiments:

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 the above requirements in order to upgrade the MaPLE facility at UCLA:** **Big challenges in satisfying all these requirements.** Key details are highlighted in the next several slides

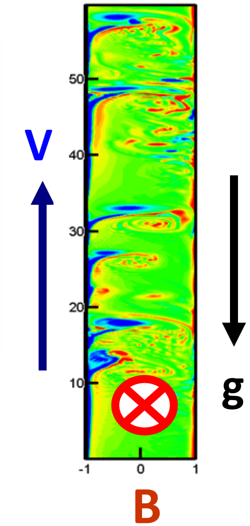
MHD Convection Phenomena:
Dependence on Gravity Orientation

- For **horizontal ducts**, the buoyancy forces are normal to the main flow direction. They induce secondary flows in the form of turbulent **"Rayleigh-Benard"** convective rolls*.



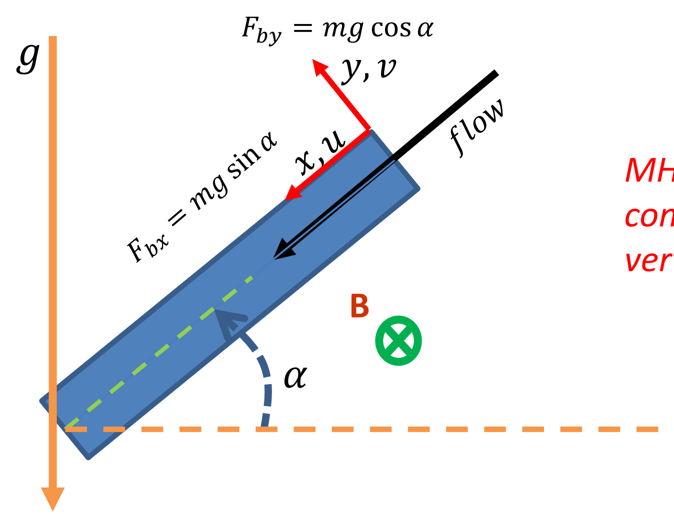
MHD Mixed convection in a horizontal duct.

- For **vertical ducts**, the buoyancy forces act in the main flow direction. Such flows experience **"Kelvin-Helmholtz"** instabilities and eventually become turbulent**.



MHD Mixed convection in a vertical duct.

- For **inclined ducts**, buoyancy forces act in both the main flow and the cross-stream directions. Given the **non-linear** nature of the flow physics, such flows cannot be predicted purely by the superposition of vertical and horizontal solutions. Detailed investigation of instabilities in inclined ducts is necessary.



Schematic illustrating the angle between the direction of gravity and fluid flow in the case of MHD convective flow in inclined ducts

* Zhang et.al, "*Mixed convection in a horizontal duct with bottom heating and strong transverse magnetic field*", J. Fluid Mech. (2014), vol. 757, pp. 33-56.

** Vetcha et.al, "*Study of instabilities and quasi-two-dimensional turbulence in volumetrically heated magnetohydrodynamic flows in a vertical rectangular duct*", Phys. Fluids 25, 024102 (2013)

Multiple effects experiments will necessarily be at <u>scaled down</u> 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, $Re = \frac{Inertial\ forces}{Viscous\ forces} = \frac{\rho u L}{\mu}$
➢ Hartmann Number, $Ha = \left(\frac{Electromagnetic\ forces}{Viscous\ forces}\right)$^0.5 $= BL\sqrt{\frac{\sigma}{\mu}}$
➢ Grashof Number, $Gr = \frac{Buoyancy\ forces}{Viscous\ forces} = \frac{g\beta\Delta T L^3}{\nu^2} = \frac{g\beta\dot{q}L^4}{\nu^2\kappa}$

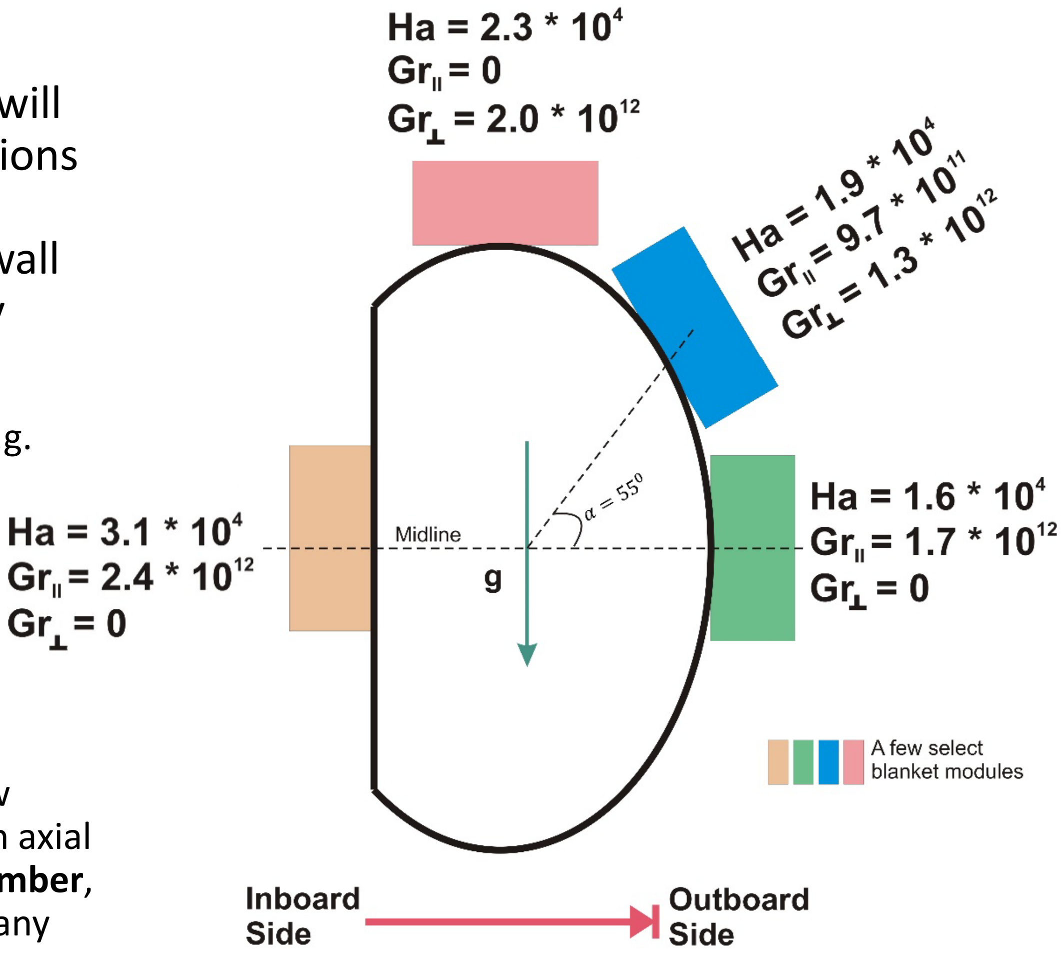
- Need to consider these parameters in a coupled manner
- **What is the "right combinations" of these Dimensionless Parameters to preserve phenomena? Discovery of the right combinations is R&D by itself.**
- Examples of coupled parameters we should attempt to preserve in the experiments:
    - Ha/Re – 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

The Blanket in DEMO/Power Reactors is <u>NOT</u> one set of conditions

- The Blanket has many modules, each will have its own MHD thermofluid conditions (e.g. different Ha, Gr) because of variations in magnetic field, neutron wall load and flow orientation w.r.t. gravity (see figure).
- We have a wide range of parameter values, e.g.
  - **Parallel radial Grashof Number**

    $Gr_{\parallel} = Gr_{eq} * \cos(\alpha);$
  - **Perpendicular radial Grashof Number**

    $Gr_{\perp} = Gr_{eq} * \sin(\alpha);$
- Furthermore, the temperature rise in the flow direction can also be fairly significant. Such an axial ΔT can be used to define an **axial Grashof number**, understanding of which is also paramount in any blanket design efforts.



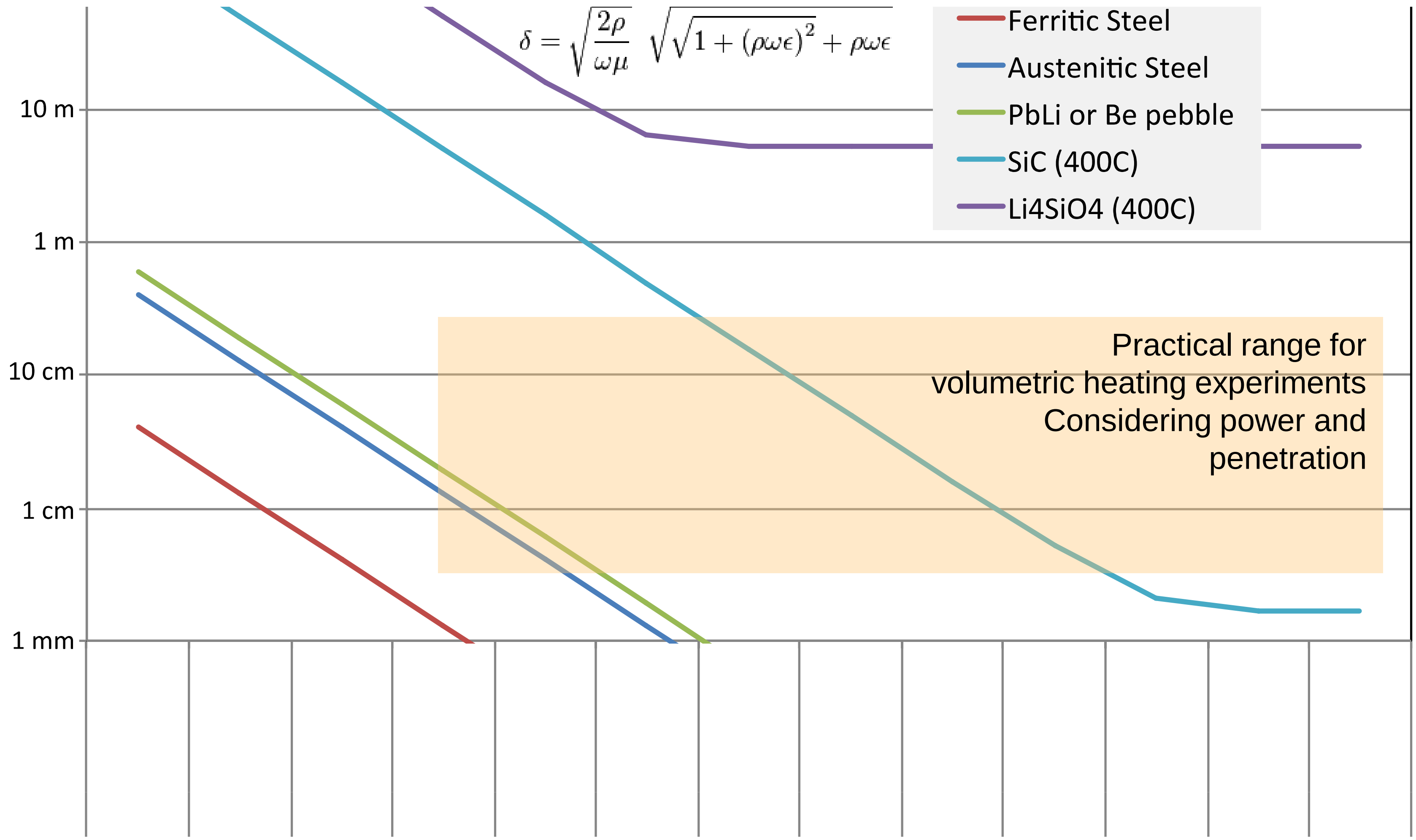
- **Therefore, each module needs to have its own design**
- **Experiments need to cover the range of conditions & phenomena in various modules.**

- *Rapisarda et.al, *"Overview of DCLL research activities in the EU/Spain"*, Pulsed Power Conference & Symposium on Fusion Engineering – PPC 2015 SOFE, Austin, Texas.
- *Smolentsev et.al, *"Inboard DCLL blanket with sandwich flow channel insert using the EU DEMO1 as a reference plant layout"*, Internal Report UCLA.

Options are limited for simulating volumetric nuclear heating in lab facilities

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

Skin Depth for various materials show only limited opportunities to use microwave or induction heating



Hard to get high power at very low frequency

Cost effective ~ 2.5 GHz

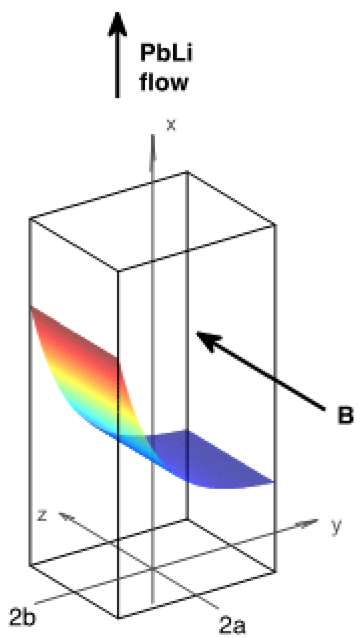
There is no practical method for simulating volumetric heating in LM laboratory experiments. So What should we do?

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

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

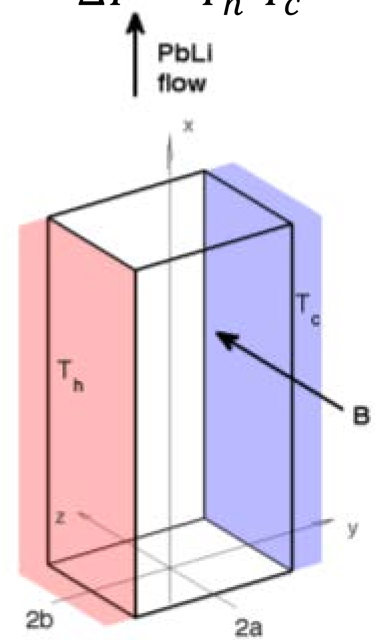
Reference Blanket:
volumetric Nuclear heating

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



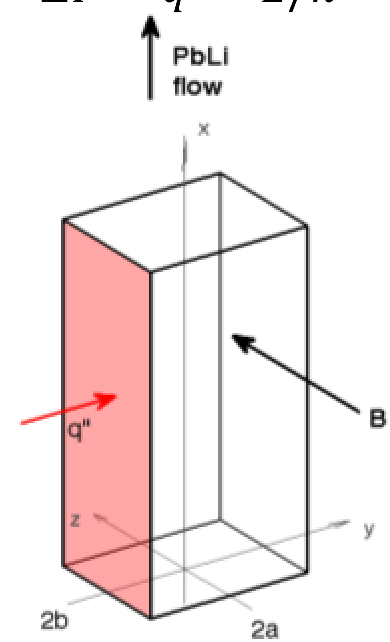
Experiment:
Flowing external hot fluids and constant T B.C.

$$\Delta T = T_h\text{-}T_c$$



Experiment:
surface heating/insulation

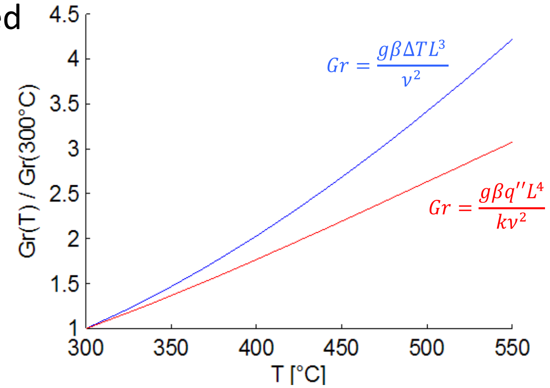
$$\Delta T = q'' * L/k$$



How high Gr, Ha, Re can we reach in experiments?

	Flowing external hot fluids with constant T B. C. ΔT [°C] $Gr = \frac{g\beta\Delta T L^3}{\nu^2}$			Surface Heating / Insulation q" [MW/m²] $Gr = \frac{g\beta q'' L^4}{k\nu^2}$		
PbLi Temp.	10 °C	50 °C	100 °C	0.1 MW/m^2	0.5 MW/m^2	1.0 MW/m^2
300 °C	0.4 x 10^8	2.1 x 10^8	4.2 x 10^8	1.6 x 10^9	8.0 x 10^9	16.0 x 10^9
550 °C	1.8 x 10^8	8.9 x 10^8	17.8 x 10^8	4.9 x 10^9	24.6 x 10^9	49.2 x 10^9

1) In calculations of experimental Ha, Re, Gr MaPLE PbLi loop at UCLA is assumed
2) Gr is strongly depended on temperature and channel size



BLANKET (DCLL): Ha~10^4, Gr~10^{12}, Re~10^5

EXPERIMENT: Ha~10^3, Gr~10^9, Re~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 DEMO Blanket?**
  - 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?**

ALL Liquid Metal Blankets are Affected by Buoyant forces resulting in MHD Mixed Convection Phenomena

Helium-Cooled Lead Lithium (HCLL)

- **Most affected**
- Forced flow velocity, V_f, is only ~ 1 mm/sec compared to buoyant flow velocity V_b ~ 20 cm/sec **(V_b/V_f ~ 200)**

Dual Coolant Lead Lithium (DCLL)

- **Strong effect**
- Forced flow velocity is ~ 10 cm/sec **(V_b/V_f ~ 2)**

Self-Cooled LM

- **Smaller effect** with volumetric heating
- Forced flow velocity is ~ 0.5 – 1.0 m/sec **(V_b/V_f ~ 0.2 – 0.4)**
- But **Surface Heating will substantially increase buoyancy effects** (this may help make self-cooled LM blankets feasible again?!)

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

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

  Compelling examples from recent discoveries show that blankets designed with current knowledge of 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
- **But even with the aggressive R&D in non-fusion facilities that we must do, we will still have serious uncertainties in predicting the blanket behavior in the fusion nuclear environment**

What should the next DT Fusion Facilities (Other than ITER) be?
Three key facts must be considered in deliberating on this question

- **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 (at least the 1st stage) is to perform FNST experiments to discover synergistic effects and learn about blanket/PFC/Materials integrated behavior in the fusion nuclear environment. The next DT fusion facility cannot be for validation or demonstration.

- **RAMI is the "Achilles heel" for fusion. RAMI will be the key issue in determining the feasibility of plasma confinement configurations and blanket concepts**
  - MTBF for Blanket/FW/PFC in any DT fusion Device is estimated to be very short while MTTR is predicted to be too long – leading to very low availability of only a few percent - **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.**

Necessary R&D Stages of Testing FNST components in the fusion nuclear environment prior to DEMO

Non-fusion facilities

Preparatory R&D

Modeling and experiments in non-fusion facilities

- Basic property measurement
- Understand issues through modeling and single and multiple-effect experiments

None of the top level technical issues can be resolved before testing in the fusion environment

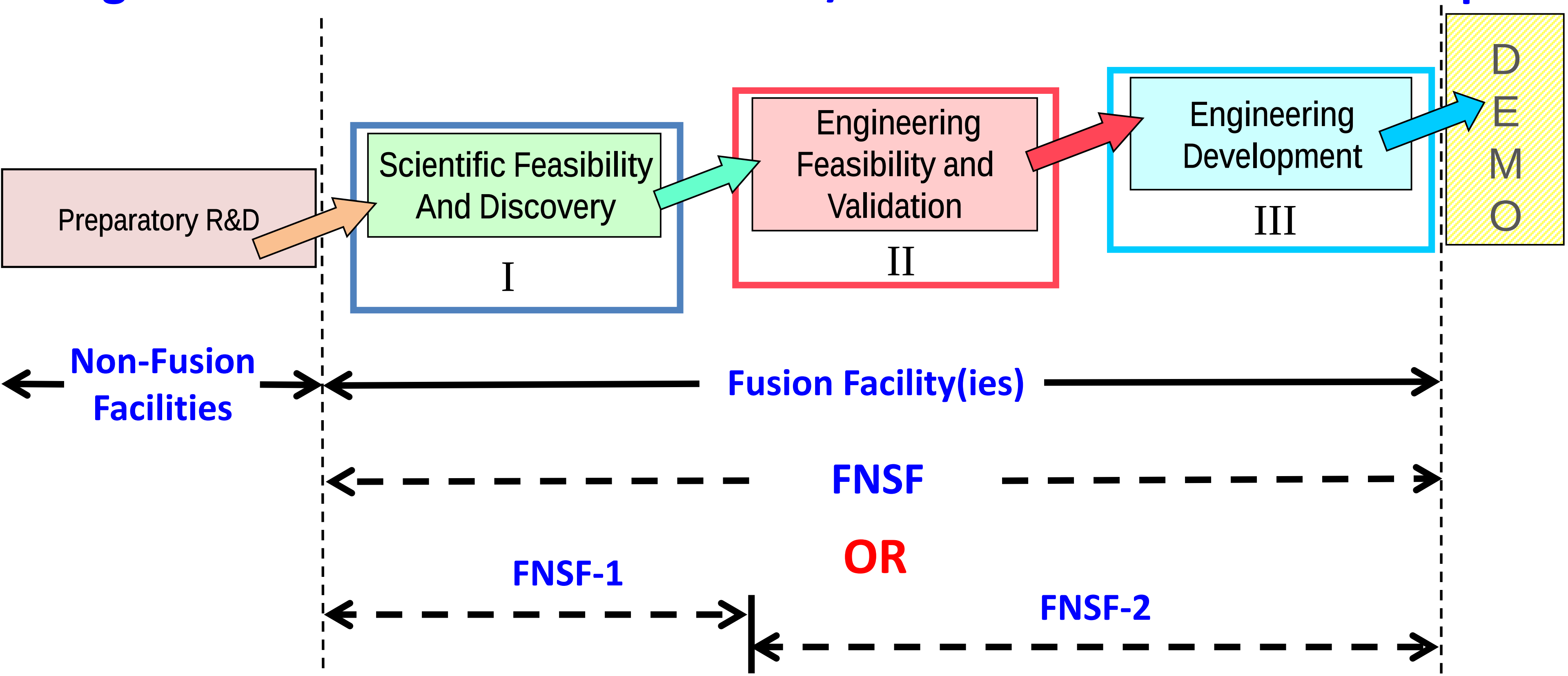
FNST Testing in Fusion Facilities

Scientific Feasibility	Engineering Feasibility	Engineering Development
Stage I	Stage II	Stage III
0.1 - 0.3 MW-y/m²	**1 - 3 MW-y/m²**	**> 4 - 6 MW-y/m²**
≥ 0.5 MW/m² **burn > 200 s**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**	**1-2 MW/m²** **steady state or long burn** **COT ~ 1-2 weeks**
Sub-Modules/Modules	Modules (10-20m²)	Modules/Sectors (20-30m²)
• Discover and understand new synergistic phenomena • Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid property changes in early life	• Establish engineering feasibility of blankets/PFC/materials (satisfy basic functions & performance, up to 10 to 20% of MTBF and of lifetime) • Show basic RAMI feasibility	• RAMI: Failure modes, effects, and rates and mean time to replace/fix components and reliability growth • Verify design and predict availability of FNST components in DEMO

DEMO

- **We need to build one (or more) Fusion Nuclear Science Facility (FNSF) as an experimental DT fusion facility in which we do the necessary experiments (Stages I, II, III) of FNST components development in the fusion nuclear environment prior to DEMO**

Planning the Pathway to DEMO Must Account for Unexpected Negative Results for Current Blanket/PFC 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?! (2 or 3 around the world)

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)

Why FNSF should be low fusion power, small size

- To reduce risks associated with external T supply and internal breeding shortfall
- Reduce Capital, operating cost, and replacement time (note Blanket/FW/ Divertor will fail and get replaced many times)
- Avoid accumulating "mountains" of Radwaste from failed FNST components
- Satisfy FNST key requirement 1-2 MW/m^2 on 20-30 m^2 test area

- Cost/risk/benefit analyses* led to recommendations for Tokamak FNSF:
  – Fusion Power < 150 MW
  – Size comparable to JET (R < 3 m)
  – Low Q plasma (2-3) - and minimize extrapolation in physics from JET
  – Normal conducting TF coils (to reduce inboard B/S thickness, also increase maintainability e.g. by using demountable coils).

Plan FNSF scope, mission, power, and size such that we can build it the soonest (parallel to ITER). Avoid planning FNSF to be very ambitious since this has the risk of ever rising costs and very lengthy schedule delays (learn the lesson of ITER)

**References IEA study: M. Abdou et al., Fusion Technology 23:1-57 (1996); also UCLA/GA/ORNL studies 2010-2013; see www.fusion.ucla.edu*

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. (for internal use in FNSF and to accumulate the required T inventory for DEMO startup)
  - 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 selected 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

- The DD phase of FNSF should be utilized to optimize the plasma and test divertor and blankets with true materials and design

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

- DD phase has important 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)**

After first stage, 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 & other materials:
  - no uncertainty in spectrum or other environmental effects
  - prototypical responses, e.g., gradients, materials interactions, joints, …

Degree of "prototypicality" between FNSF and DEMO?

- Some researchers have recently advocated that FNSF should be as close as possible to DEMO in order to minimize the gap between FNSF and DEMO
  - But our analysis in comprehensive studies over 30 years provides different conclusion
- The major issue in fusion development now is that
  - We don't know how FNST components will behave in the fusion nuclear environment
  - R&D to test and qualify the FNST components is likely to require long time with success not assured (we do not even have scientific feasibility yet!)
  - The seriousness of the RAMI issue makes the risks very high

- Our concern now should be how to build a practical FNSF with minimum extrapolation of physics and technology (Be technically credible!)
- The focus of FNSF should be on **prototypical "in-vessel" fusion nuclear components** which are missing from ITER
- Components outside the vacuum vessel (e.g. S.C. magnets) are already prototypical and tested in ITER at an almost the same scale as DEMO- no need to be prototypical in FNSF
- An approach that makes FNSF close to DEMO will have:
  - Much larger size than needed for FNSF testing mission
  - Much larger capital and operating costs
  - Longer replacement time and accumulation of much Radwaste
  - Extremely Risky

Think of: "Now + 1" NOT "DEMO – 1"

Trying to skip FNSF is like if we had tried to skip ITER and go directly from a JET plasma to DEMO

- The stated motivation to skip FNSF and proceed to DEMO is to shorten the time for development and commercialization of fusion power
  - DEMO studies are important for the world to provide a vision for a DEMO
  - Trying to shorten the time for development of fusion power is important if a credible pathway is found
- **But any DT device which will be built going forward in which the fusion nuclear components are exposed to the fusion nuclear environment for the first time will serve the function of FNSF regardless of name DEMO or FNSF**
- We should think of a new approach to international collaboration much different from the ITER model. For example:
  - 2 or 3 countries each build its own FNSF and share results and experience
  - Other countries can contribute more to R&D for FNSF and DEMO
  - Each Major Country builds its own DEMO when there is enough data, experience, testing, and qualification of fusion nuclear components in the fusion nuclear environment (from FNSF)

ITER TBM is Important and Must be fully supported

- ITER TBM will provide important information in the fusion nuclear environment
- But ITER TBM has limitations
  - Fluence limited to 0.1 MW · y/m^2
  - Limitations on replacing failed TBMs
  - One test module per blanket concept
  - Not all blankets will be tested (e.g. DCLL)

- Even with FNSF parallel to ITER, it is still prudent to utilize ITER for TBM testing in addition to testing in FNSF because:
  1. No extra cost for facility: Substantial capital investment infrastructure for TBM testing; and facility operating cost is free for TBM
  2. Big saving on R&D costs because of international collaboration
     - Six parties, each is paying for R&D for one blanket concept
     - Sharing the results of R&D and ITER testing of six blanket concepts among the parties saves the world money and effort
  3. TBM testing in ITER complements FNSF:
     ITER has more prototypical magnetic configuration compared to the smaller size FNSF. ITER TBM tests can help benchmark FNSF results in the more prototypical magnetic fields and plasma current/confinement

Urge the world TBM program to devote more effort to: What to measure, how to measure, how results extrapolate, how to deal with early TBM failures

Concluding Remarks (1 of 2)

- Right now, we do not know and cannot predict how the blanket/FW will work in the fusion nuclear environment.
- 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. There are many Challenges in planning multiple effects experiments that need to be confronted now.
- RAMI especially is the "Achilles heel" for fusion. RAMI will be the key issue in determining the feasibility of plasma confinement configurations and blanket concepts. RAMI must be the most critical factor in any planning, design and R&D we do.
- Even with the aggressive R&D 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 (or at least the first stage) is to perform FNST experiments to discover synergistic effects and learn about blanket/PFC/Materials integrated behavior in the fusion nuclear environment. It can not be for validation or demonstration.

Concluding Remarks (2 of 2)

- We need to build **one (or more) FNSF** as an **"experimental"** DT fusion facility in which we do the necessary experiments of FNST components in the fusion nuclear environment **prior** to DEMO.
- One FNSF or a sequence of FNSFs will be needed to do the 3 necessary stages of R&D: I. Scientific Feasibility and Discovery, II. Engineering Feasibility and Validation, and III. Engineering Development and Reliability Growth
- To be timely, practical and affordable FNSF should be low power (< 150 MW), low tritium consumption, small sized (comparable to JET) facility with neutron wall load ~ 1 MW/m^2 with a highly driven plasma and minimum extrapolation of JET-type physics
- Trying to skip FNSF is like if we had tried to skip ITER and go directly from a JET plasma to DEMO. Could we have done this? At what risks?

Resolving the challenging FNST issues will require "ingenuity" and "time". FNST needs to attract and train bright young scientists and engineers.

Thank you!

For more details and for “references” on topics in this presentation, please see the following article (just appeared in Fusion Engineering and Design last week)

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 (in press)