# Blanket, Divertor, and Materials
# Design Concepts, Technical Issues and Development Facilities


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# Blanket, Divertor, and Materials: Design Concepts, Technical Issues and Development Facilities

## Outline

1. Introduction: DEMO, FNST, Blankets, Divertor

2. World Current Primary Blanket Concepts
   Main Features, Advantages, Issues, challenges

3. Fusion Materials Challenges

4. Divertors

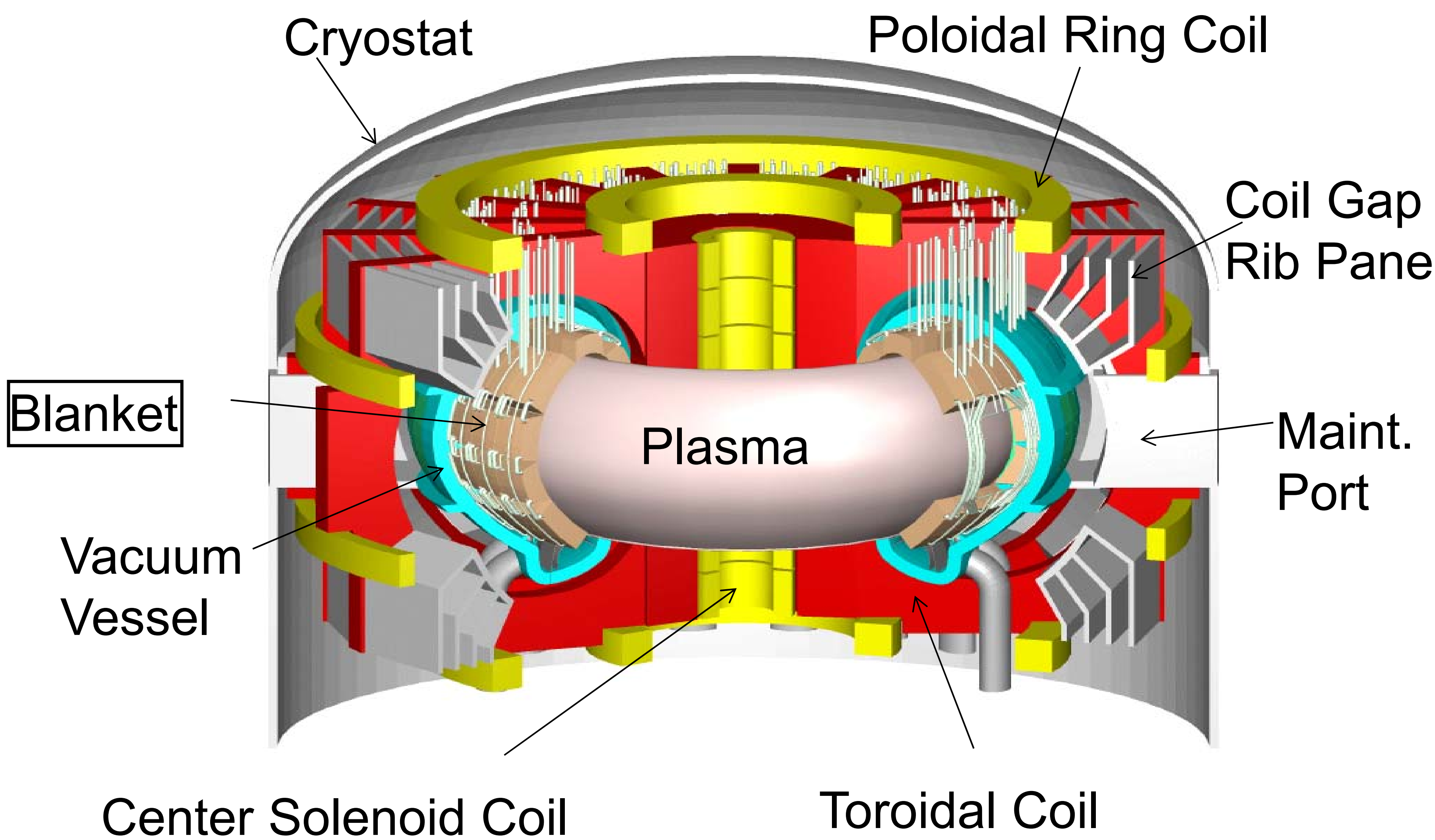
   Solid Walls, Liquid Walls Motivation and Issues

5. FNST and Material Development Strategy

6. Closing Remarks

# The World Fusion Program has a Goal for a Demonstration Power Plant (DEMO) by ~2040(?)

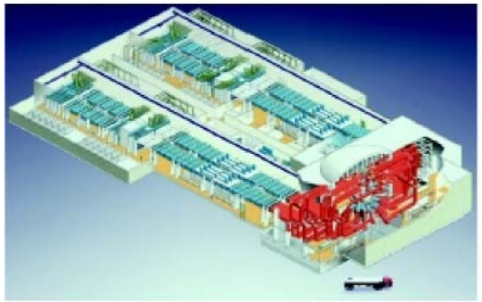
**Plans for DEMO are based on Tokamaks**



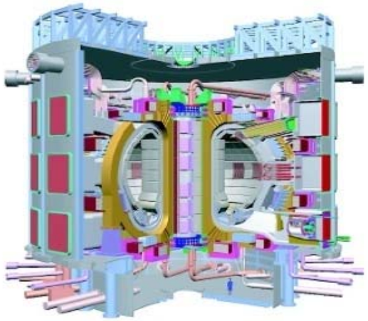

**(Illustration is from JAEA DEMO Design)**

# Fusion Research is about to transition from Plasma Physics to Fusion 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. Until blankets have been built, tested, and operated, prediction of the timescale of fusion entry into the energy market is difficult***

# Fusion Nuclear Science and Technology (FNST)

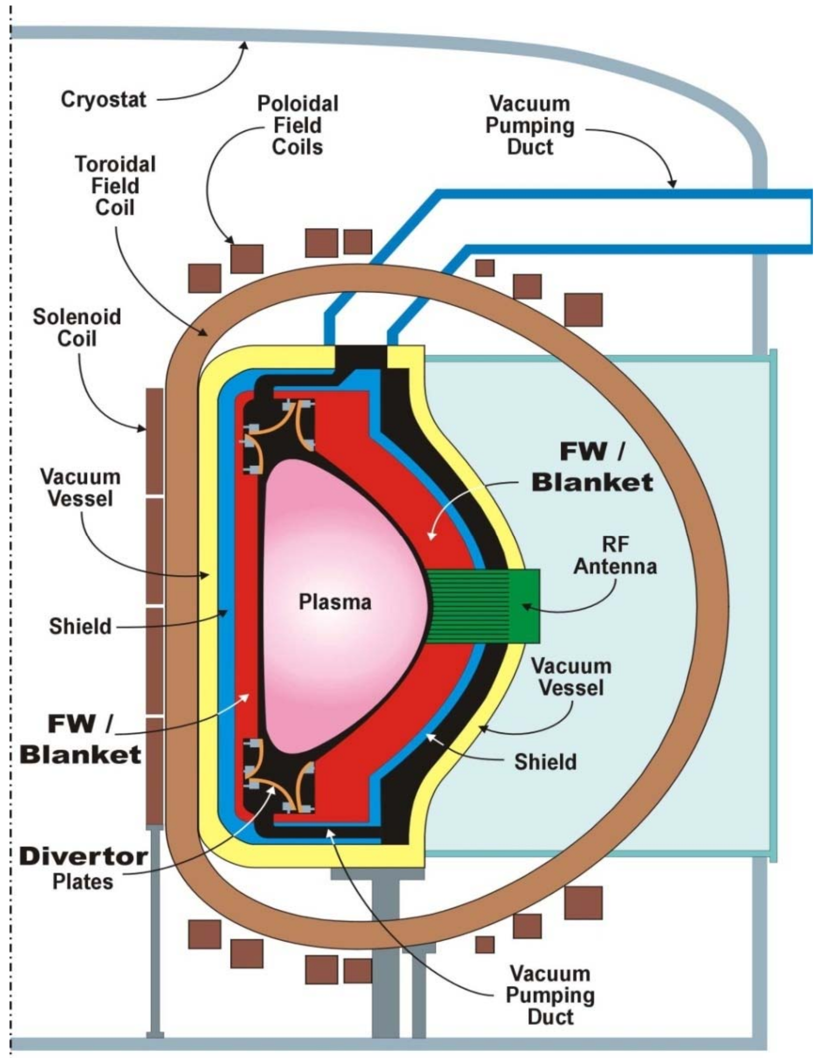
**FNST** is the **science**, **engineering**, **technology** and **materials**
for the fusion nuclear components that
generate, control and utilize neutrons, energetic particles & tritium.

**Inside the Vacuum Vessel**
**"Reactor Core":**

- **Plasma Facing Components**
  divertor, limiter and nuclear aspects of plasma heating/fueling
- **Blanket (with first wall)**
- **Vacuum Vessel & Shield**

**Other Systems / Components affected by the Nuclear Environment:**

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



# Fusion Nuclear Environment is Complex & Unique

**Neutrons** *(flux, spectrum, gradients, pulses)*

- Radiation Effects
- Tritium Production
- Bulk Heating
- 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)*

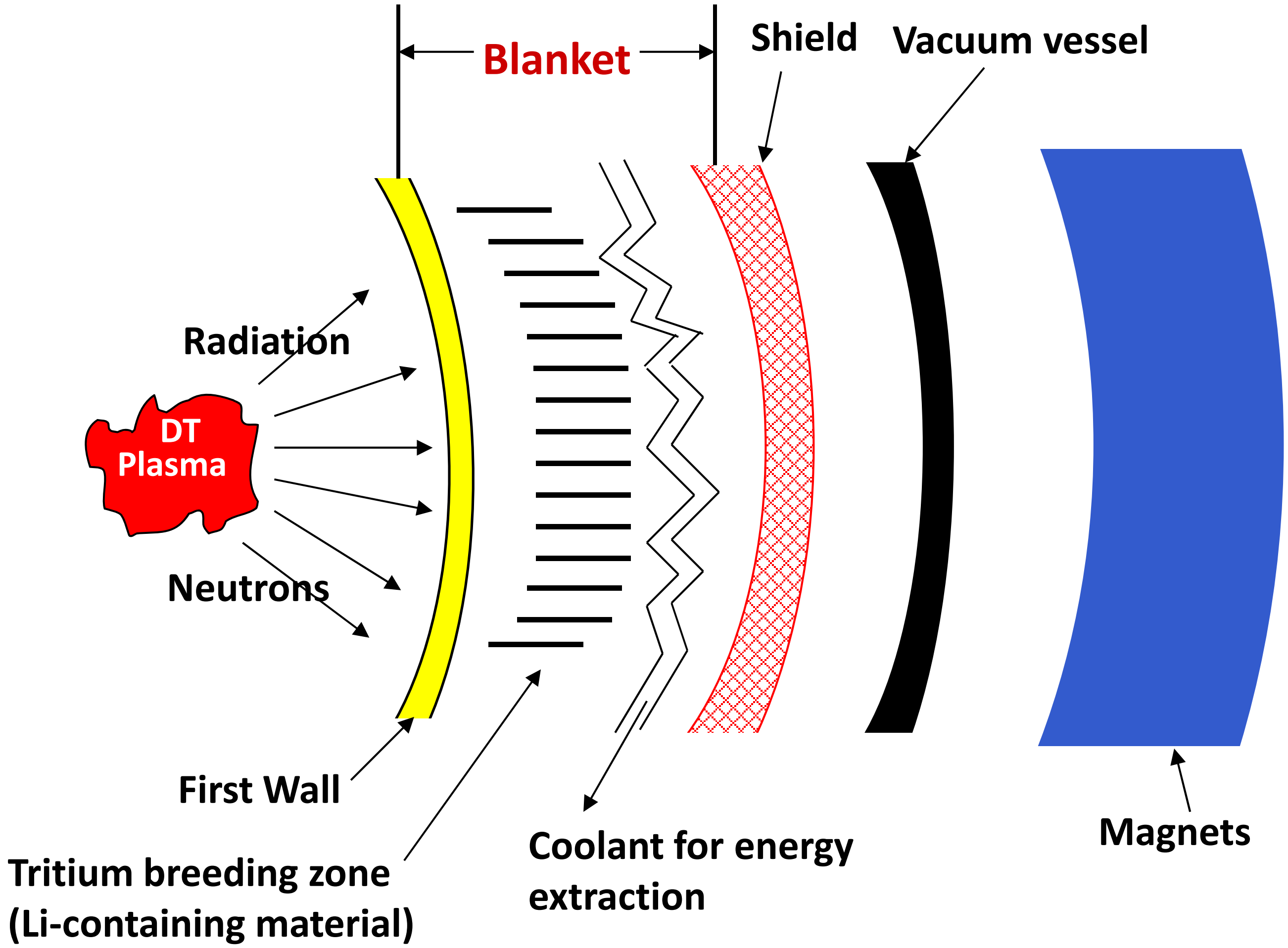
**Multiple functions, materials, and many interfaces in highly constrained system**

**Combined Loads, Multiple Environmental Effects**

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

Non-fusion facilities (Laboratory experiments) need to be substantial to simulate multiple effects
Simulating nuclear **bulk heating in a large volume** is the most difficult and is most needed
Most phenomena are temperature (and neutron-spectrum) dependent– it needs DT fusion facility
The full fusion Nuclear Environment can be simulated only in DT plasma–based facility

# The primary functions of the blanket are to provide for: Power Extraction & Tritium Breeding




- **Liquid metals (Li, PbLi) are strong candidates as breeder/coolant.**
- **Ceramic Breeders with He cooling are also strong candidates.**

# There are many material and configuration options for the blanket

| Material or Configuration | Options |
|---|---|
| Structural Materials | Reduced Activation Ferritic Steel Alloys (including ODS), Vanadium Alloys, SiC Composites |
| Coolant Media | Helium, Water, Liquid Metals, Molten Salts |
| Breeder Media | Lithium-Bearing: Ceramic Breeders ($Li_4SiO_4$, $Li_2TiO_3$, $Li_2O$); Liquid Metals (Li, PbLi, SnLi); Molten Salts (FLiBe, FLiNaBe); Varying enrichments in Li-6 |
| Neutron Multiplier Materials | Beryllium, $Be_{12}Ti$, Lead |
| MHD/Thermal Insulator Materials | SiC composites and foams, $Al_2O_3$, CaO, AlN, $Er_2O_3$, $Y_2O_3$ |
| Corrosion and Permeation Barriers | SiC, $Al_2O_3$, others |
| Plasma Facing Materials | Beryllium, Carbon, Tungsten alloys, others |
| HX or TX Materials | Ferritic Steels, Ni-based alloys, Refractory Alloys, SiC, Direct Gas Contact |
| Blanket Configurations | He or Water Cooled Ceramic Breeder/Be; Separately Cooled, Self-Cooled, Dual-Coolant LM or MS |
| Ceramic Breeder Configurations | Layered, Mixed, Parallel, Edge-On (referenced to FW), Breeder-In-Tube |
| Liquid Breeder Configurations | Radial-Poloidal Flow, Radial-Toroidal Flow, others |
| MHD/Thermal Insulator Config. | Flow Channel Inserts, Self-Healing Coatings, Multi-Layer Coatings |
| Structure Fabrication Routes | HIP; TIG, Laser and E-beam Welding; Explosive Bonding; Friction Bonding; Investment Casting; and others |

**But there are only a few compatible combinations possible**

**(because of considerations of chemical compatibility, safety, etc)**

# Classes of Blanket Concepts
## (many concepts proposed worldwide)

## A. Solid Breeder Concepts

- Solid Breeder: Lithium Ceramic ($Li_2O$, $Li_4SiO_4$, $Li_2TiO_3$, $Li_2ZrO_3$)
- Neutron Multiplier: Be or $Be_{12}Ti$
- Coolant: Helium or Water

## B. Liquid Breeder Concepts

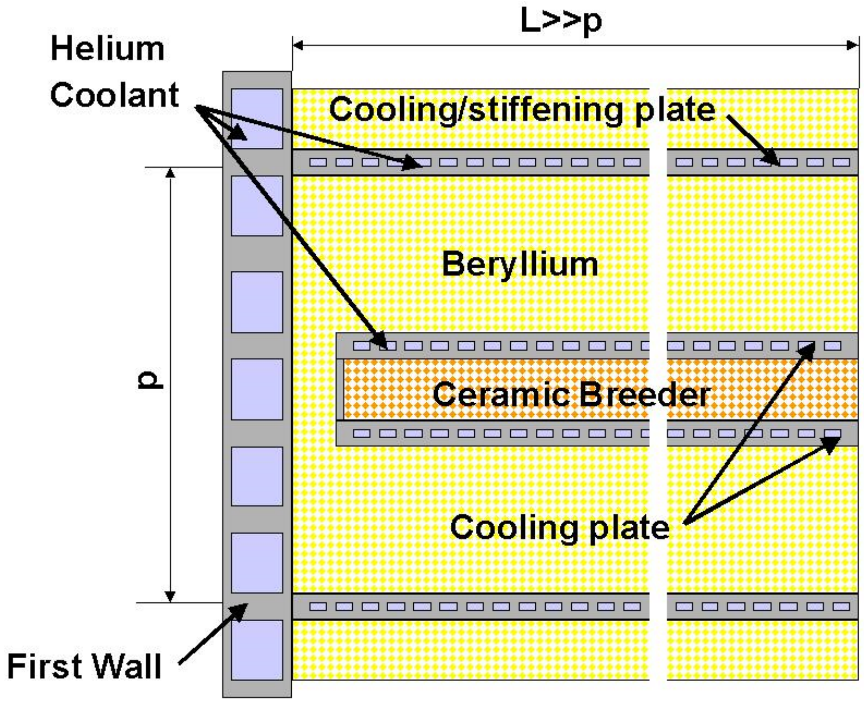
Liquid breeder can be:

a) **Liquid metal** (high electrical/thermal conductivity, low viscosity): Li, or PbLi

b) **Molten salt** (low electrical/thermal conductivity, high viscosity): Flibe $(LiF)_n \cdot (BeF_2)$, Flinabe ($LiF$-$BeF_2$-$NaF$)

# A Helium-Cooled Li-Ceramic Breeder Concept : Example

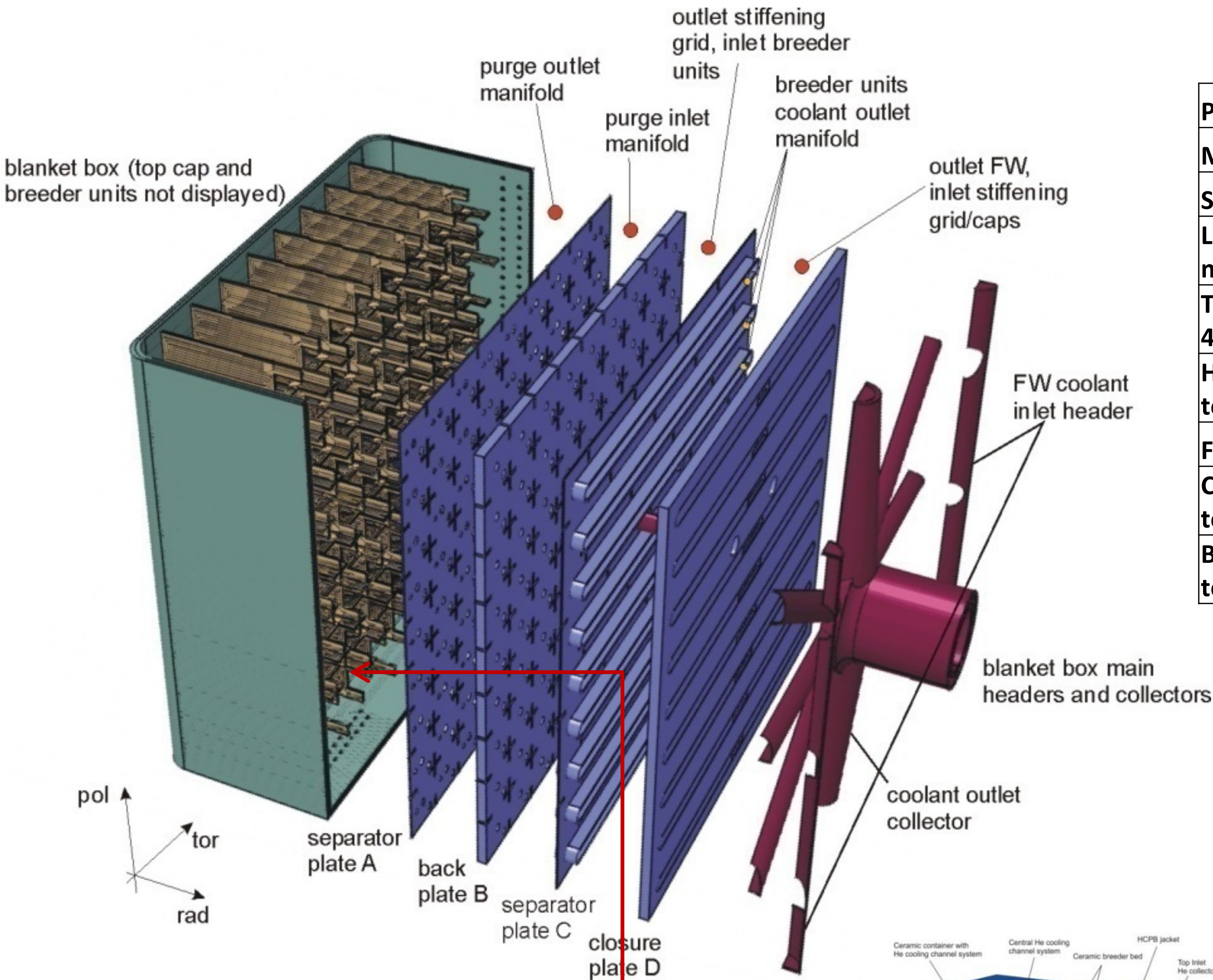
- **High pressure Helium** **cooling in structure (ferritic steel)**
- **Ceramic breeder** **($Li_4SiO_4$, $Li_2TiO_3$, $Li_2O$, etc.) for tritium breeding**
- **Beryllium** **(pebble bed) for neutron multiplication**
- **In-situ tritium removal* with Helium purge** **(low pressure) to remove tritium through the "interconnected porosity" in ceramic breeder**




Several configurations exist (e.g. wall parallel or "head on" breeder/Be arrangements)

*** "In-situ" is necessary to keep tritium inventory in the system low.**
**"Batch" processing is not appropriate for fusion (>150 kg/yr 1000MWe fusion power plant).**

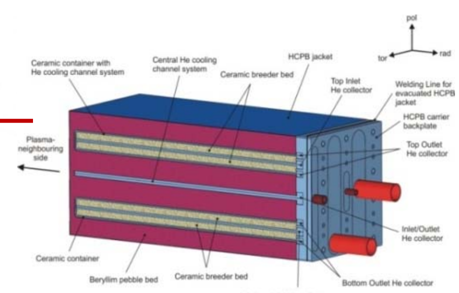
# Helium-Cooled Pebble Bed Module Structural Configuration




## EU HCPB DEMO

| | |
|---|---|
| Plant fusion power | 3300 MW |
| Mid-plane neutron wall load | 2.24 MW/m$^2$ |
| Surface heat flux | 0.5 MW/m$^2$ |
| Local blanket energy multiplication | 1.25 |
| Tritium Breeding Ratio (with 40% $^6$Li enrichment and 46 cm) | 1.14 |
| Helium coolant inlet/outlet temperature | 300 - 500$^o$C |
| FW maximum temperature | 550$^o$C |
| Ceramic breeder pebble bed temperature | 400-920$^o$C |
| Beryllium pebble bed temperature | 400-650$^o$C |

**Tritium Inventory***
**Ceramic**: earlier estimation gave ~250 g in $Li_4SiO_4$
**Beryllium**: Low production of T, but high uncertainties in the effective release rate. It is still an open issue, R&D is ongoing in EU.



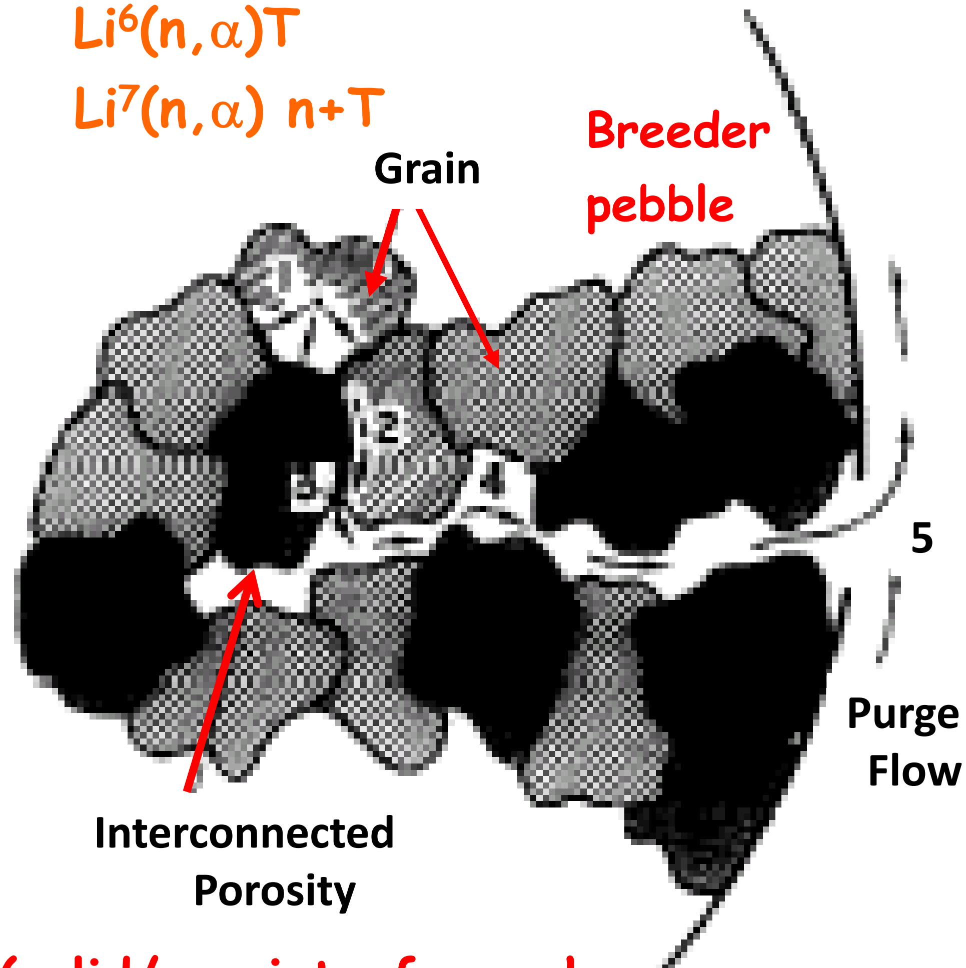
**Breeder Unit to be inserted into the space between the grid plates**

*L.V. Boccaccini, The concept of the breeding blanket for T-self sufficiency, comparison of different schemes, SOFT 25, Sep. 18, 2008

# Mechanisms of tritium transport (for solid breeders)

$Li^6(n,\alpha)T$

$Li^7(n,\alpha)\ n+T$




(solid/gas interface where adsorption/desorption occurs)

<u>Mechanisms of tritium transport</u>

1) Intragranular diffusion
2) Grain boundary diffusion
3) Surface Adsorption/desorption
4) Pore diffusion
5) Purge flow convection

**Purge gas composition:**

He + 0.1% $H_2$

**Tritium release composition:**

$T_2$, HT, $T_2O$, HTO

Reference: G. Federici, Ph.D. Dissertation, University of California at Los Angeles (October 1989); UCLA-FNT-30 Report (November 1989).

# "Temperature Window" for Solid Breeders

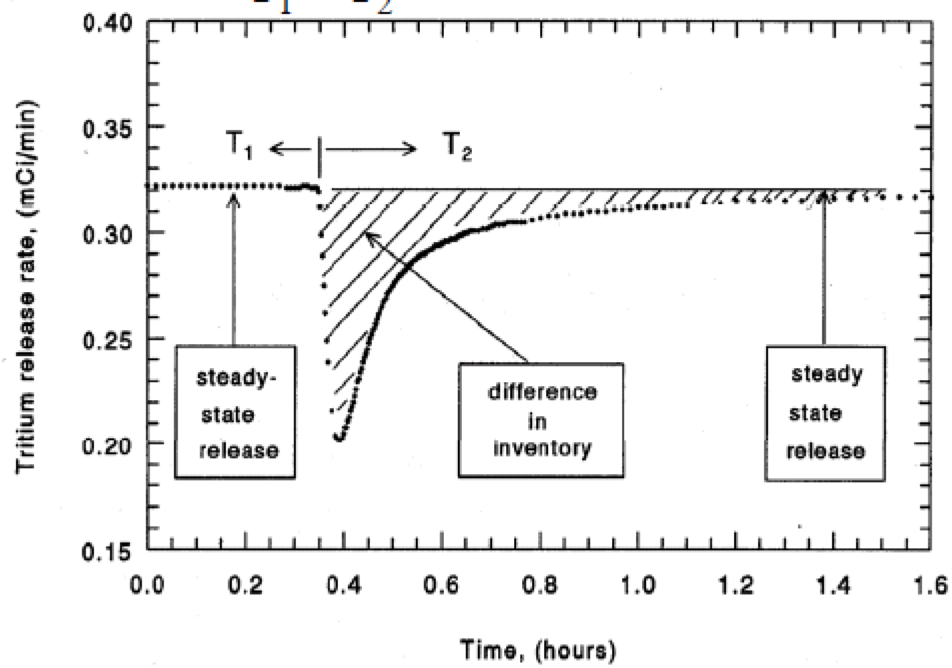
- The operating temperature of the solid breeder is limited to an acceptable "temperature window": $T_{min} – T_{max}$
  - $T_{min}$, lower temperature limit, is based on acceptable tritium transport characteristics (typically bulk diffusion). Tritium diffusion is slow at lower temperatures and leads to unacceptable tritium inventory retained in the solid breeder
  - $T_{max}$, maximum temperature limit, to avoid sintering (thermal and radiation-induced sintering) which could inhibit tritium release; also to avoid phase change/mass transfer (e.g., LiOT vaporization)
- Low *k (thermal conductivity)*, combined with the allowable operating "temperature window" for solid breeders, results in:
  - Limitations on power density, especially behind first wall and next to the neutron multiplier (limits on wall load and surface heat flux)
  - Limits on achievable tritium breeding ratio (beryllium must always be used; still TBR is limited) because of increase in structure-to-breeder ratio
  - Higher "effective" k is obtainable with a homogenous mixture of ceramic breeder (low k) and $Be_{12}$ Ti (high k)

# Many irradiation experiments were performed in fission reactors to quantify tritium release characteristics for various ceramic breeders

**Recent experiment: EXOTIC 9/1 (EXtraction Of Tritium In Ceramics) in HFR-Petten with in-pile gas purge to quantify tritium release behavior. (The average total $^{6}$Li burn-up is 3%. The total measured activity from tritium during irradiation is 220.42 Ci.)**

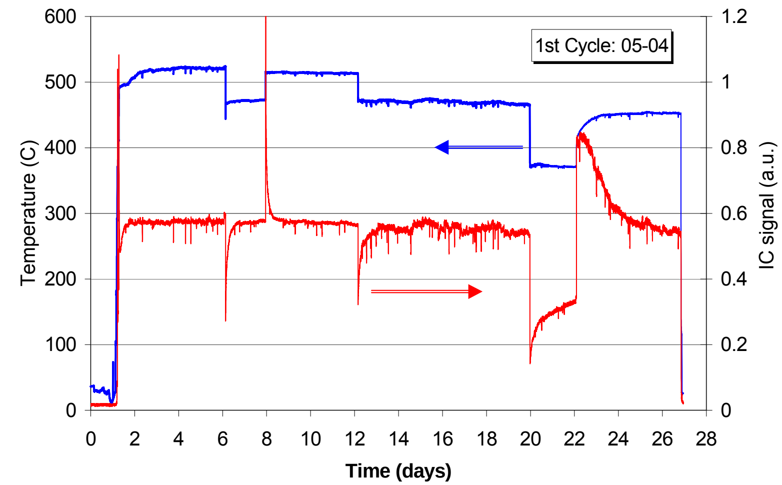
**Method** (The **temperature step** technique is usually adopted to study in-pile tritium release kinetics)

$T_1 > T_2$




**In-pile tritium release data**

**Temperature varies between 340 and 580 °C**



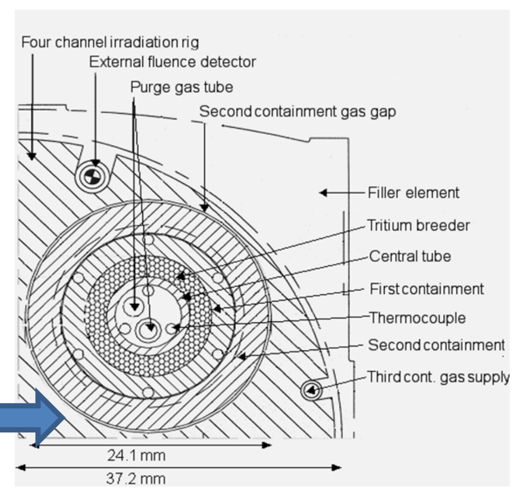

**determine Tritium residence ($\tau$):**

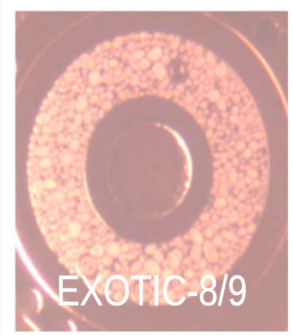
$$\tau = \frac{I}{G}$$

**I = tritium inventory (mCi)**

**G = tritium production rate (mCi/min)**

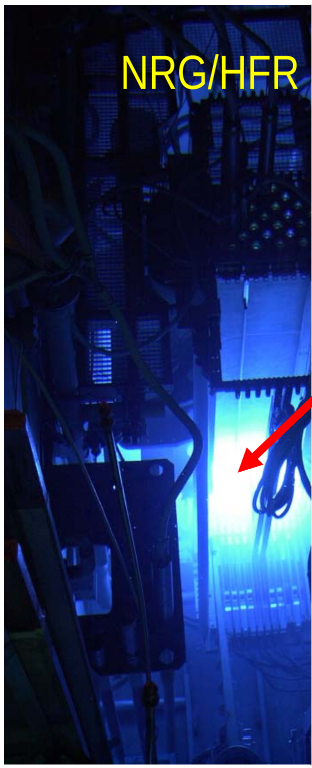
Annular breeder pebble-bed, modest radial temperature gradient, 120 mm stack height

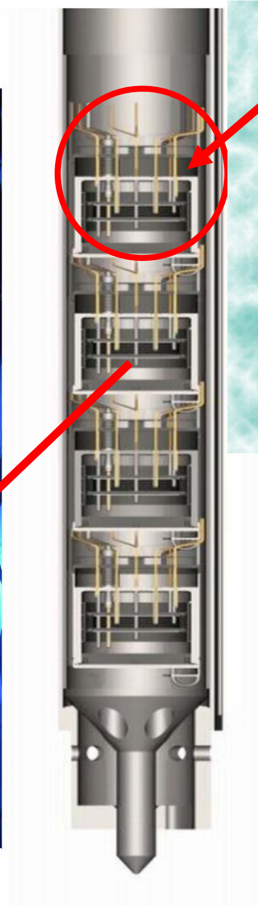


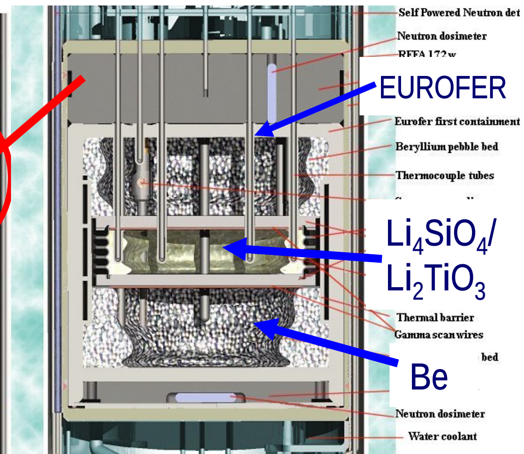



# Neutron irradiation experiments in fission reactors were also performed to study thermal-mechanical behavior of EU HCPB unit cell at DEMO relevant temperatures and mechanical constraints

Example: Pebble bed assembly (PBA) test

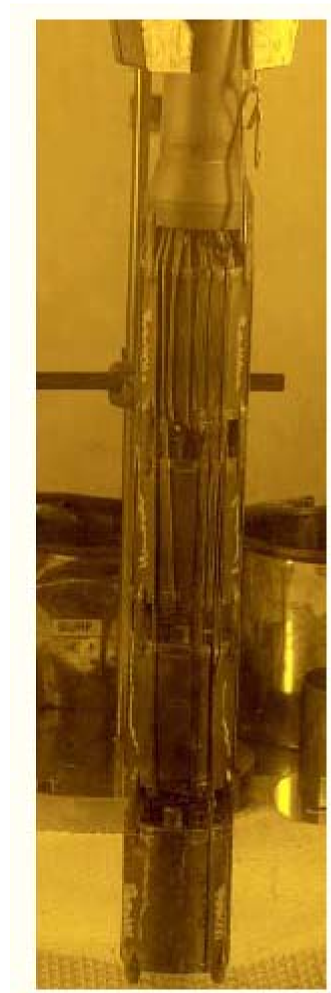





A HCPB unit cell
6.75 cm D x 12.5 cm H

**Total 4 HCPB Unit Cells were tested**
2- $Li_4SiO_4$ beds (650°C and 850°C)
2- $Li_2TiO_3$ beds (650°C and 850°C)

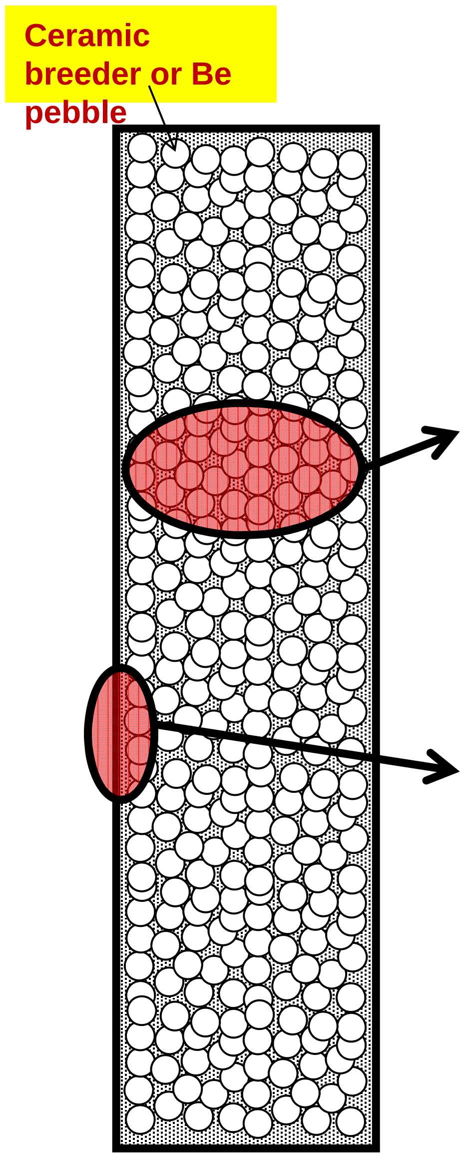


**End of Irradiation of the PBA (ITER testing EOL)**

- PBA has been operated in-pile for 12 irradiation cycles, 300 FPD
- Accumulate in 12 cycles, or 7200 hours:
  - **8 x10$^{22}$ at T production**
  - **Lithium burn ups 2 to 3%**
  - **~2 dpa in Eurofer**

- Experimental results with $Li_4SiO_4$ pebble bed qualitatively benchmarks FEM predicted stress/strain gradients.

# Material Database for Solid Breeder Blanket Pebble Bed Thermo-mechanics




Pebble bed schematics

**Pebble bed thermo-physical and mechanical data**

(1) Effective thermal conductivity
(2) Effective modulus
(3) Thermal creep correlation
(4) Effective thermal expansion rate
(5) Pebble failure data
(6) Increase of effective thermal conductivity with compressive and creep strain
(7) criteria of pebble surface roughness and sphericity

Pebble bed – wall interface thermo-mechanical data

(1) Heat conductance
(2) Friction coefficient

**Modeling and analysis method**

(1) Modification of **continuous model** for large scale analysis
(2) Discrete Element Method **(DEM)** for investigation of contact characteristics

# Liquid Breeder Blanket Concepts

1. Self-Cooled
   - Liquid breeder circulated at high speed to serve as coolant
   - Concepts: Li/V, Flibe/advanced ferritic, flinabe/FS
2. Separately Cooled
   - A separate coolant, typically helium, is used. The breeder is circulated at low speed for tritium extraction.
   - Concepts: LiPb/He/FS, Li/He/FS
3. Dual Coolant
   - First Wall (highest heat flux region) and structure are cooled with a separate coolant (helium). The idea is to keep the temperature of the structure (ferritic steel) below 550ºC, and the interface temperature below 480ºC.
   - The liquid breeder is self-cooled; i.e., in the breeder region, the liquid serves as breeder and coolant. The temperature of the breeder can be kept higher than the structure temperature through design, leading to higher thermal efficiency.

# Flows of electrically conducting coolants will experience complicated **MHD** effects in the magnetic fusion environment 3-component magnetic field and complex geometry

- Motion of a conductor in a magnetic field produces an EMF that can induce current in the liquid. This must be added to Ohm's law:

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B})$$

- Any induced current in the liquid results in an additional body force in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla)\mathbf{V} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{V} + \mathbf{g} + \frac{1}{\rho}\mathbf{j} \times \mathbf{B}$$

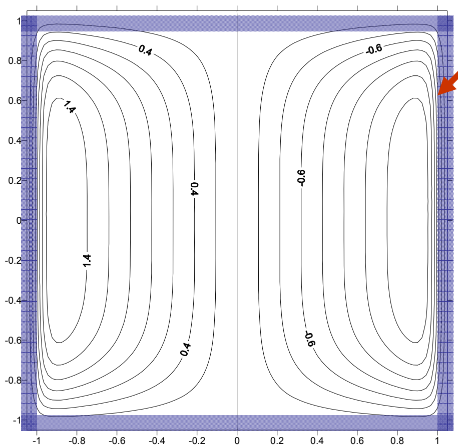
- For liquid metal coolant, this body force can have dramatic impact on the flow: e.g. enormous MHD drag, highly distorted velocity profiles, non-uniform flow distribution, modified or suppressed turbulent fluctuations.

Dominant impact on LM design.
Challenging Numerical/Computational/Experimental Issues

**Self-Cooled liquid Metal Blankets are NOT feasible now because of MHD Pressure Drop.**

**A perfectly insulated "WALL" can solve the problem, but is it practical?**

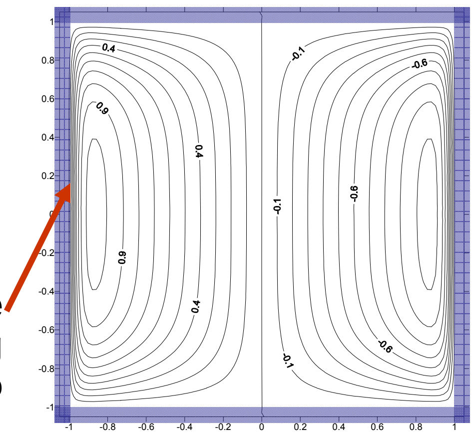
**Conducting walls**



**Lines of current enter the low resistance wall – leads to very high induced current and high pressure drop**

**All current must close in the liquid near the wall – net drag from jxB force is zero**

**Insulated walls**



- **Net JxB body force**

  $\nabla p = VB^2\, t_w\, \sigma_w / a$

- **For high magnetic field and high speed (self-cooled LM concepts in inboard region) the pressure drop is large**
- **The resulting stresses on the wall exceed the allowable stress for candidate structural materials**

- **Perfect insulators make the net MHD body force zero**
- **But insulator coating crack tolerance is very low (~$10^{-7}$).**
  - **It appears impossible to develop practical insulators under fusion environment conditions with large temperature, stress, and radiation gradients**
- **Self-healing coatings have been proposed but none has yet been found (research is on-going)**



**Impact of MHD and no practical Insulators: No self-cooled blanket option**

# Separately-cooled LM Blanket

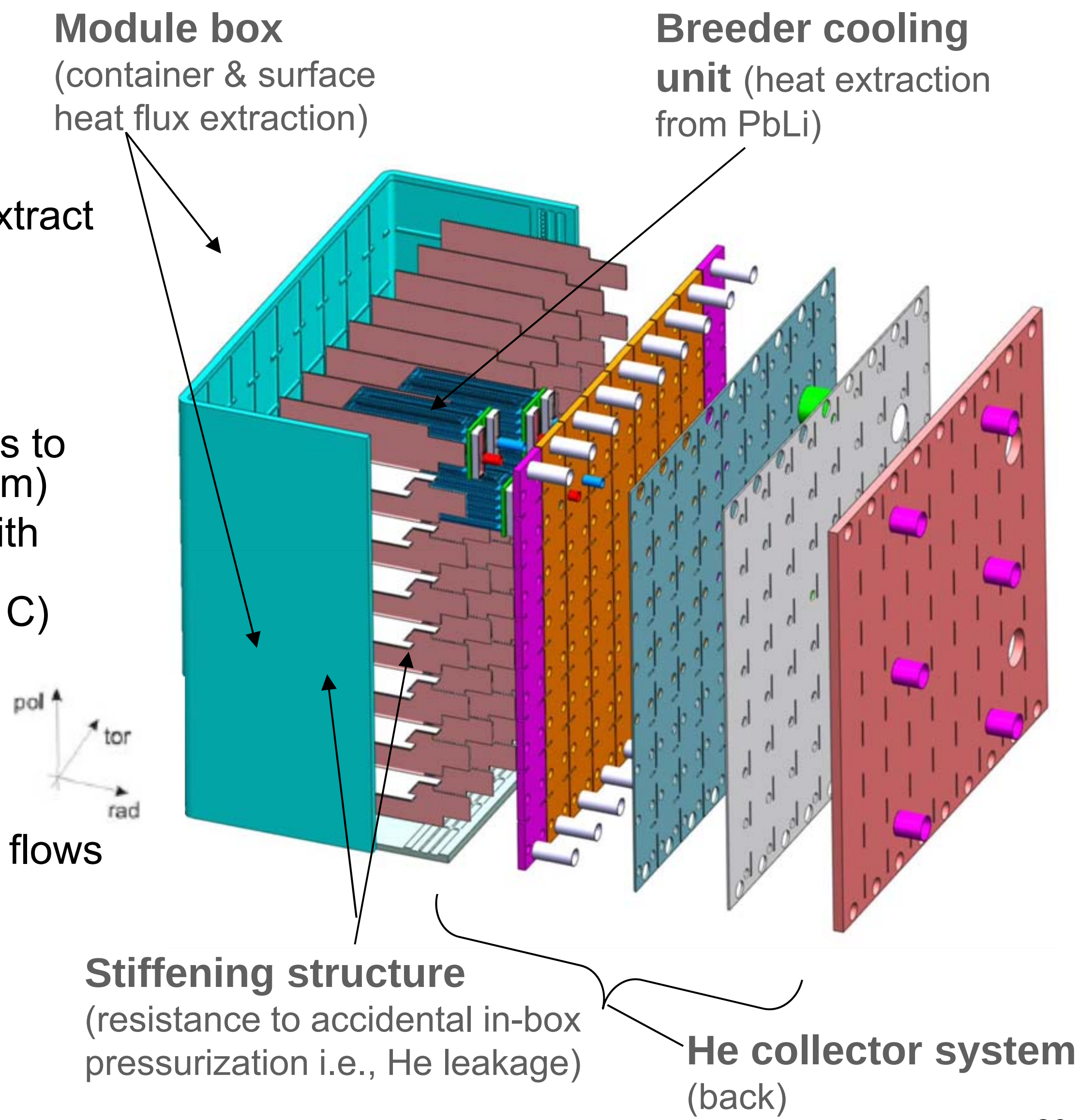
## Example: PbLi Breeder / Helium Coolant with RAFM

- EU mainline blanket design
- **All energy removed by separate Helium coolant**
- ***The idea is to avoid MHD issues***
  But, PbLi must still be circulated to extract tritium

- ISSUES:
  - Low velocity of PbLi leads to high tritium partial pressure, which leads to tritium permeation (Serious Problem)
  - $T_{out}$ limited by PbLi compatibility with RAFM steel structure ~ 470 C
    (and also by limit on Ferritic, ~550 C)

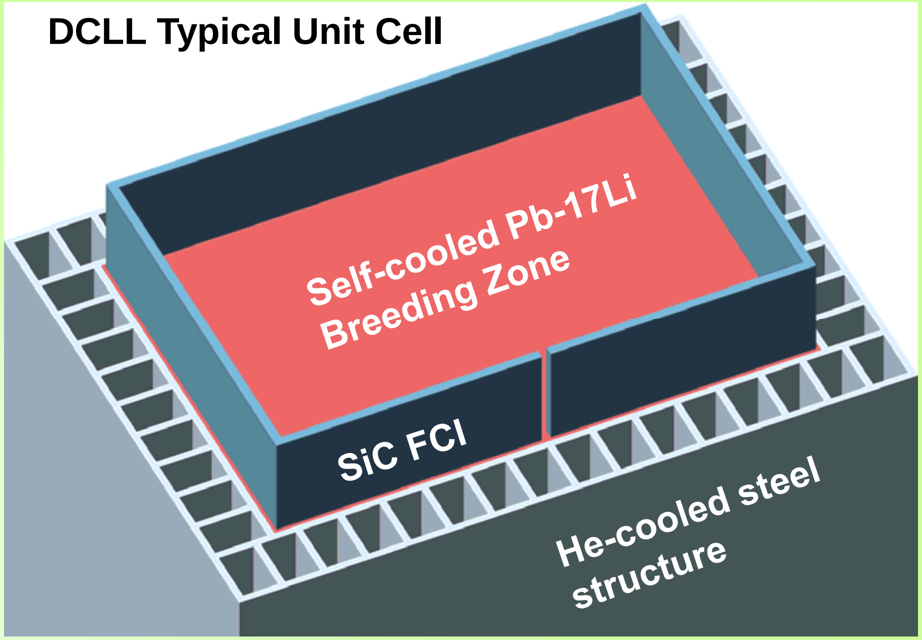
- Possible MHD Issues :
  - MHD pressure drop in the inlet manifolds
  - B- Effect of MHD buoyancy-driven flows on tritium transport

Drawbacks: Tritium Permeation and limited thermal efficiency



# Pathway Toward Higher Temperature Through Innovative Designs with Current Structural Material (Ferritic Steel): *Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept*

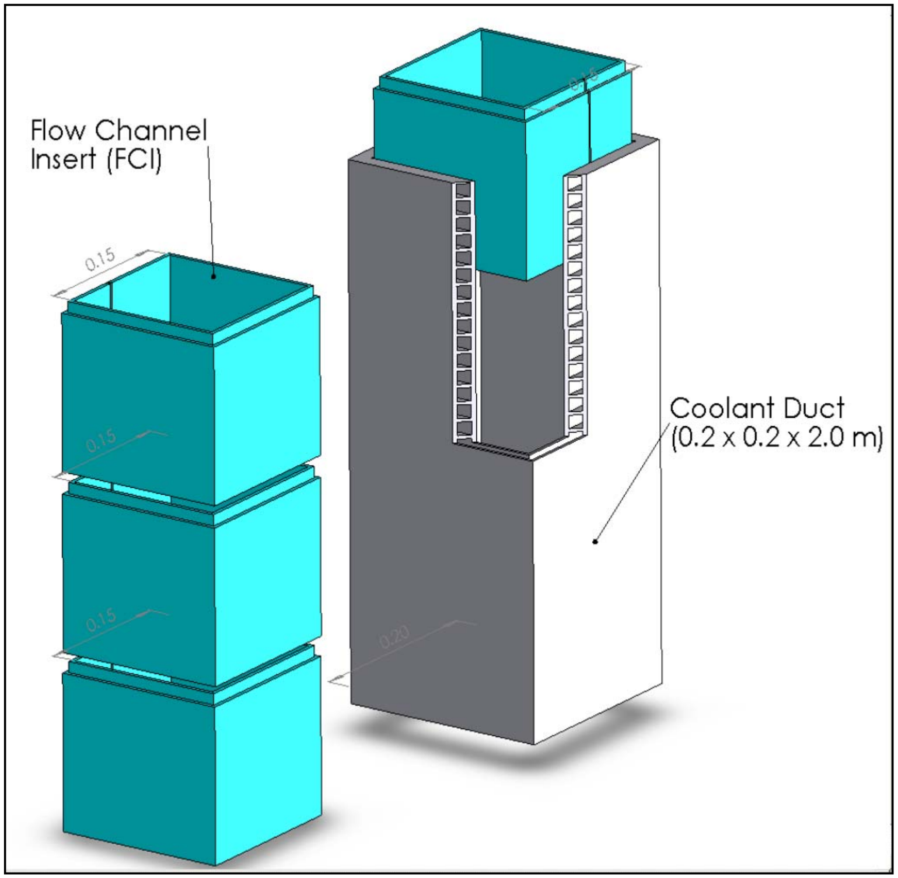
- **First wall and ferritic steel structure cooled with helium**
- **Breeding zone is self-cooled**
- **Structure and Breeding zone are separated by SiCf/SiC composite *flow channel inserts (FCIs)* that**
  - **Provide thermal insulation to decouple PbLi bulk flow temperature from ferritic steel wall**
  - **Provide electrical insulation to reduce MHD pressure drop in the flowing breeding zone**




***Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure ⇒ High Efficiency***

# Flow Channel Inserts are a critical element of the high outlet temperature DCLL

- **FCIs are roughly box channel shapes made from some material with low electrical and thermal conductivity**
  - **SiC/SiC composites and SiC foams are primary candidate materials**
- **They will *slip* inside the He Cooled RAFS structure, but not be rigidly attached**
- **They will slip fit over each other, but not be rigidly attached or sealed**
- **FCIs may have a thin slot or holes in one wall to allow better pressure equalization between the PbLi in the main flow and in the gap region**



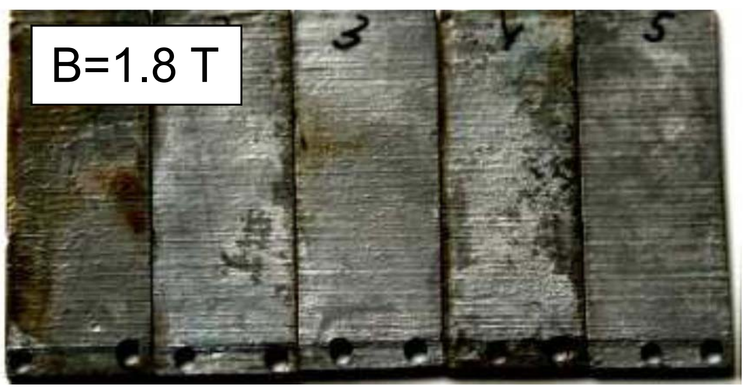

- **FCIs in front channels, back channels, and access pipes will be subjected to different thermal and pressure conditions; and will likely have different designs and thermal and electrical property optimization**

# R&D ISSUES of PbLi BLANKETS

- MHD pressure drop and flow distribution / balancing
- T permeation
- SiC FCI related issues (e.g., insulation, thermal stress, degradation of thermophysical properties under neutron irradiation)
- Compatibility between PbLi and structural and functional materials in the presence of a strong magnetic field
- Limits on operating temperature, re-deposition of radioactive corrosion products in the transport/HX system; clogging of the LM tract with corrosion products

# Experiments in Riga (funded by Euratom)
# Show Strong Effect of the Magnetic Field on Corrosion
# (Results for Ferritic Steel in PbLi)

**Macrostructure of the washed samples after contact with the PbLi flow**

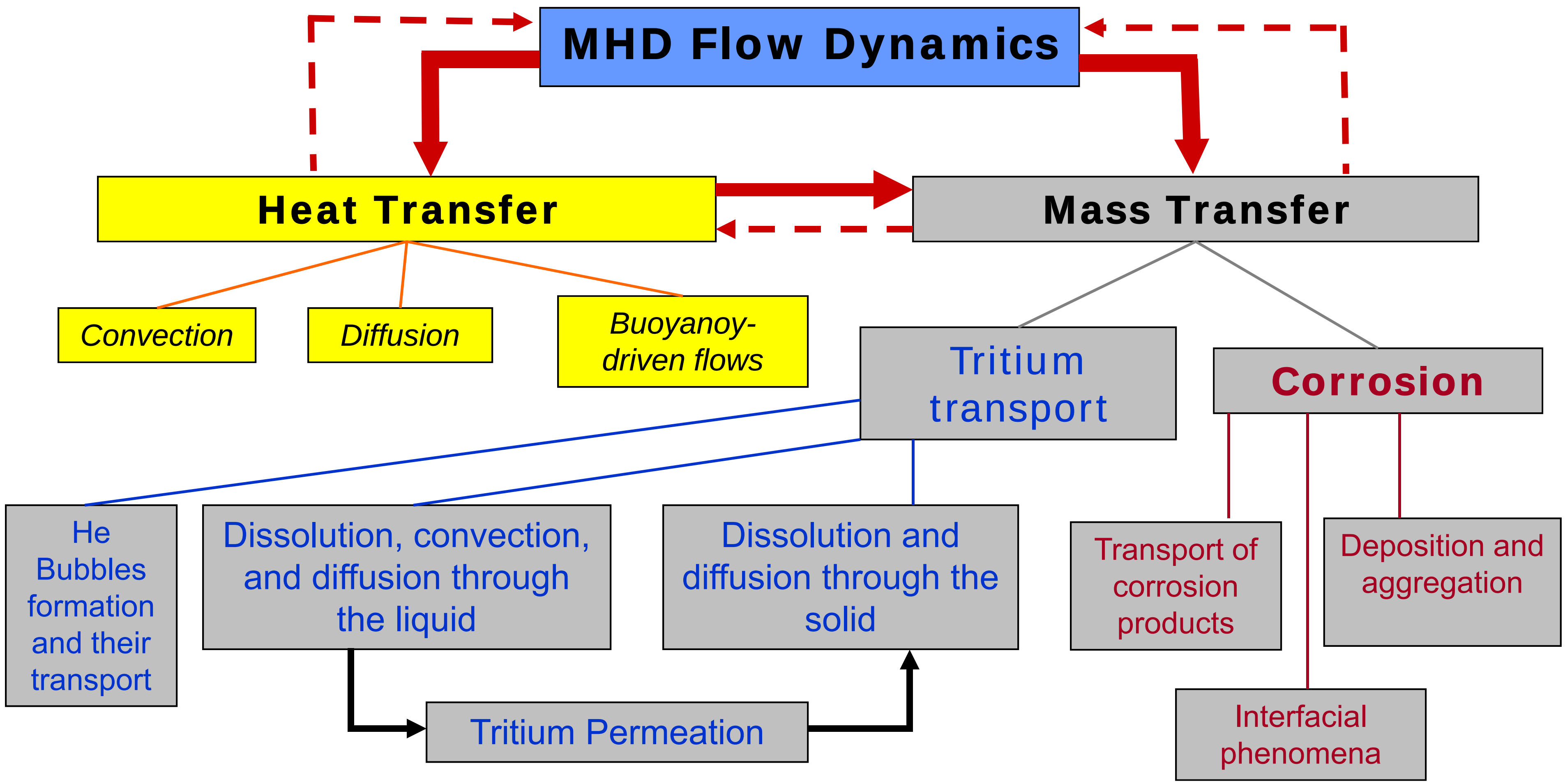

**From: F. Muktepavela et al. *EXPERIMENTAL STUDIES OF THE STRONG MAGNETIC FIELD ACTION ON THE CORROSION OF RAFM STEELS IN Pb17Li MELT FLOWS*, PAMIR 7, 2008**

Corrosion rate $h_n$ for samples without and with magnetic field

| n | $h_n$ , µm/year | |
|---|---|---|
| | $B_o = 0$ | $B_o = 1.8$ T |
| 1 | 523 | 967 |
| 2 | 458 | 877 |
| 3 | 381 | 694 |
| 4 | 293 | 846 |
| 5 | 388 | 726 |

**Strong experimental evidence of significant effect of the applied magnetic field on corrosion rate. The underlying physical mechanism has not been fully understood yet.**

## Need More Substantial Effort on Modeling of *Interfacial Phenomena* (fluid-material interaction) Such effort must include fundamental phenomenological modeling as well as coupling/integration of MHD and heat and mass transfer, thermodynamics, and material properties




Also, ***experiments*** should progress from single effects to multiple effects in laboratory facilities and then to integrated tests in the fusion environment.

# 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 integrate the many technical disciplines of fluid dynamics, heat transfer, mass transfer, thermodynamics and material properties in the presence of the multi-component fusion environment** **(must be done jointly by blanket and materials researchers)**

# Fusion Material Challenges

# Scientific & Technical Challenges for Fusion Materials

- Fusion materials are exposed to a hostile environment that includes combinations of high temperatures, reactive chemicals, large time-dependent thermal-mechanical stresses, and intense damaging radiation.
- Key issues include thermal stress capacity, coolant compatibility, waste disposal, and radiation damage effects.
- The 3 leading structural materials candidates are ferritic/martensitic steel, V alloys and SiC composites (based on safety, waste disposal, and performance considerations).

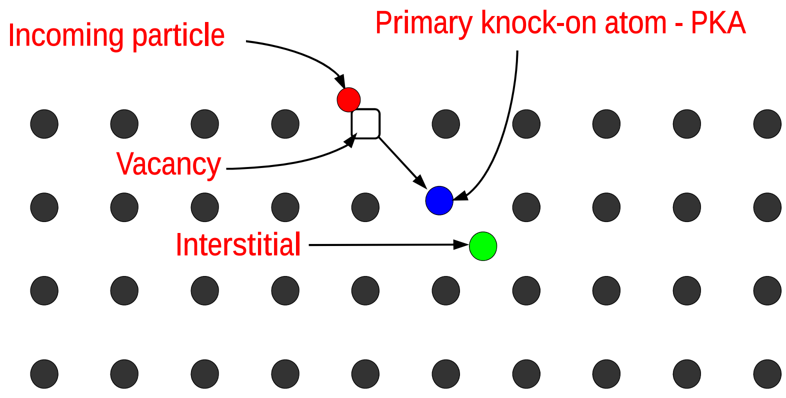
➢ **The ferritic/martensitic steel is the reference structural material for DEMO**

– (Commercial alloys (Ti alloys, Ni base superalloys, refractory alloys, etc.) have been shown to be unacceptable for fusion for various technical reasons).

- *Structural materials are most challenging, but many other materials (e.g. breeding, insulating, superconducting, plasma facing and diagnostic) must be successfully developed.*

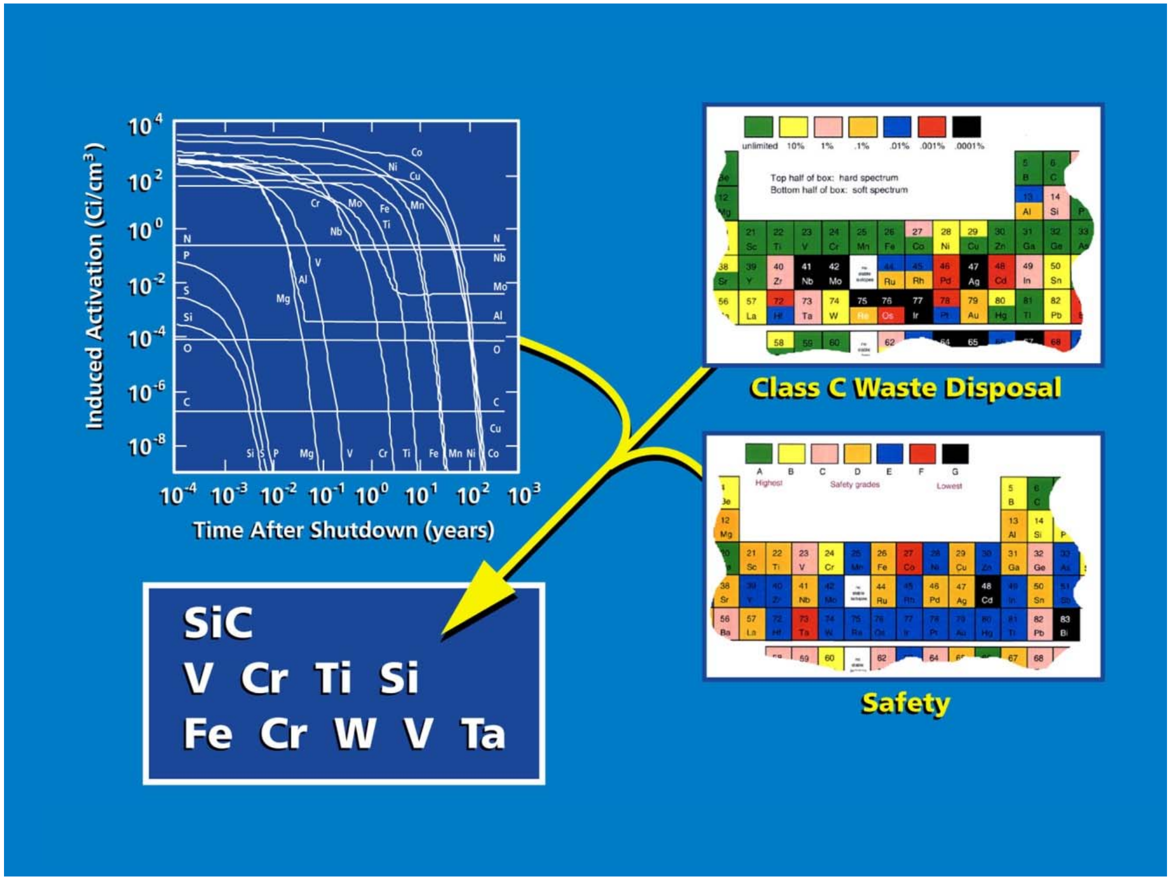
# Radiation Damage Fundamentals

- Material properties are determined by microstructure.
  - Grain size, other internal interfaces
  - Dislocation structures
  - Size and density of second phases
- Irradiation with energetic particles leads to atomic displacements:
  - Neutron exposure can be expressed in terms of the number of atomic displacements per atom – dpa
  - Lifetime exposures range from ~0.01 to >100 dpa (0.001 – 10 MW-y/$m^2$).
  - Atomic displacements lead to microstructural evolution, which results in substantial property degradation.
- One key to achieving highly radiation resistant materials is to enhance vacancy-interstitial recombination or self-healing.

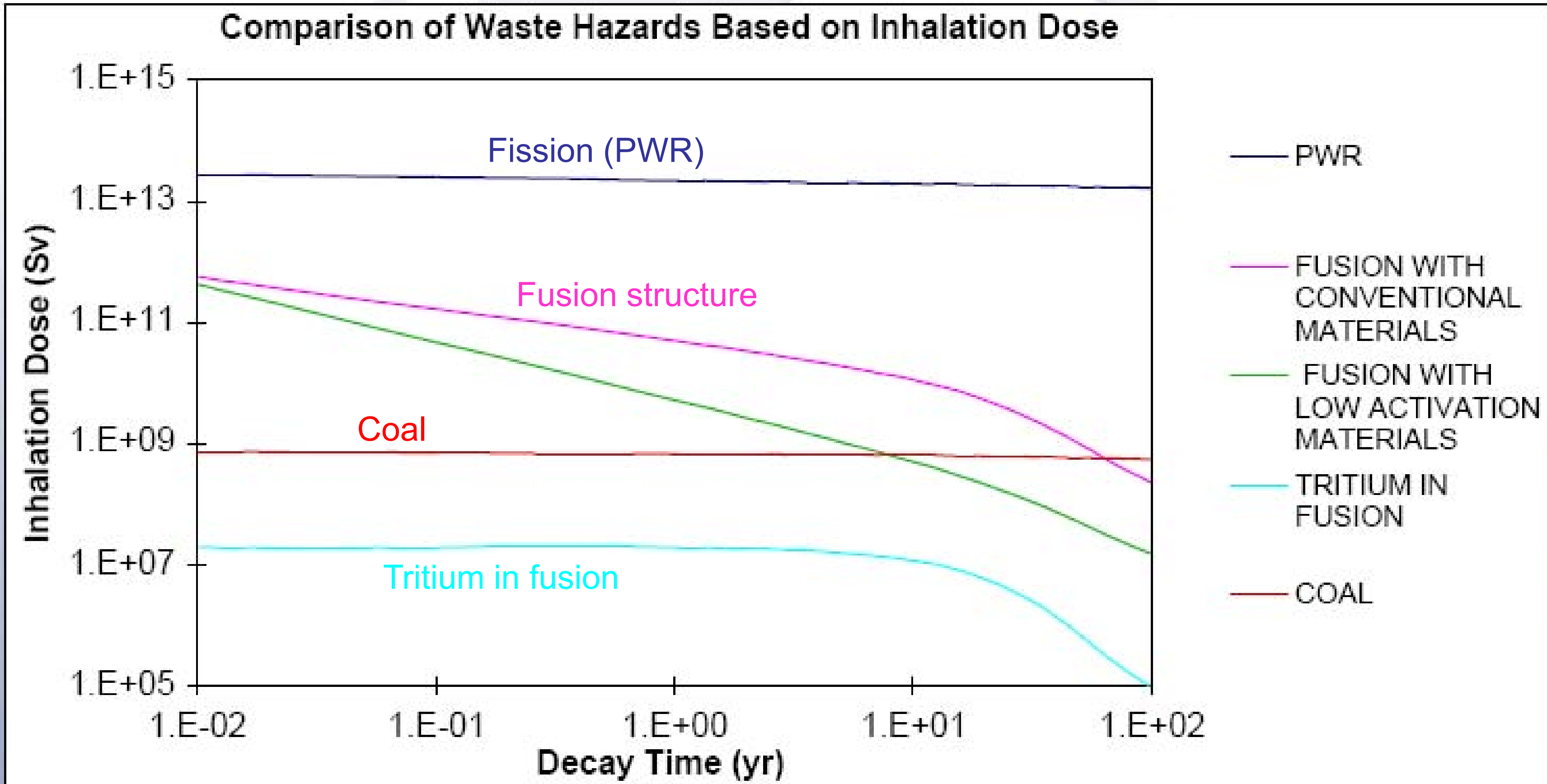



# In fusion, the fusion process does not produce radioactive products. Long-term radioactivity and waste disposal issues can be minimized by careful SELECTION of MATERIALS

- This is in contrast to fission, where long term radioactivity and waste disposal issues are "intrinsic" because the products of fission are radioactive.
- Based on safety, waste disposal, and performance considerations, the three leading candidates are:
  - RAF/M and NFA steels
  - SiC composites
  - Tungsten alloys (for PFC)



# Radiotoxicity (inhalation) of waste from fusion is less than fission and similar to that from coal at 100 years.



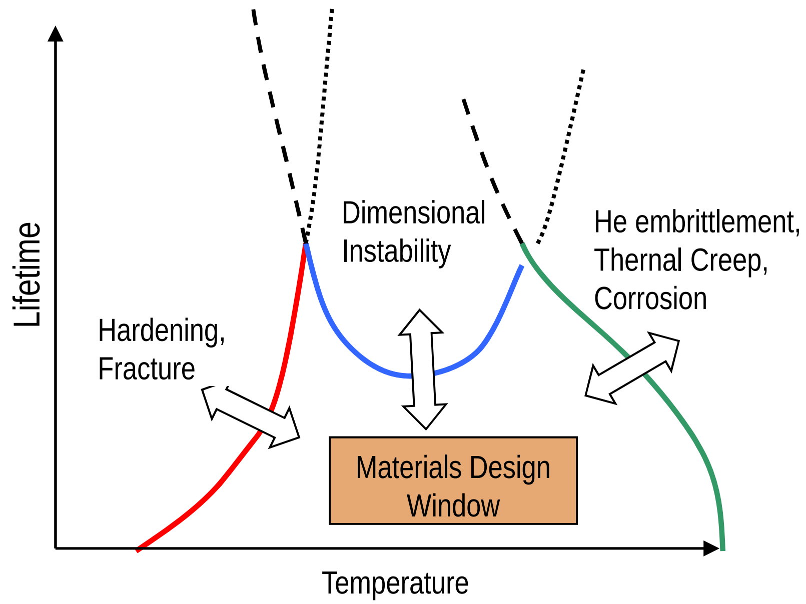

- From "A Study of the Environmental Impact of Fusion" (AERE R 13708).
- Coal radiotoxicity is based on Radon, Uranium, Thorium, and Polonium in coal ash
- Inhalation represents major pathways for uptake of material by the human body
- Dose hazard used here is a relative measure of radiotoxicity of material

# Effects of Fusion Environment on Bulk Material Properties

*High dpa and He (unique to fusion) coupled with high stresses result in:*

- Microstructure and property changes over long time.
  - Voids, bubbles, dislocations and phase instabilities.
  - Dimensional instabilities (swelling and irradiation-thermal creep).
  - Loss of strain hardening capability.
  - He embrittlement at low and high temperatures.
  - Fatigue, creep-fatigue, crack growth.
  - Enhanced corrosion, oxidation and impurity embrittlement (refractories).
  - Transient and permanent changes in electrical and thermal properties.

High He may narrow or even close the window




N. Ghoniem & B.D. Wirth, 2002

# Common interest of fission and fusion structural materials: operating temperature and radiation dose (dpa)

(There are many other areas of synergy between fission and fusion technologies )

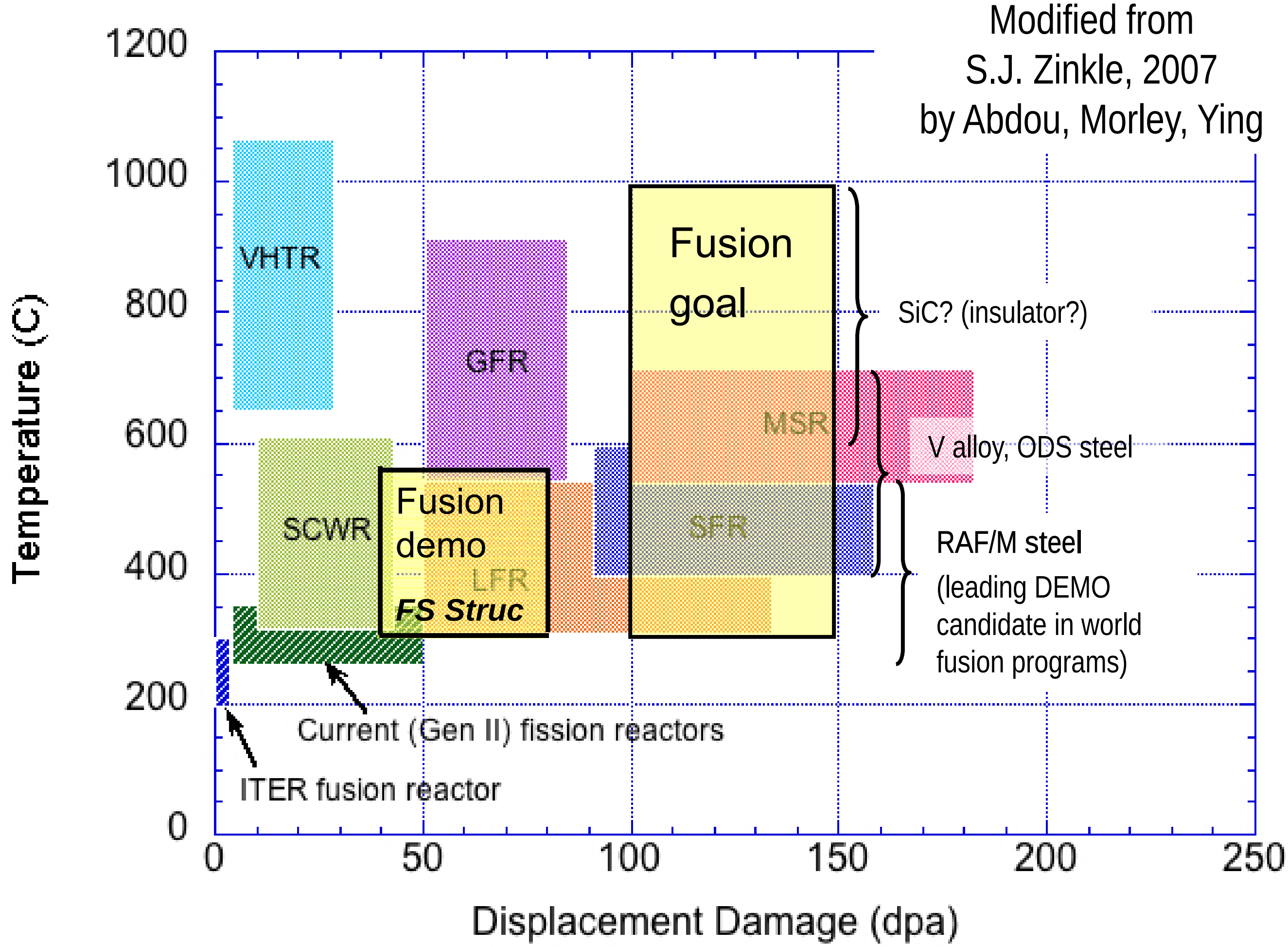
Notes:

- Fusion values presented here are the maximum at front of the FW/B.
- Dose in fusion structural material has steep radial gradients. Deeper in the blanket:
  - o Damage decreases by ~an order of magnitude
  - o Spectrum is softer and helium production is smaller, similar to fission

GEN IV

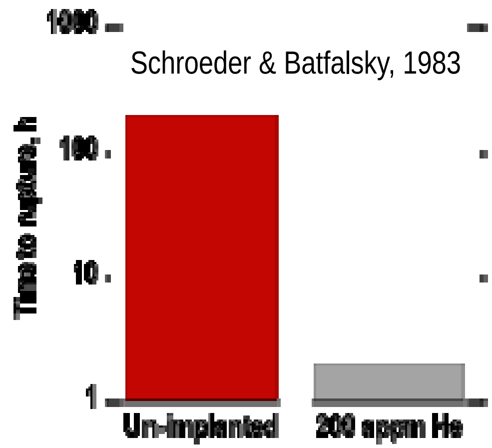
| | |
|---|---|
| VHTR: | Very High temperature reactor |
| SCWR: | Super-critical water cooled reactor |
| GFR: | Gas cooled fast reactor |
| LFR: | Lead cooled fast reactor |
| SFR: | Sodium cooled fast reactor |
| MSR: | Molten salt cooled reactor |

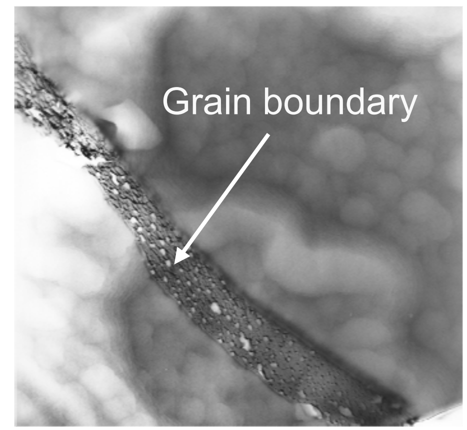
Modified from S.J. Zinkle, 2007 by Abdou, Morley, Ying



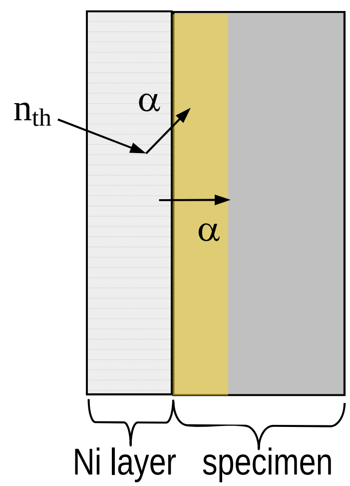
# Impact of He-Rich Environment on Neutron Irradiated Materials

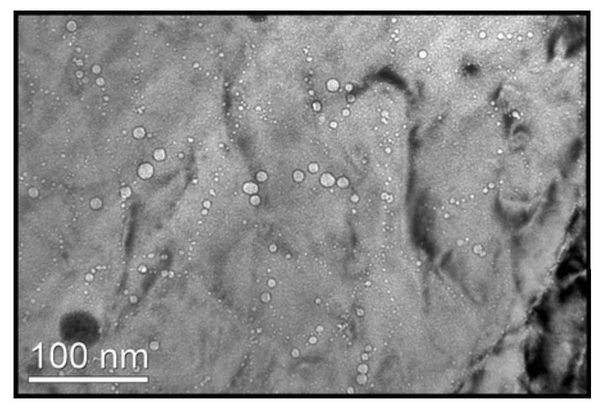
- A unique aspect of the DT fusion environment is large production of gaseous transmutant He and H.
- Accumulation of He can have major consequences for the integrity of fusion structures such as:
  - Loss of high-temperature creep strength.
  - Increased swelling and irradiation creep at intermediate temperatures.
  - Loss of ductility and fracture toughness at low temperatures.
- *In situ* He injection technique developed to inform models of He transport, fate and consequences.




*In situ* He injector
micro-IFMIF
technique




Yamamoto, et al., 2009

# Role of Irradiation Sources in Fusion Materials Science

- Overcoming *neutron-induced* radiation damage degradation is a key step in fusion materials development. Other Important Issues: fabrication and joining, corrosion and compatibility, and thermophysical properties , etc
- Evaluation of fusion radiation effects requires simultaneous displacement damage and He generation, with He /dpa ratio ~ 10-12
- Ion irradiations – effects of dpa and gas generation can be studied to high levels, but cannot simulate neutron damage because charged particle damage rates are ~1000 times larger than for fusion conditions. In addition, ions produce damage over micron length scales thereby preventing measurement of bulk material properties.
- **Ferritic Steel 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).**

***Two primary sources of impurities*** **in plasma** exist:

***Helium "ash"*** from the fusion reaction

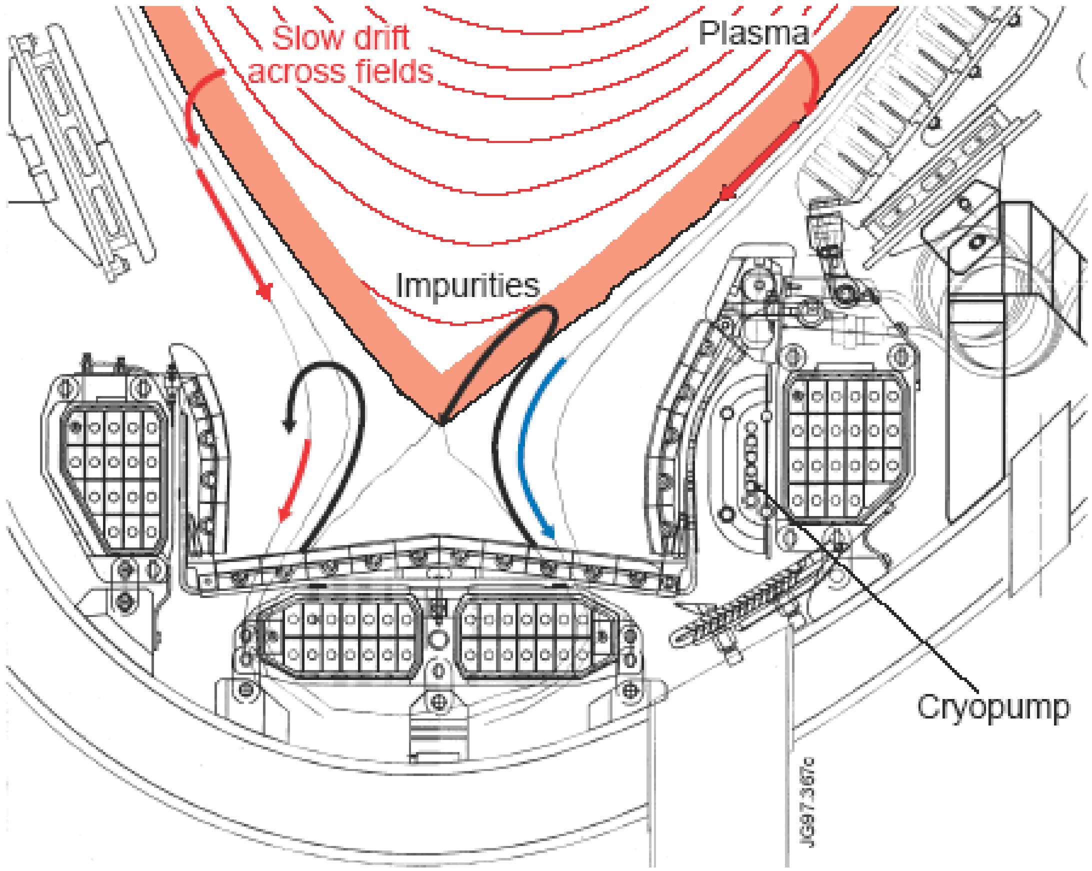
Material impurities from ***plasma-wall interactions***

***Impurities must be controlled*** since they:

Radiate energy, and reduce the plasma temperature

Dilute the fuel, thereby preventing ignition

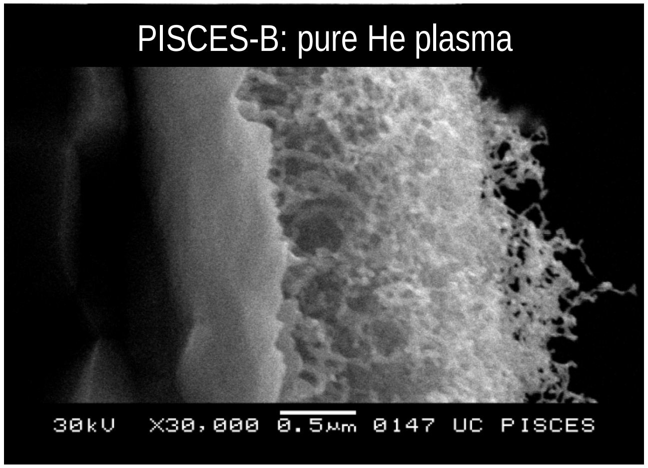
The ***"Magnetic Divertor"*** is a device for controlling impurities.



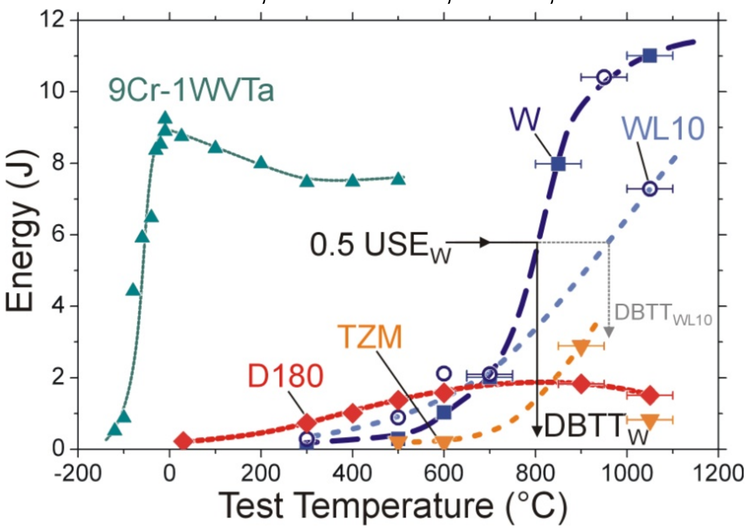
# Plasma Facing Materials Must Tolerate Extreme Heat, Neutron & Particle Fluxes

- Typical materials considered for PFC (e.g. Divertor) include graphite, beryllium and tungsten.
- Tungsten alloys (or other refractory alloys) are the only possible structural materials for divertor applications (q">10 MW/m$^2$) due to their excellent thermo-physical properties.
- However, critical issues need to be addressed:
  - Creep strength
  - Fracture toughness
  - Microstructural stability
  - Low & high cycle fatigue
  - Oxidation resistance
  - Effects of neutron irradiation (hardening & embrittlement, He)
- An effort to explore ways to improve the properties of tungsten is being initiated.

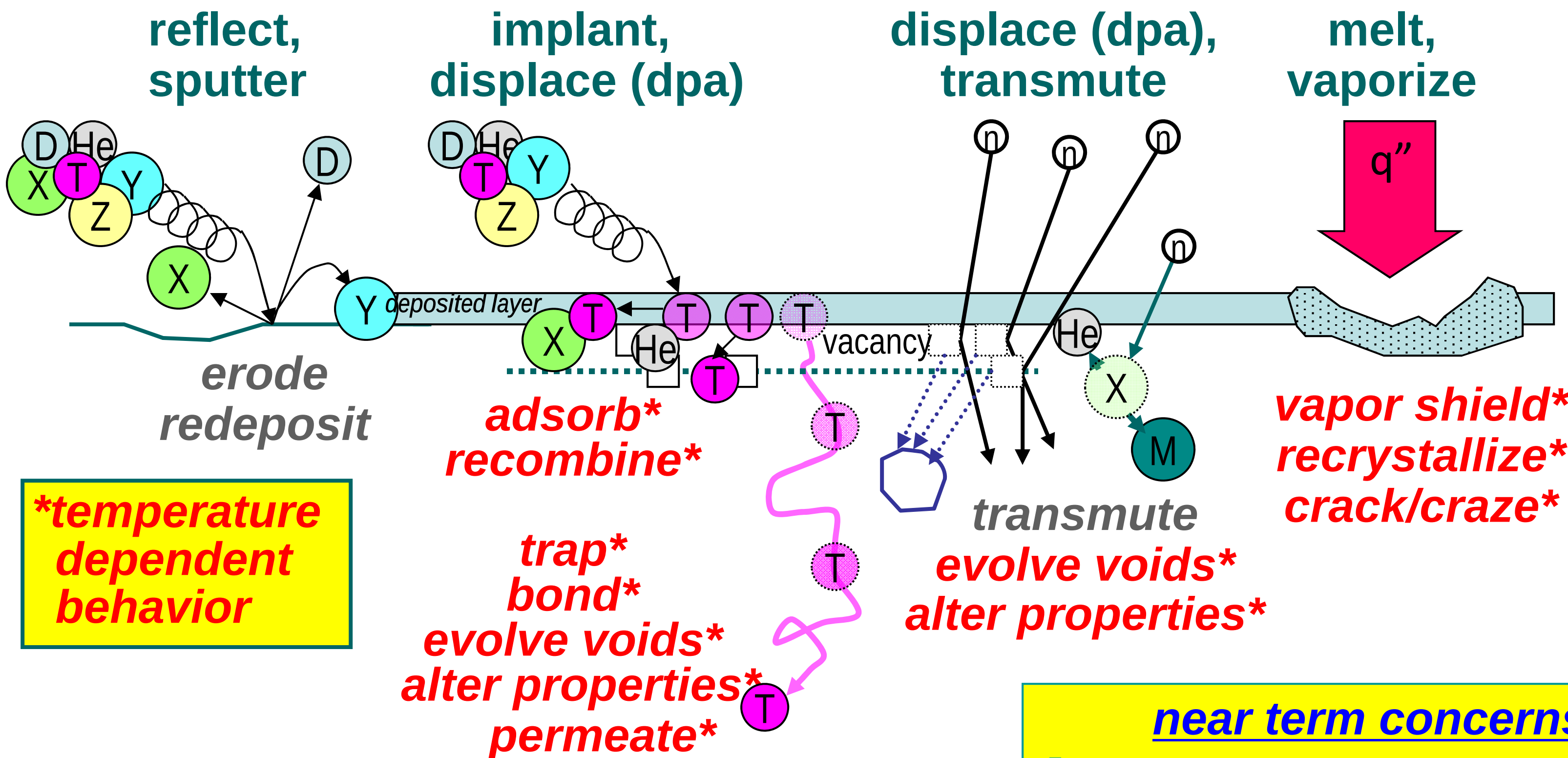
Baldwin, Nishijima, Doerner, et. al, courtesy of Center for Energy Research, UCSD, *La Jolla, CA*




M. Rieth, A. Hoffmann, HHFC, 2008



# Plasma-Surface Interaction (PSI) Processes temperature dependence



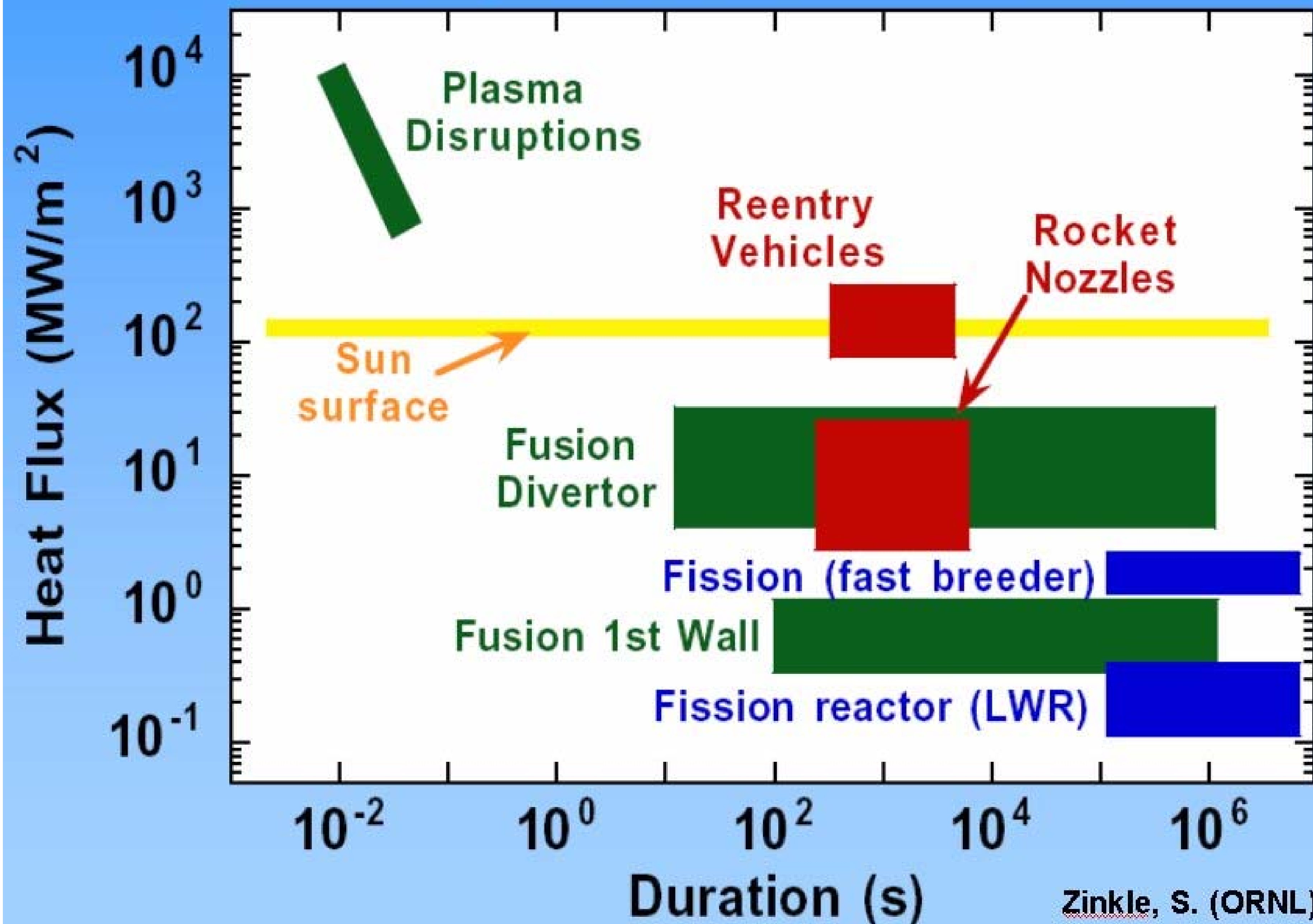

**The physical chemistry of PSI processes on high temperature walls will determine the strong interaction between wall and plasma in DEMO (or FNSF).**

***near term concerns***

- ..
- Prediction/modeling of damage from ions, neutrons & thermal gradients at high temperature, related tests, benchmark data
- Deploying actively-cooled PFCs and large area “hot” walls
- ..

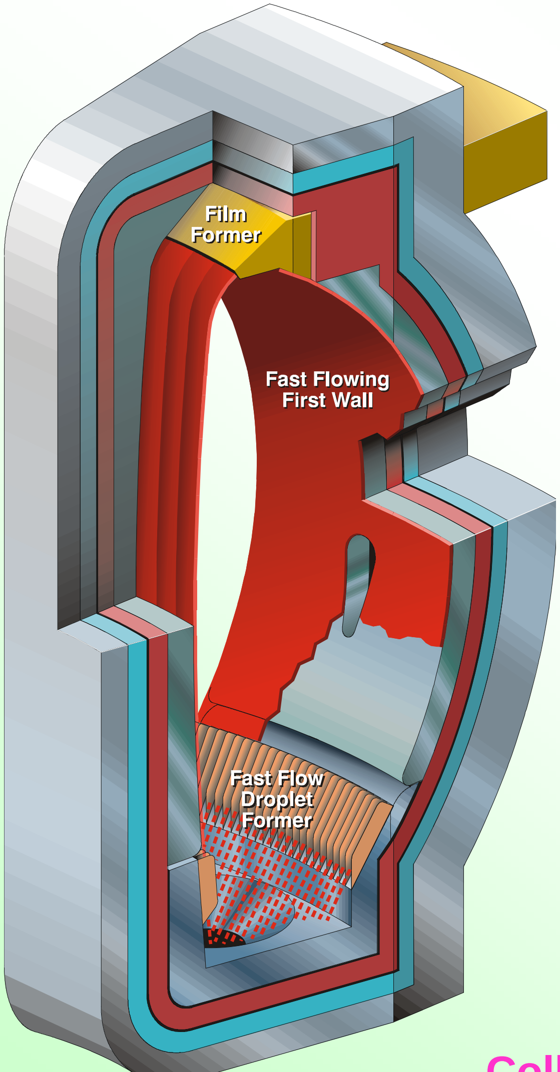
*more complete presentation of critical issues in backup slides

# Comparison of Heat Fluxes

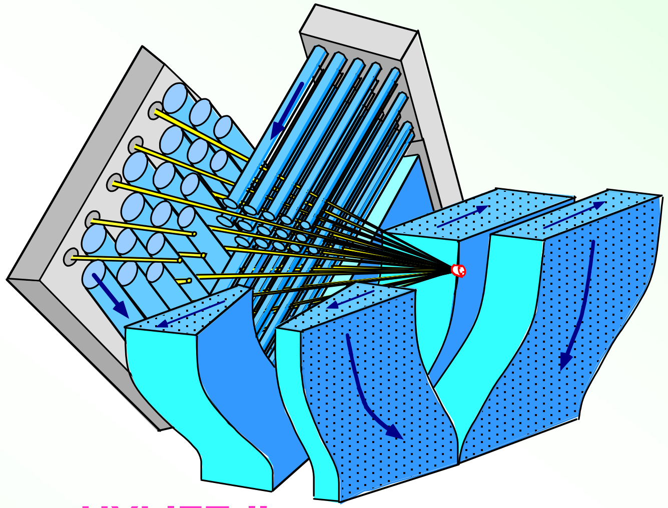



Zinkle, S. (ORNL)

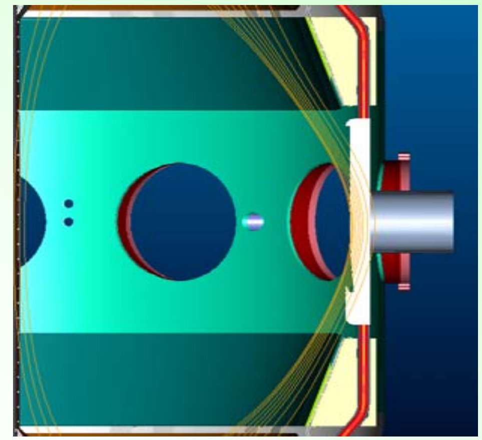
# Liquid Walls ("Free Surface") Concepts have been Considered in MFE & IFE to solve PFC Issues



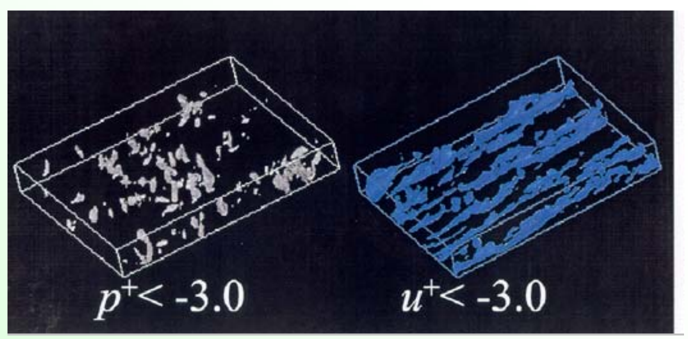

APEX CLiFF



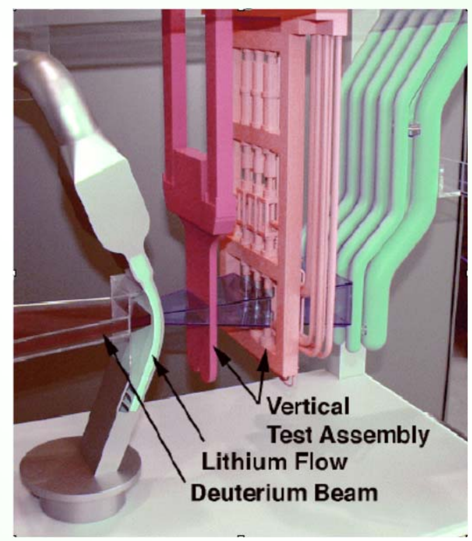
HYLIFE-II



ALPS/APEX NSTX Li module




DNS Free Surface Simulation
Collaboration with non-fusion scientists
US-Japan Collaboration




IFMIF

# 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!

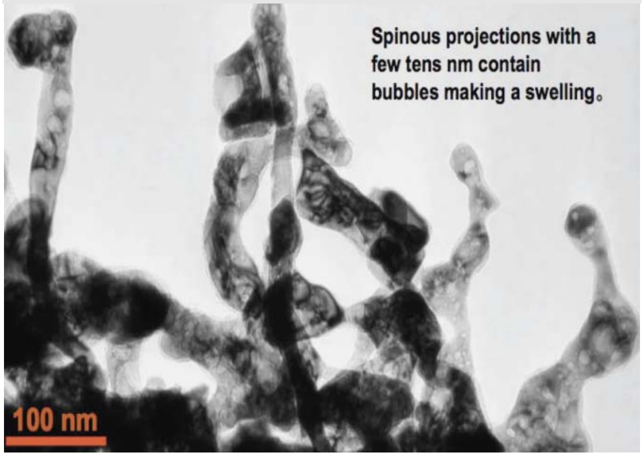
- **Liquid walls** have a completely different set of advantages and issues
  - Continuously renewed surface: **immune** to erosion, particle and neutron damage
  - Can potentially do two functions:

    **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**, 3.5x10$^{27}$ He$^{+}$/m$^{2}$, $E_{ion}$ = 11 eV

# *Top-Level* Technical Issues for FNST (set 1 of 2)

**(Details of these issues published in many papers, Last update: December 2009)**

## 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**
4. **Interfacial phenomena, chemistry, compatibility, surface erosion and 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 (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

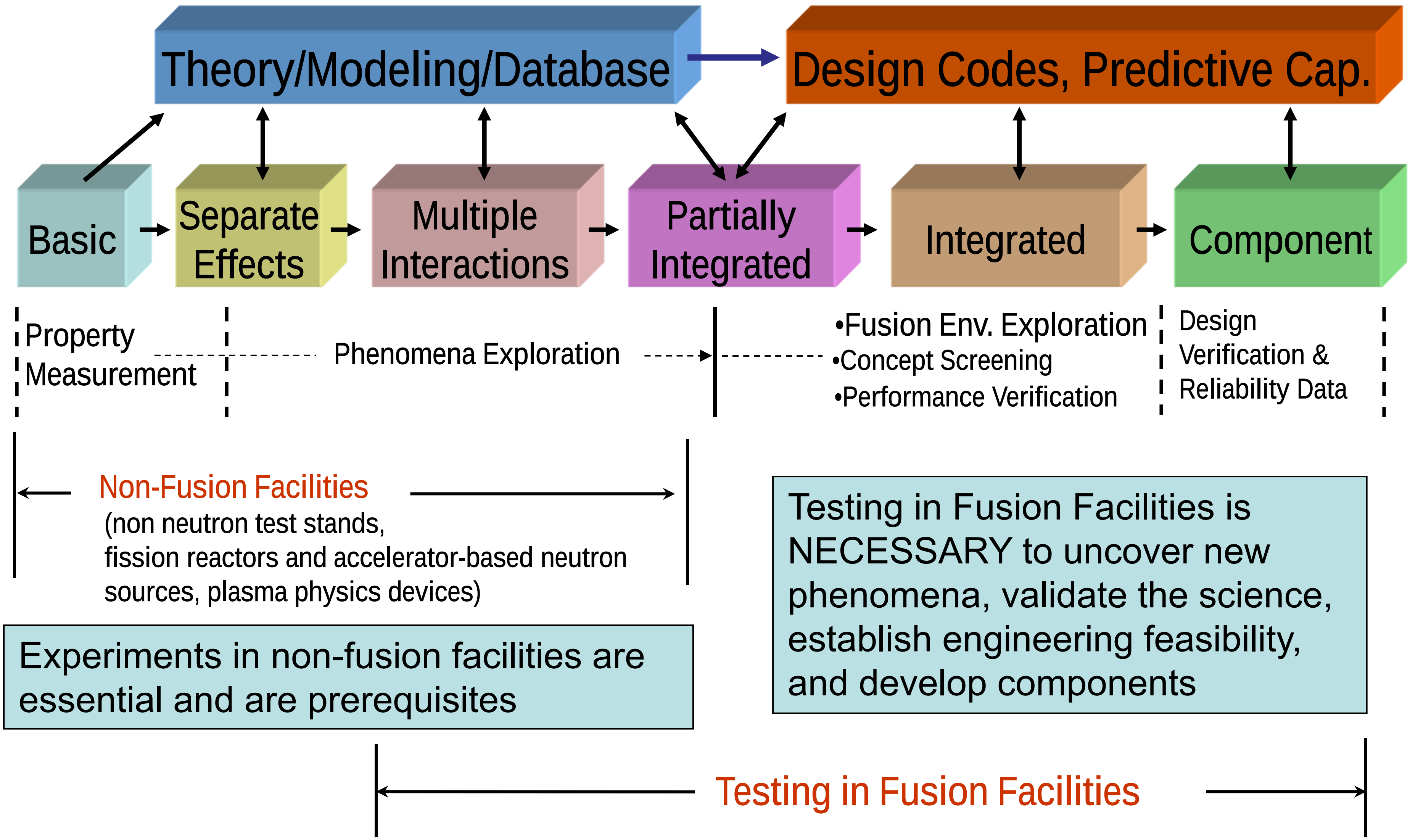
**Reliability, Availability, Maintainability (RAMI)**

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

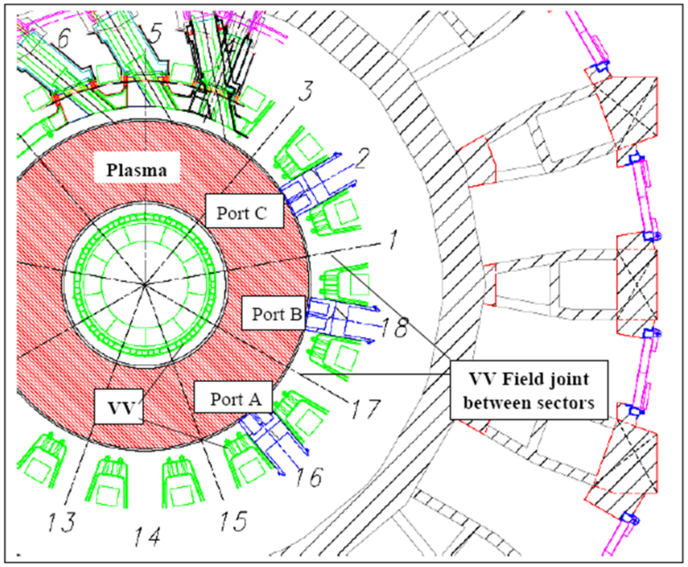
**All issues are strongly interconnected:**

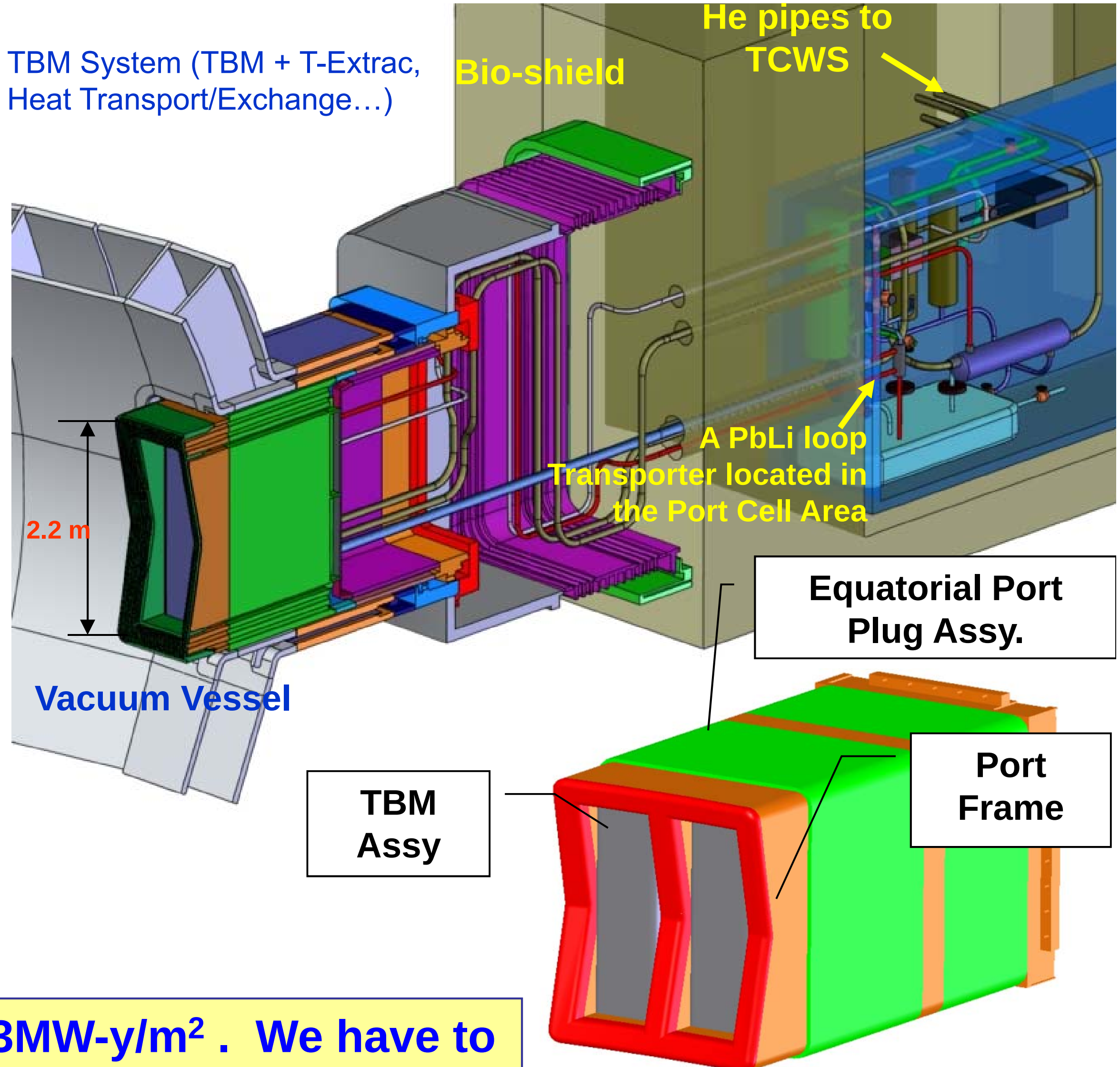
- they span requirements
- they span components
- they span many technical disciplines of science & engineering

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



# ITER Provides Substantial Hardware Capabilities for Testing of Blanket System

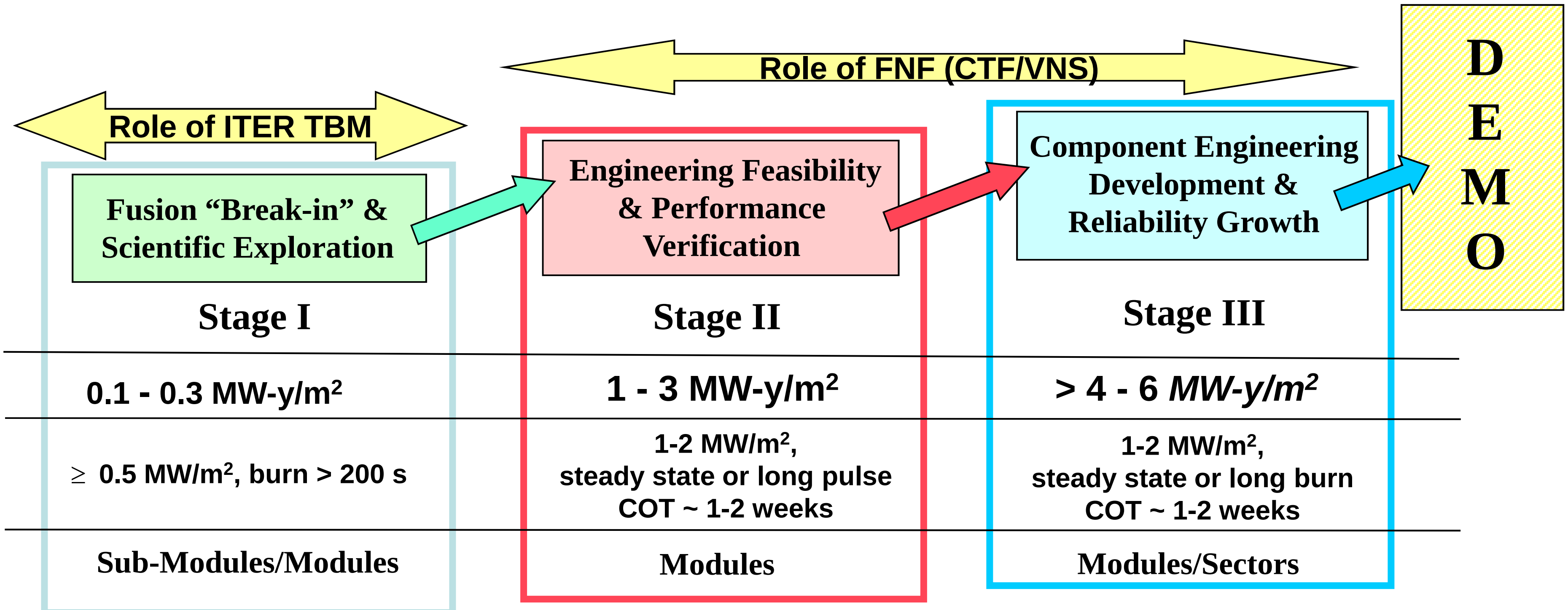



- ITER has allocated **3 ITER equatorial ports** (1.75 x 2.2 $m^2$) for TBM testing
- Each port can accommodate only 2 modules **(i.e. 6 TBMs max)**

**Fluence in ITER is limited to 0.3MW-y/$m^2$. We have to build another facility, for FNST development**

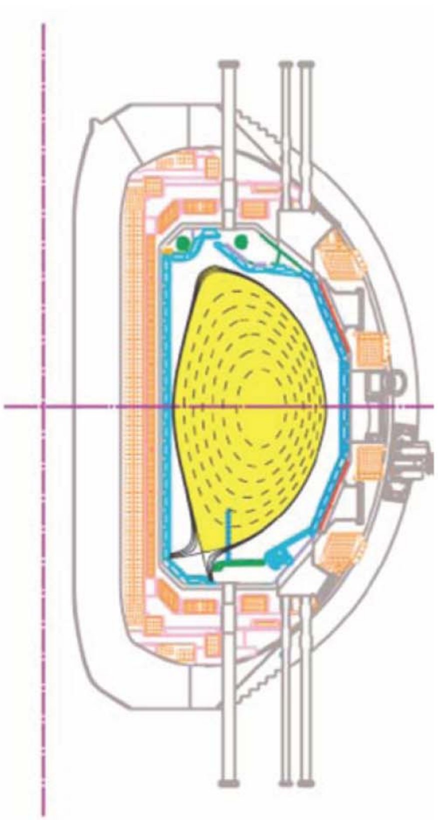
# THREE Stages of FNST Testing in Fusion Facilities are Required Prior to DEMO

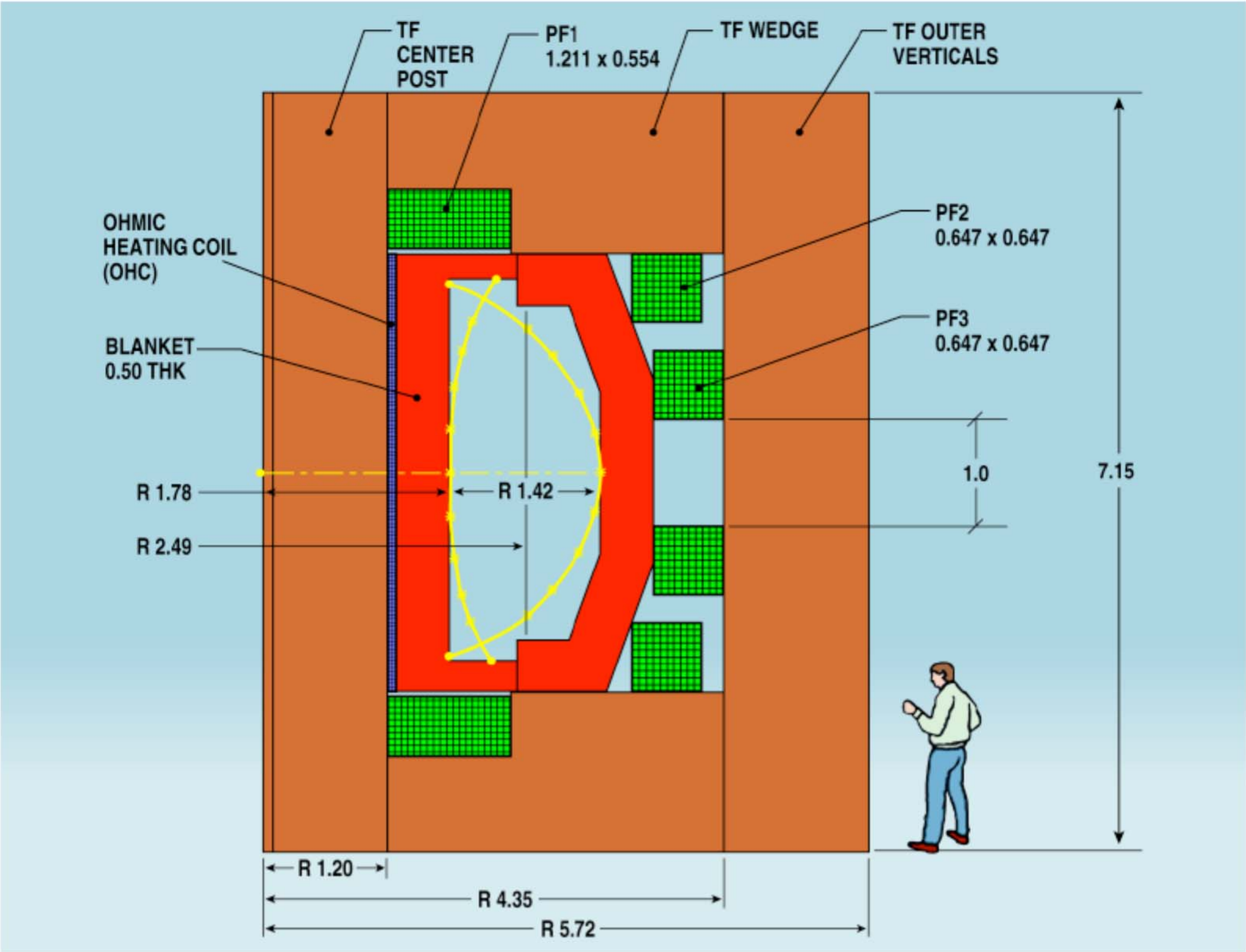



- **ITER is designed to fluence < 0.3MW-y/m$^2$. ITER can do only Stage I**

- **A Fusion Nuclear Facility, FNSF is needed , in addition to ITER, to do Stages II (Engineering Feasibility) and III (Reliability Growth)**
  - **FNSF must be small-size, low fusion power (< 150 MW), hence, a driven plasma with Cu magnets.**

## Example of Fusion Nuclear Facility (FNF) Device Design Option : Standard Aspect Ratio (A=3.5) with demountable TF coils (GA design)






- High elongation, high triangularity double null plasma shape for high gain, steady-state plasma operation

**Challenges for Material/Magnet Researchers:**

- **Development of practical "demountable" joint in Normal Cu Magnets**
- **Development of Inorganic Insulators (to reduce inboard shield and size of device)**

## FNST research requires advancing the state-of-the-art, and developing highly integrated predictive capabilities for many cross-cutting scientific and engineering disciplines

- neutron/photon transport
- neutron-material interactions
- plasma-surface interactions
- heat/mass transfer
- MHD thermofluid physics
- thermal hydraulics
- tritium release, extraction, inventory and control
- tritium processing
- gas/radiation hydrodynamics
- phase change/free surface flow
- structural mechanics
- radiation effects
- thermomechanics
- chemistry
- radioactivity/decay heat
- safety analysis methods and codes
- engineering scaling
- failure modes/effects and RAMI analysis methods
- design codes

**FNST research requires the talents of many scientists and engineers in many disciplines.**
**Need to attract and train bright young students and researchers.**

# Thank You for Your Attention!