Fast Introduction to
Fusion Nuclear Science and Technology
Blankets, PFC, Materials, Neutronics, MHD,
Thermofluids, and Thermomechanics

Mohamed Abdou

Distinguished Professor of Engineering and Applied Science (UCLA)
Director, Center for Energy Science & Technology (UCLA)
President, Council of Energy Research and Education Leaders, CEREL (USA)

Seminar at **Shanghai Jiao Tong University**

Shanghai, China April 20, 2011

The Oriental Pearl TV Tower,
Shanghai, China

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What is fusion?

- **Fusion powers the Sun and Stars.** Two light nuclei combine to form a heavier nuclei (the opposite of nuclear fission).

Deuterium

$E = mc^2$

17.6 MeV

Neutron

Tritium

Helium

80% of energy release (14.1 MeV)

Used to breed tritium and close the DT fuel cycle

$Li + n \rightarrow T + He$

Li in some form must be used in the fusion system
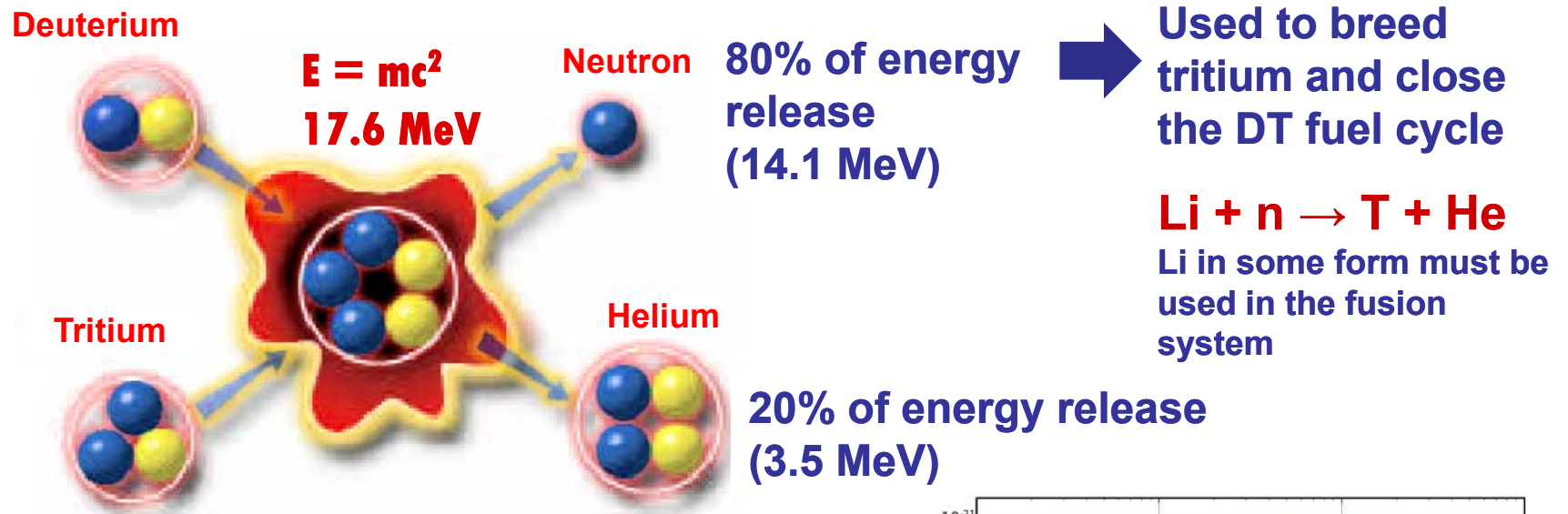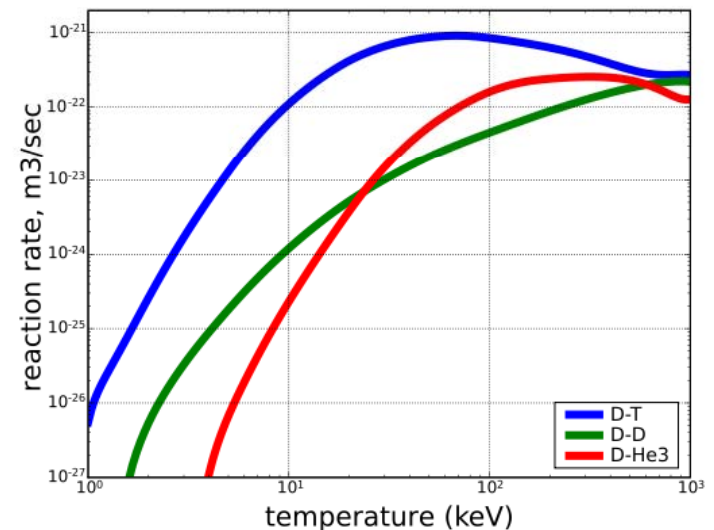
20% of energy release (3.5 MeV)

Illustration from DOE brochure

- **Deuterium and tritium is the easiest, attainable at lower plasma temperature, because it has the largest reaction rate and high Q value.**
- **The World Program is focused on the D-T Cycle**

reaction rate, m3/sec — temperature (keV)

D-T
D-D
D-He3

Incentives for Developing Fusion

- Sustainable energy source

  (for DT cycle: provided that Breeding Blankets are successfully developed and tritium self sufficiency conditions are satisfied)

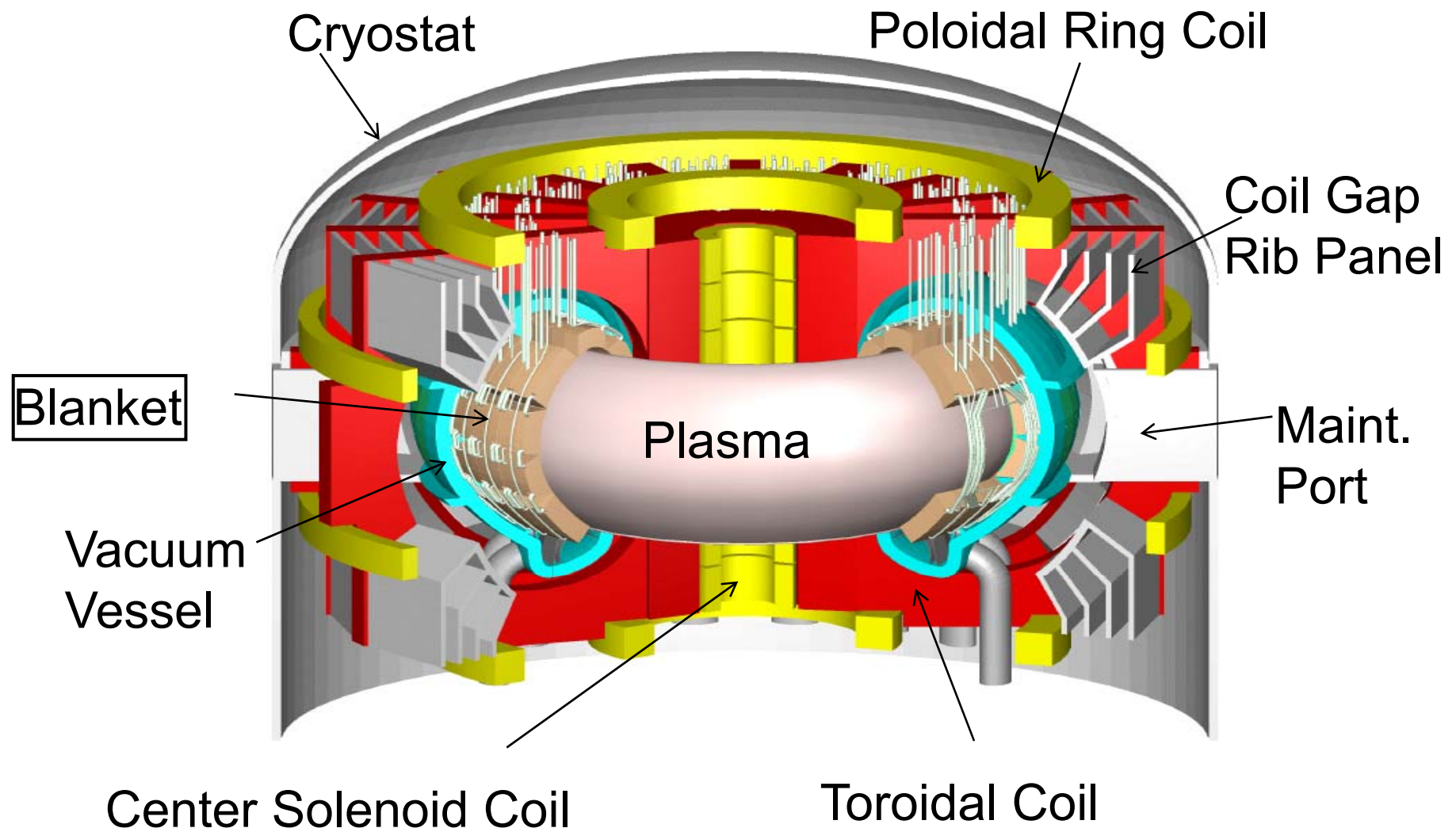- No emission of Greenhouse or other polluting gases

- No risk of a severe accident

- No long-lived radioactive waste

Fusion energy can be used to produce electricity and hydrogen, and for desalination.

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

Plans for DEMO are based on Tokamaks

Cryostat

Poloidal Ring Coil

Coil Gap Rib Panel

Blanket

Plasma

Maint. Port

Vacuum Vessel

Center Solenoid Coil

Toroidal Coil

(Illustration is from JAEA DEMO Design)

ITER

- The World has started construction of the **next step** in fusion development, a device called ITER.

- ITER will demonstrate the **scientific and technological feasibility** of fusion energy for peaceful purposes.

- ITER will produce **500 MW** of fusion power.

- Cost, including R&D, is ~15 billion dollars.

- **ITER is a collaborative effort among Europe, Japan, US, Russia, China, South Korea, and India. ITER construction site is Cadarache, France.**

- ITER will begin operation in hydrogen in ~2019. **First D-T Burning Plasma in ITER in ~ 2026.**

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**
    - **$Q = (E_f / E_{input})\sim10$**
    - **ITER (MFE) and NIF (inertial fusion)**

- **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)**

National Ignition Facility
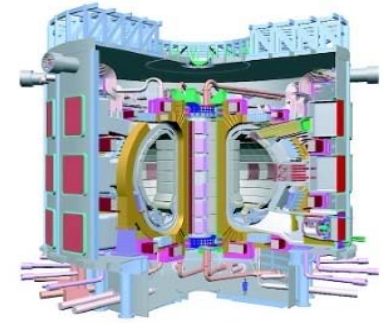
ITER

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
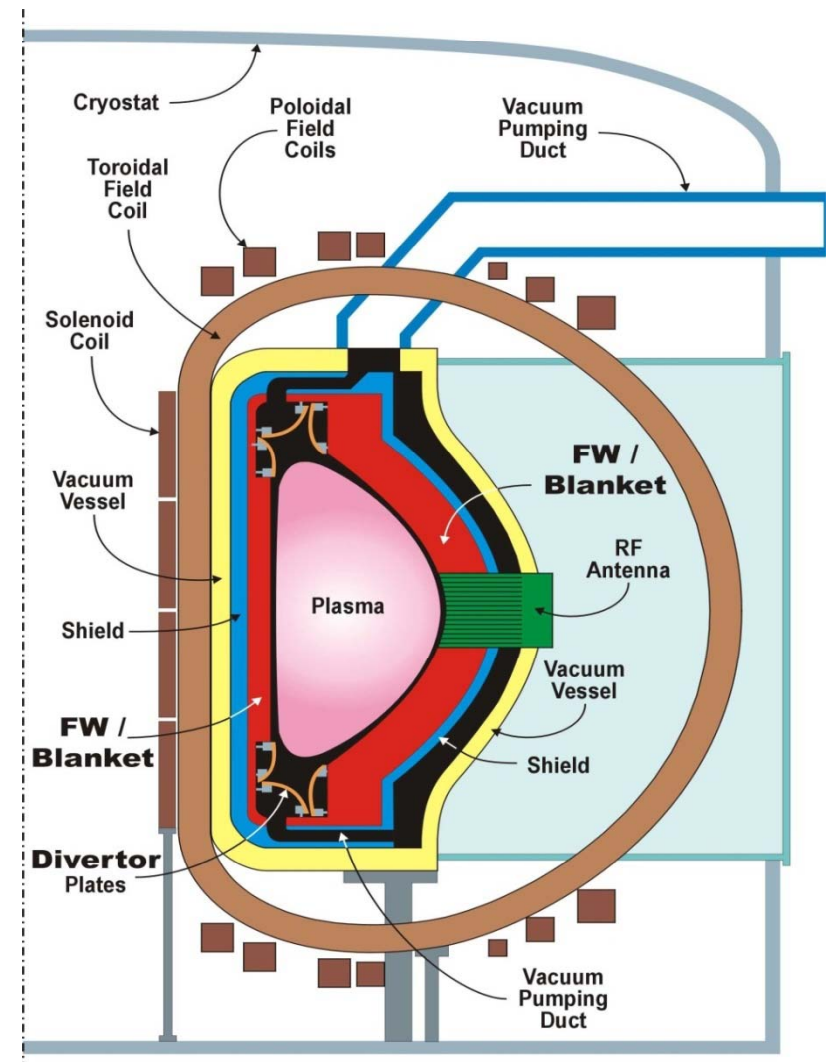
The primary functions of the blanket are to provide for: Power Extraction & Tritium Breeding
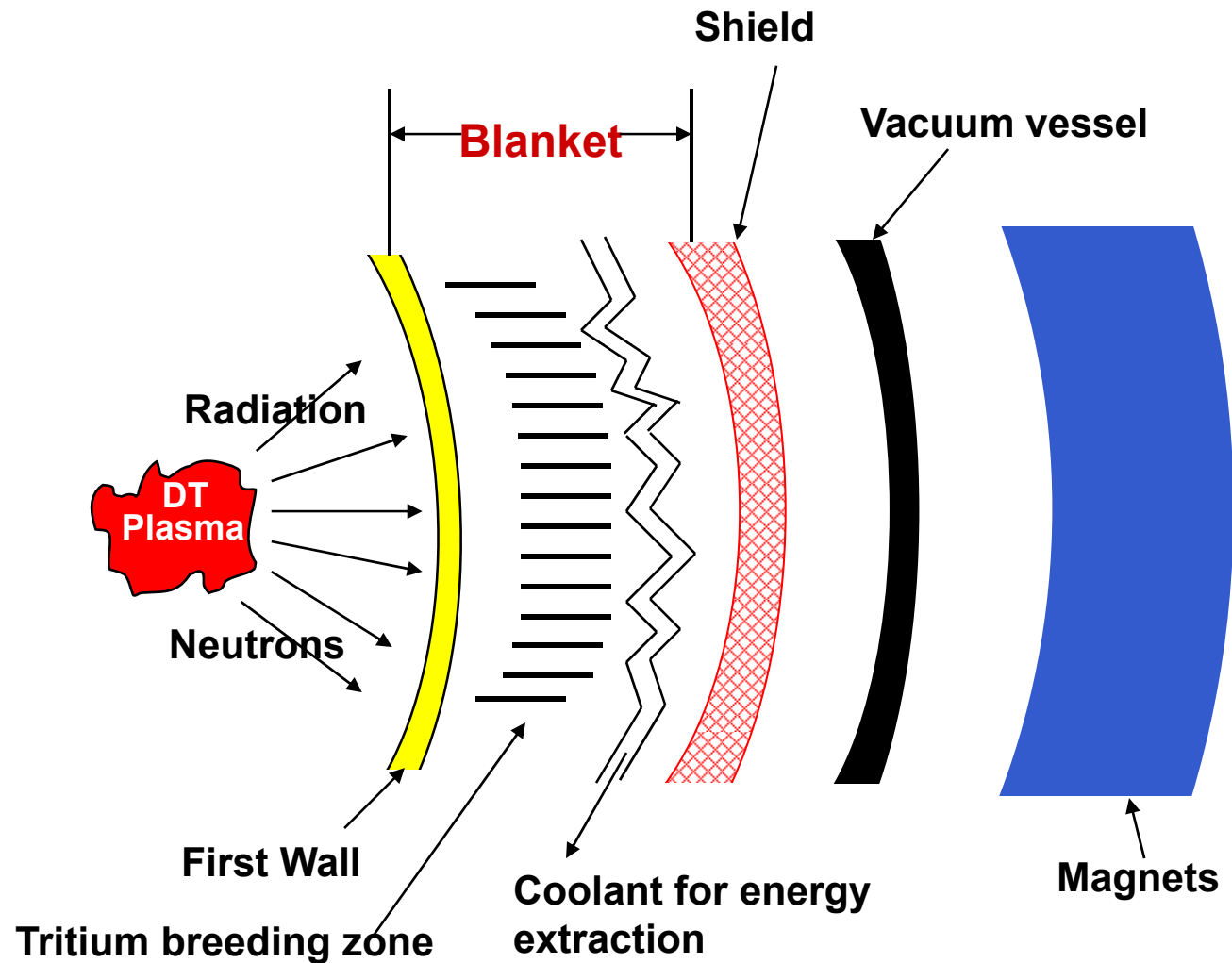
Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. Lithium ceramics are candidates for breeder with He cooling

Possible Blanket/FW Materials

1. Tritium Breeding Material (Lithium in some form)

   Liquid: Li, LiPb (Pb $^{15.7at\%}$Li), LiSn; molten salts (Flibe, Flinabe, Flinak)

   Solid: Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3

2. Neutron Multiplier (for most blanket concepts)

   Beryllium (Be, $Be_{12}Ti$),　　Lead (in LiPb)

3. Coolant

   – Li, LiPb　　　– Molten Salt　　　– Helium　　– Water

4. Structural Material

   – Ferritic Steel (nearer term reference for DEMO)

   – Longer-term: Vanadium alloy (compatible only with Li), and SiC/SiC, ODS ferritic steels

5. MHD insulators (for concepts with self-cooled liquid metals)

6. Thermal insulators (only in some concepts with dual coolants)

7. Tritium Permeation Barriers (in some concepts)

8. Neutron Attenuators and Reflectors (in some concepts)

9. Armors / plasma facing surface (W, Be)

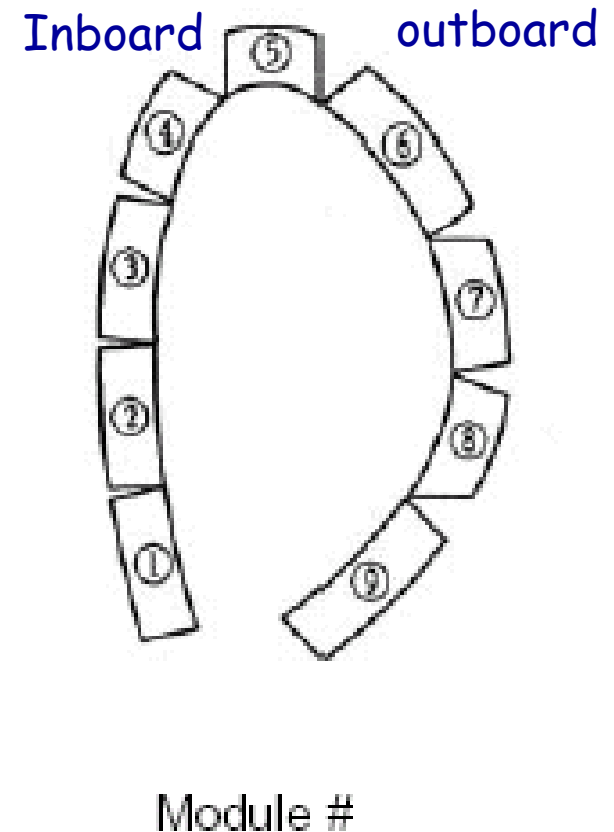9

UCLA

Neutron Wall Load:

Fusion Neutron Power Incident on the First Wall per unit area

– Neutron wall load has profile along the poloidal direction (due to combination of toroidal and poloidal geometries).Peak to average is typically about 1.4
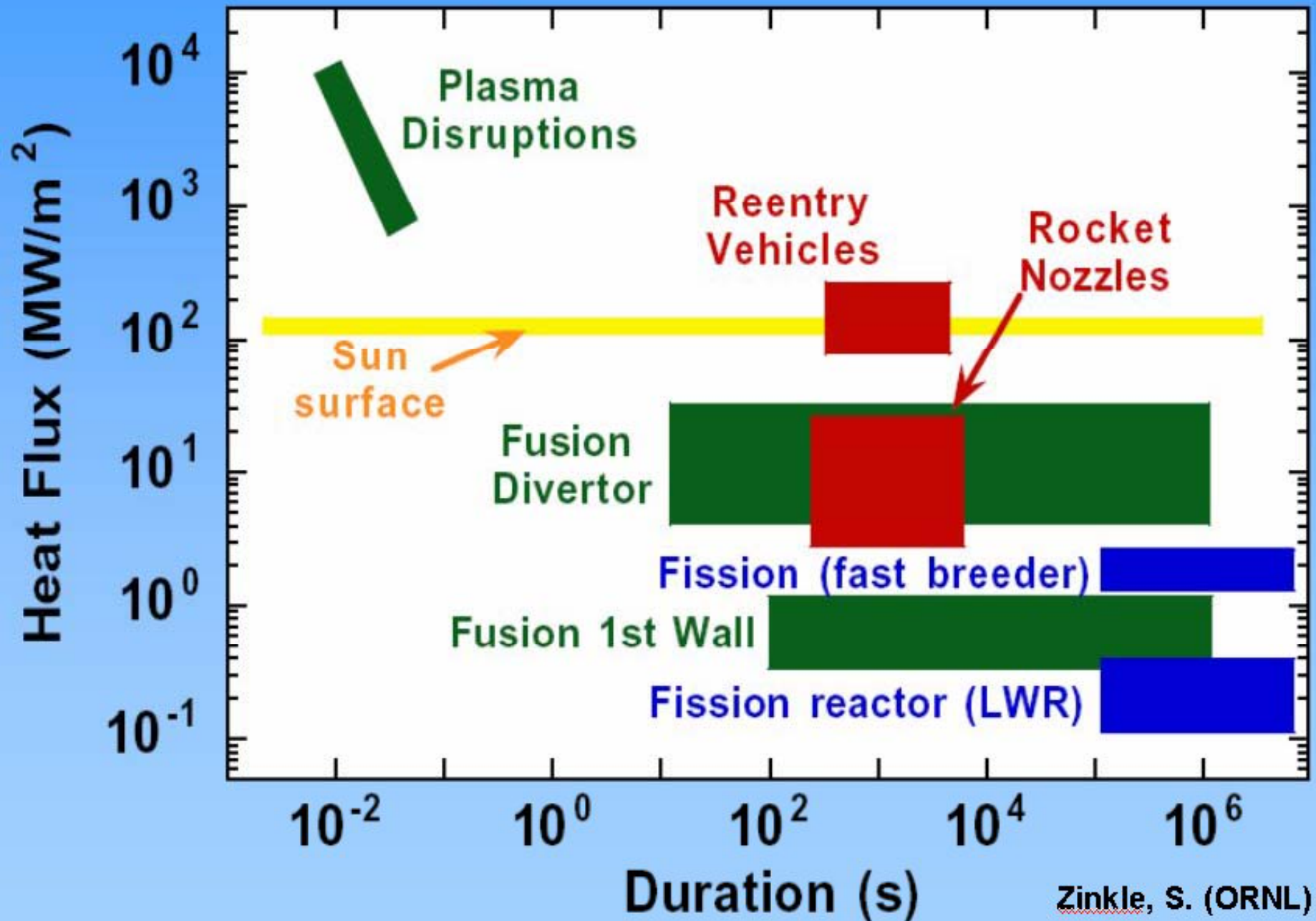
#1, #2, etc. represent module numbers.

Inboard   outboard
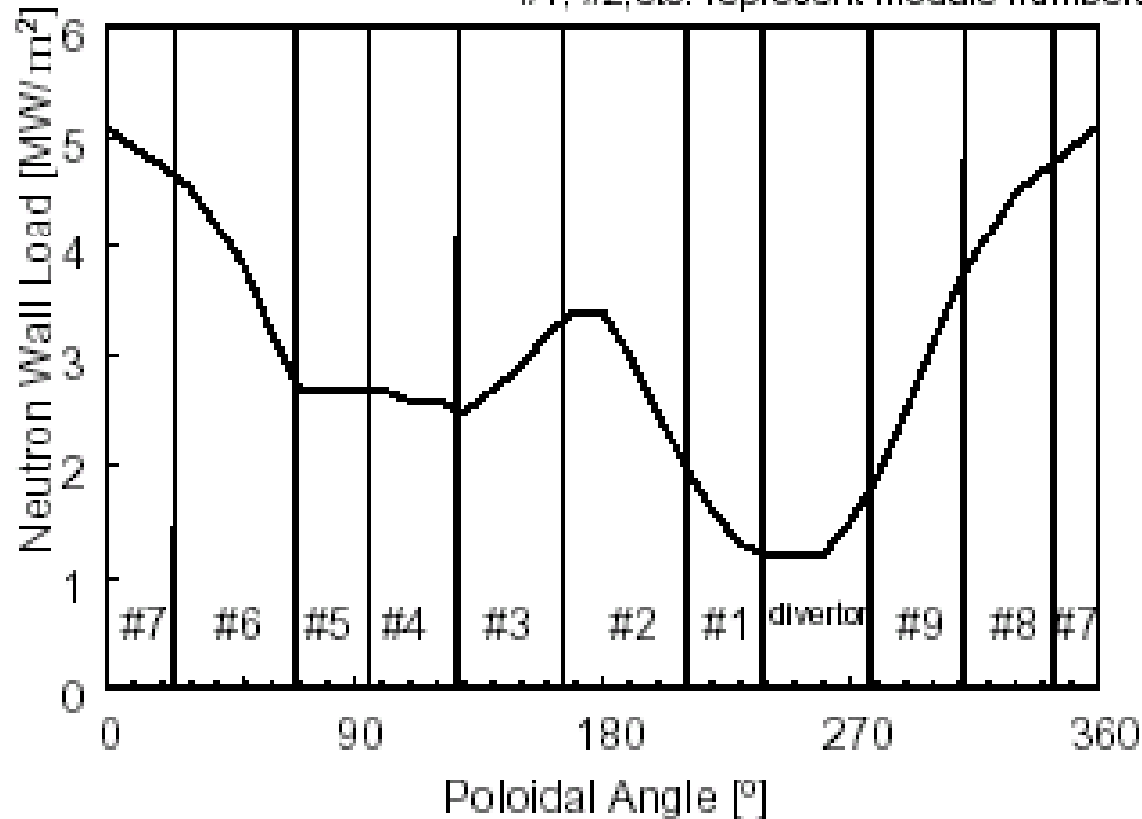
Profile of Neutron Wall Load
(equatorial plane, outboard, in 0°)

Module #

Comparison of Heat Fluxes

Zinkle, S. (ORNL)
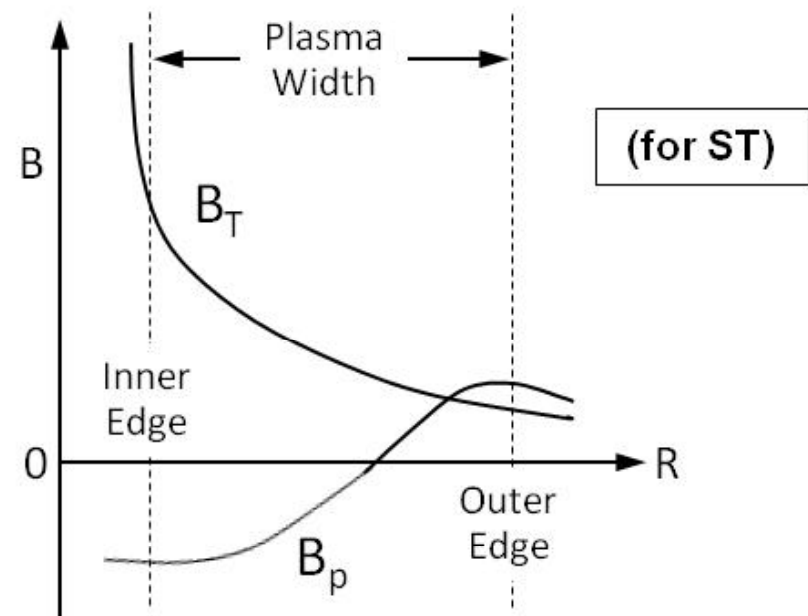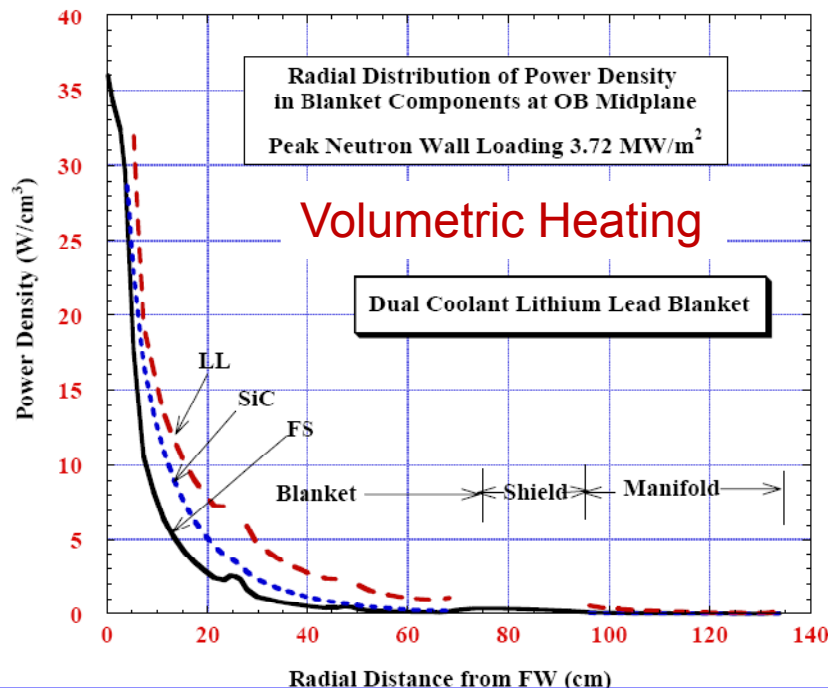
Fusion environment is unique and complex: multi-component fields with gradients

- Neutron and Gamma fluxes
- Particle fluxes
- Heat sources (magnitude and gradient)
  – Surface (from plasma radiation)
  – Bulk (from neutrons and gammas)

- Magnetic Field (3-component)
  – Steady field
  – Time varying field
- With gradients in magnitude and direction

Radial Distribution of Power Density in Blanket Components at OB Midplane

Peak Neutron Wall Loading 3.72 MW/m²

Volumetric Heating

Dual Coolant Lithium Lead Blanket

(for ST)

Multi-function blanket/divertor in multi-component field environment leads to:

- *Multi-Physics, Multi-Scale Phenomena* ⟹ *Rich Science to Study*
- **Synergistic effects** that cannot be anticipated from simulations & separate effects tests. Modeling and Experiments are challenging
- Such unique fusion environment and synergistic effects can be reproduced only in plasma-based devices.

Tritium Breeding by capturing neutrons in Lithium

D+T --→ n+ alpha

Li-6(n,alpha)t and Li-7(n,n,alpha)t Cross-Section
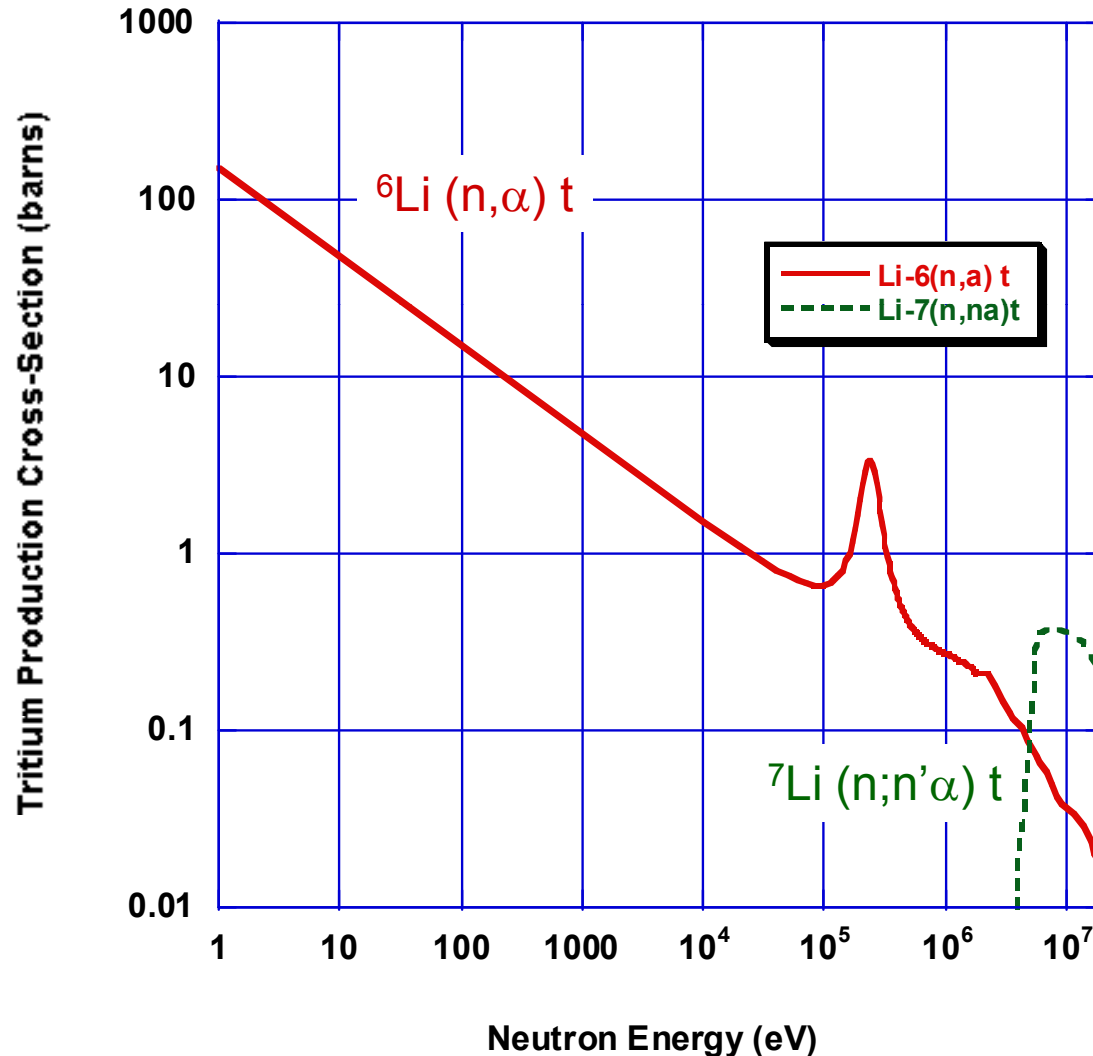
Natural lithium contains 7.42% ^{6}Li and 92.58% ^{7}Li.

$$^6Li + n \rightarrow t + \alpha + 4.78MeV$$
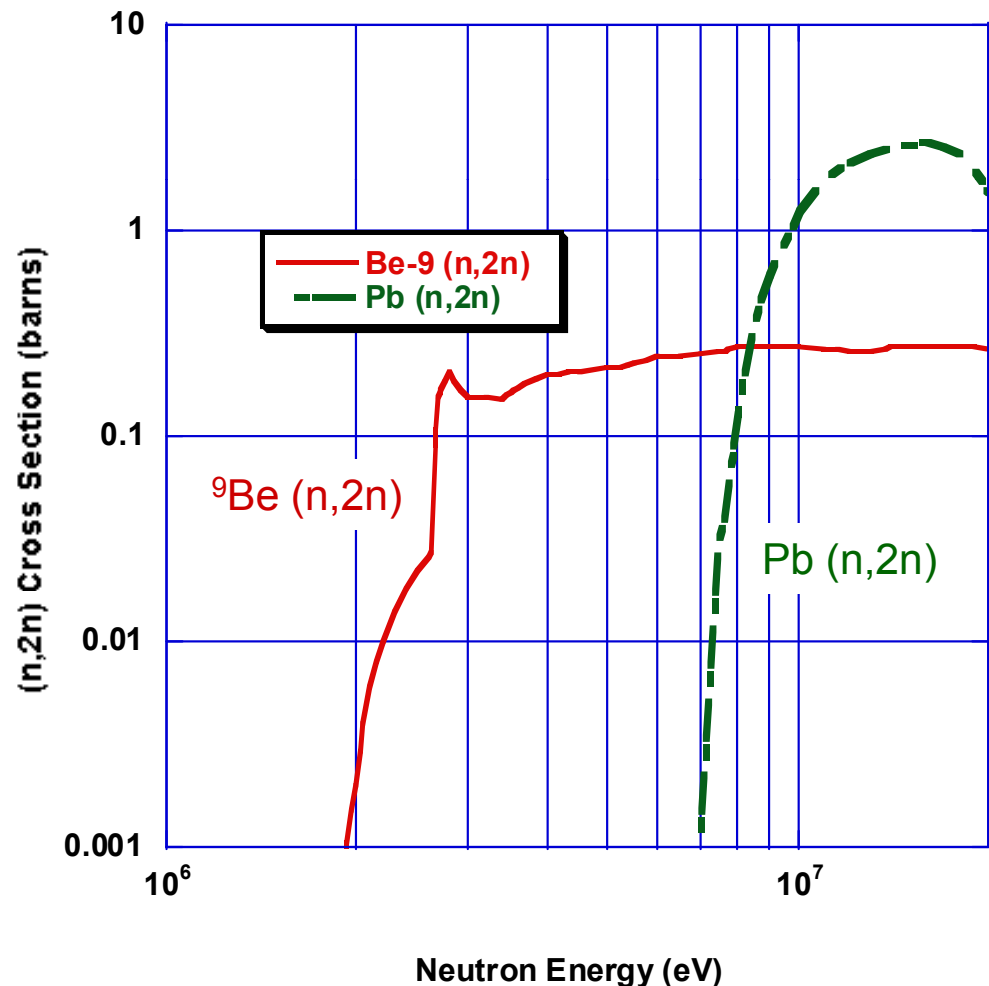$$^7Li + n \rightarrow t + \alpha + n - 2.47MeV$$
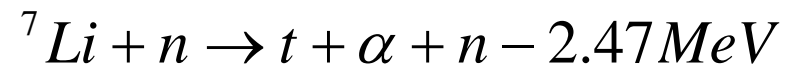
The ^{7}Li(n;n'α)t reaction is a threshold reaction and requires an incident neutron energy in excess of 2.8 MeV.

Neutron Multipliers

- Almost all concepts need a neutron multiplier to achieve adequate tritium breeding.

  (Possible exceptions: concepts with Li and Li_2O)

- Desired characteristics:
  - Large (n, $2n$) cross-section with low threshold
  - Small absorption cross-sections

- Candidates:
  - Beryllium is the best (large n, $2n$ with low threshold, low absorption)
  - $Be_{12}Ti$ may have the advantage of less tritium retention
  - Pb is less effective except in LiPb
  - Beryllium results in large energy multiplication, but resources are limited.

Examples of Neutron Multipliers Beryllium, Lead

Be-9 (n,2n) and Pb(n,2n) Cross-Sections- JENDL-3.2 Data

Legend:
- Be-9 (n,2n)
- Pb (n,2n)

^9Be (n,2n)

Pb (n,2n)

y-axis: (n,2n) Cross Section (barns)

x-axis: Neutron Energy (eV)

Tritium self-sufficiency condition:
$$\Lambda a \geq \Lambda r$$

Λr = Required tritium breeding ratio

> *Λr is 1 + G, where G is the margin required to account for:*
>> 1) Supply tritium inventory for start-up of other reactors (for a specified doubling time)
>>
>> 2) Tritium inventory holdup in plant components (e.g. fueling system, plasma exhaust/vacuum pumping systems, etc.)
>>
>> 3) Losses via radioactive decay (5.47% per year)

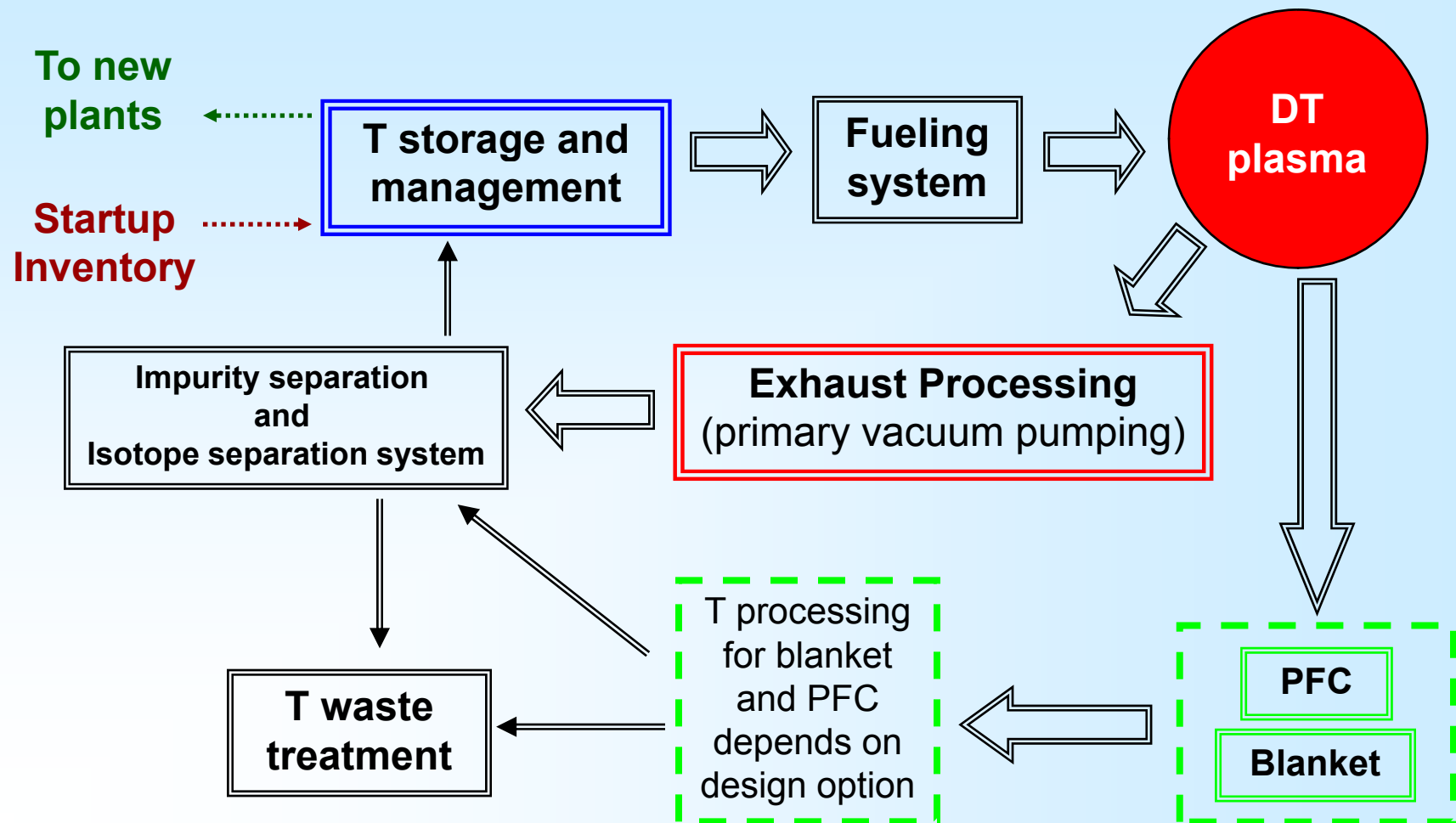**Λr is dependent on many system physics and technology parameters.**

Λa = Achievable tritium breeding ratio

Λa is a function of technology, material and physics.

Dynamic fuel cycle models were developed to calculate time-dependent tritium flow rates and inventories

(Dynamic Fuel Cycle Modelling: Abdou/Kuan et al. 1986, 1999)

Simplified Schematic of Fuel Cycle

Blanket Concepts
(many concepts proposed worldwide)

A.   Solid Breeder Concepts

- Always separately cooled
- Solid Breeder: Lithium Ceramic (Li_2O, Li_4SiO_4, Li_2TiO_3, Li_2ZrO_3)
- Coolant: Helium or Water

B.   Liquid Breeder Concepts

Liquid breeder can be:

a) **Liquid metal** (high conductivity, low Pr): Li, or ^{83}Pb ^{17}Li

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

B.1. Self-Cooled

- Liquid breeder is circulated at high enough speed to also serve as coolant

B.2. Separately Cooled

- A separate coolant is used (e.g., helium)
- The breeder is circulated only at low speed for tritium extraction

B.3. Dual Coolant

- FW and structure are cooled with separate coolant (He)
- Breeding zone is self-cooled

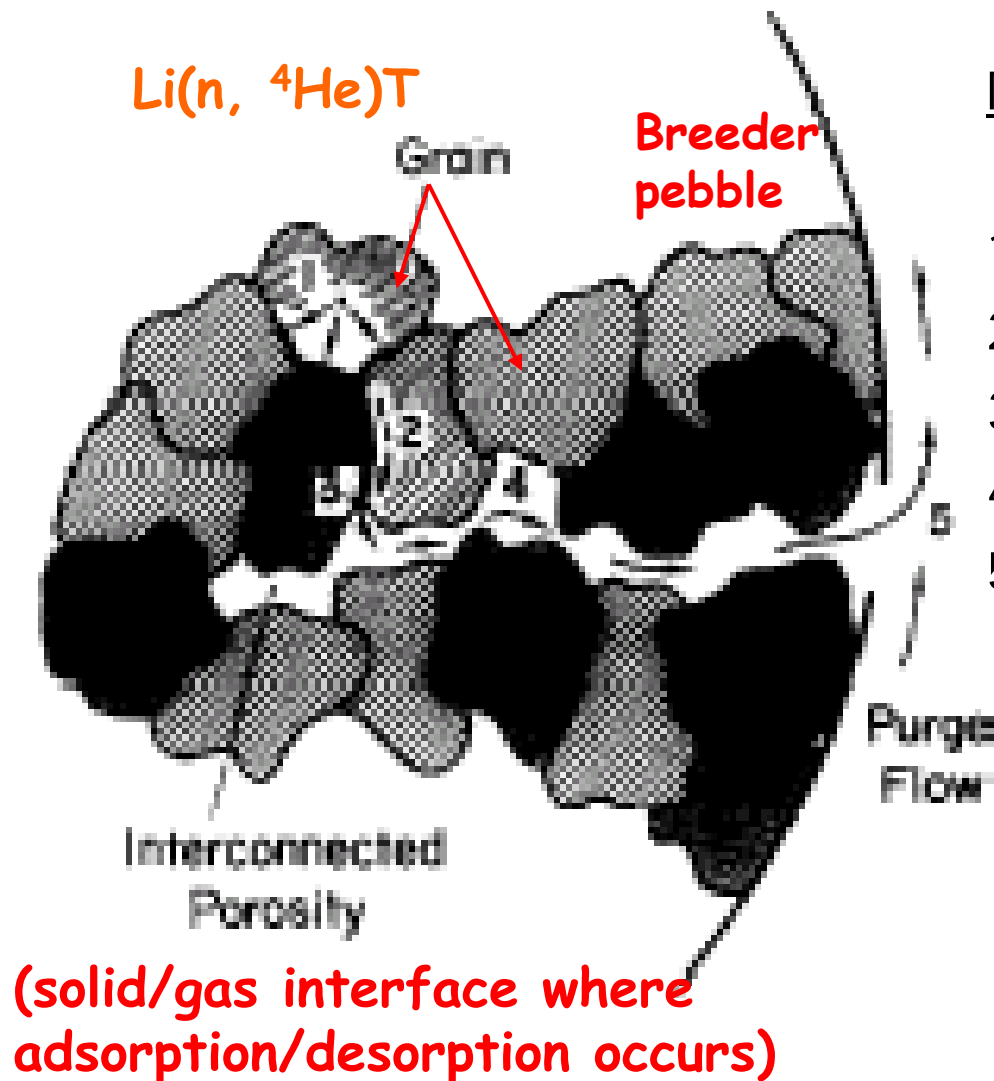# A Helium-Cooled Li-Ceramic Breeder Concept: Example

Material Functions

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

Helium Coolant

L>>p

Cooling/stiffening plate

Beryllium

Ceramic Breeder

Cooling plate

First Wall

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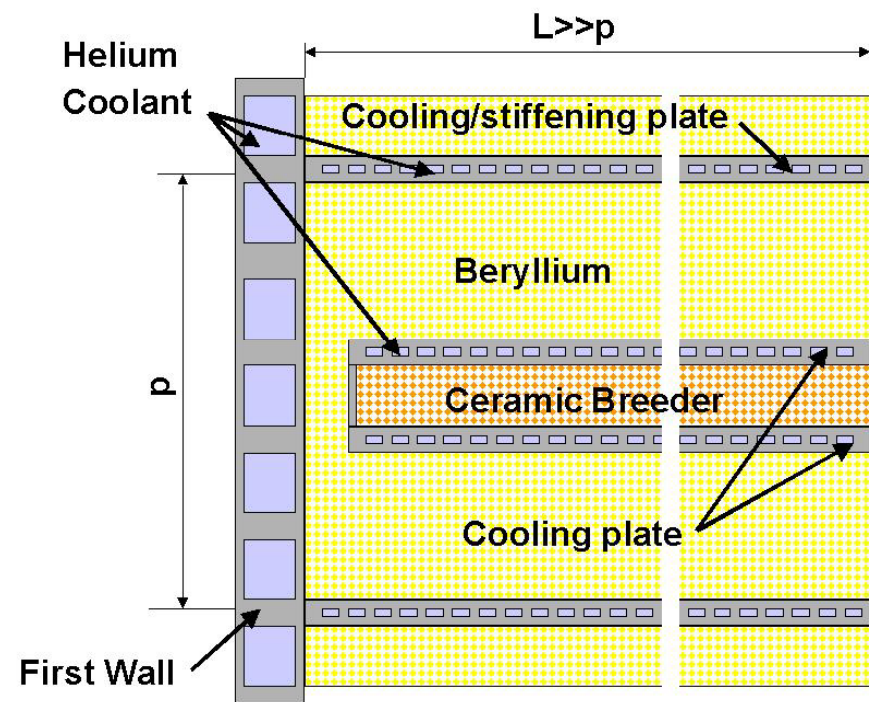
Several configurations exist (e.g. wall parallel or "head on" breeder/Be arrangements)

Mechanisms of tritium transport

Li(n, ^{4}He)T

Breeder pebble

Grain

Purge Flow

Interconnected Porosity

(solid/gas interface where adsorption/desorption occurs)

Mechanisms of tritium transport

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
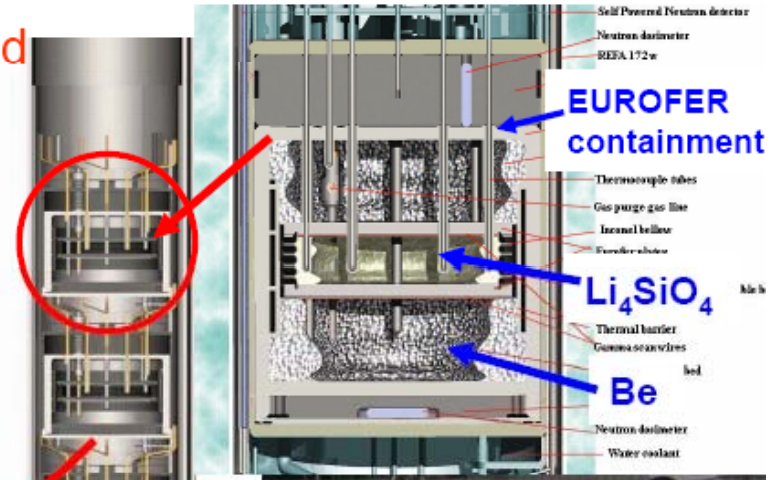**Tritium release composition:**
T_2, HT, T_2O, HTO

Irradiation experiments in fission reactors to test tritium release/retention in lithium ceramics

- Using lithium bearing ceramics is one option, often in the form of small pebble beds

- But this material must release tritium and resist damage by neutrons and extreme thermal conditions

- Fission experiments are being used to explore this behavior prior to testing in fusion


In-pile pebble bed assembly tests

NRG

EUROFER containment

Li_4SiO_4

Be

Self Powered Neutron detector
Neutron dosimeter
REFA 172 w
Thermocouple tubes
Gas purge gas line
Inconel bellow
Eurofer plates
Thermal barrier
Gamma scan wires
bed
Neutron dosimeter
Water coolant

Ceramic breeder irradiation experiments
Unit cells of Beryllium and Li4SO4 have been tested in the NRG reactor in Petten, Netherlands to investigate tritium release characteristics and combine neutron and thermomechanical damage to ceramic breeder and beryllium pebble beds

Configurations and Interactions among solid breeder/Be/coolant/ structure represent the most critical feasibility issues.

- **Configuration** (e.g. wall parallel or "head on" breeder/Be arrangements) affects TBR and performance
- **Tritium breeding and release**
  - **Max. allowable temp. (radiation-induced sintering in solid breeder inhibits tritium release; mass transfer, e.g. LiOT formation)**
  - **Min. allowable Temp. (tritium inventory, tritium diffusion**
  - **Temp. window (Tmax-Tmin) limits and k_e for breeder determine breeder/structure ratio and TBR**
- **Thermomechanics interactions** of breeder/Be/coolant/structure involve many feasibility issues (cracking of breeder, formation of gaps leading to big reduction in interface conductance and excessive temperatures)
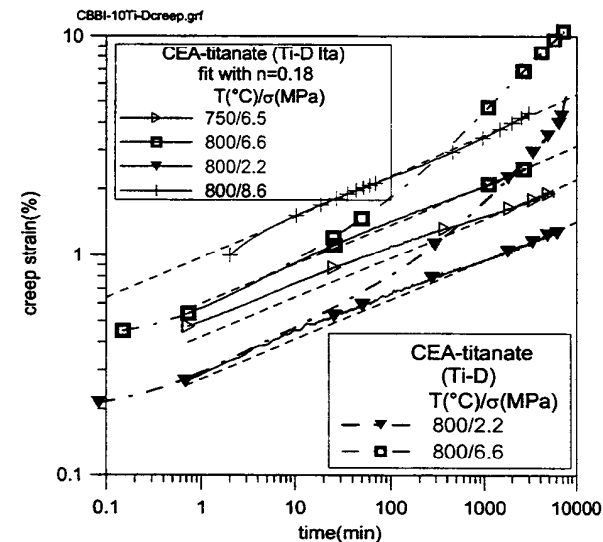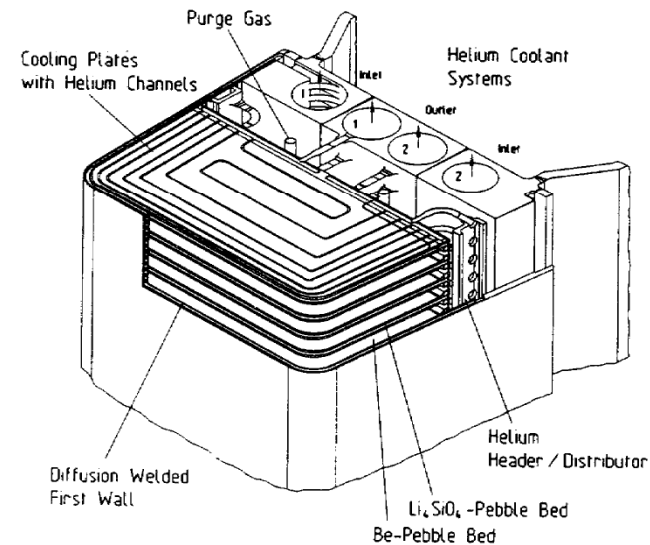
Thermal creep trains of Li_2TiO_3 pebble bed at different stress levels and temperatures

Material Database for Solid Breeder Blanket Pebble Bed Thermo-mechanics

Ceramic breeder or Be pebble
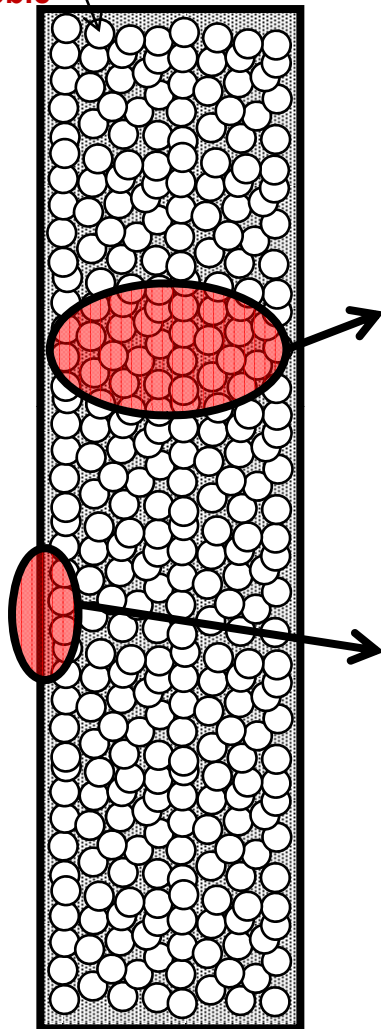
Pebble bed thermo-physical and mechanical data
(1) Effective thermal conductivity
(2) Effective modulus
(3) Thermal creep correlation
(4) Effective thermal expansion rate
(5) Pebble failure data
(6) Increase of effective thermal conductivity with compressive and creep strain
(7) criteria of pebble surface 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

Pebble bed schematics

DEM Pebble bed Thermomechanics Simulation: Numerically, the non-linear elastic behavior of a particle bed is modeled as a collection of rigid particles interacting via Mindlin-Hertz type contact interactions

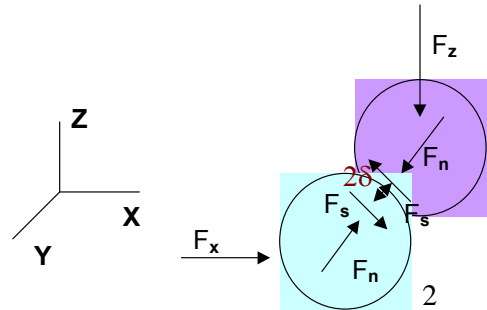**F_n** = normal force

$$= \frac{4}{3} E^* \sqrt{R\delta^3}$$

$$\frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}$$

δ = the compliance between 1 and 2

F_s = shear force = $\kappa\, F_n \leq \mu\, F_n$
(*μ: frictional coefficient*)

F_z = force in z-direction or external imposed compressive force (packing structure dependent)

F_x = force in horizontal or x-direction (packing structure dependent)
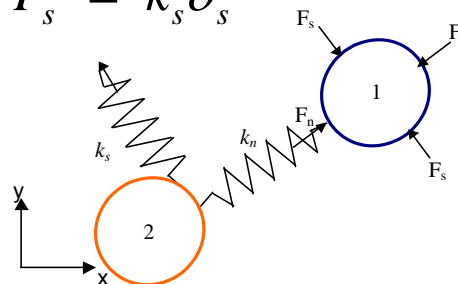
Forces at contact point include normal and tangential (shear) forces

Representation of the force-displacement relation at contact between two particles

$$F_n = k_n \delta_n$$
$$F_s = k_s \delta_s$$

Incremental displacement of the particle in the X-direction is derived, based on the net active force along the x-axis according to:

$$\Delta D_x = \frac{F_x}{k_t} = \frac{\sum_c F_{xc}}{k_n + k_s}$$

$$for, \frac{k_s}{k_n + k_s} \left|\sum_c F_{xc}\right| < k_f \sqrt{\left(\sum_c |F_{yc}|\right)^2 + \left(\sum_c |F_{zc}|\right)^2},$$

otherwise

$$\Delta D_x = \frac{F_x - k_f|F_t|}{k_n} =$$

$$\frac{\sum_c F_{xc} \pm k_f \sqrt{\left(\sum_c |F_{yc}|\right)^2 + \left(\sum_c |F_{zc}|\right)^2}}{k_n}$$

Bed stiffness in the normal direction gives:

$$k_n = \frac{8E^* \sqrt{R\delta_f}}{7}$$

where δ_f is the maximum value among all deformation at particle contact points.

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

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A Key Issue for Flowing Liquid Metal in Blankets: MHD Pressure Drop

Feasibility issue – Lorentz force resulting from LM motion across the magnetic field generates MHD retarding force that is very high for electrically conducting ducts and complex geometry flow elements

Thin wall MHD pressure drop formula

$$\Delta p_{MHD} = LJB \approx L\sigma VB^2 \underbrace{\frac{\sigma_w t_w}{\sigma a}}_{c}$$
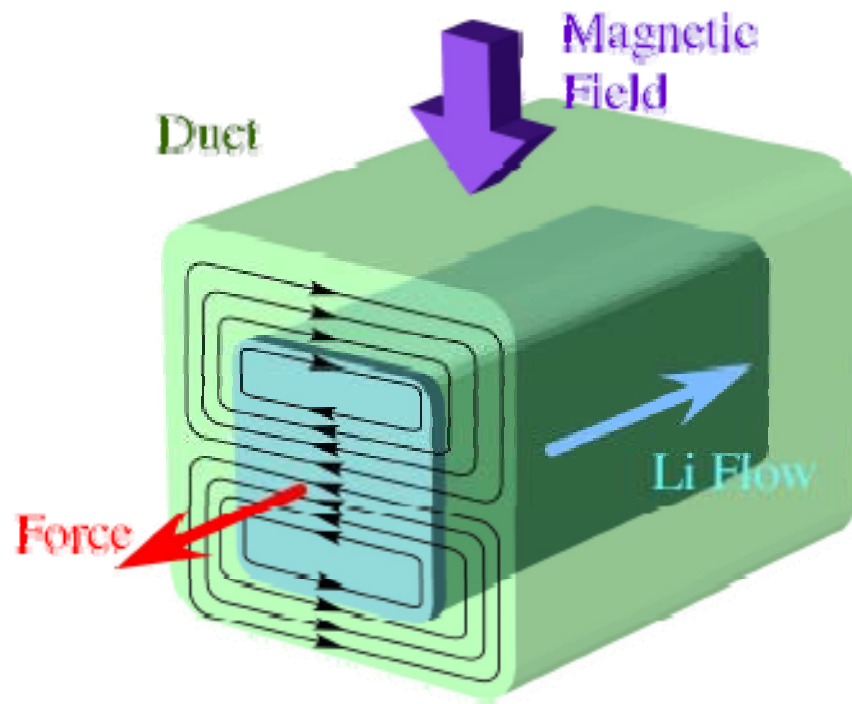
p, pressure
L, flow length
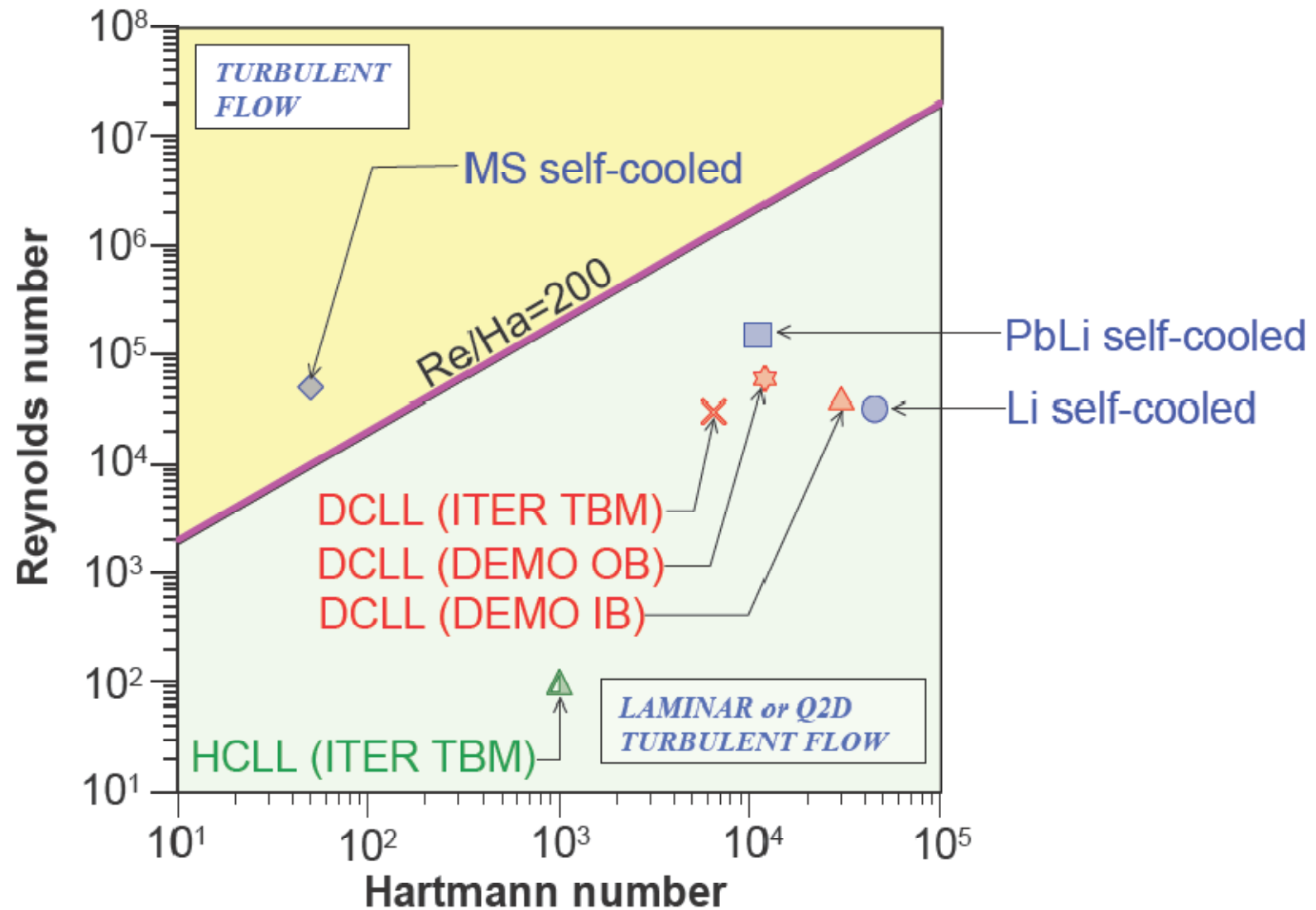*J, current density*
B, magnetic induction
V, velocity
σ, conductivity (LM or wall)
a,t, duct size, wall thickness

MHD Characteristics of Fusion Liquid Breeder Blanket Systems

Development of 3-D MHD Codes is very challenging
HIMAG: Joint development UCLA- HyPerCom

➢ HIMAG is a parallel, unstructured mesh based MHD solver.

➢ Goal: High accuracy at high Hartmann numbers (even on non-orthogonal meshes)

➢ HIMAG can model single-phase as well as two-phase (free surface) flows

➢ Multiple conducting solid walls may be present in the computational domain

➢ Graphical User Interfaces are provided for the full execution of HIMAG

➢ Heat transfer, natural convection, temperature dependent properties can be modeled

➢Extensive validation and benchmarking has been performed for canonical problems. <u>Cases involving Ha > 1000 have never been demonstrated on non-rectangular meshes prior to HIMAG</u>

HIMAG: Single-phase flow studies

Cylinder flow with MHD, Ha = 1000
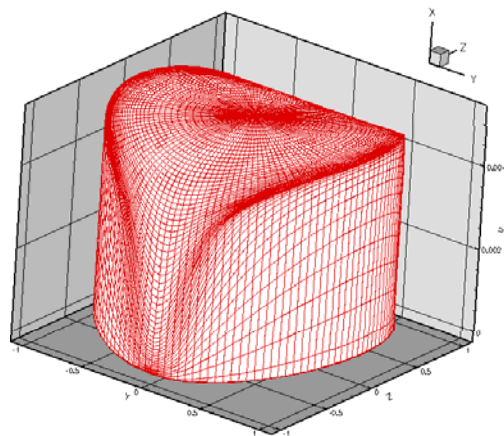
Ha = 1000, circular duct
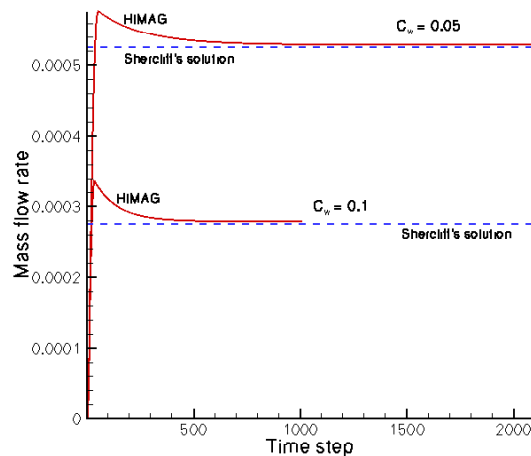
Very high Hartmann number (>10,000) computed and verified
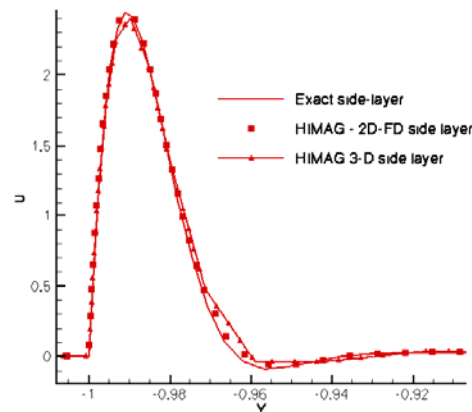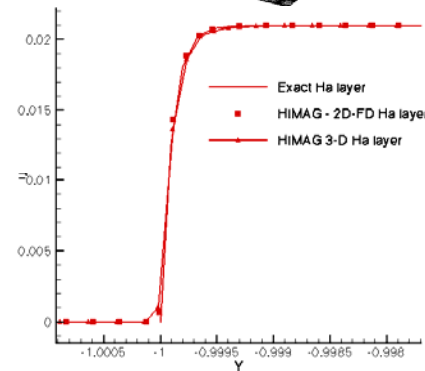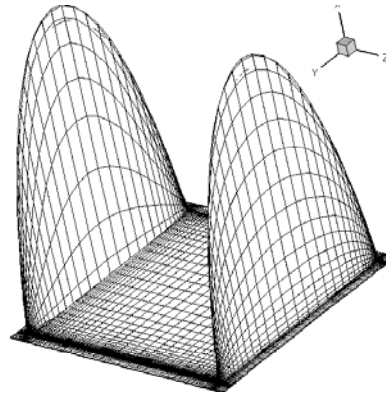
Natural convection with MHD streamlines (above), current lines (below), against temperature contours
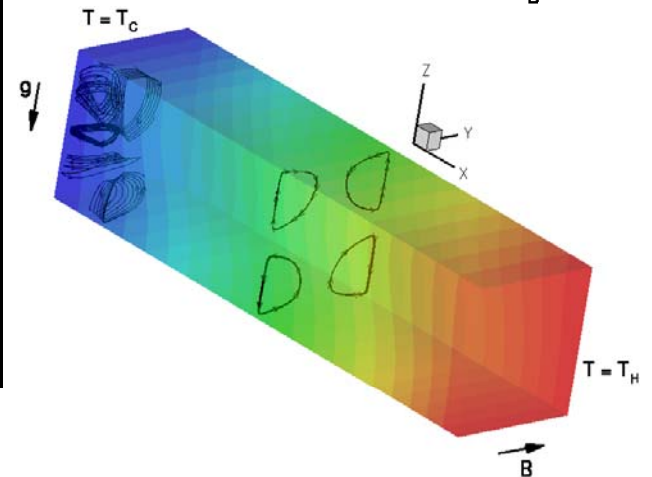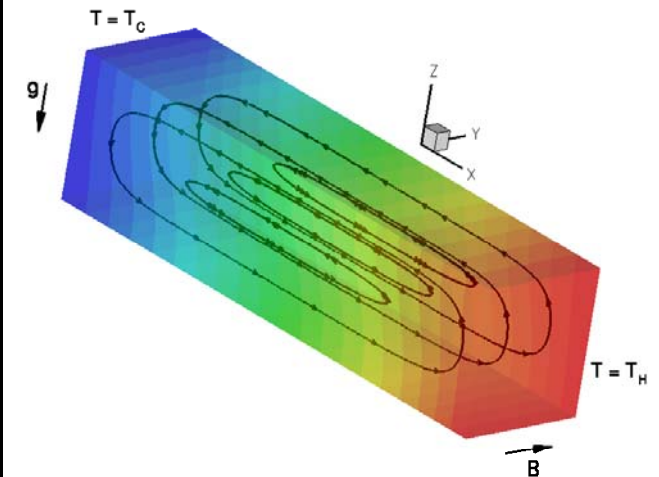
MHD flows in fusion context are characterized by very unique effects not seen in ordinary fluid dynamics

- High interaction parameter ~10^3 to 10^5 (ratio Magnetic / Inertial Forces)
  - Inertia forces are small compared with electromagnetic forces, except in some thin layers
- Result: Joule dissipation associated with the strong magnetic field induces a strong flow anisotropy, ultimately leading to a quasi-2D state.

MTOR Thermofluid/MHD facility at UCLA

1 m/s flow, B = 0   **B = 1.2 T**
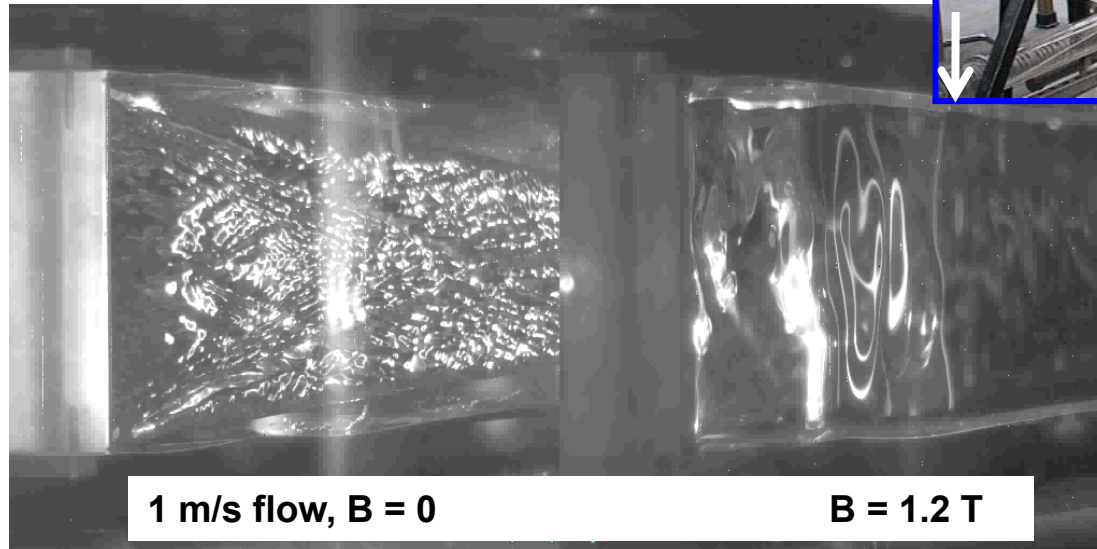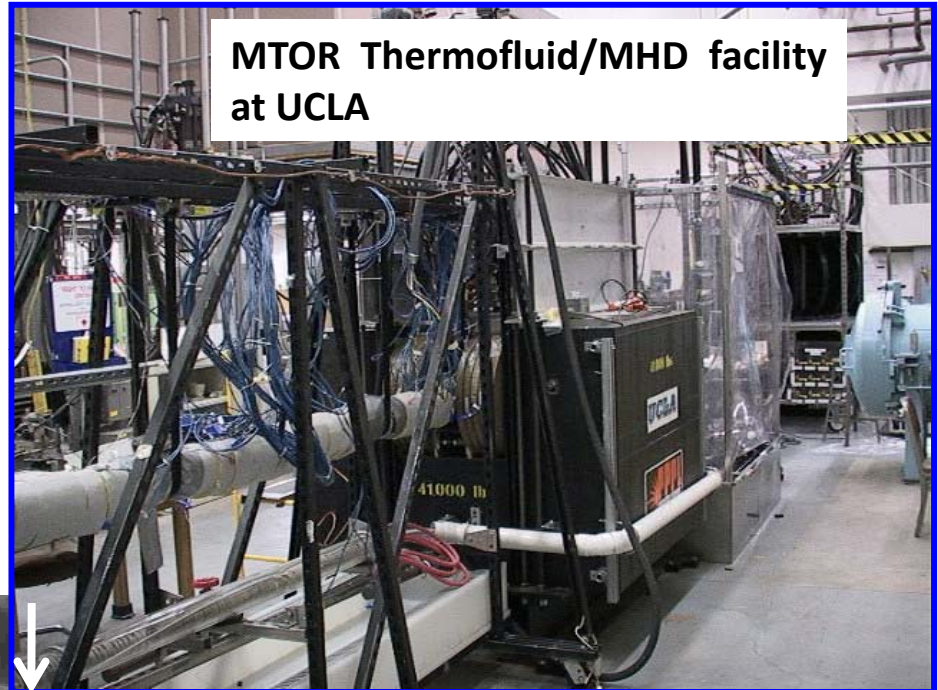
Liquid metal free surface flow experiment
Magnetic field suppresses short wavelength surface oscillations and consolidates them into larger surface disturbances aligned with the field

Ying (UCLA)

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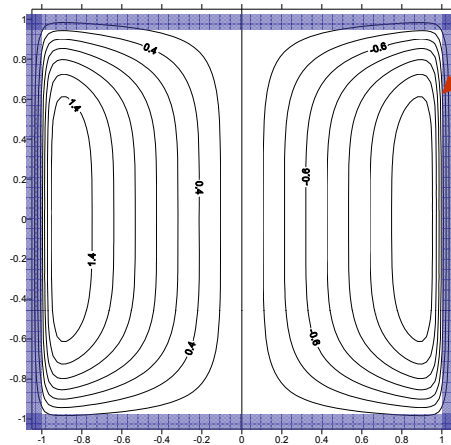
Lines of current enter the low resistance wall – leads to very high induced current and high pressure drop

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

Insulated walls
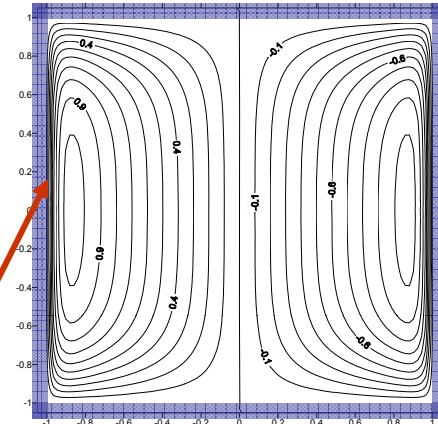
- **Net JxB body force**

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

- 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

Module box (container & surface heat flux extraction)

Breeder cooling unit (heat extraction from PbLi)

pol
tor
rad

Stiffening structure (resistance to accidental in-box pressurization i.e., He leakage)

He collector system (back)

32
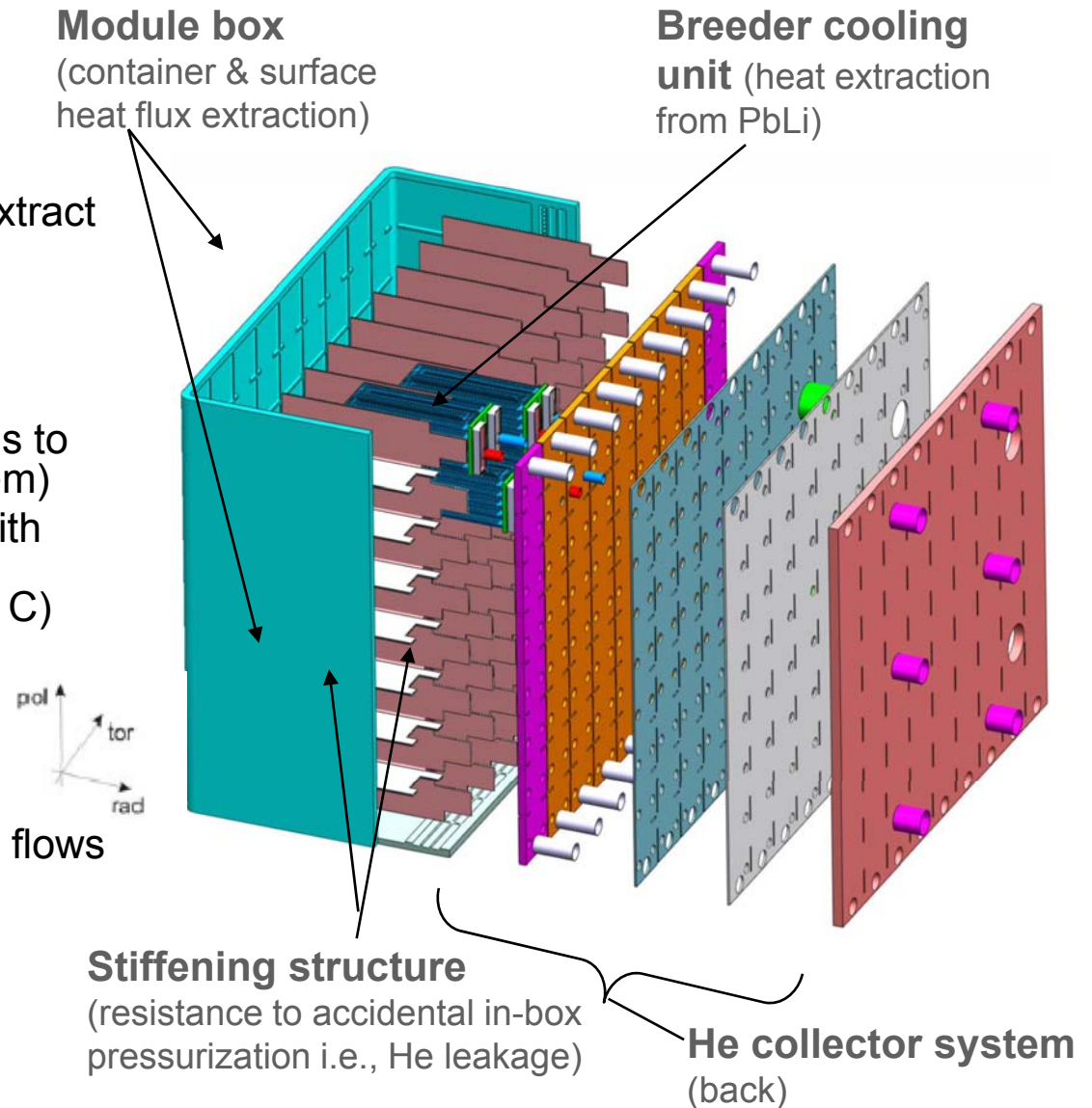
Pathway Toward Higher Temperature Through Innovative Designs with Current Structural Material (Ferritic Steel): *Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept*

- ❑ **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**

DCLL Typical Unit Cell

Self-cooled Pb-17Li Breeding Zone

SiC FCI

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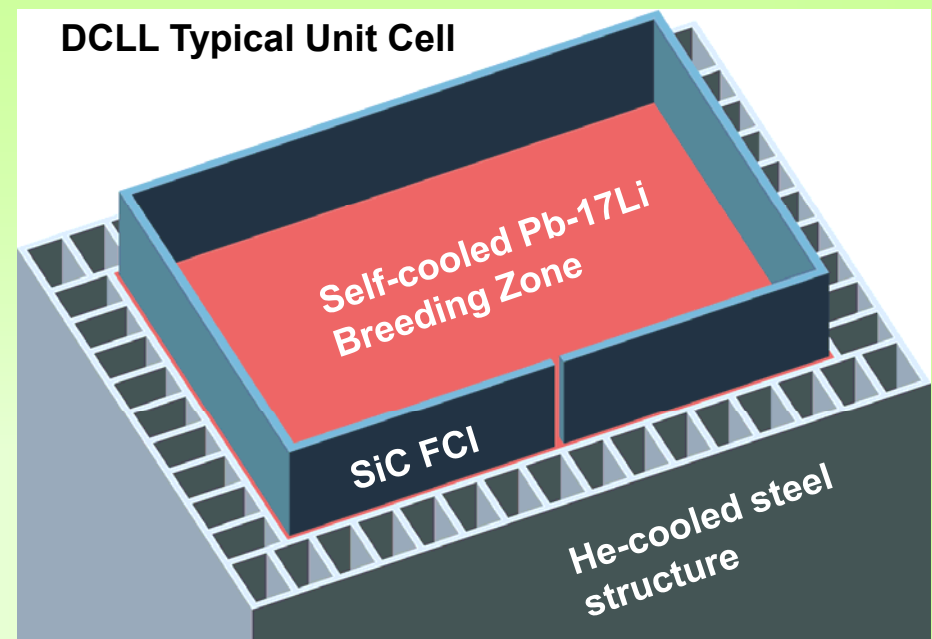
Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure ⇒ High Efficiency

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**

Flow Channel Insert (FCI)

0.15

0.15

0.15

0.20

Coolant Duct (0.2 x 0.2 x 2.0 m)

- **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**

34
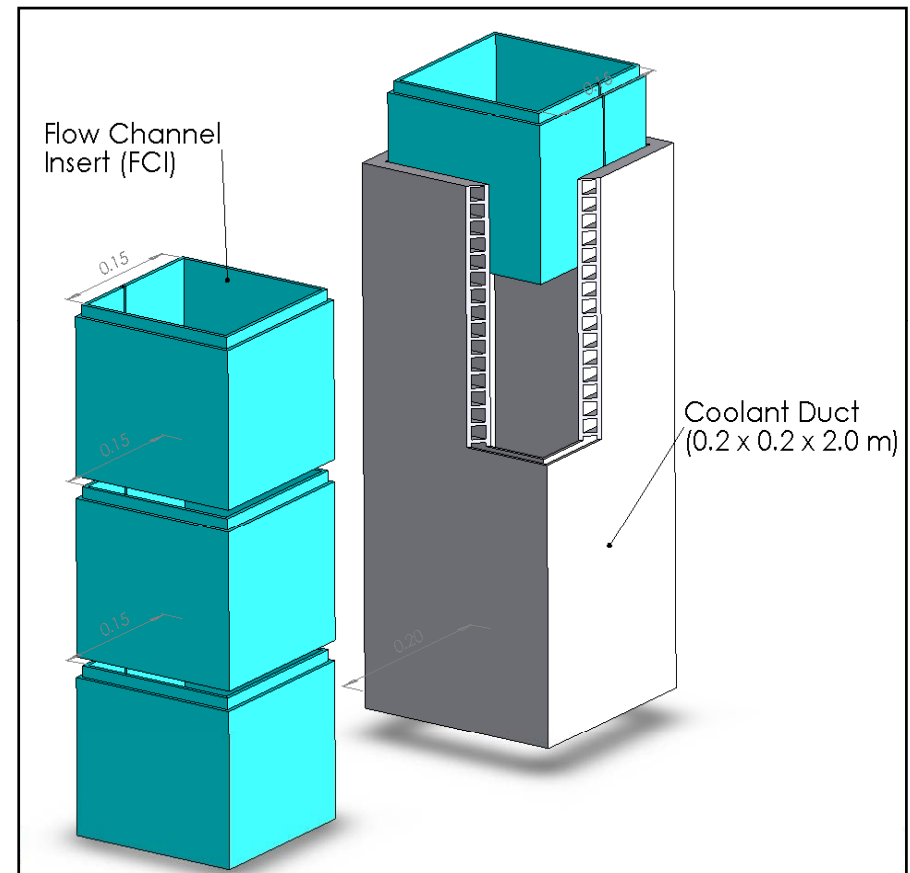
MHD fluid Flow and Mass Transfer

Fluid-Material Interactions

Interfacial Phenomena

High pressure drop is only one of the MHD issues for LM blankets; MHD heat and mass transfer are also of great importance!

Instabilities and 3D MHD effects in complex detailed geometry and configuration with magnetic and nuclear fields gradients have major impact:

- Unbalanced pressure drops (e.g. from insulator cracks) leading to flow control and channel stagnation issues

- Unique MHD velocity profiles and instabilities affecting *transport of mass and energy.*

Accurate Prediction of MHD Heat &Mass Transfer is essential to addressing important issues such as:

- thermal stresses,

- temperature limits,

- failure modes for structural and functional materials,

- thermal efficiency, and

- tritium permeation.

FCI overlap gaps act as conducting breaks in FCI insulation

and hence disturb current flow and velocity, and redistribute energy

Y = 192

Y = 450 (near outflow)

Courtesy of Munipalli et al.
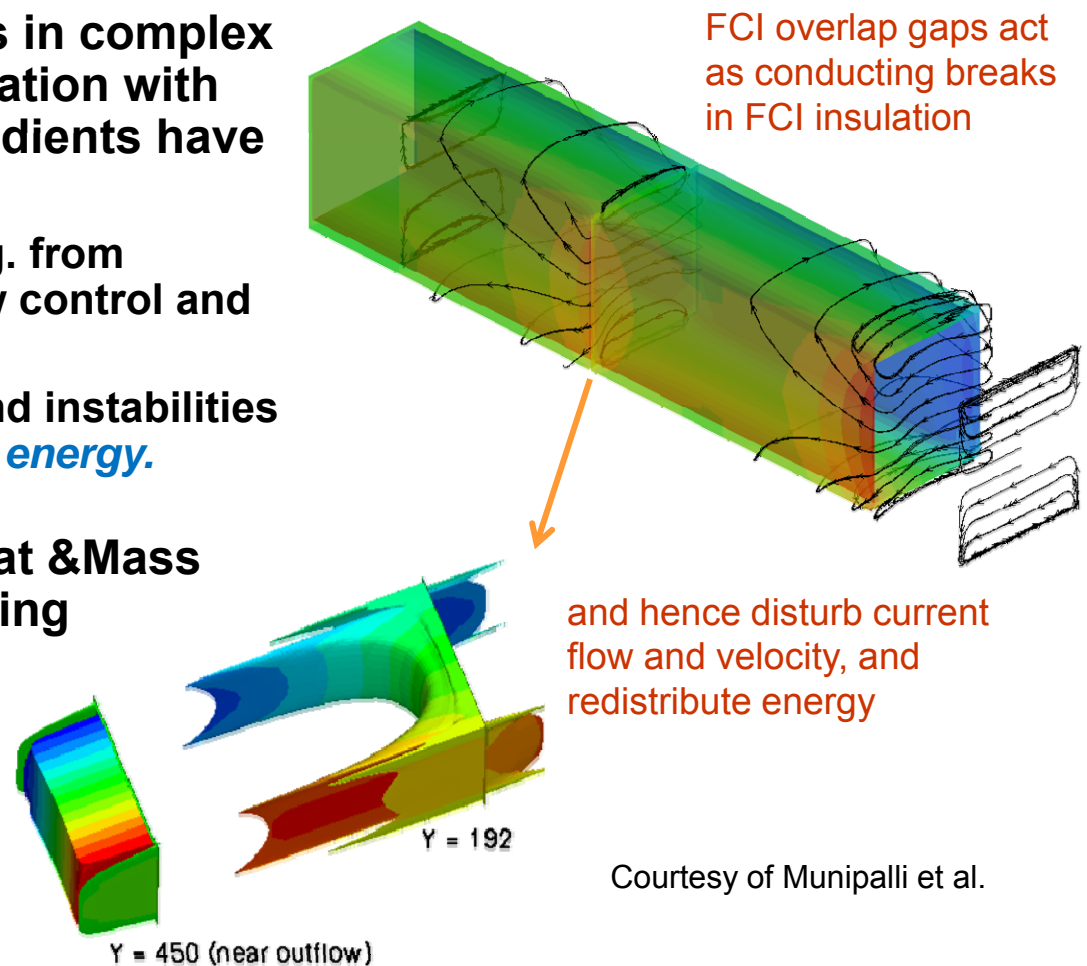
(Ha=1000; Re=1000; σ=5 S/m, cross-sectional dimension expanded 10x)

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Buoyancy effects in DCLL blanket

L=60, Ha=100,
Re=10,000,
Gr=4x10^8,
Pr=0.01, a/b=1,
m=1, r=6.32

DCLL DEMO blanket, US

B-field
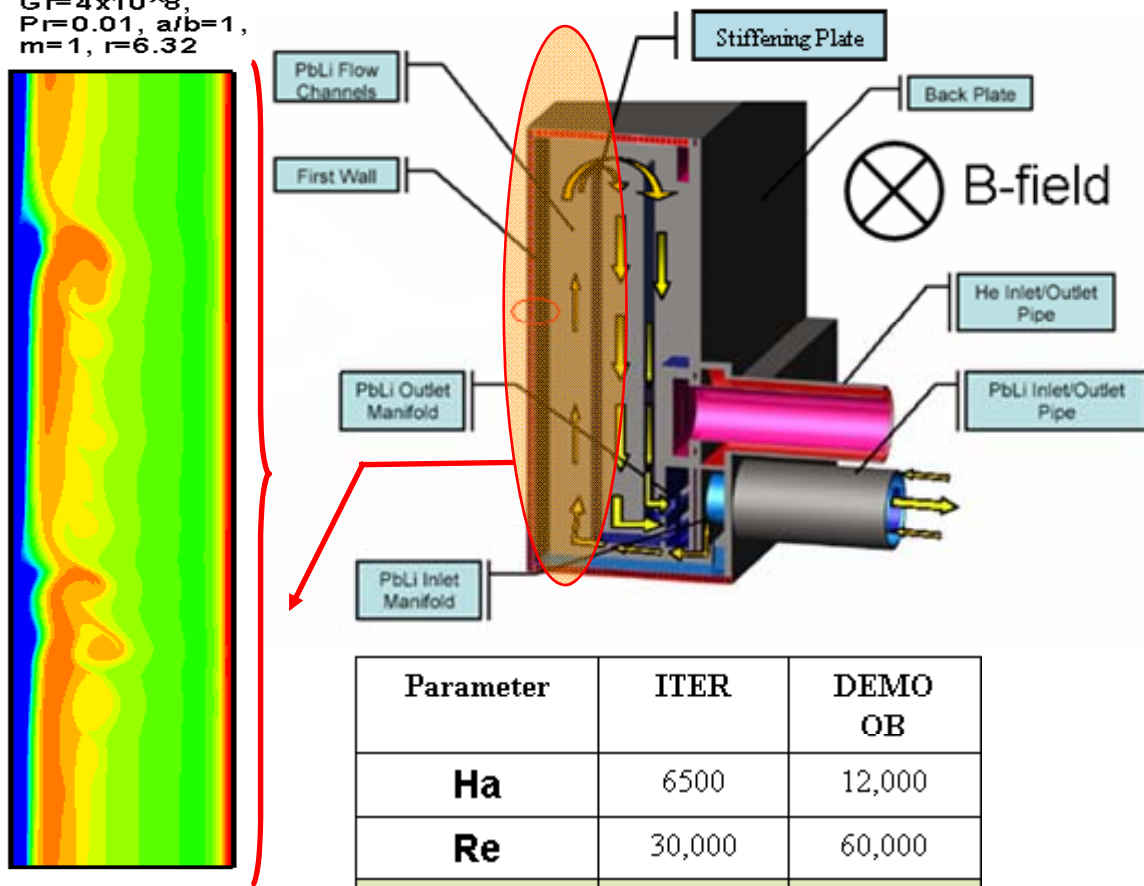
Parameter	ITER	DEMO OB
Ha	6500	12,000
Re	30,000	60,000
Gr	7.0×10^9	3.5×10^{12}

Caused by $\quad q'''(r) = q'''_{max} Exp(-\alpha r)$

and associated $\Delta T = \dfrac{q'''_{max} a^2}{k} \sim 10^3 K$

Can be 2-3 times stronger than forced flows. Forced flow: 10 cm/s. Buoyant flow: 25-30 cm/s.

In buoyancy-assisted (upward) flows, buoyancy effects may play a positive role due to the velocity jet near the "hot" wall, reducing the FCI ΔT.

In buoyancy-opposed (downward) flows, the effect may be negative due to recirculation flows.

Effect on the interface T, FCI ΔT, heat losses, tritium transport.

Vorticity distribution in the buoyancy-assisted (upward) poloidal flow

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Example: Corrosion – A serious issue for LM Blankets

- **At present, the interface temperature between PbLi and Ferritic steel is limited to < 470° C because of corrosion.**

- Such limits are derived from limited corrosion experiments with no magnetic field and very approximate modeling.

- Corrosion rate is highly dependent on temperature and velocity of LM.

- **Recent results from Riga show strong dependence of corrosion rate on magnetic field.**

- Corrosion deposition in the "cold section" is often the limiting criteria for determining the allowable interface temperature.

- **Corrosion includes many physical mechanisms that are currently not well understood** (dissolution of the metals in the liquid phase, chemical reactions of dissolved non-metallic impurities with solid material, transfer of corrosion products due to convection and thermal and concentration gradients, etc.).

- **We need new models and experiments that can predict corrosion rates and transport and deposition of corrosion products throughout the heat transport system.**

  – Need to account for MHD velocity profiles, complex geometry and temperature gradients in the "hot" and "cold" sections.

Corrosion rate for samples with and without a 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

B=0   B=1.8 T

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

Strong experimental evidence of significant effect of the applied magnetic field on corrosion rate.

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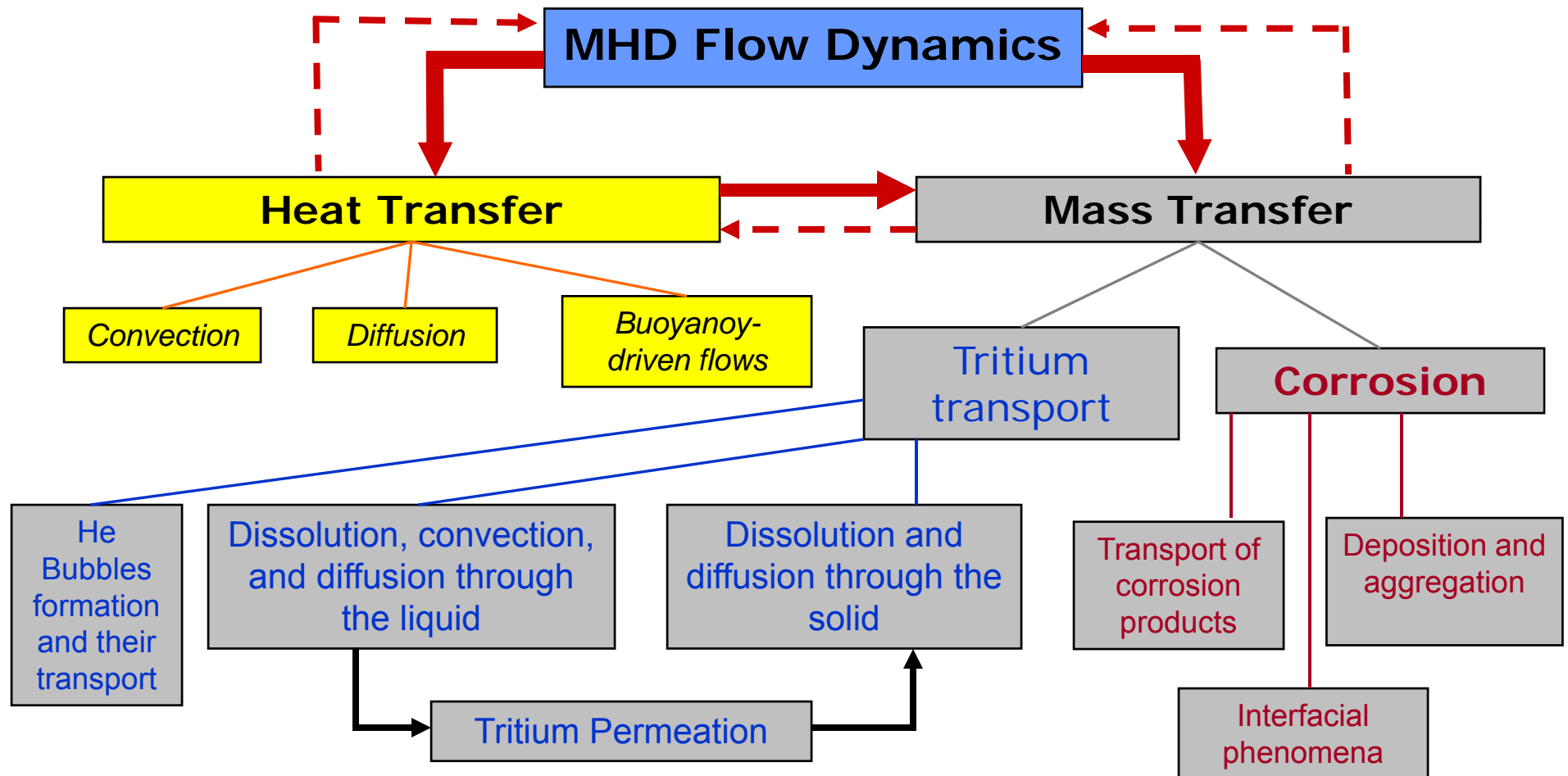
Also, ***experiments*** should progress from single effects to multiple effects in laboratory facilities and then to integrated tests in the fusion environment.

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)**

Other common issues for Helium cooled blanket / FW systems

- Helium cooling / thermomechanical structural response in complex flow structures

- Helium cooling / thermomechanical structural response of large surface area FW

- Tritium transport and permeation
  - plasma to coolant
  - breeder to coolant
  - removal from coolant

Radial-poloidal plate

Grooves for helium coolant

Helium

Radial-toroidal plate

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UCLA
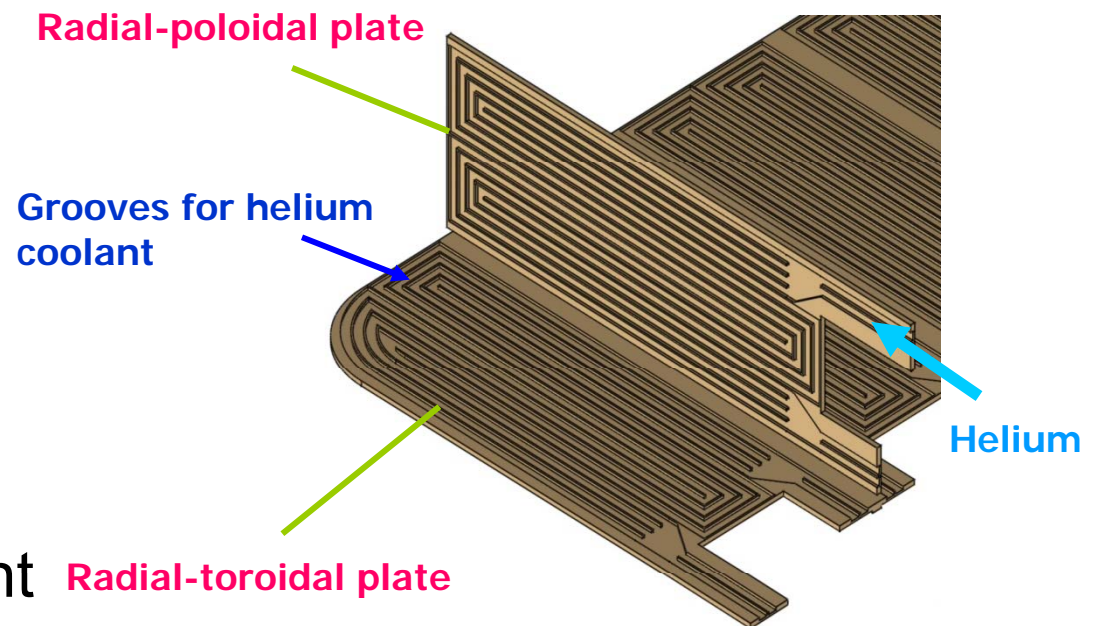
The US has initiated an important program on integrated multi-physics simulation
- Important tool to model complex systems, explore design options and guide R&D
- It will evolve as the "FNST Predictive Capability" with advances in modelling of subsystems and with experimental validation

High temperature at upper structures

TEMPC

Velocity :m/s

Initial results with simplified geometry & operating condition

PbLi velocity

PbLi velocity

- Location of the instrument and the associated perturbation to the data
- Analysis with a detailed geometric drawing with instrumentations in-place needed

Mid-plane nuclear heating (gamma: left; neutron: right)

W/cc

Stress

Thermomechanics Analysis

Inlet to 2nd FW cooling panel

DCLL He-coolant inlet manifold

He-velocity

□ **Proper manifold designs to provide uniform flow distributions among many parallel flow paths**
□ **Adequate cooing to all parts**

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Neutronics

Nuclear Analysis for Fusion Systems

- Energetic 14 MeV neutrons are produced from the D-T fusion reaction
- Nuclear analysis for components surrounding the plasma is essential element of FNST
  - Tritium production in breeding blankets to ensure tritium self-sufficiency
  - Nuclear heating (energy deposition) for thermal analysis and cooling requirement
  - Radiation damage in structural material and other sensitive components for lifetime assessment
  - Provide adequate shielding for components (e.g., magnets) and personnel access
  - Activation analysis for safety assessment and radwaste management
- State-of-the-art predictive capabilities (codes and data) are needed to perform required nuclear analyses

Neutron/Gamma Transport Methods

- Fusion must use Transport Theory (not diffusion methods) because of high energy, highly anisotropic collisions. (Must use Pn or higher)

- Two most common approaches to obtaining solutions for Boltzmann transport equation :
  - Stochastically – Monte Carlo
  - Deterministically – Discrete Ordinates (S_N), Spherical Harmonics (P_N)

- Both are used in fusion applications – each is suitable for particular problems

Abdou Lecture 5

Main Objectives of the Neutronics R&D Program

- To provide the experimental database required for approval and licensing of the device

- To verify the prediction capabilities and generation of design safety factors

- To reduce the high cost associated with large safety factors used to compensate for uncertainties

Inter-relationship Between Fusion Design Analysis and Blanket/Shield Neutronics R&D
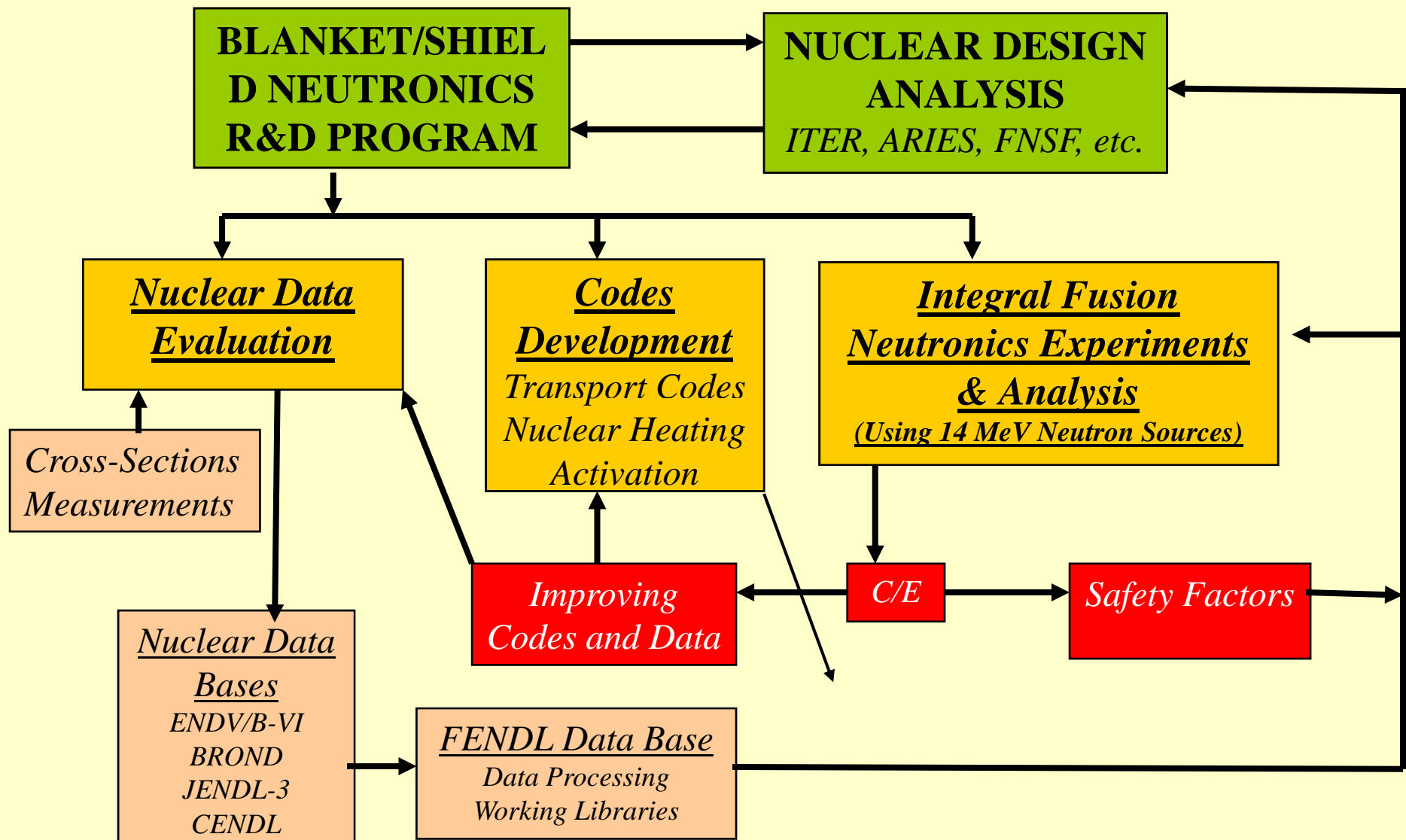
Leading 14 MeV Fusion Source Facilities

Facility	Location	Mode of Operation	Type	Source Intensity
FNS	JAERI (Japan)	Pulsed	Point	3×10^{11} and 5×10^{12} n/s
		Continuous	Simulated line source	3×10^{11} n/s
FNG (Ref. 52)	Frascati (Italy/EC)	Pulsed Continuous	Point	5×10^{11} n/s
TUD	Dresden (Germany/EC)	Pulsed Continuous	Point	2×10^{11} n/s

Other Facilities Available

Switzerland:	LOTUS, S ~ 5×10^{12} n/s (Ref. 50) Shut down
Japan:	OKTAVIAN, Osaka University, S ~ 5×10^{11} n/s (Ref. 53)
Germany:	KfK, Karlsruhe, S ~ 10^{9} n/s (Ref. 31)
Russia:	IAE, Kurchatov, Moscow, S ~ 5×10^{10}/s (Ref. 54)
	MEPI, Moscow, S ~ 5×10^{10} n/s (Ref. 54)
	KPI, Moscow, S ~ 5×10^{10} n/s (Ref. 54)
China:	SWINPS, Chengdu, S ~ 10^{9} n/s (Ref. 30)
USA:	ORNL, Oak Ridge, S ~ 10^{10} n/s Shut down
	ANL, S ~ 10^{10} n/s Shut down
	INEL, Idaho, S ~ 10^{8} n/s (Ref. 29) Shut down

SNEG-13 (Moscow, RF): Point source. It is said to have the largest source intensity (3×10^{13} n/s)

US-JAERI Collaboration (1984-1993)

1984-1989:

The FNS Intense 14MeV point source is phase I (open geometry) and Phase II (closed geometry) for measuring tritium production rate (TPR) in Li2O assembly. Progression from simple material (Li2O) to a more prototypical assembly to include engineering feature: (SS FW, coolant channels, neutron multiplier (Be). 15 experiments were performed in phase I and II

1989-1993:

Test assembly is annular in shape surrounding a simulated line source Phase III). TPR, induced activation and nuclear heating were measured and analyzed. Steaming from large opening experiment (26 Experiments Total)

1993-1998: Shifting to ITER shielding experiments. Radioactivity, nuclear heating and shielding verification experiments

Analysis: (US): MCNP, DOT4.3 and DOT5.1, RUFF code, ENDF/B-V

JAERI: MORSE-DD, GMVP JENDL3-PR1,2

Measuring Techniques: TPR: (T6) Li-glass, Li-metal, Li2O pellet, (T7): NE213, Li-metal, (Tn): zonal method.Nuclear Heating: microcalorimeter method

Concepts of the Experimental Arrangement in US/JAERI Collaboration

Phase-II Phase-I Phase-III

Pseudo-Line Source

Fixed Target

Rotating Neutron Target
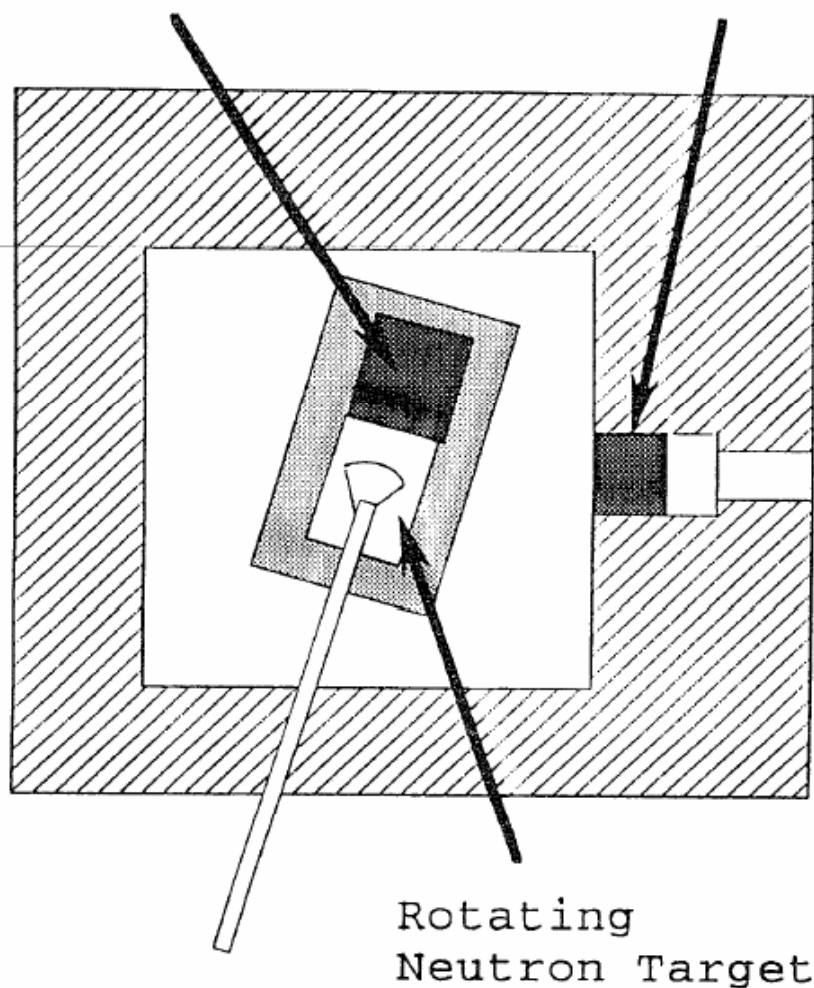
Fusion Material Challenges

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.

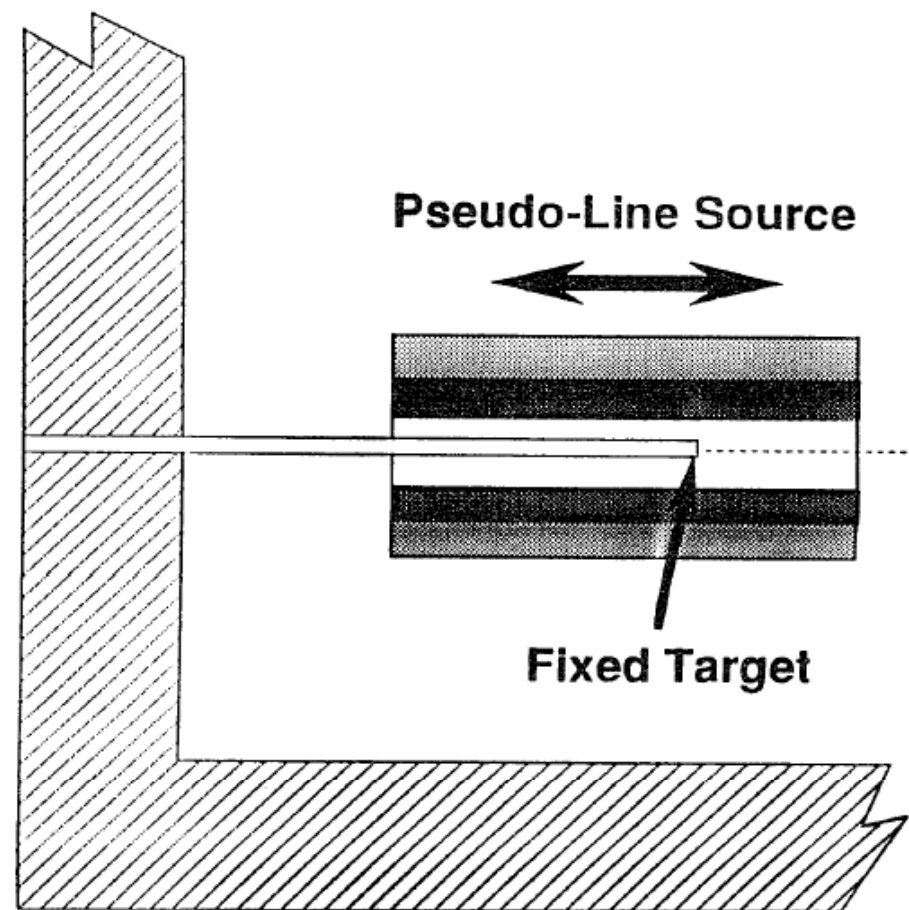❑ Key issues include thermal stress capacity, coolant compatibility, waste disposal, and radiation damage effects.

❑ 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.*

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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.

Incoming particle

Primary knock-on atom - PKA

Vacancy

Interstitial

316 SS

1 cm
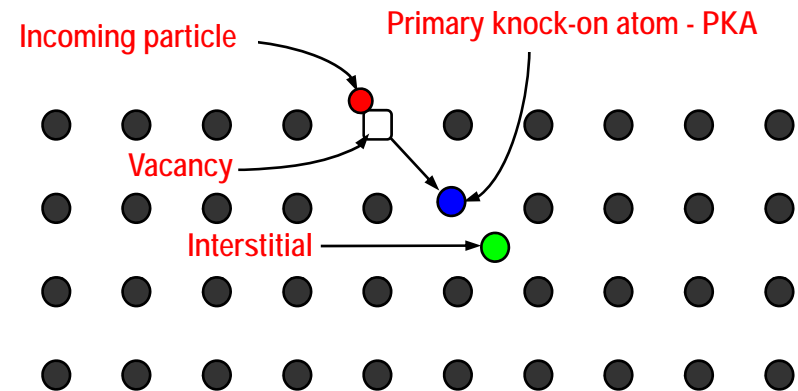
Common interest of fission and fusion structural materials: operating temperature and radiation dose (dpa)
(There are many other areas of synergy between fission and fusion technologies)

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:
  - Damage decreases by ~an order of magnitude
  - 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
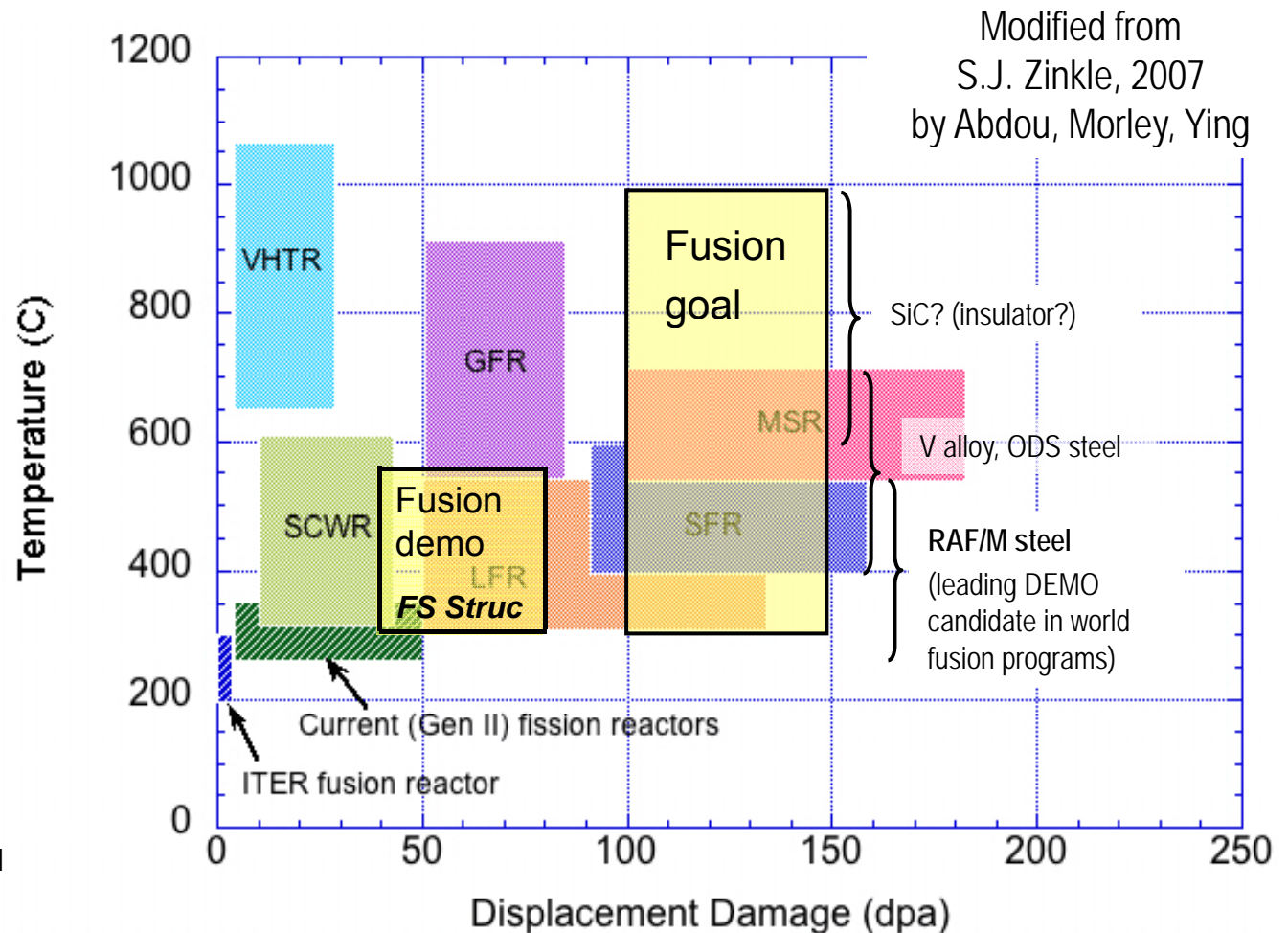
In fusion, the fusion process does not produce radioactive products. Long-term radioactivity and waste disposal issues can be minimized by careful SELECTION of MATERIALS

- 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)

Class C Waste Disposal

Safety

SiC
V Cr Ti Si
Fe Cr W V Ta
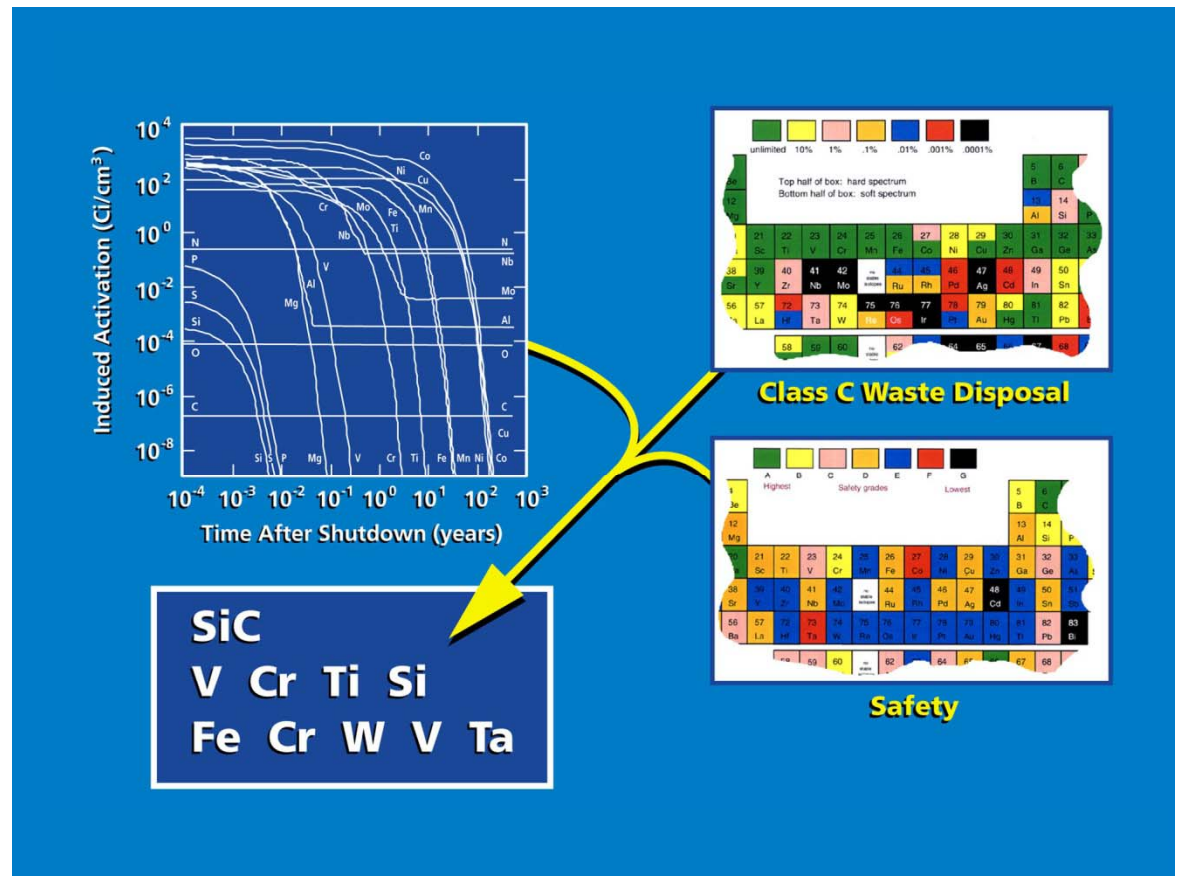
Radiotoxicity (inhalation) of waste from fusion is less than fission and similar to that from coal at 100 years.

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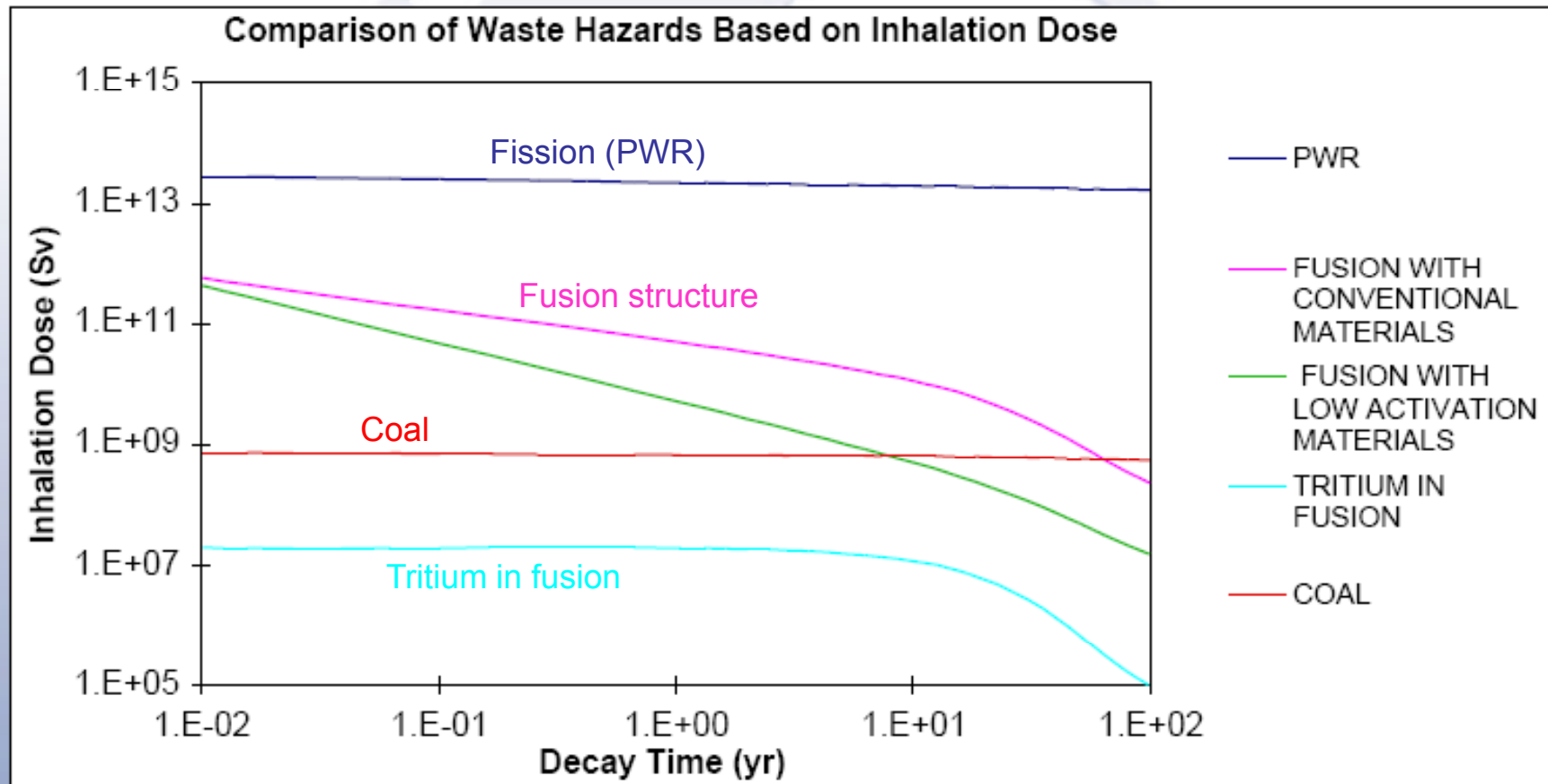
- From "A Study of the Environmental Impact of Fusion" (AERE R 13708).
- Coal radiotoxicity is based on Radon, Uranium, Thorium, and Polonium in coal ash
- Inhalation represents major pathways for uptake of material by the human body
- Dose hazard used here is a relative measure of radiotoxicity of material

Plasma-Surface Interaction (PSI) Processes temperature dependence

reflect, sputter

implant, displace (dpa)

displace (dpa), transmute

melt, vaporize

erode redeposit

adsorb*
recombine*
trap*
bond*
evolve voids*
alter properties*
permeate*

transmute
evolve voids*
alter properties*

vapor shield*
recrystallize*
crack/craze*

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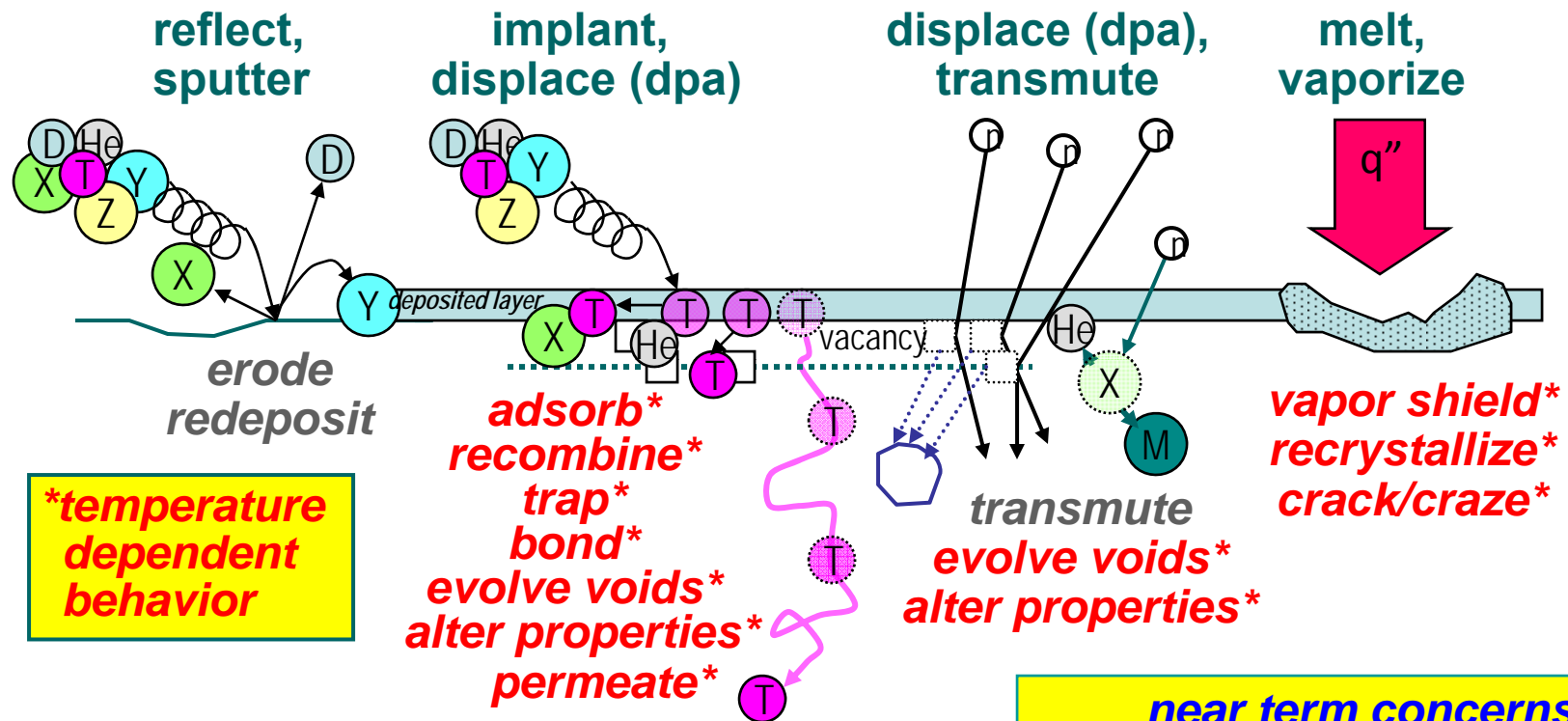
The physical chemistry of PSI processes on high temperature walls will determine the strong interaction between wall and plasma in DEMO (or FNSF).

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

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

- ❑ Typical materials considered for PFM 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*

PISCES-B: pure He plasma

30kV   X30,000 0.5µm 0147 UC PISCES
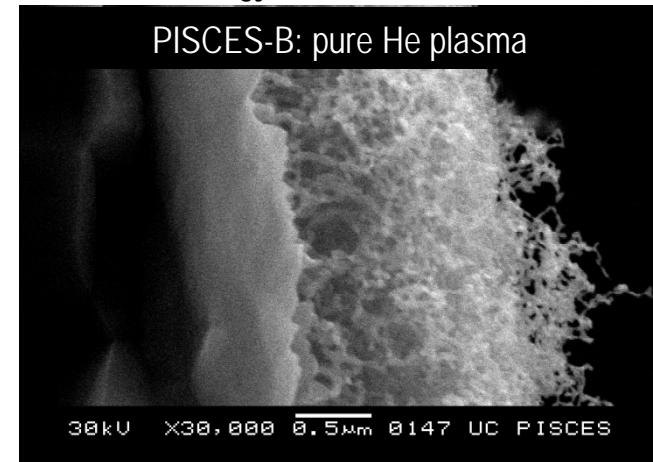
M. Rieth, A. Hoffmann, HHFC, 2008

19
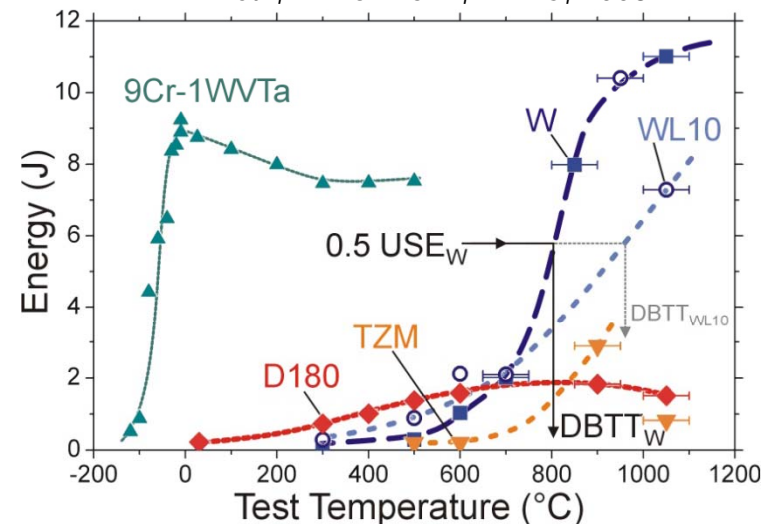
Top-Level Technical Issues for FNST (set 1 of 2)
(Details of these issues published in many papers, Last update: December 2009)

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

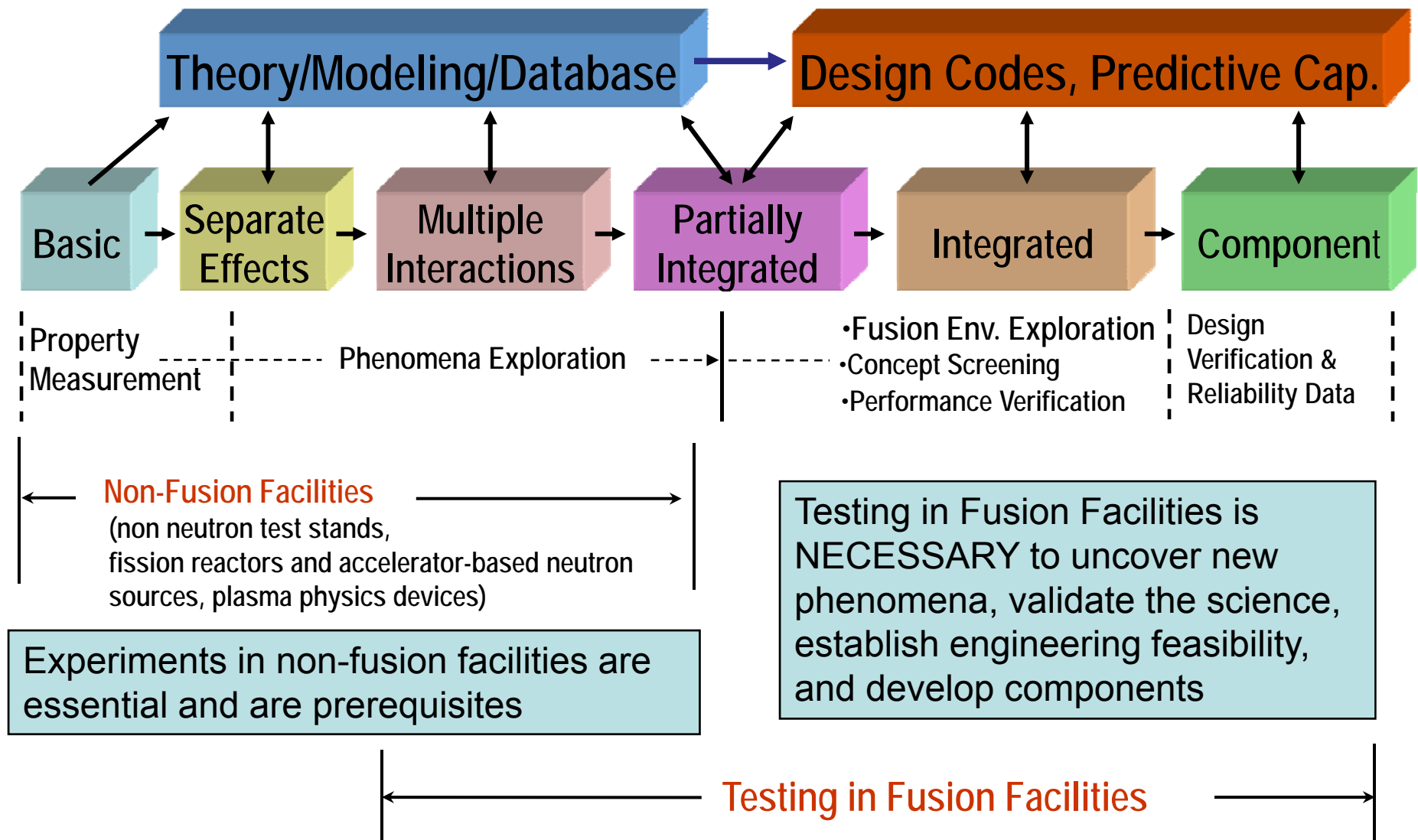**Reliability, Availability, Maintainability (RAMI)**

10. Failure modes, effects, and rates in blankets and PFC's in the integrated fusion environment

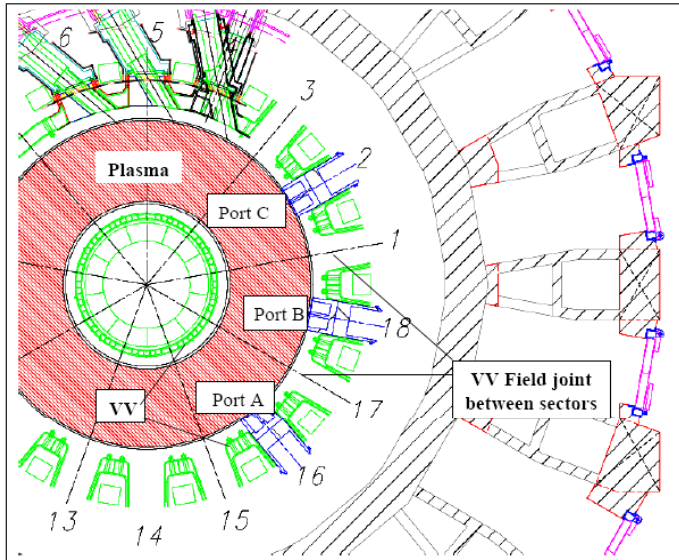11. System configuration and remote maintenance with acceptable machine down time

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

Theory/Modeling/Database → Design Codes, Predictive Cap.

Basic → Separate Effects → Multiple Interactions → Partially Integrated → Integrated → Component

Property Measurement

Phenomena Exploration

- Fusion Env. Exploration
- Concept Screening
- Performance Verification

Design Verification & Reliability Data

Non-Fusion Facilities
(non neutron test stands, fission reactors and accelerator-based neutron sources, plasma physics devices)

Experiments in non-fusion facilities are essential and are prerequisites

Testing in Fusion Facilities is NECESSARY to uncover new phenomena, validate the science, establish engineering feasibility, and develop components

Testing in Fusion Facilities

ITER Provides Substantial Hardware Capabilities for Testing of Blanket System

TBM System (TBM + T-Extrac, Heat Transport/Exchange…)

Bio-shield

He pipes to TCWS

2.2 m

Vacuum Vessel

A PbLi loop Transporter located in the Port Cell Area

Equatorial Port Plug Assy.

TBM Assy

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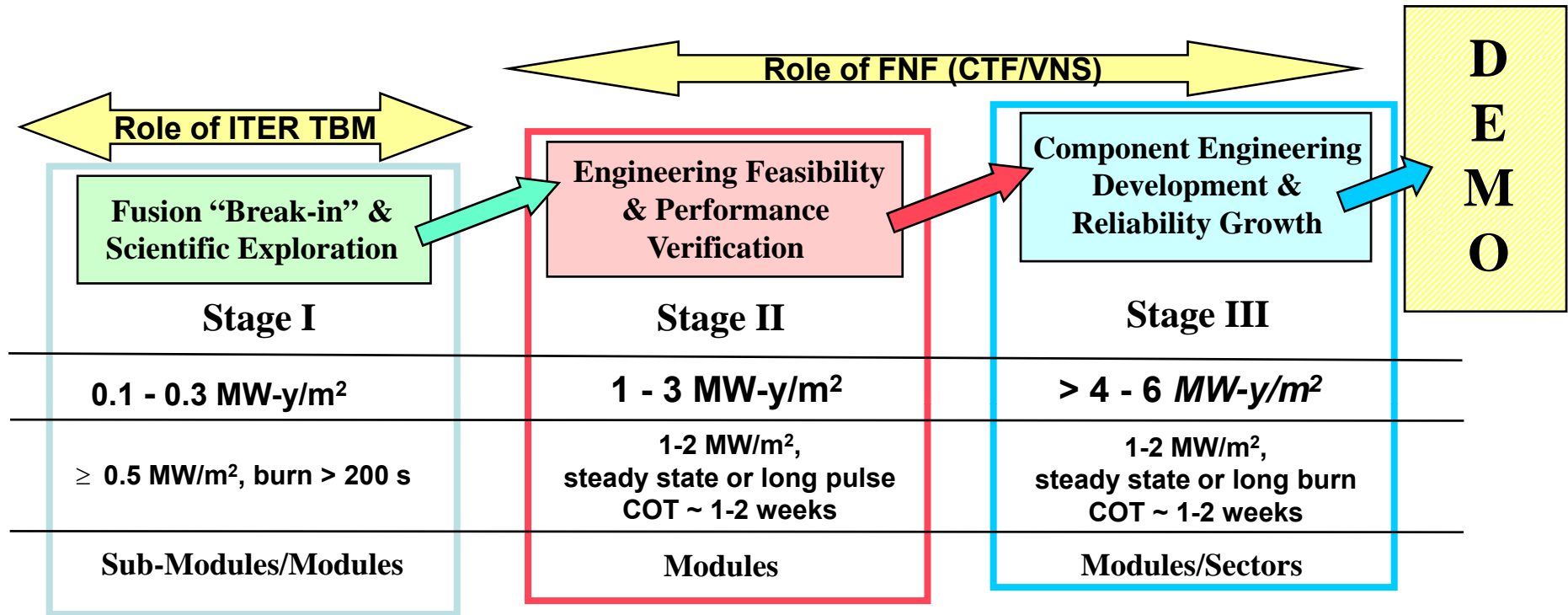
- ❏ ITER has allocated **3 ITER equatorial ports** (1.75 x 2.2 m^2) for TBM testing
- ❏ Each port can accommodate only 2 modules **(i.e. 6 TBMs max)**

Fluence in ITER is limited to 0.3MW-y/m^2 . We have to build another facility, for FNST development
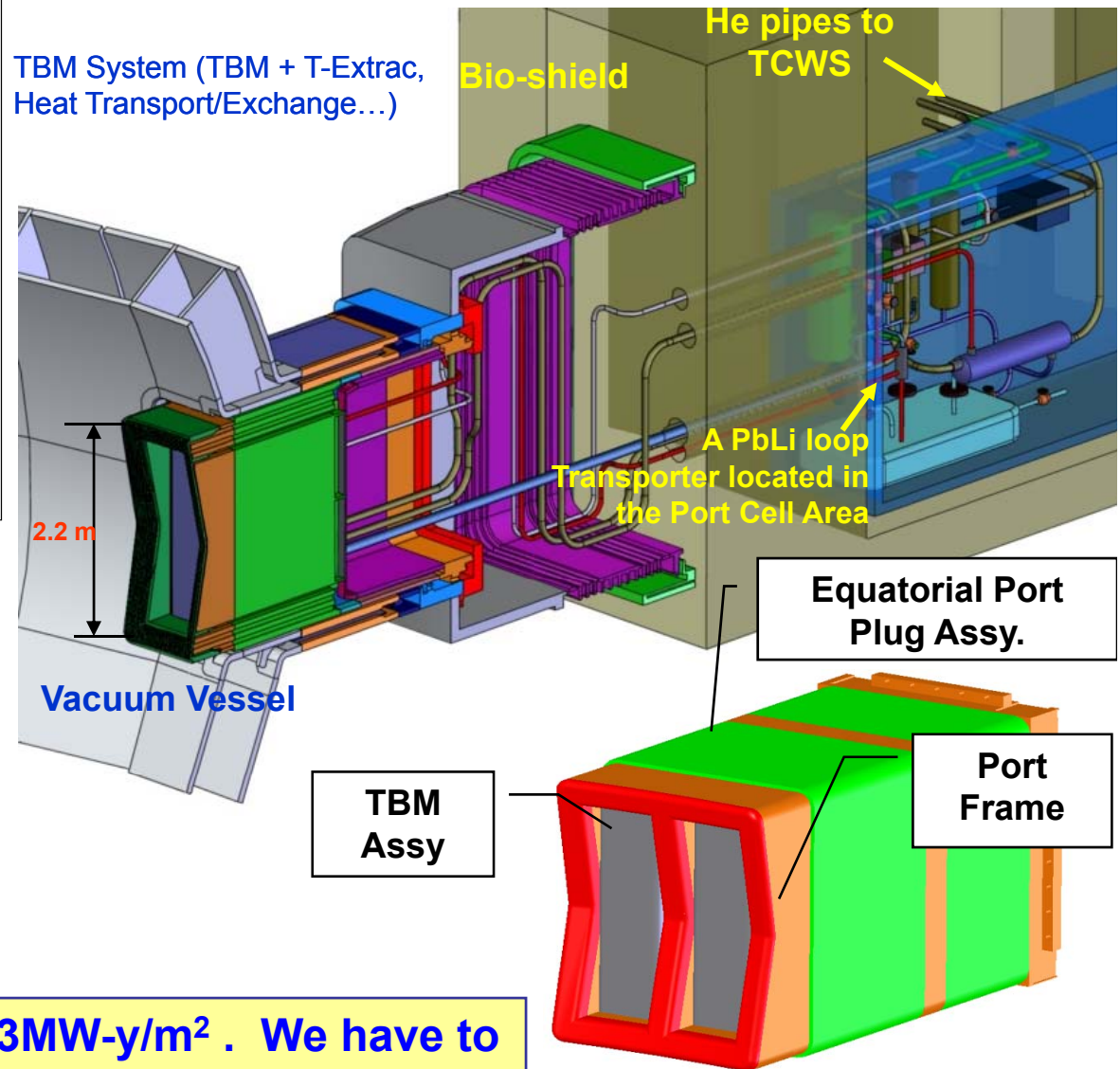
THREE Stages of FNST Testing in Fusion Facilities are Required Prior to DEMO

Stage I	Stage II	Stage III
Fusion "Break-in" & Scientific Exploration	**Engineering Feasibility & Performance Verification**	**Component Engineering Development & Reliability Growth**
$0.1 - 0.3$ MW-y/m^2	$1 - 3$ MW-y/m^2	$> 4 - 6$ *MW-y/m^2*
≥ 0.5 MW/m^2, burn > 200 s	1-2 MW/m^2, steady state or long pulse COT ~ 1-2 weeks	1-2 MW/m^2, steady state or long burn COT ~ 1-2 weeks
Sub-Modules/Modules	Modules	Modules/Sectors

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

- **A Fusion Nuclear Facility, FNF is needed , in addition to ITER, to do Stages II (Engineering Feasibility) and III (Reliability Growth)**
    - **FNF 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)
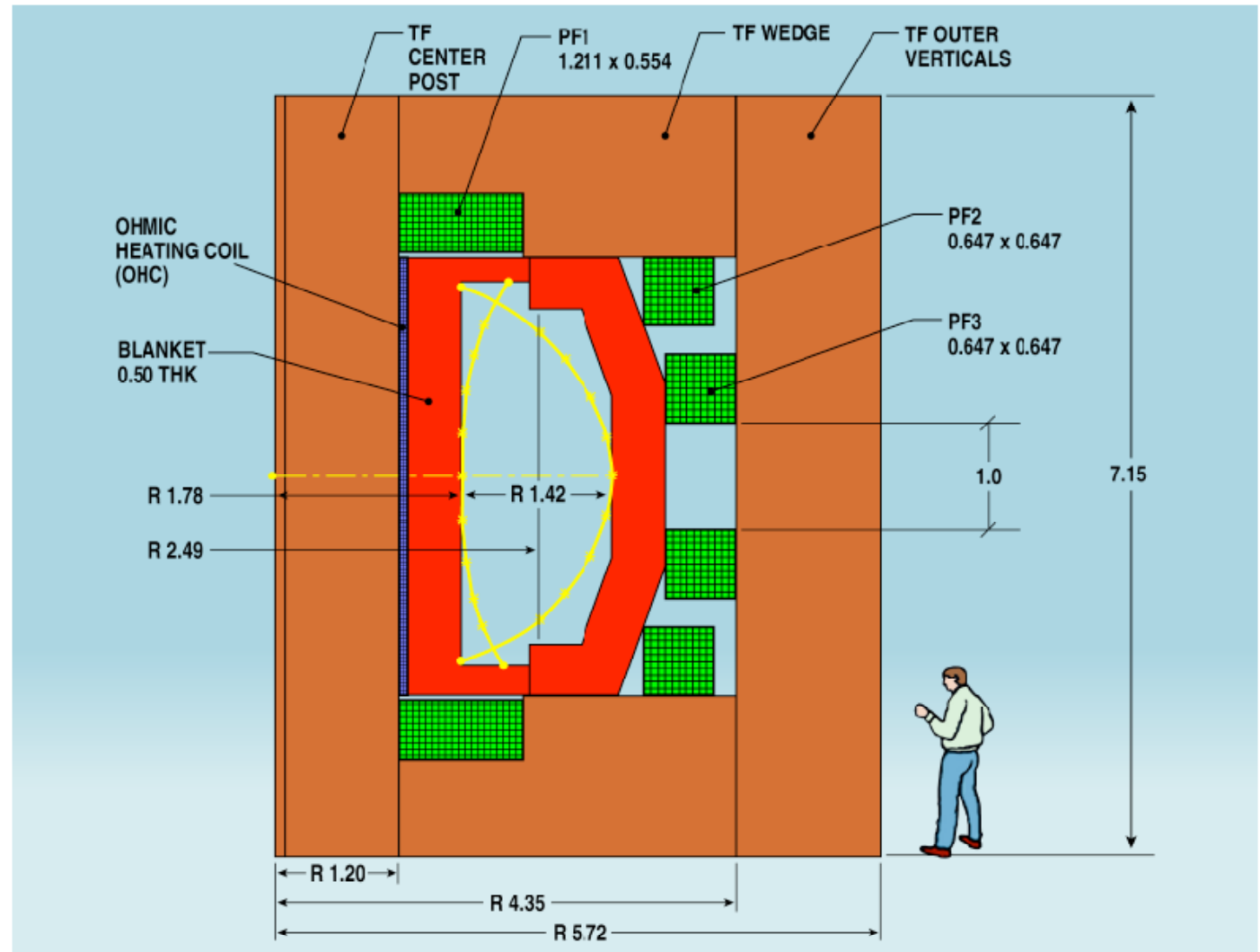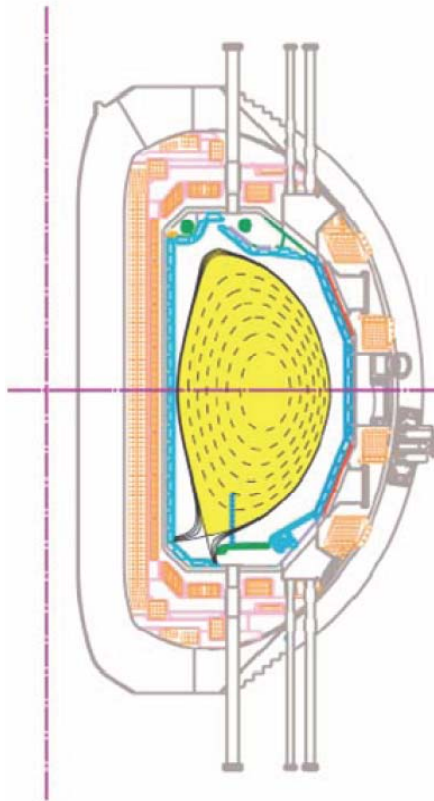
- High elongation, high triangularity double null plasma shape for high gain, steady-state plasma operation

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!