# Scientific and Engineering Challenges and New Strategy for Development of Practical Fusion Energy


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# Challenges and Strategy to Practical Fusion Energy

## OUTLINE

### 1. Introduction

Fusion research transition to Fusion Engineering

DEMO goal

### 2. Fusion Nuclear Environment and Issues

Blankets, Divertors, Materials

Fusion Nuclear environment components and interactions

Technical issues summary

Definition of Fusion Nuclear Science and Technology (FNST)

### 3. FNST Development Strategy

Science-based framework for FNST

Requirements for experiments in non-fusion facilities and fusion devices

Role and examples of designs and testing strategy (TBM & FNSF)

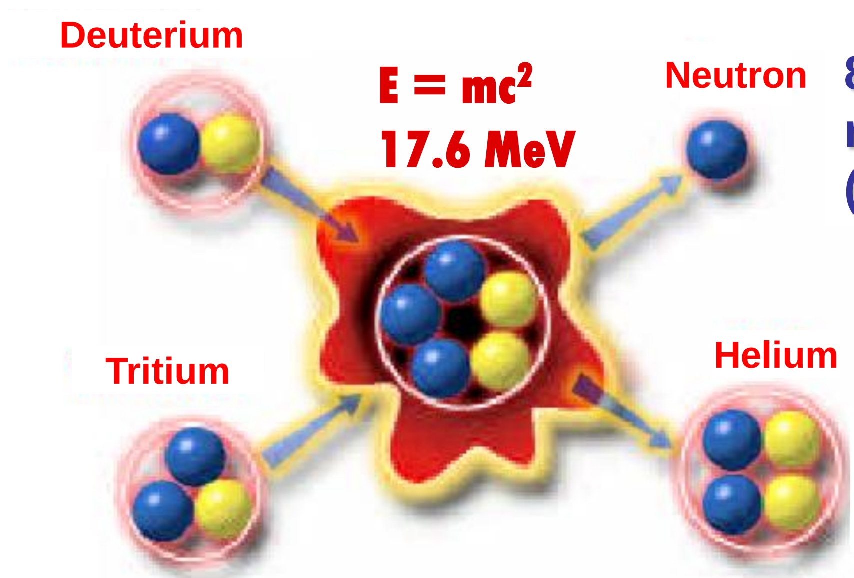
Fusion development road map

### 4. FNST Development Issues: T Supply and RAMI

### 5. Summary

# What is fusion?

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




80% of energy release (14.1 MeV) → Used to breed tritium and close the DT fuel cycle

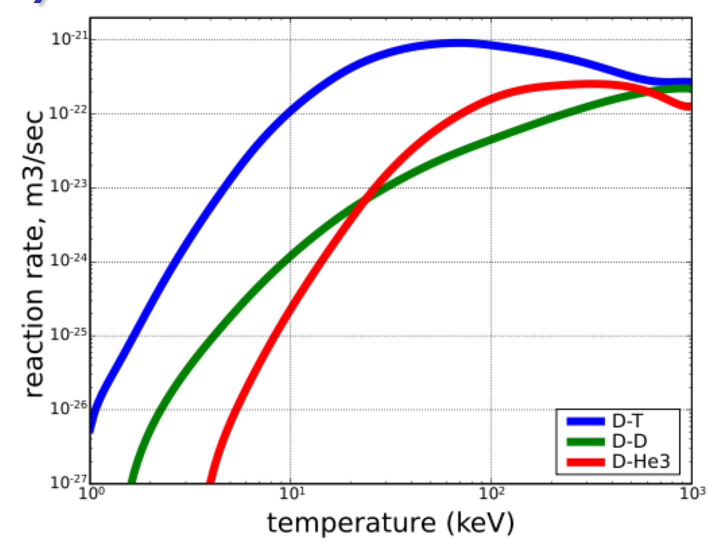
Li + n → T + He

Li in some form must be used in the fusion system

20% of energy release (3.5 MeV)

- Deuterium and tritium is the easiest: attainable at lower plasma temperature, has the largest reaction rate and high Q value.

- The World Program is focused on the D-T Cycle.



# Incentives for Developing Fusion

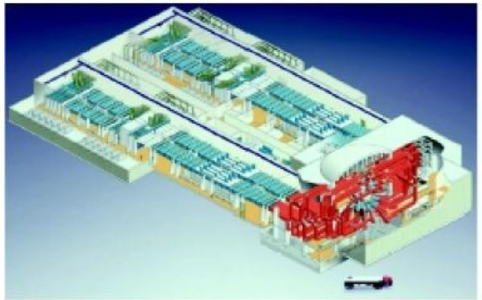
- Sustainable energy source

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

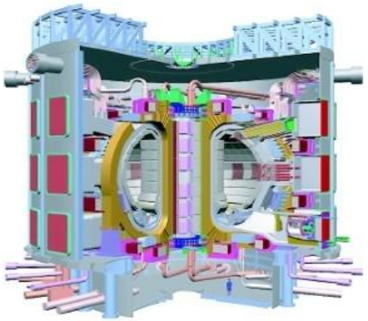
- No emission of Greenhouse or other polluting gases
- No risk of a severe accident
- No long-lived radioactive waste

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

# Fusion Research is about to transition from Plasma Physics to Fusion Nuclear Science and Engineering



National Ignition Facility



ITER

- **1950-2010**
  - **The Physics of Plasmas**

- **2010-2035**
  - **The Physics of Fusion**
  - **Fusion Plasmas-heated and sustained**
    - **$Q = (E_f / E_{input})$~10**
    - **ITER (MFE) and NIF (inertial fusion)**

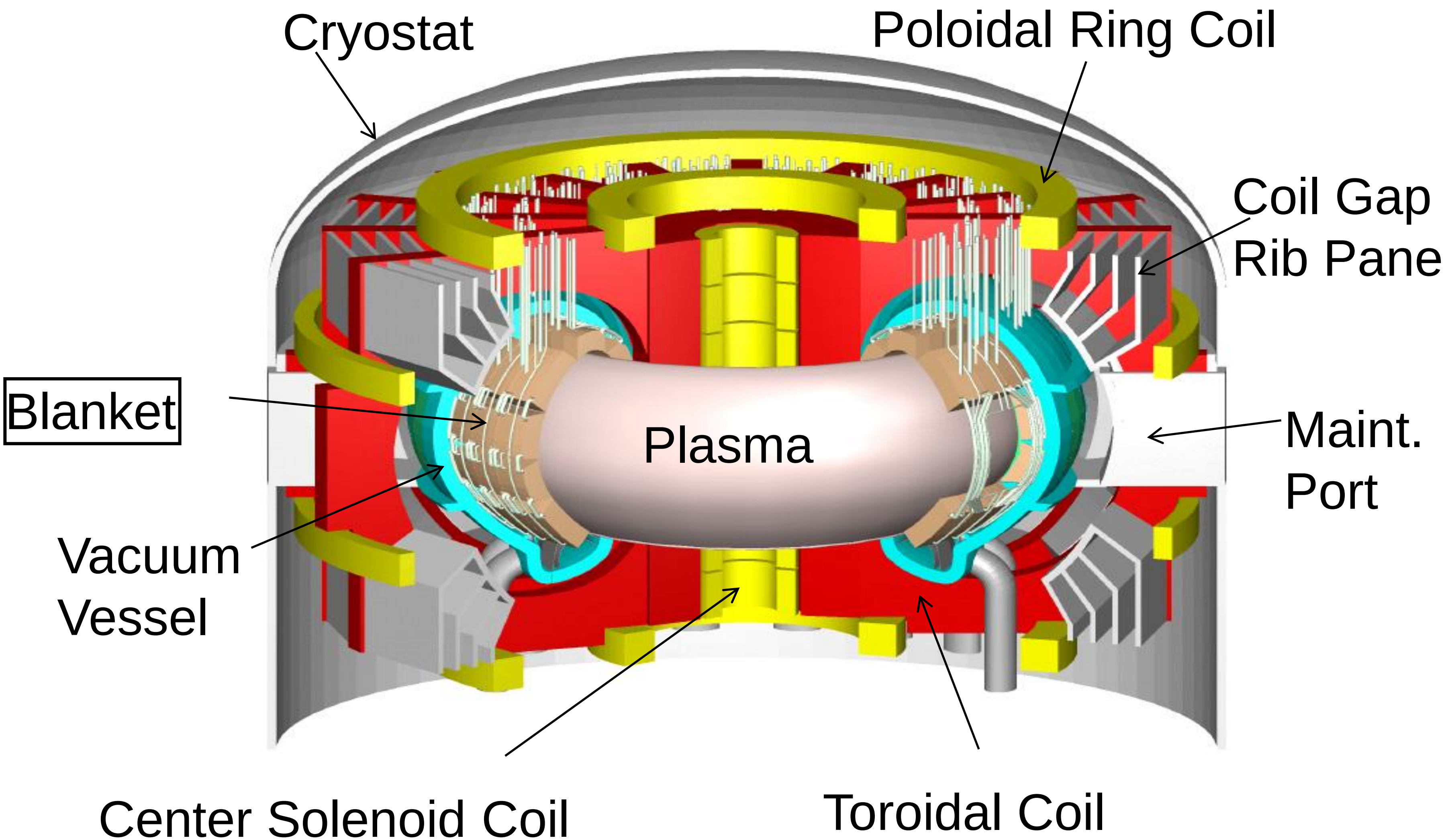
- **ITER is a major step forward for fusion research. It will demonstrate:**
  1. **Reactor-grade plasma**
  2. **Plasma-support systems (S.C. magnets, fueling, heating)**

**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.***

# 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)**

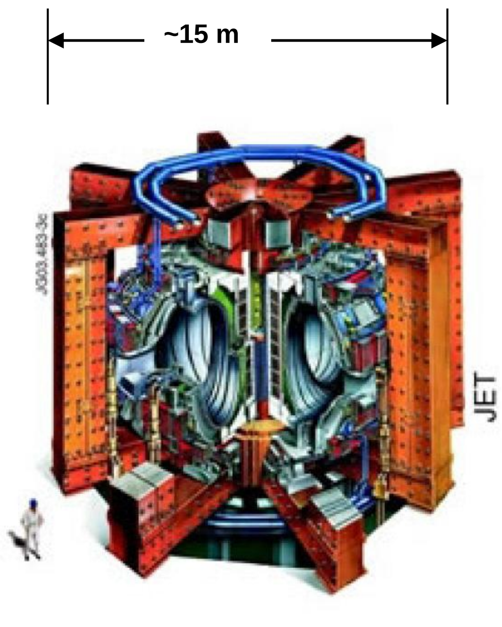
# ITER

- 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 ~ 2027.**

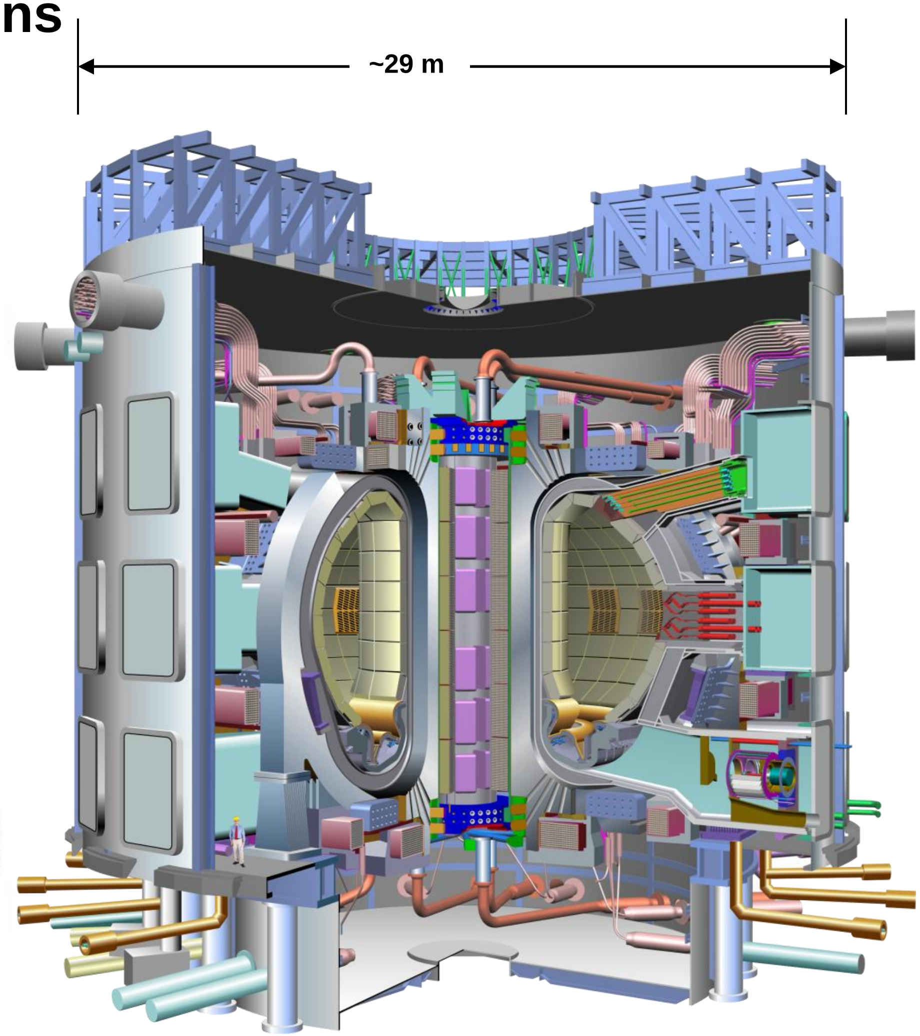
# ITER is a reactor-grade tokamak plasma physics experiment - A huge step toward fusion energy

- Will use D-T and produce neutrons
- 500MW fusion power, Q=10
- Burn times of 400s
- Reactor scale dimensions
- Actively cooled PFCs
- Superconducting magnets

By Comparison, JET
- ~10 MW
- ~1 sec
- Passively Cooled

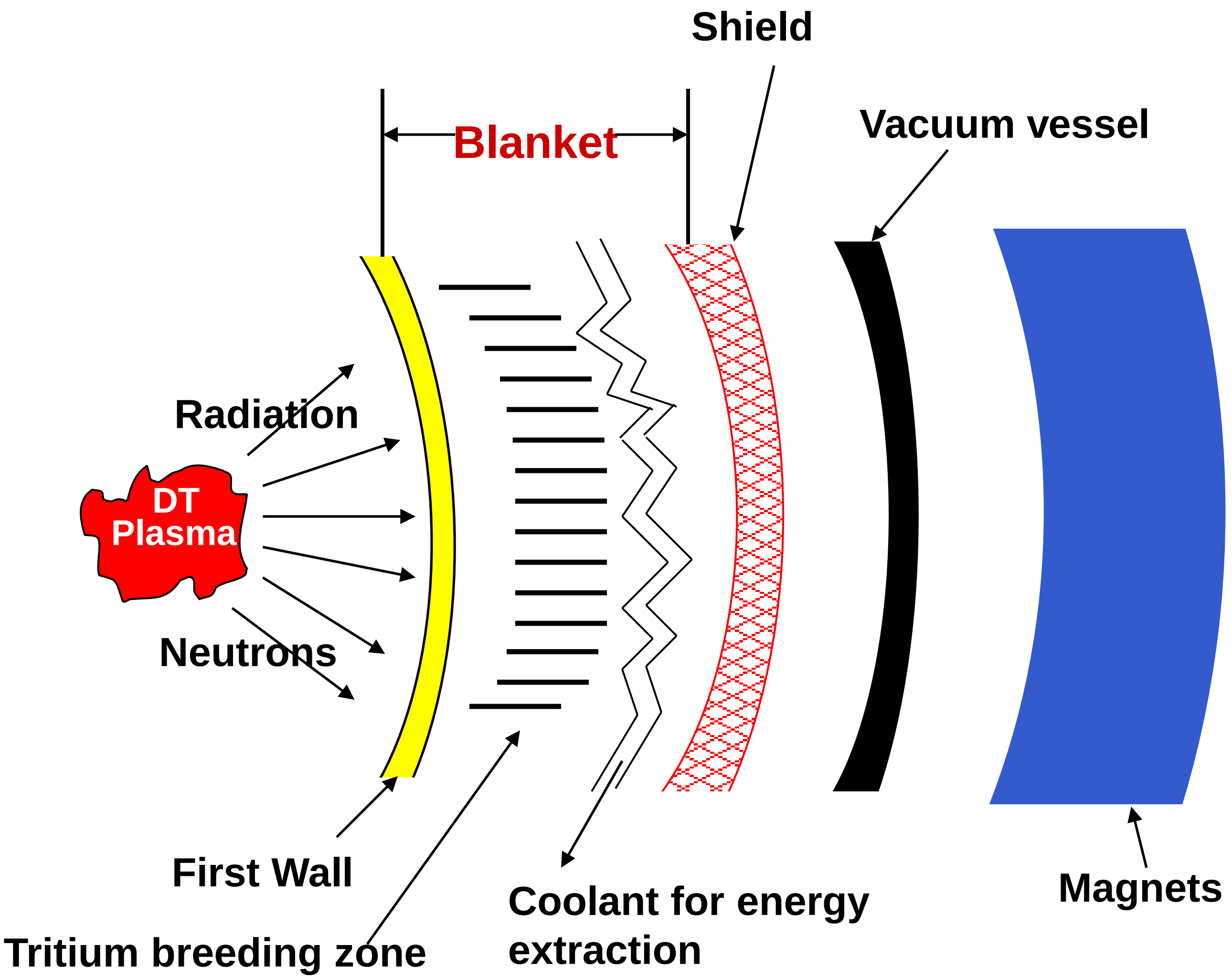



JET




ITER

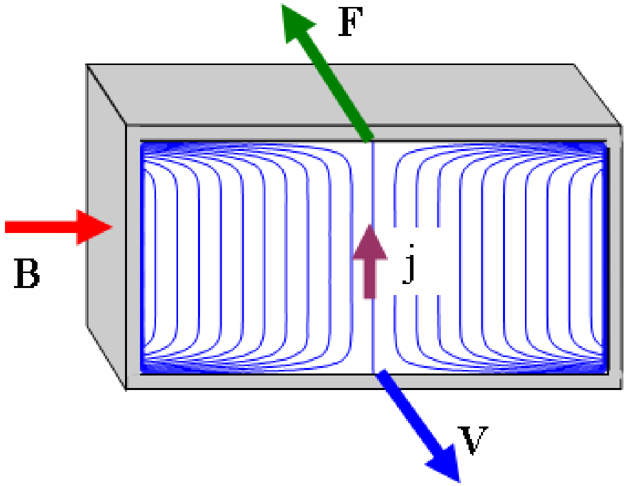
# The primary functions of the blanket are to provide for: Power Extraction & Tritium Breeding

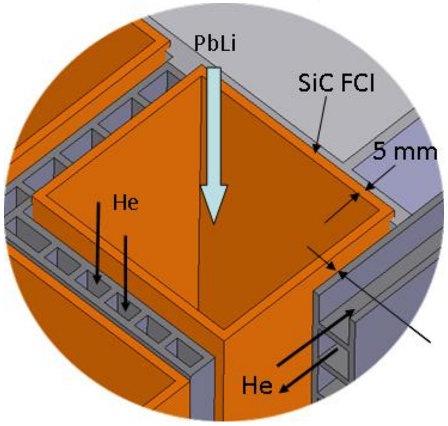



**Lithium-containing Liquid metals (Li, PbLi) are strong candidates as breeder/coolant. He-cooled Li ceramics are also candidates.**

# MHD fluid flow and heat/mass transfer issues are primary drivers of liquid metal blanket designs

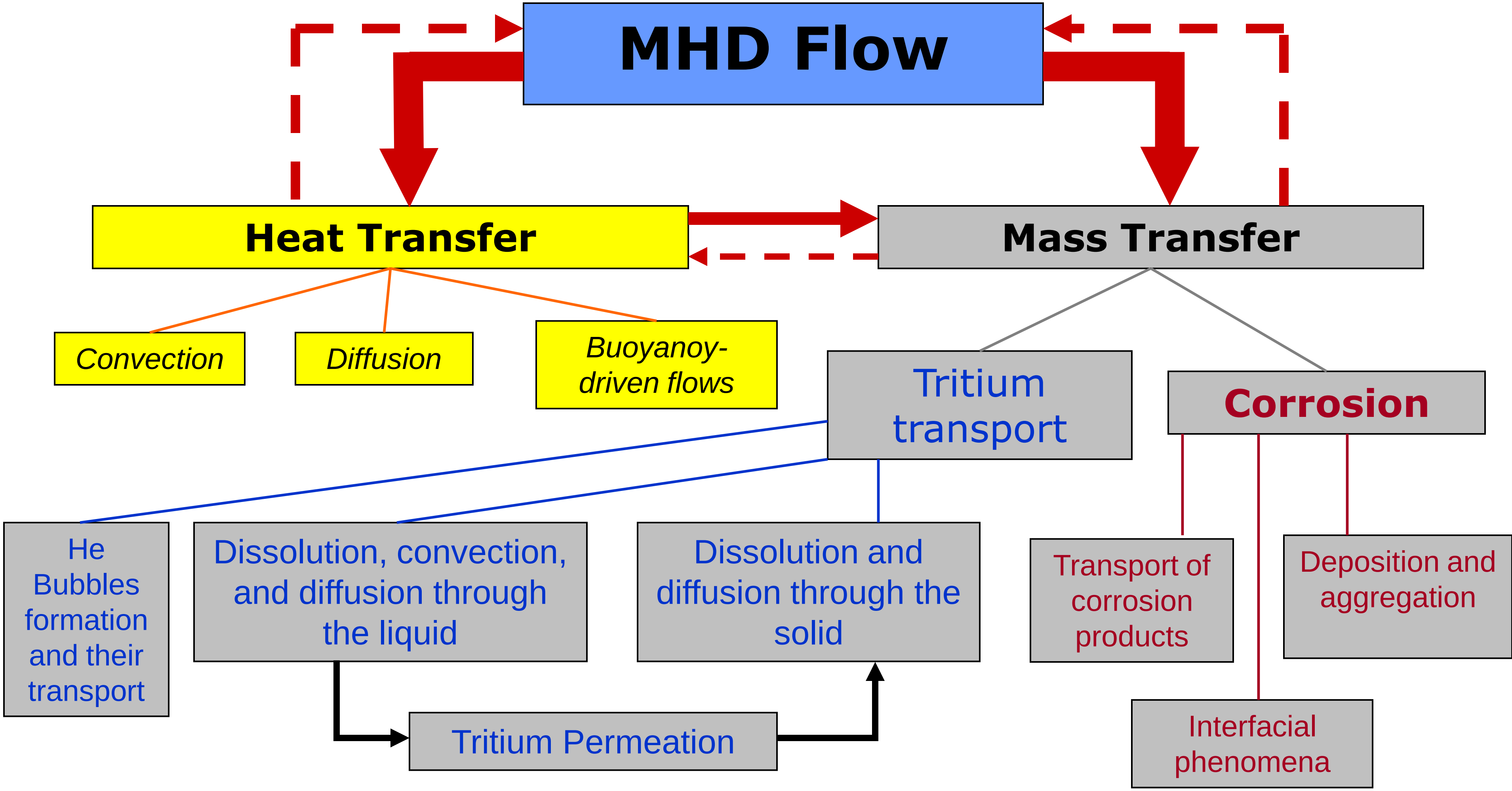
- The motion of electrically conducting breeder/coolant in strong, plasma-confining, magnetic field induces electric currents, which in turn interact with the magnetic field, resulting in Lorentz forces that modify the original flow in many ways. This is a subject of **magnetohydrodynamics** (***MHD).***
- MHD forces in fusion blankets are typically 4 to 5 orders of magnitude larger than inertial and viscous forces, changing the fluid dynamics in remarkable ways.
- MHD forces are non-local, flow in one location can be controlled by current closure in boundary layers or structure in another location.
- These unique MHD coolant/breeder flows are non-linearly coupled to other transport phenomena (heat/mass transfer) – blanket performance and design requires an in-depth understanding of all these phenomena.




The electromagnetic *Lorentz force* is orders of magnitude higher than viscous or inertial forces, strongly affecting LM flows in the blanket

# Integrated, multi-physics modelling of MHD flow dynamics and heat and mass transfer in blanket flows




Coupling through the source / sink term, boundary conditions, and transport coefficients

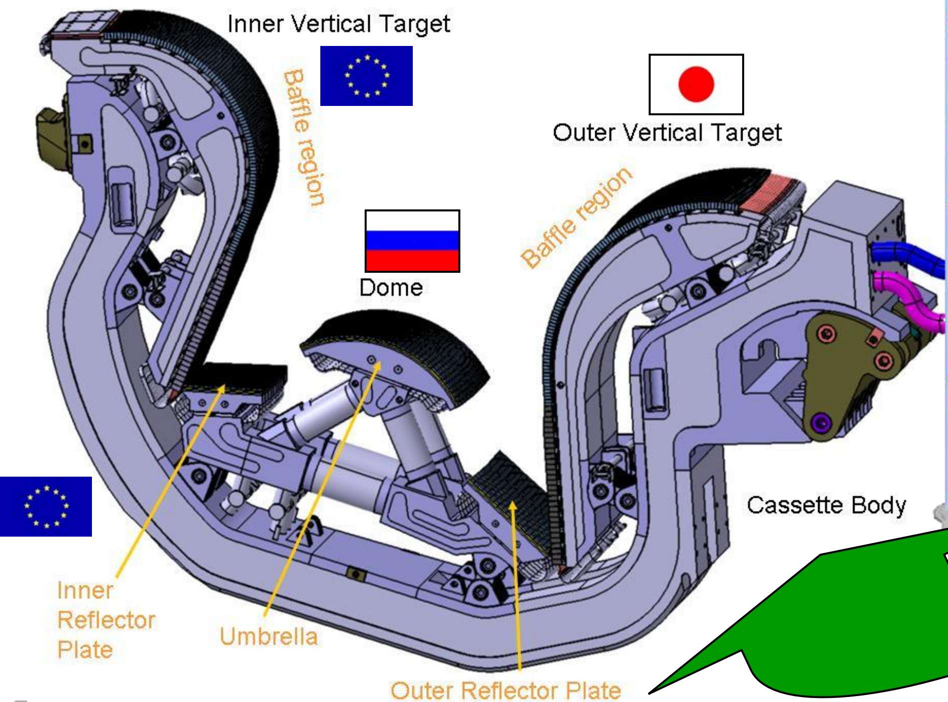
# Divertor

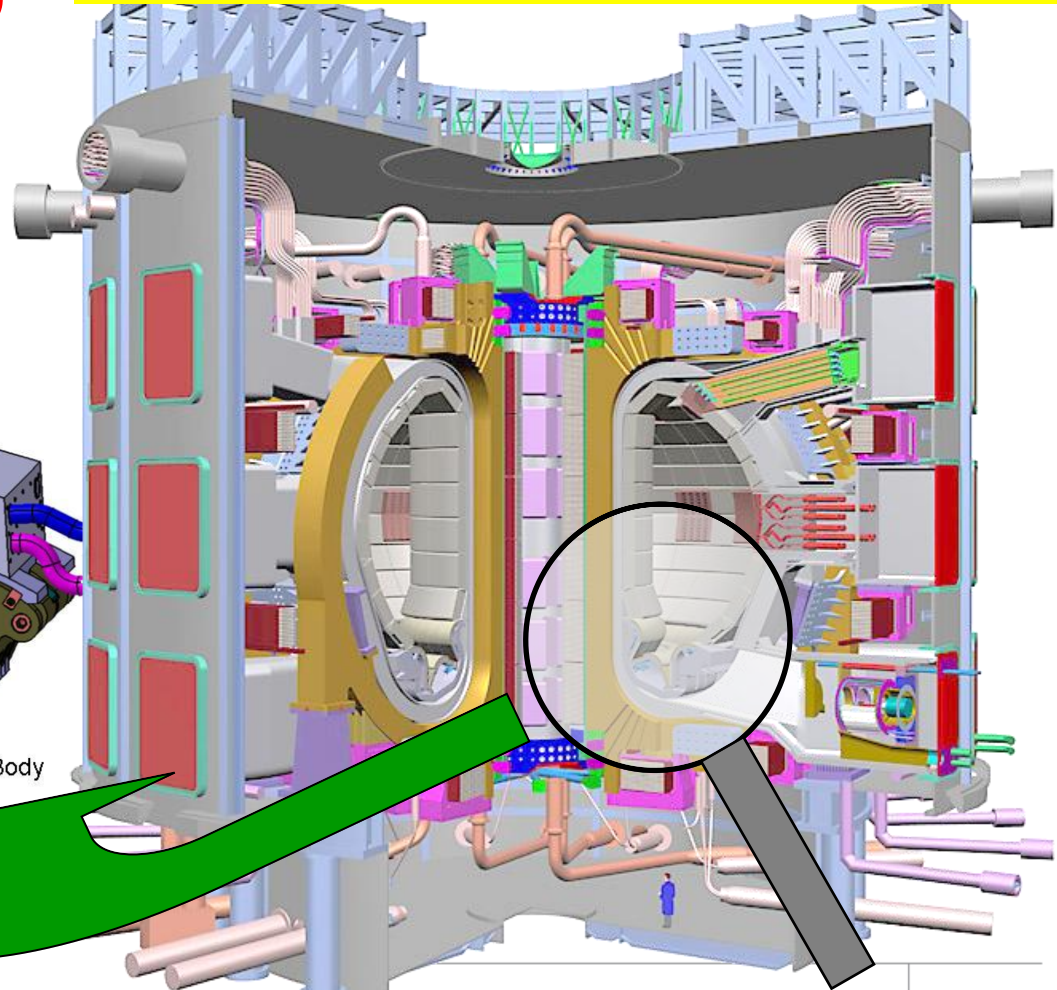
## Divertor system main functions :

• Exhaust the major part of the plasma thermal power (including alpha power)

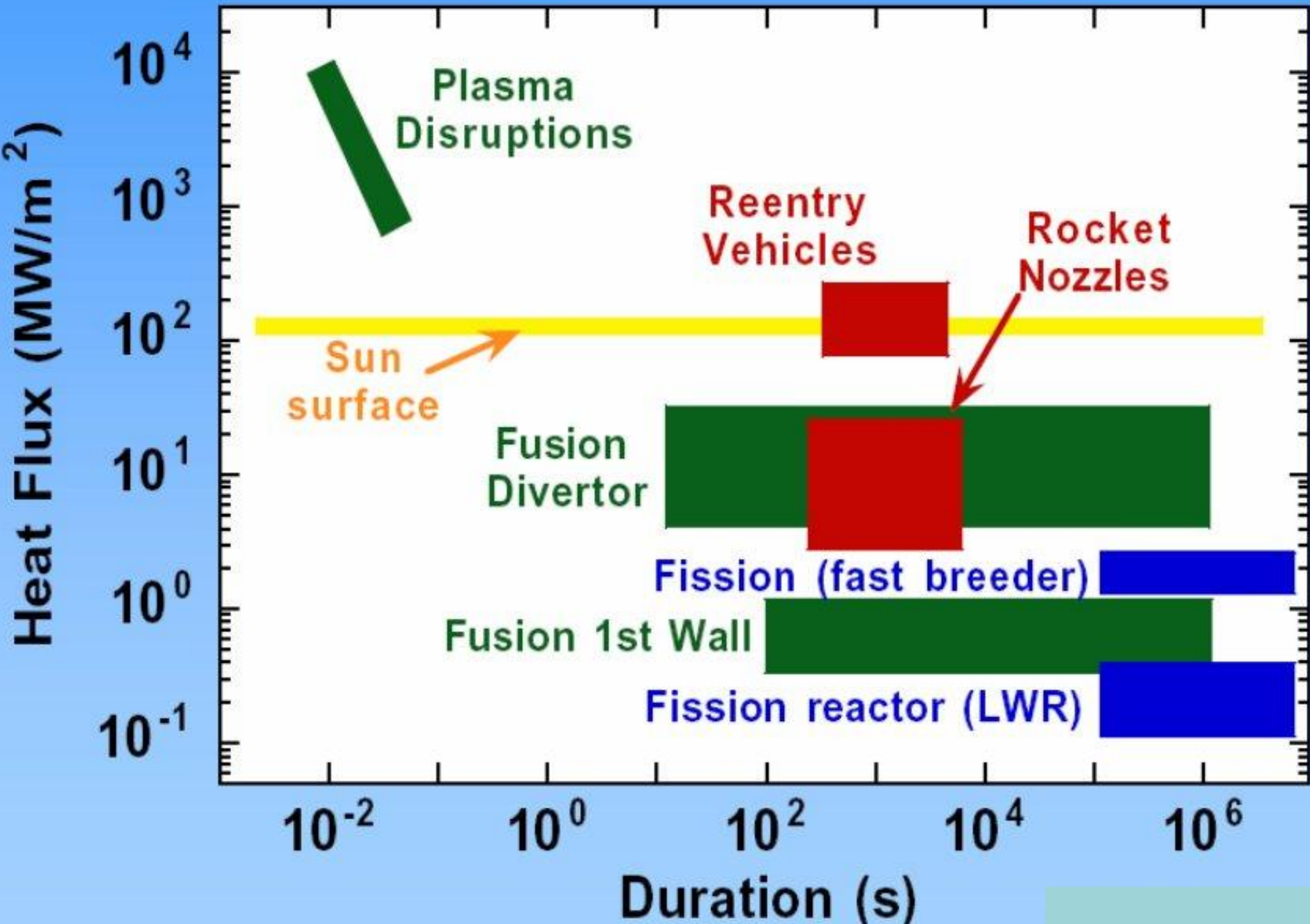
• Minimize the helium and impurities content in the plasma

**Challenge to develop HHF Componets capable of 20 MW/m²**



# Comparison of Heat Fluxes



# 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**

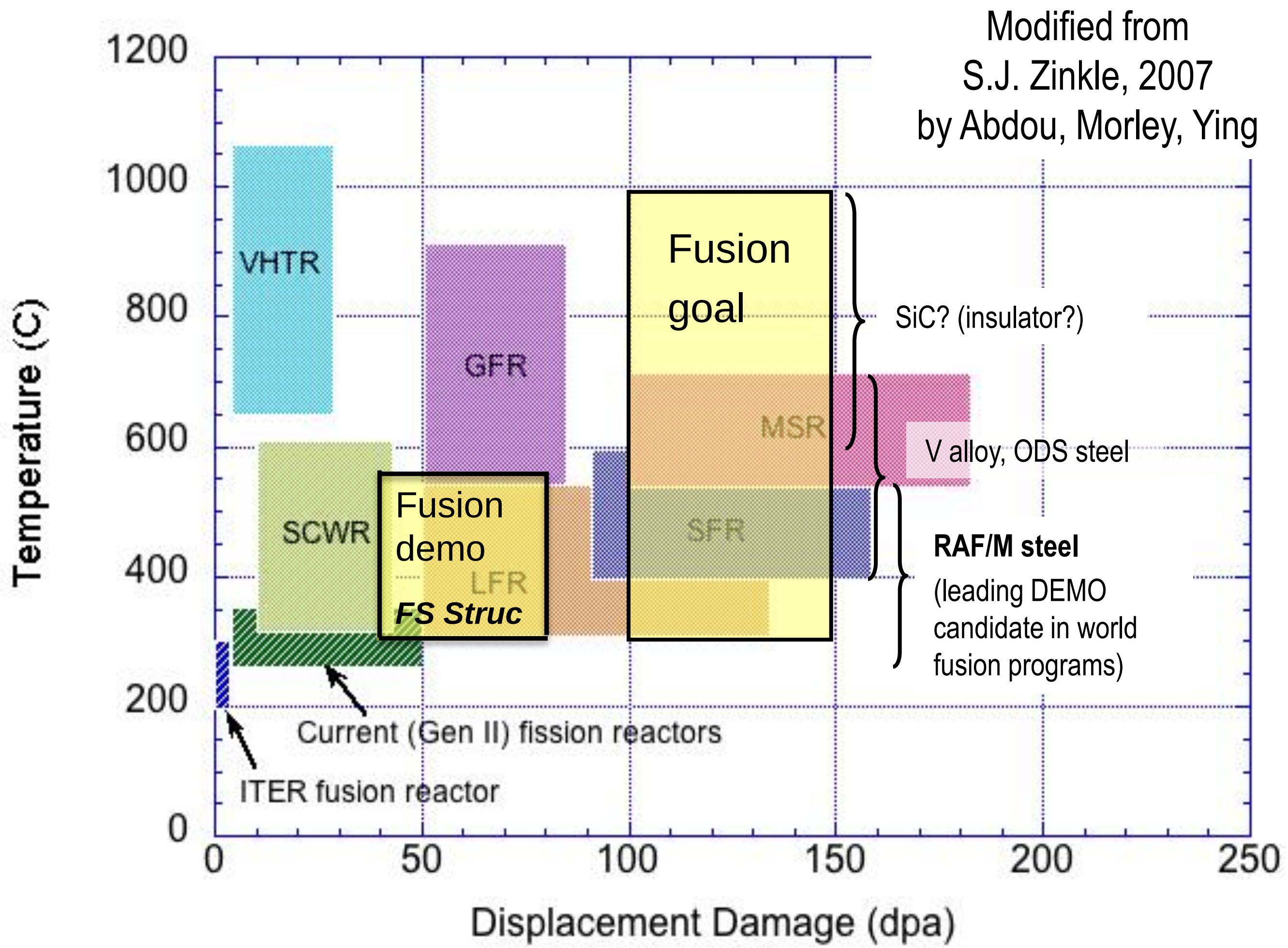
- *Structural materials are most challenging, but many other materials (e.g. breeding, insulating, superconducting, plasma facing and diagnostic) must also be successfully developed.*

# 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

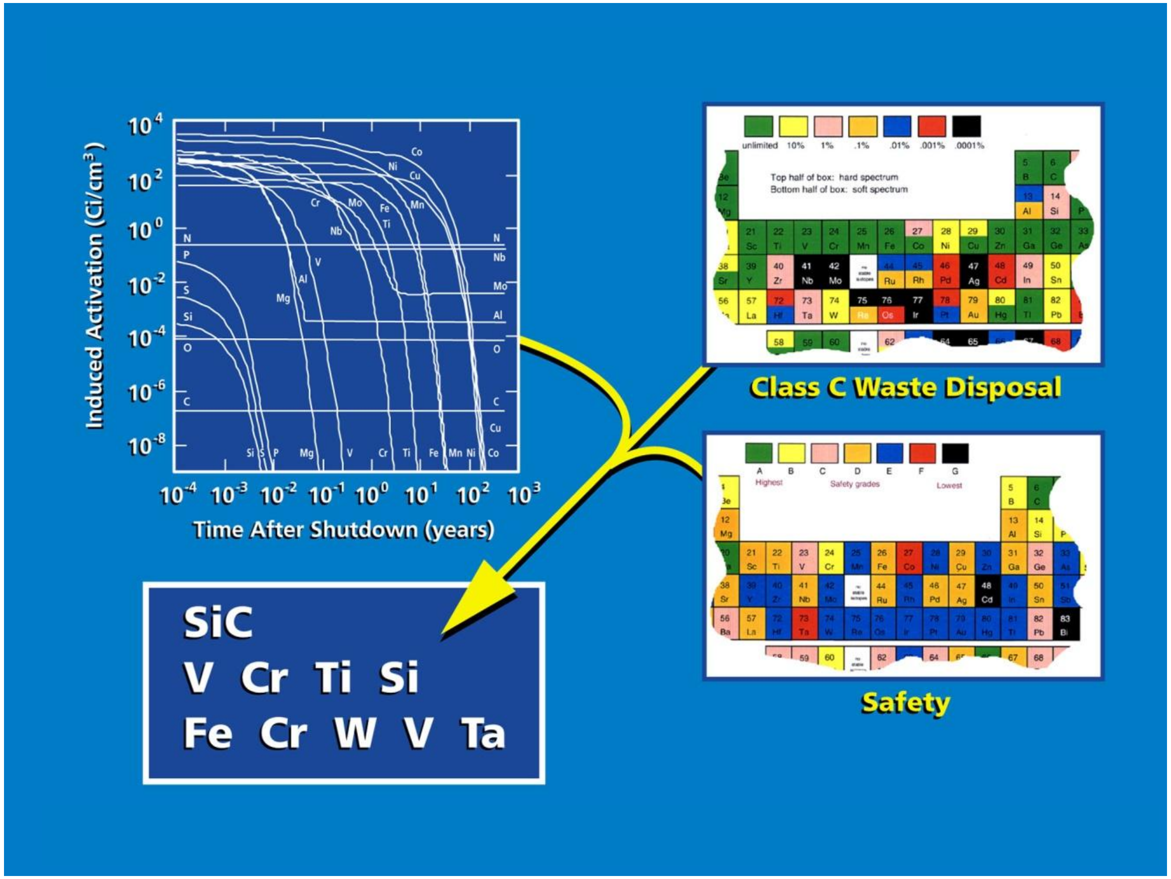
LFR: Lead cooled fast reactor

SFR: Sodium cooled fast reactor

MSR: Molten salt cooled reactor

# 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)



# 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.

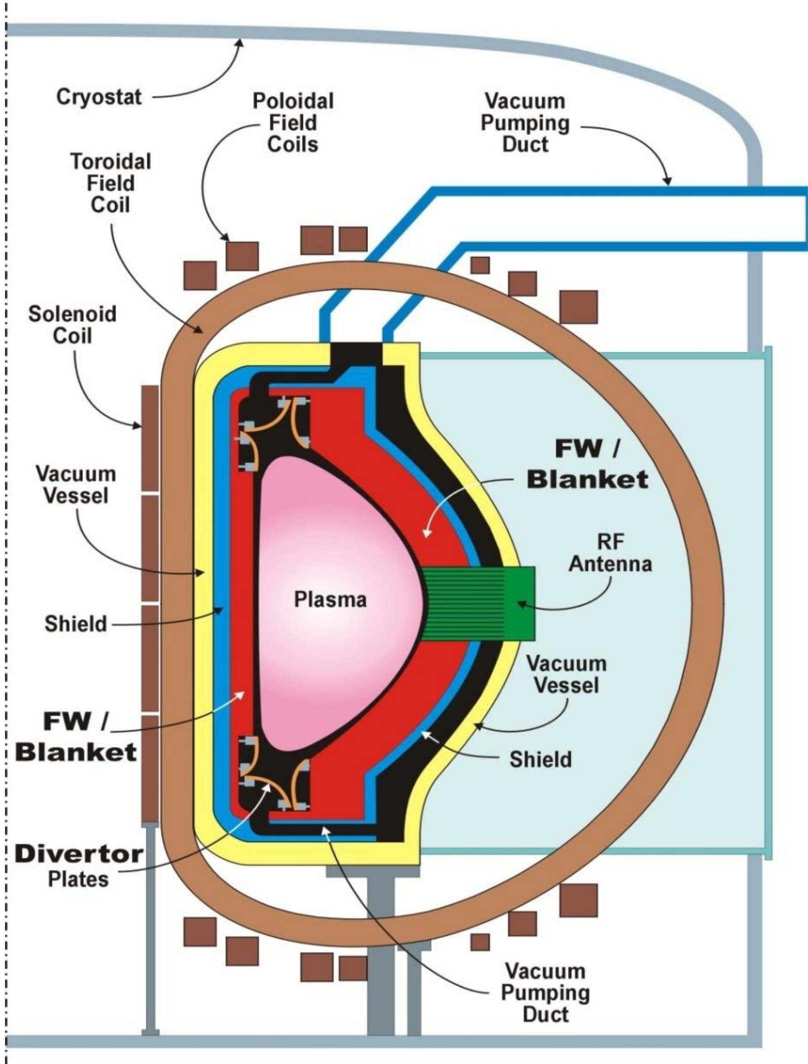
**Inside the Vacuum Vessel "Reactor Core":**

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

***The location of the Blanket / Divertor inside the vacuum vessel is necessary but has major consequences*:**

***a- many failures (e.g. coolant leak) require immediate shutdown***

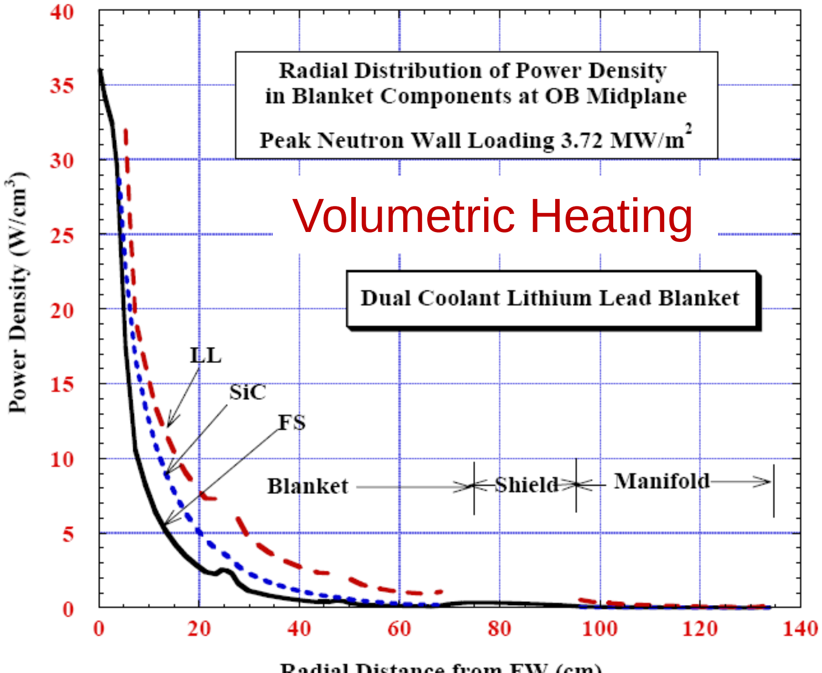
***b- repair/replacement take long time***

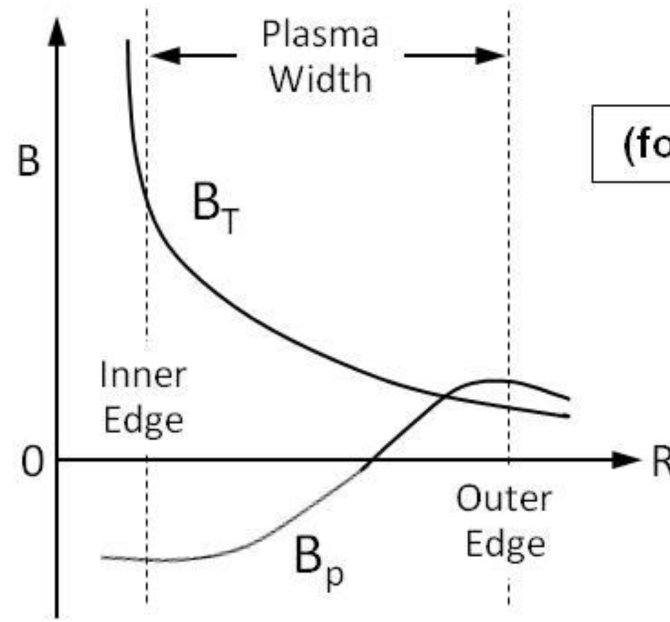


# Fusion nuclear environment is unique and complex: multi-component fields with gradients

- 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




**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.

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

## 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

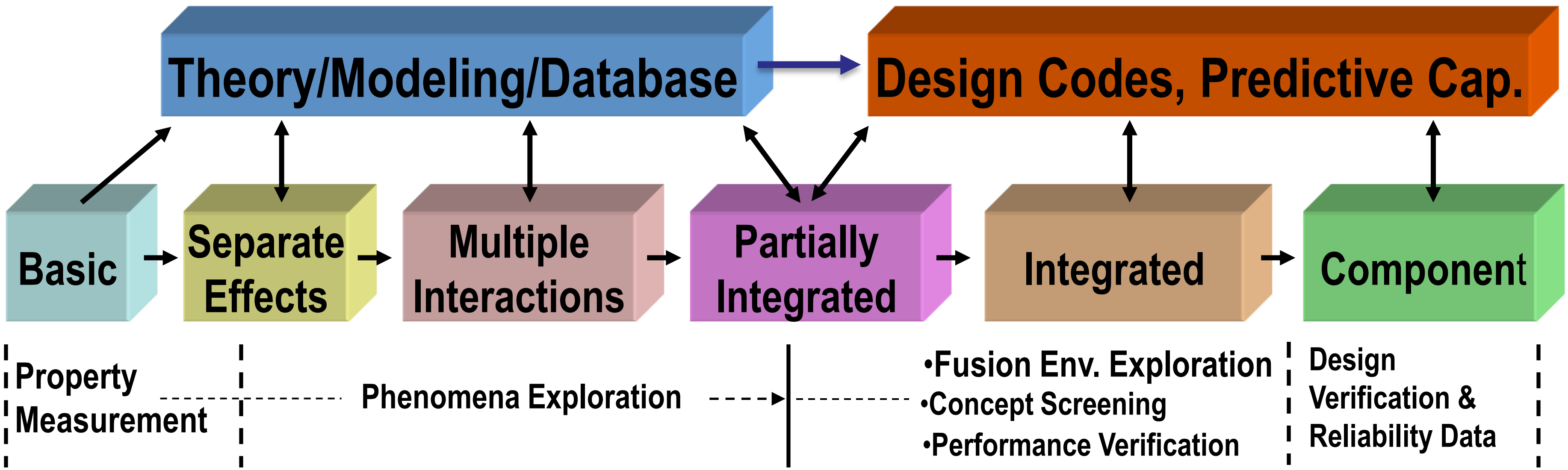
**Reliability, Availability, Maintainability (RAMI)**

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




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

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

Experiments in non-fusion facilities are essential and are prerequisites

**Testing in Fusion Facilities**

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

| Scientific Feasibility | Engineering Feasibility & Performance Verification | Component Engineering Development & Reliability Growth |
|---|---|---|
| Stage I | Stage II | Stage III |
| 0.1 - 0.3 MW-y/m$^2$ | 1 - 3 MW-y/m$^2$ | > 4 - 6 MW-y/m$^2$ |
| $\geq$ 0.5 MW/m$^2$<br>burn > 200 s | 1-2 MW/m$^2$<br>steady state or long burn<br>COT ~ 1-2 weeks | 1-2 MW/m$^2$<br>steady state or long burn<br>COT ~ 1-2 weeks |
| Sub-Modules/Modules | Modules | Modules/Sectors |

**DEMO**

**Stage I**

- Establish scientific feasibility of basic functions under prompt responses and under the impact of rapid property changes in early life

**Stage II**

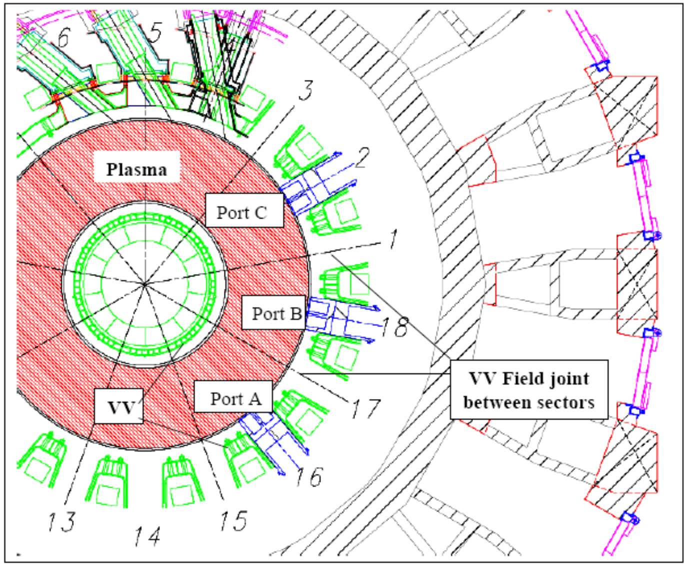
- Establish **engineering feasibility** of blankets/PFC (satisfy basic functions & performance, up to 10 to 20 % of MTBF and lifetime)

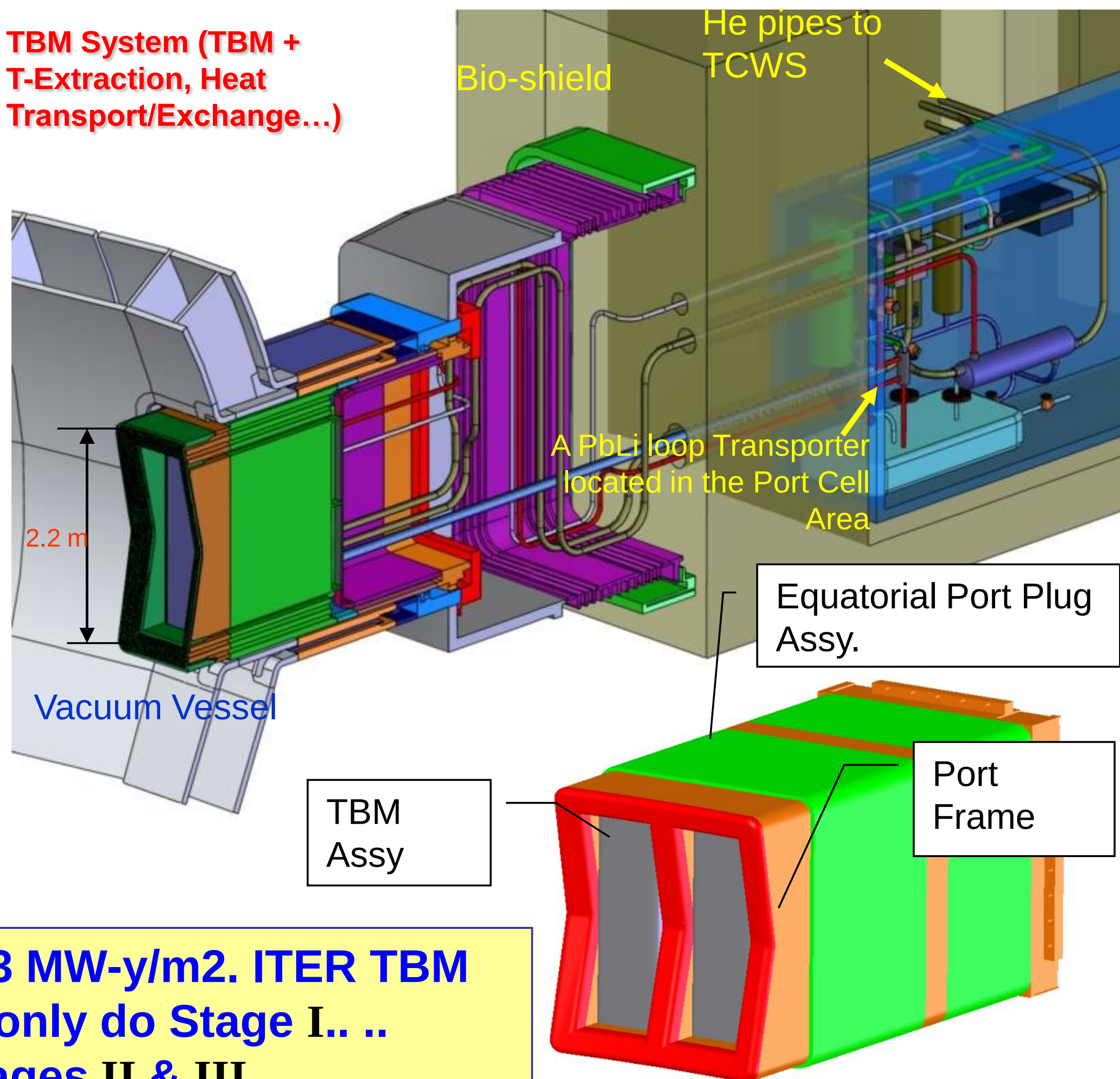
**Stage III**

- Failure modes, effects, and rates and mean time to replace/fix components (for random failures and planned outage)
- Iterative design / test / fail / analyze / improve programs aimed at **reliability growth** and safety
- **Verify design** and **predict availability** of FNT components in DEMO

**Where to do Stages I, II, and III?**

# ITER Provides Substantial Hardware Capabilities for Testing of Blanket Systems




- ITER has allocated 3 equatorial ports (1.75 x 2.2 m2) for TBM testing
- Each port can accommodate only 2 modules **(i.e. 6 TBMs max)**

**Fluence in ITER is limited to 0.3 MW-y/m2. ITER TBM has an important role but can only do Stage I.. ..**
**We need another facility for Stages II & III.**

# Fusion Nuclear Science Facility (FNSF)

- The idea of FNSF (also called VNS, CTF) is to build a small size, low fusion power DT plasma-based device in which Fusion Nuclear Science and Technology (FNST) experiments can be performed in the relevant fusion environment:

  *1- at the smallest possible scale, cost, and risk, and*

  *2- with practical strategy for solving the tritium consumption and supply issues for FNST development.*

**In MFE: small-size, low fusion power can be obtained in a low-Q (driven) plasma device, with normal conducting Cu magnets**

  – Equivalent in IFE: reduced target yield (and smaller chamber radius?)

- There are at least TWO classes of Design Options for FNSF:

  – Tokamak with Standard Aspect Ratio, A ~ 2.8 – 4

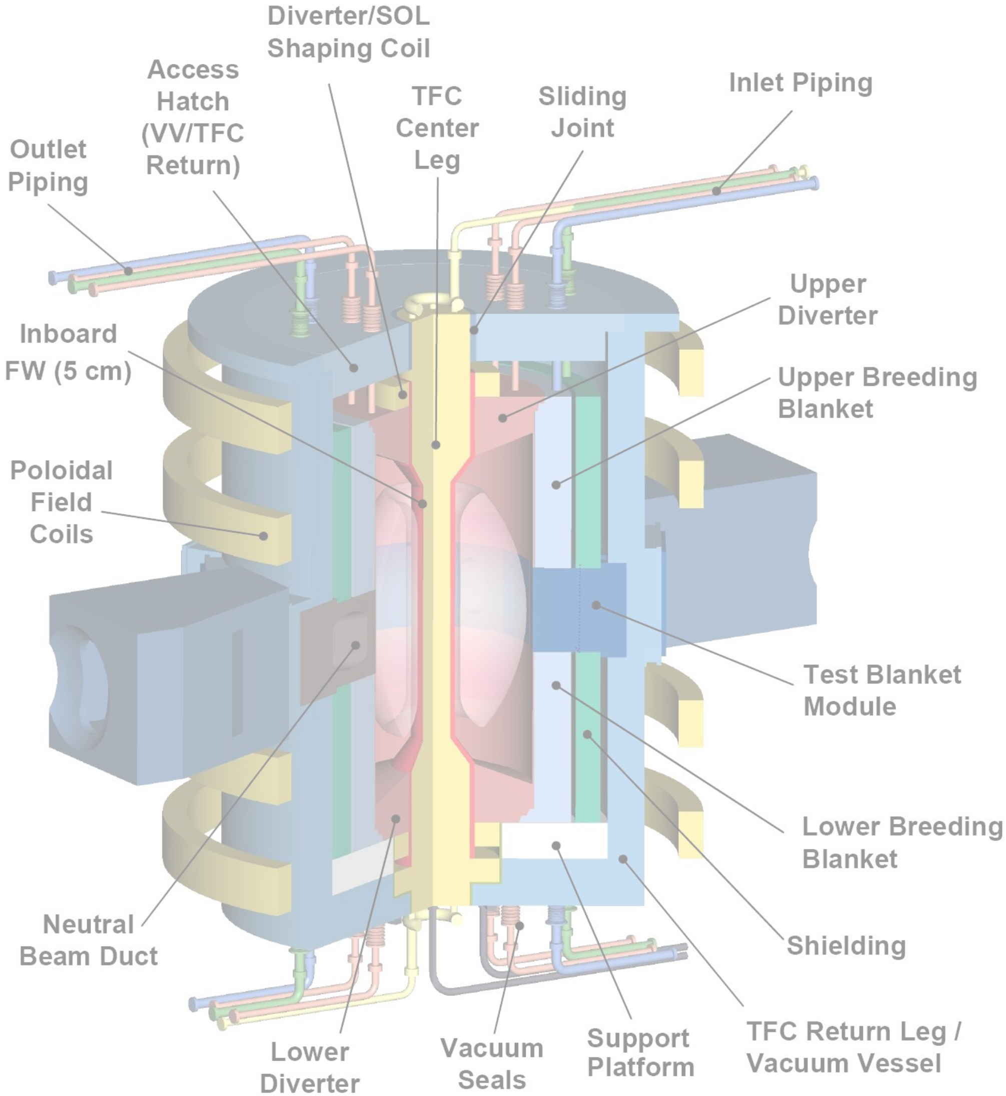
  – ST with Small Aspect Ratio, A ~ 1.5

**Differences are in the physics, configuration, and TF Coil resistive power.**

# Example Option for FNSF Design: Small Aspect Ratio (ST)

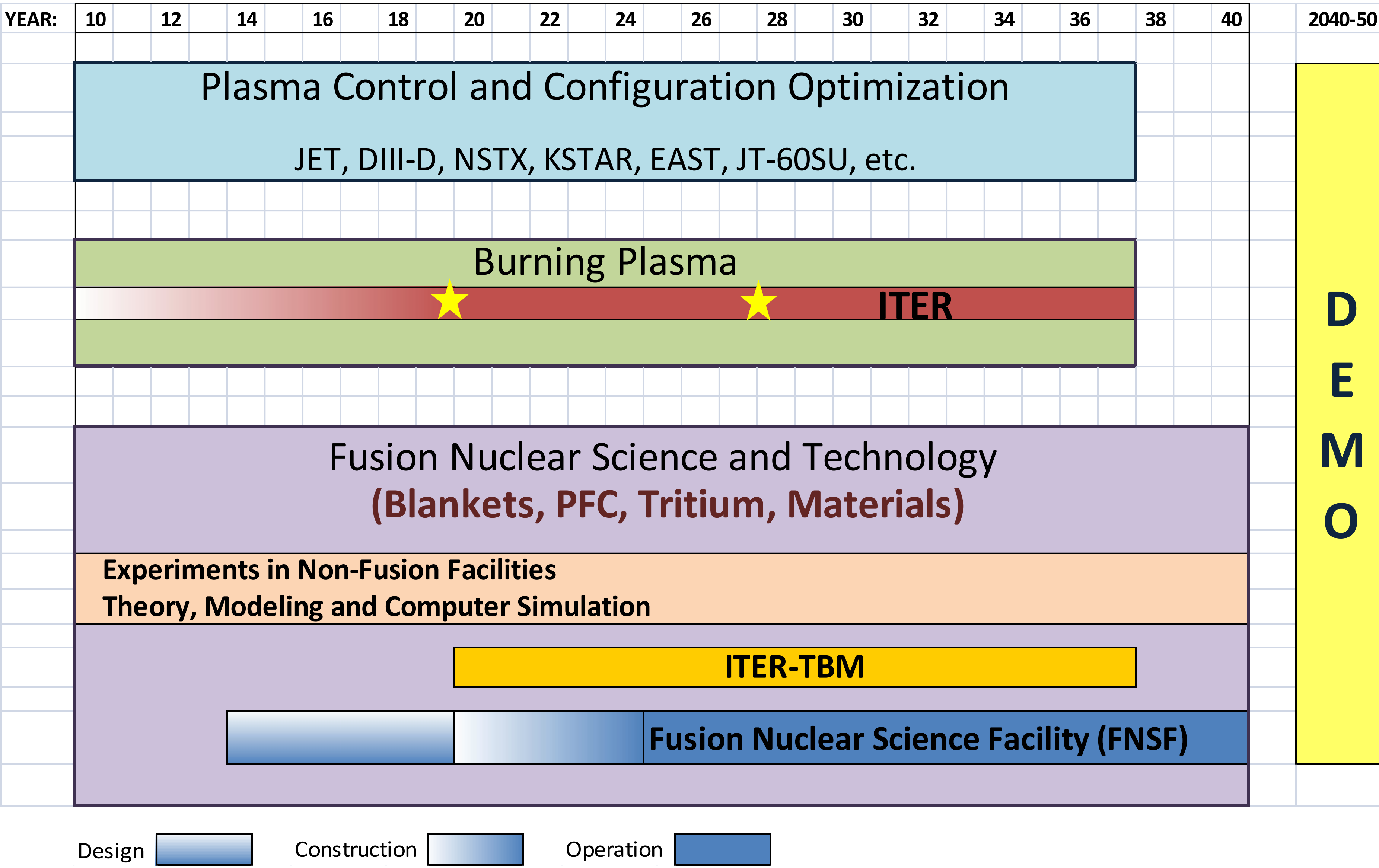
## Smallest power and size, Cu TF magnet, Center Post

(Example from Peng et al, ORNL) R=1.2m, A=1.5, Kappa=3, Pfusion=75MW




| $W_L$ [MW/m$^2$] | 0.1 | 1.0 | 2.0 |
|---|---|---|---|
| R0 [m] | 1.20 | | |
| A | 1.50 | | |
| Kappa | 3.07 | | |
| Qcyl | 4.6 | 3.7 | 3.0 |
| Bt [T] | 1.13 | 2.18 | |
| Ip [MA] | 3.4 | 8.2 | 10.1 |
| Beta_N | 3.8 | | 5.9 |
| Beta_T | 0.14 | 0.18 | 0.28 |
| $n_e$ [$10^{20}$/m$^3$] | 0.43 | 1.05 | 1.28 |
| $f_{BS}$ | 0.58 | 0.49 | 0.50 |
| $T_{avgi}$ [keV] | 5.4 | 10.3 | 13.3 |
| $T_{avge}$ [keV] | 3.1 | 6.8 | 8.1 |
| HH98 | 1.5 | | |
| Q | 0.50 | 2.5 | 3.5 |
| $P_{aux-CD}$ [MW] | 15 | 31 | 43 |
| $E_{NB}$ [keV] | 100 | 239 | 294 |
| $P_{Fusion}$ [MW] | 7.5 | 75 | 150 |
| T M height [m] | 1.64 | | |
| T M area [m$^2$] | 14 | | |
| Blanket A [m$^2$] | 66 | | |
| $F_{n-capture}$ | 0.76 | | |

# MFE Fusion Development Road Map (Time approximate)



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

## Tritium Consumption in Fusion is HUGE! Unprecedented!

**55.6 kg per 1000 MW fusion power per year**

**Production in fission is much smaller & Cost is very high:**

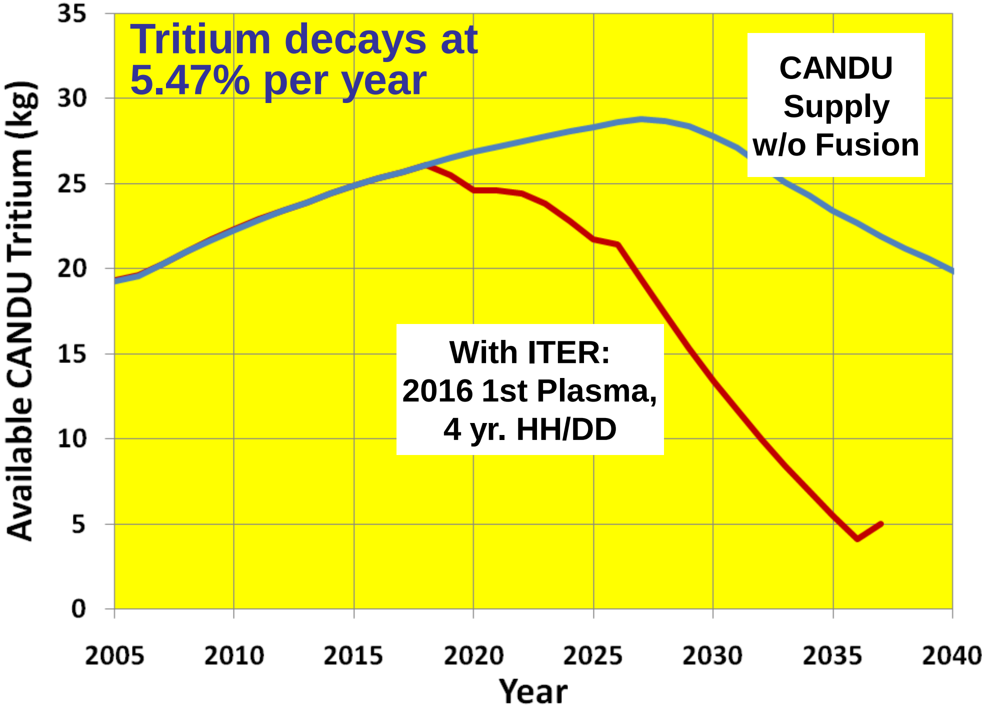
**Fission reactors: 2–3 kg/year**

**$84M-$130M/kg (per DOE Inspector General*)**

*www.ig.energy.gov/documents/CalendarYear2003/ig-0632.pdf

**CANDU Reactors: 27 kg from over 40 years, $30M/kg (current)**

- **A Successful ITER will exhaust most of the world supply of tritium**
- **No DT fusion devices other than ITER can be operated without a breeding blanket**
- **Development of breeding blanket technology must be done in small fusion power devices.**




## Two Issues In Building A DEMO:

**1 – Need Initial (startup) inventory of >10 Kg per DEMO**
**(How many DEMOS will the world build? And where will startup tritium come from?)**

**2 – Need Verified Breeding Blanket Technology to install on DEMO**

➢ **CONCLUSION: Building FNSF is NECESSARY to resolve these issues**

# Reliability/Availability/Maintainability/Inspectability (RAMI) is a Serious Issue for Fusion Development

**Availability required for each component needs to be high**

| Component | # | failure rate (1/hr) | MTBF (yrs) | MTTR/type Major (hrs) | MTTR/type Minor (hrs) | Fraction Failures Major | Outage Risk | Component Availability |
|---|---|---|---|---|---|---|---|---|
| Toroidal Coils | 16 | 5 x$10^{-6}$ | 23 | $10^{4}$ | 240 | 0.1 | 0.098 | 0.91 |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Magnet supplies | 4 | 1 x$10^{-4}$ | 1.14 | 72 | 10 | 0.1 | 0.007 | 0.99 |
| Cryogenics | 2 | 2 x$10^{-4}$ | 0.57 | 300 | 24 | 0.1 | 0.022 | 0.978 |
| **Blanket** | 100 | 1 x$10^{-5}$ | 11.4 | 800 | 100 | 0.05 | 0.135 | 0.881 |
| **Divertor** | 32 | 2 x$10^{-5}$ | 5.7 | 500 | 200 | 0.1 | 0.147 | 0.871 |
| Htg/CD | 4 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.884 |
| Fueling | 1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.998 |
| Tritium System | 1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.995 |
| Vacuum | 3 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 0.998 |
| Conventional equipment- instrumentation, cooling, turbines, electrical plant | | | | | | | [illegible] | 0.952 |
| TOTAL SYSTEM | (Due to unscheduled maintenances) | | | | | | 0.624 | 0.615 |

**Two key parameters:**
**MTBF – Mean time between failures**
**MTTR – Mean time to repair**

**DEMO availability of 50% requires:**
- **Blanket/Divertor Availability ~ 87%**
- **Blanket MTBF >11 years**
- **MTTR < 2 weeks**

**Extrapolation from other technologies shows expected MTBF for fusion blankets/divertor is as short as ~hours/days, and MTTR ~months**

# Summary of MAJOR Technical/Development Issues

## ❑ Achieving high availability is a challenge for Magnetic Fusion Concepts

- Device has many components
- Blanket/PFC are located inside the vacuum vessel
- Maintenance time is too long and must be shortened
- Reliability requirements unprecedented, need aggressive "reliability growth" program

## ❑ Tritium available for fusion development other than ITER is rapidly diminishing

- Any DT fusion development facility other than ITER must breed its own tritium, making the Breeding Blanket an Enabling Technology
- Where will the initial inventory for the world DEMOs (~ 10 kg per DEMO) come from? How many DEMOs in the world?
- **Each country aspiring to build a DEMO will most likely need to build its own FNSF** — not only to have verified breeding blanket technology, but also to generate the initial tritium inventory required for the startup of DEMO

## ❑ Achieving Tritium Self-Sufficiency in DT fusion systems imposes key requirements on Physics and Technology R&D:

- Tritium Burn-up fraction x fueling efficiency > 5%
- Tritium Processing time < 4 hours
- Practical breeding blanket with limited amount of structure, thin first wall, no significant neutron absorbers (e.g. no passive coils, etc), near full coverage

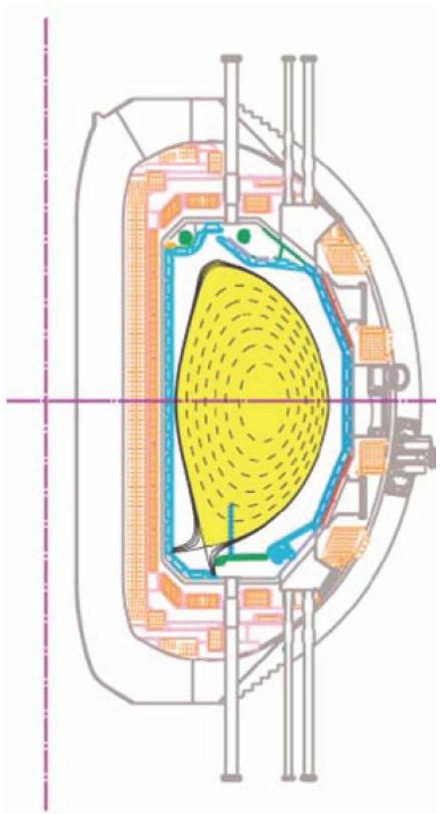
# Concluding Remarks

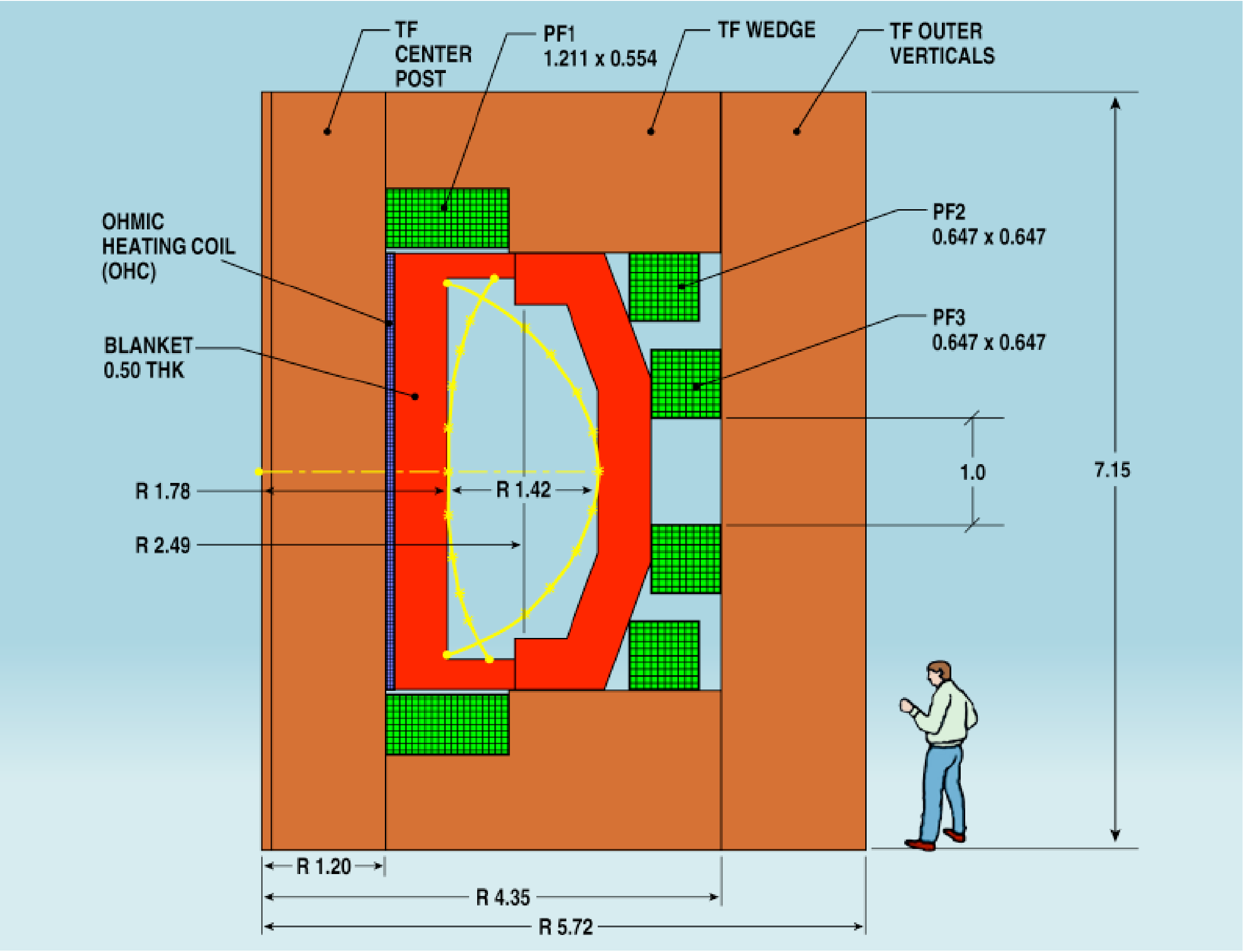
- ITER is a major step forward. (So is NIF)
- **But, the most challenging phase of fusion development still lies ahead. It is the development of Fusion Nuclear Science and Technology (FNST).**
  - **FNST development will be the "time-controlling step" for fusion entry into the energy market.**
- **There has been substantial progress on understanding and resolving many FNST technical issues.** But there are critical issues for which there has been little or no progress because: 1- these issues represent major scientific and engineering challenges, and 2- the resources available for FNST R&D have been seriously limited.
- **The World Fusion Program must immediately launch an aggressive FNST R&D program if fusion energy is to be realized in the 21st century. An effective FNST Program must include:**
  - **Fundamental and integrated modeling of important phenomena and multiple synergistic effects.**
  - **Experiments in new and existing non-fusion facilities.**
  - **TBM in ITER accompanied by both research and development programs.**
  - **A Fusion Nuclear Science Facility (FNSF) dedicated to FNST. FNSF is a small size, small power, DT, driven-plasma device.**

# BACKUP SLIDES

# Example of Fusion Nuclear Science Facility (FNSF) Design Option: Standard Aspect Ratio with demountable TF Cu coils (Stambaugh et al, GA design)

**A~ 3.5** $P_{fusion}$ 125 MW at $P_{NW}$ of 1 MW/m$^2$






- 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)**