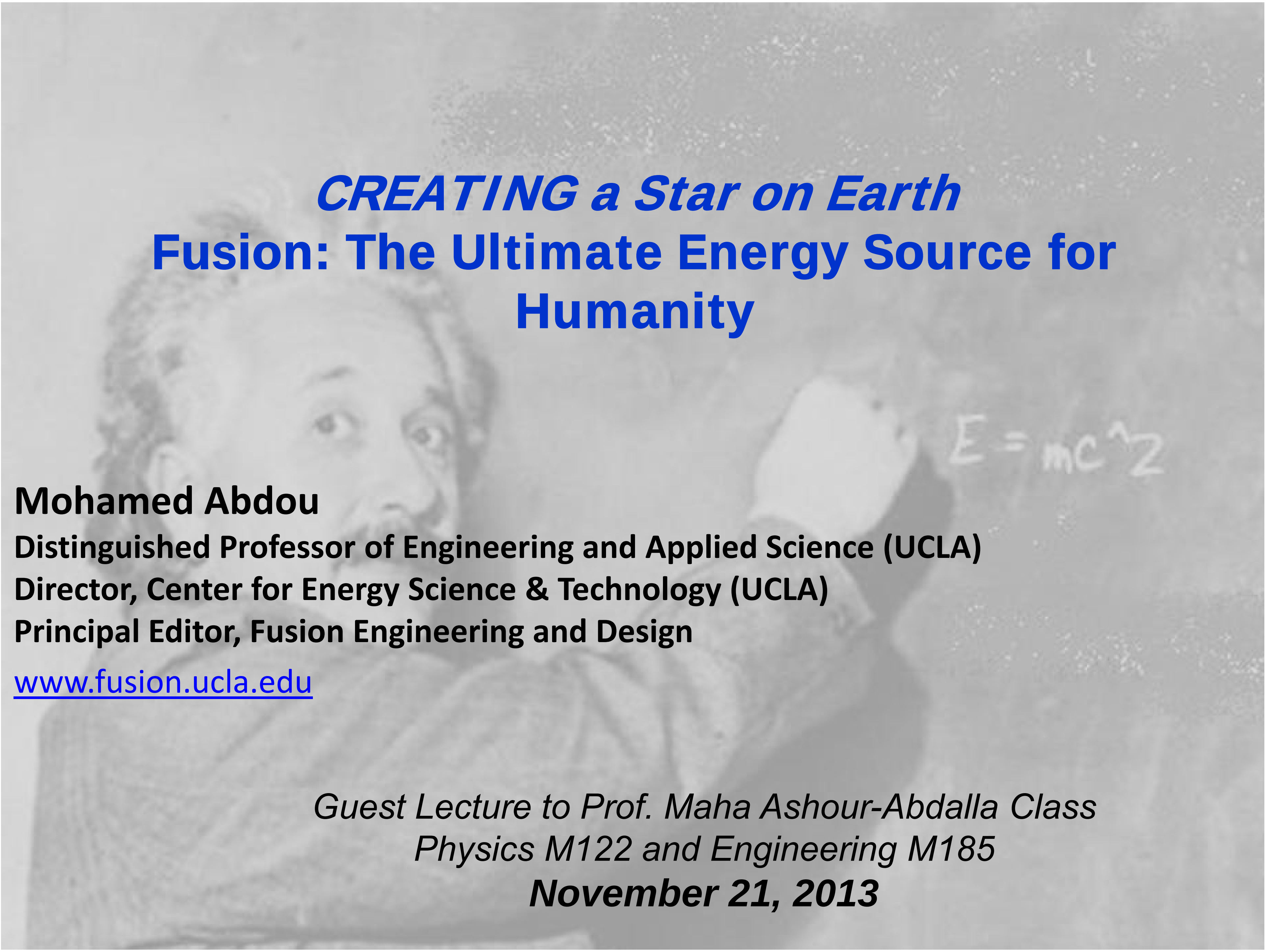

CREATING a Star on Earth
Fusion: The Ultimate Energy Source for Humanity

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Guest Lecture to Prof. Maha Ashour-Abdalla Class

Physics M122 and Engineering M185

November 21, 2013

CREATING a Star on Earth
Fusion: The Ultimate Energy Source for Humanity

Outline

1. What is fusion? And Why do we need it?

Principles of fusion

World Energy Situation and Impact on the Environment

2. Approaches to Fusion and DEMO Goal

3. ITER – International Fusion Project

4. Fusion Nuclear Science and Technology (FNST)

Introduction to FNST and fusion nuclear components

5. Closing Remarks

What is nuclear fusion?

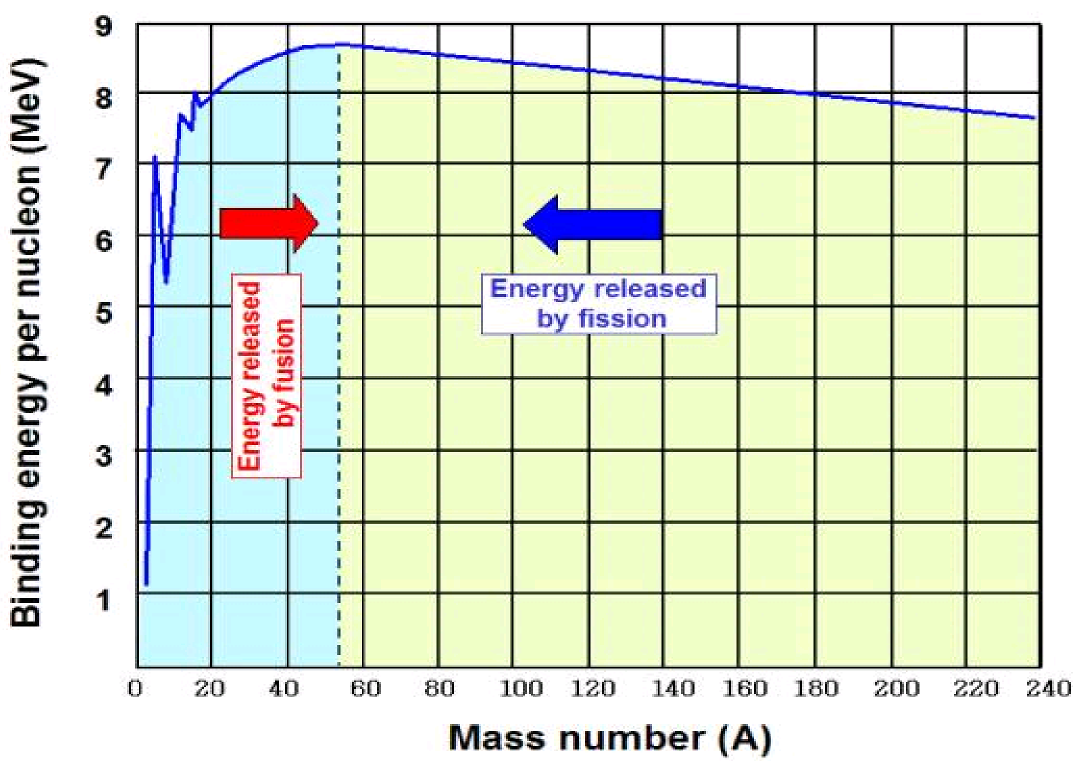
- Two light nuclei combining to form a heavier nuclei, converting mass to energy
  - the opposite of nuclear fission where heavy nuclei are split apart

- In nuclear (fission and fusion), mass is converted to energy , Einstein's famous Eq.

  $E = mC^2$

  Small mass → Huge energy

- In contrast to fossil fuels (oil, gas, coal) where chemical energy is stored, and huge mass needed to "store" energy



Nuclear Fusion is the energy-producing process taking place in the core of the sun and stars

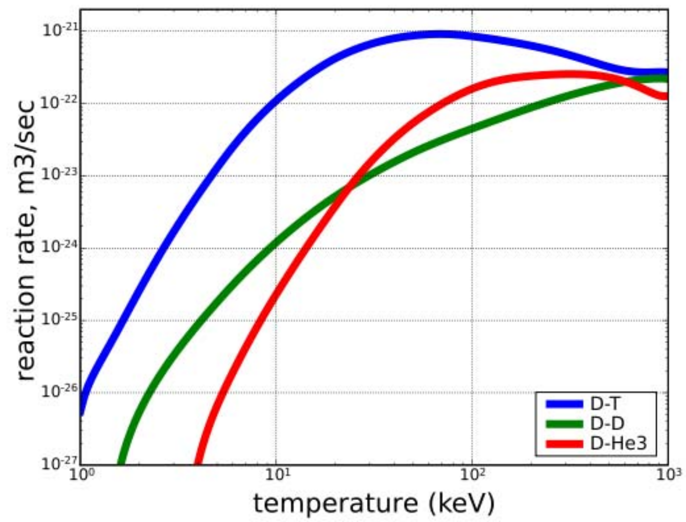
- The core temperature of the ***Sun*** is about 15 million °C. At these temperatures, ***hydrogen*** nuclei fuse to give ***Helium and Energy*****.** The energy sustains life on Earth via sunlight.

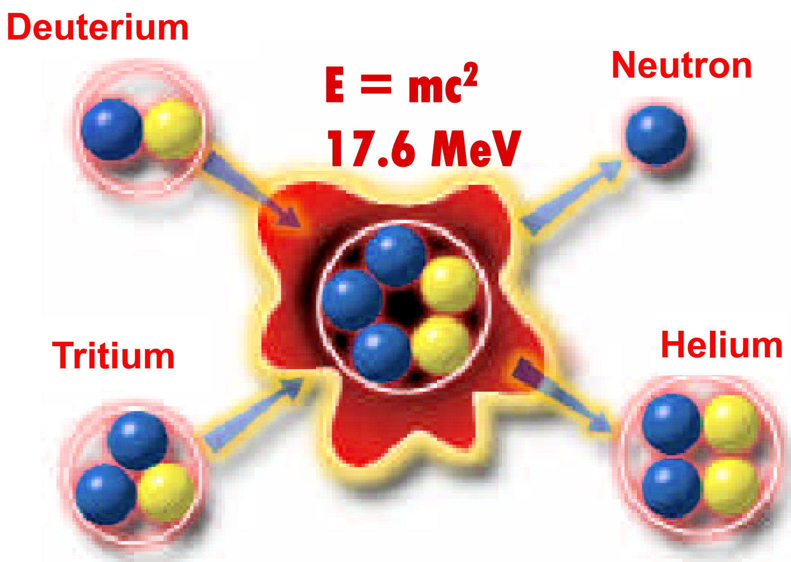
Fusion research is akin to *"creating a star on earth".*

A number of fusion reactions are possible based on the choice of the light nuclides

The World Program is focused on the
Deuterium (D) - Tritium (T) Cycle

- **D-T Cycle is the easiest to achieve: attainable at lower plasma temperature because it has the largest reaction rate and high Q value.**





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)

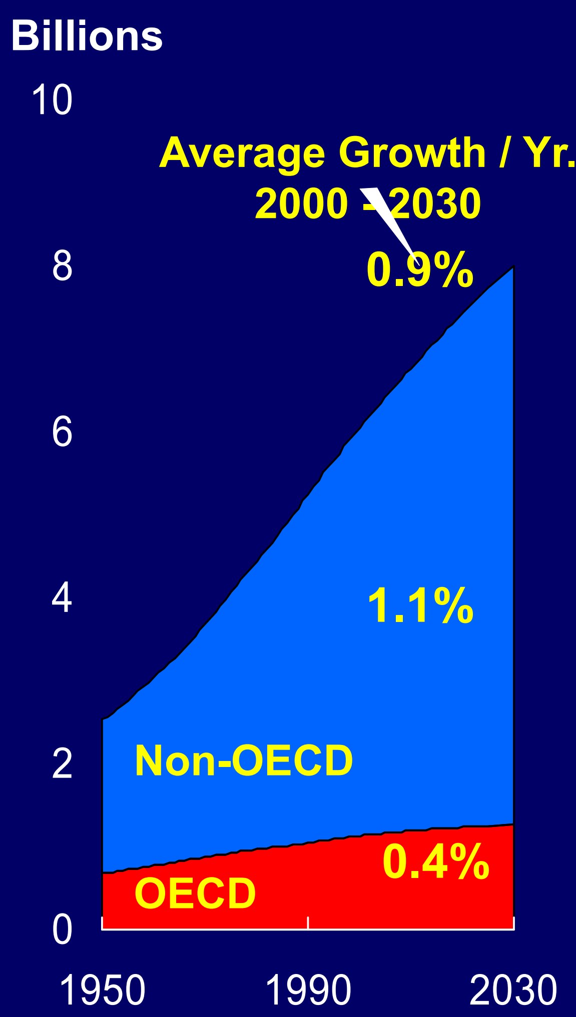
Incentives for Developing Fusion

- 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

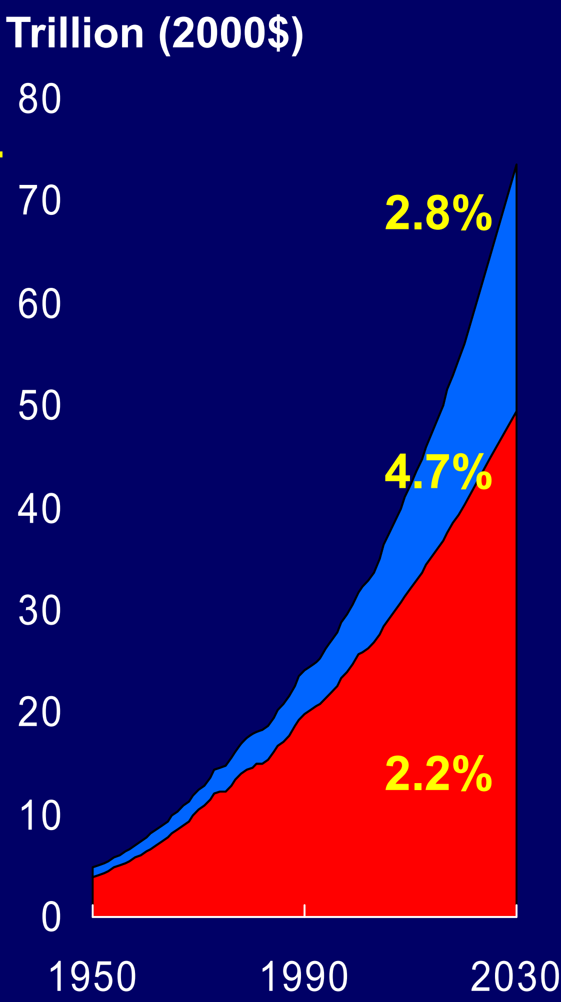
Fusion energy can be used to produce electricity and hydrogen, and for desalination.

Global Economics and Energy

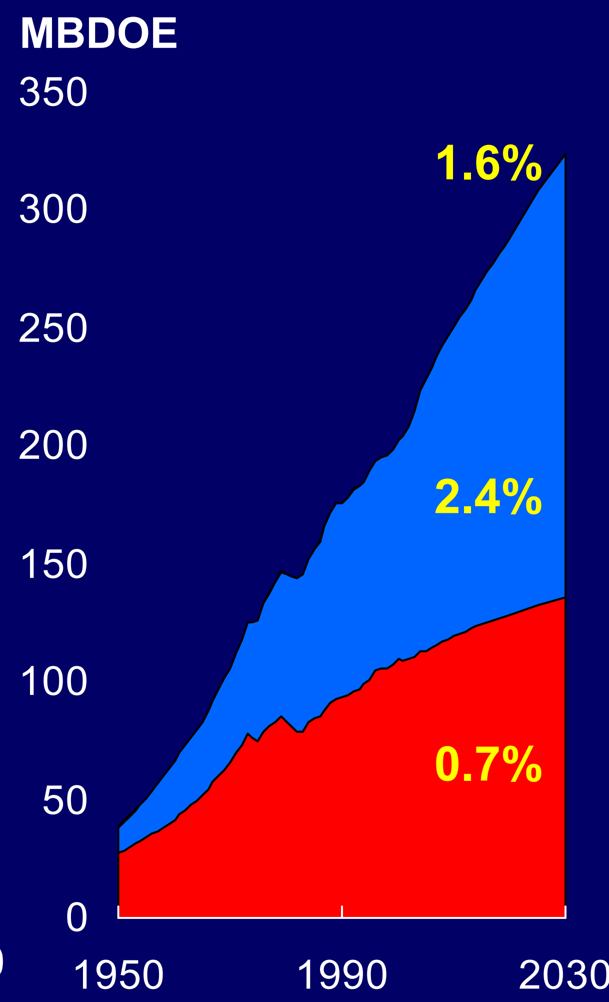
Population



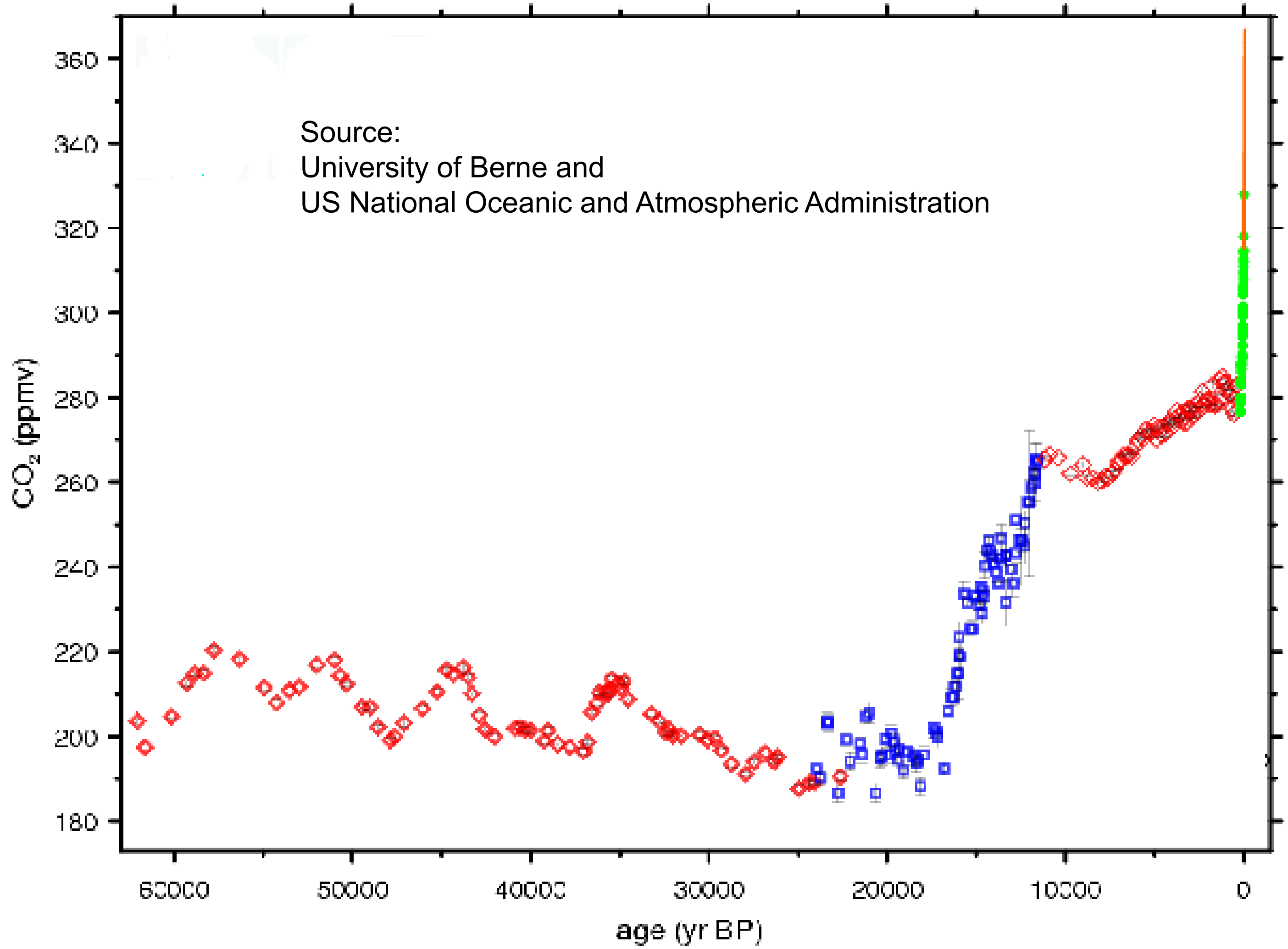
GDP



Energy Demand



Carbon dioxide levels over the last 60,000 years – we are provoking the atmosphere!



Energy Situation

- **The world uses a lot of energy**
  – Average power consumption = 13.6 TW (2.2 KW per person)
  – World energy market ~ $3 trillion / yr (electricity ~ $1 trillion / yr)

- **The world energy use is growing**
  – To lift people out of poverty, to improve standard of living, and to meet population growth

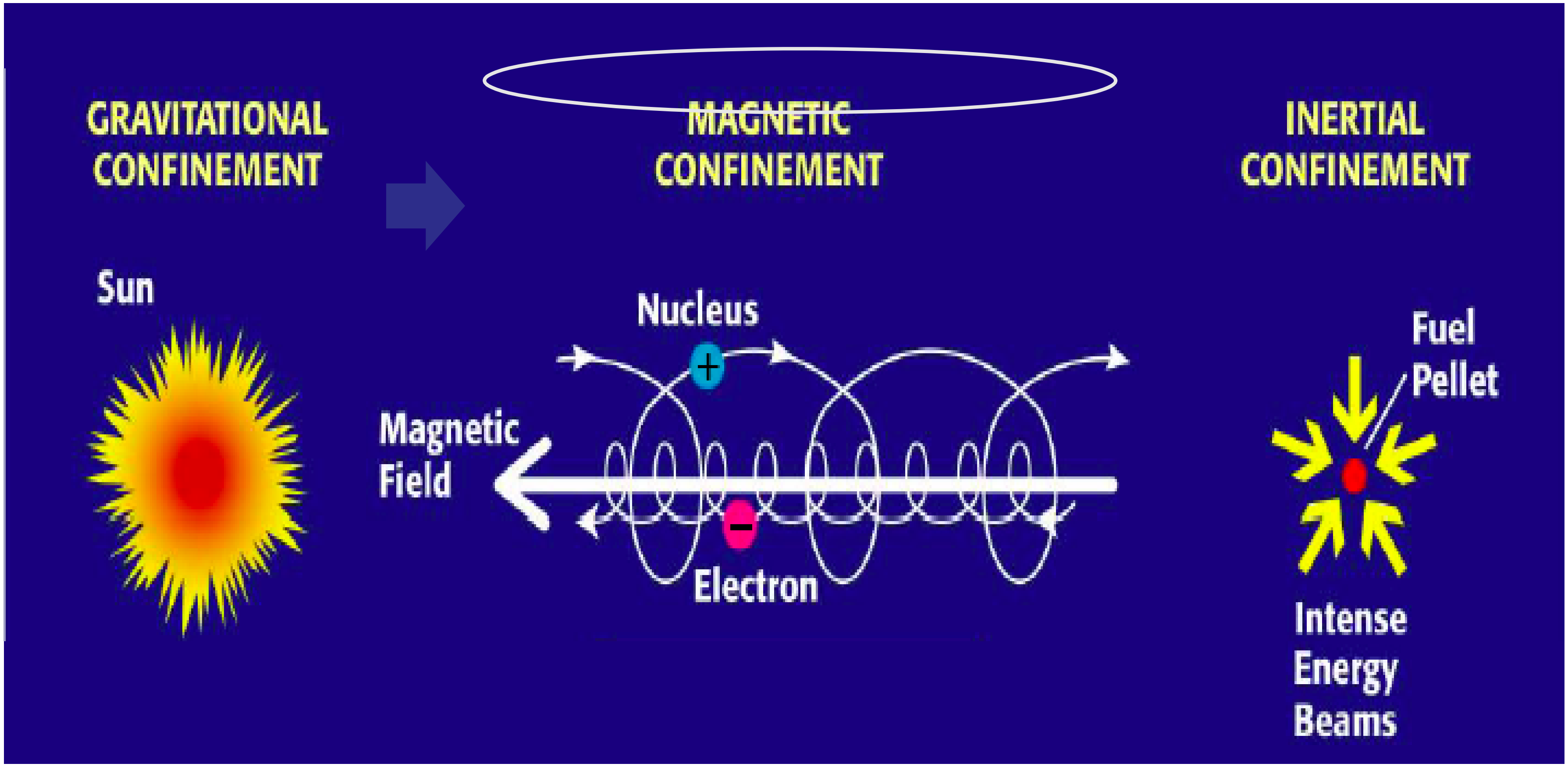
- **Climate change and debilitating pollution Concerns are on the rise**
  – 80% of energy is generated by fossil fuels
  – CO_2 emission is increasing at an alarming rate

- **Oil supplies are dwindling**
  – Special problem for transportation sector (need alternative fuel)

Solving the Energy Problem Requires a Diversified Portfolio and Pursuing Several Approaches

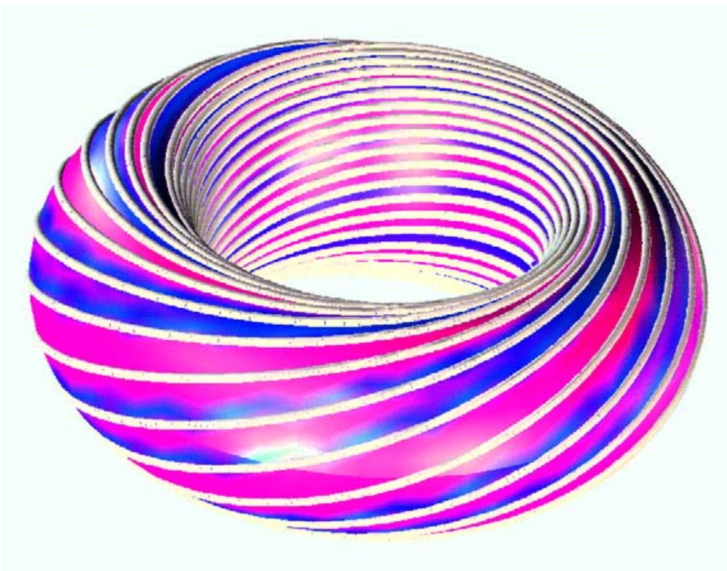
- **Develop major new (clean) energy sources (e.g. fusion)**
- **Expand use of existing “clean” energy sources (e.g. nuclear, solar, wind)**
- **Develop technologies to reduce impact of fossil fuels use (e.g. carbon capture and sequestration)**
- **Improve energy efficiency**
- **Develop alternate (synthetic) fuels and Electrical Energy Storage for transportation**

There are several ways to create a self-sustaining fusion plasma

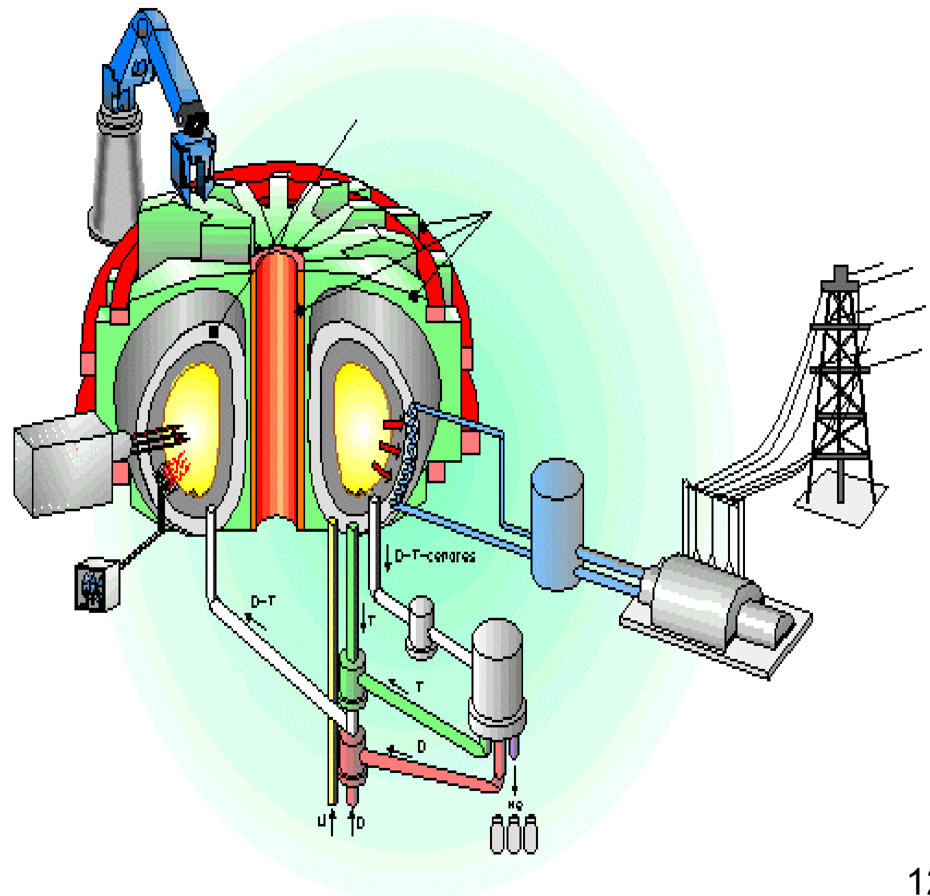


- $m \cdot dv/dt = F_{Lorentz} = q \cdot (v \times B)$ ➡ cyclotron motion with Larmour radius $r_L = mv_{\perp}/|q|B$

Toroidal Magnetic Confinement

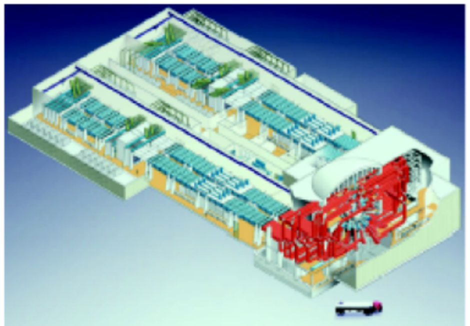


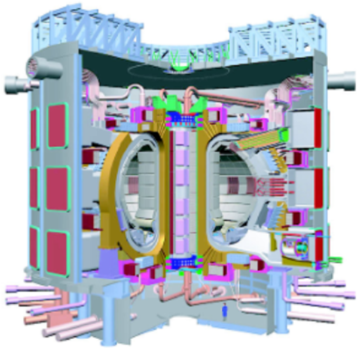
High-density, high-temperature "thermonuclear" plasmas must be confined long enough for fusion reactions to occur (sufficient reaction rate).



Net energy gain (high Q), enables a power conversion cycle

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

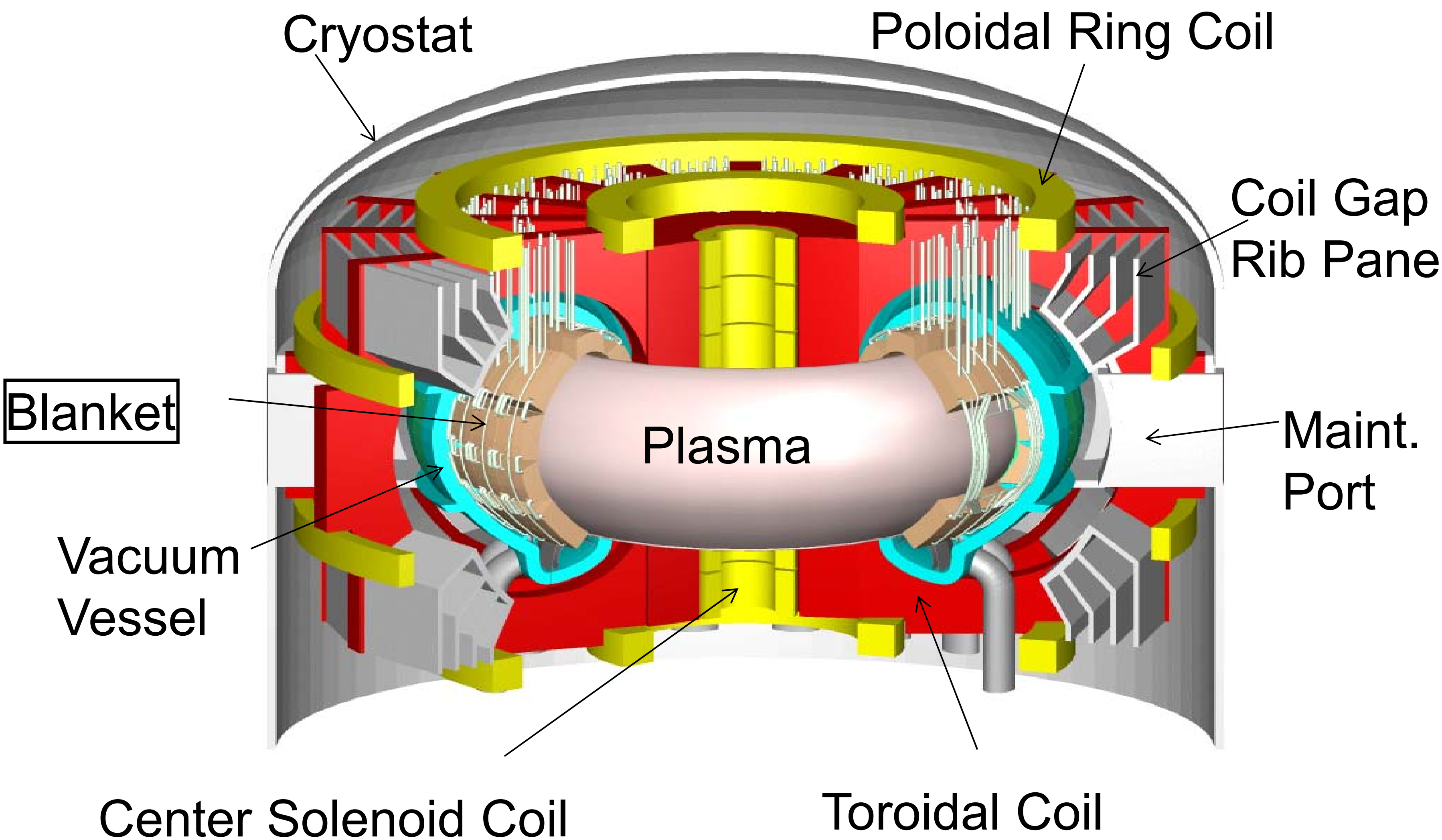

National Ignition Facility


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 (magnetic fusion) and NIF (inertial fusion)**
- **2010-2040 ?**
  - **Fusion Nuclear Science and Technology for Fusion**
- **> 2050 ?**
  - **DEMO by 2050?**
  - **Large scale deployment > 2050!**

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 ~2020. **First D-T Burning Plasma in ITER in ~ 2027.**

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

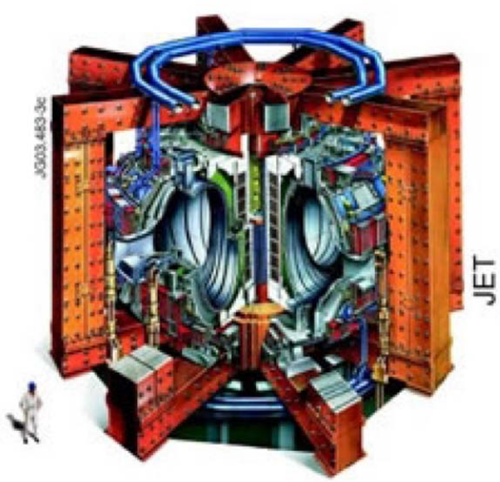
- Will use D-T and produce neutrons
- 500MW fusion power, Q=10
- Burn times of 400s
- Reactor scale dimensions
- Actively cooled PFCs
- Superconducting magnets

<u>By Comparison</u>

JET

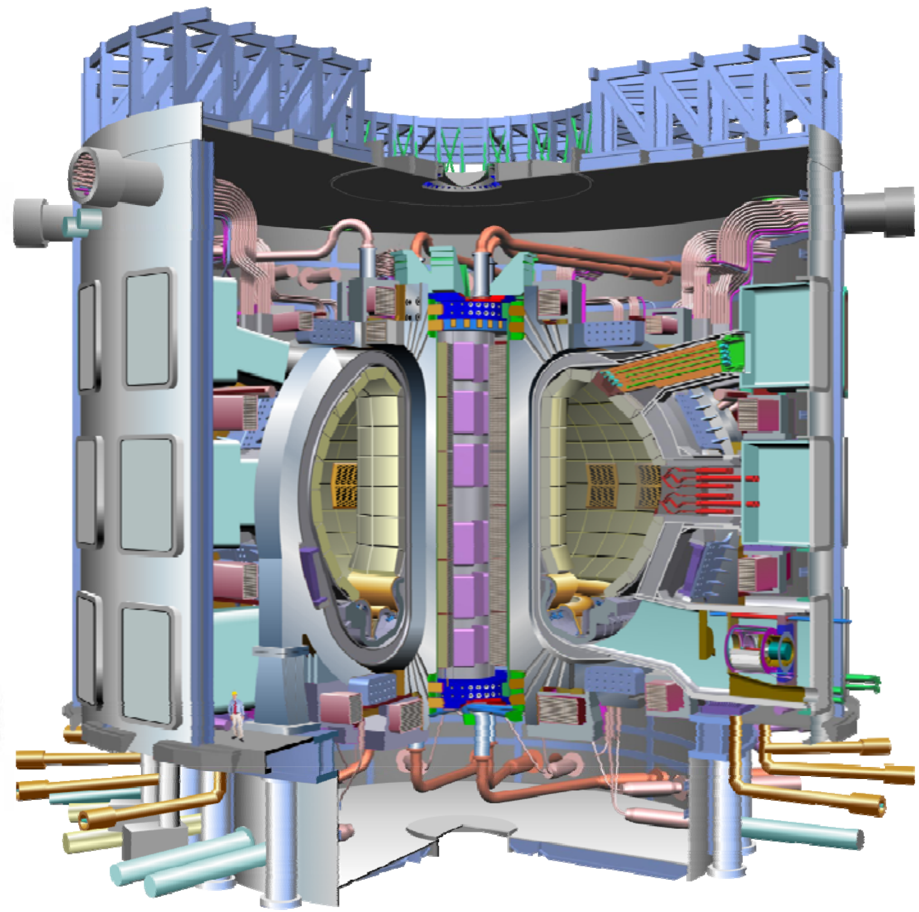
- ~10 MW
- ~1 sec
- Passively Cooled

~15 m



JET

~29 m



ITER

New Long-Pulse Confinement and Other Facilities Worldwide will Complement ITER

China

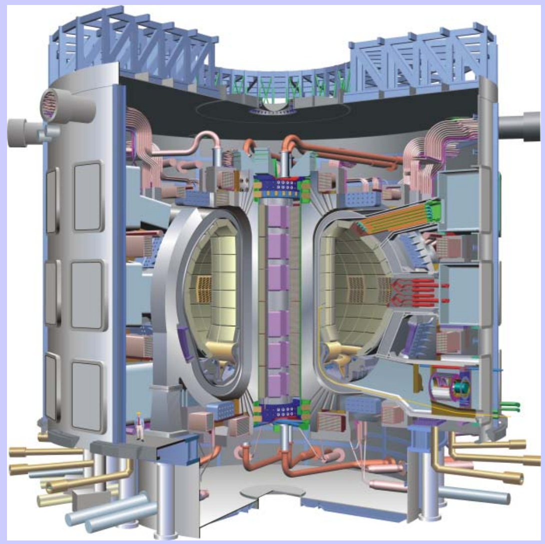
EAST

Europe

W7-X (also JT-60SA)

India

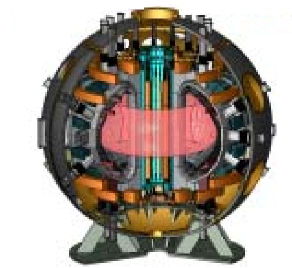
SST-1



ITER Operations:

34%	Europe
13%	Japan
13%	U.S.
10%	China
10%	India
10%	Russia
10%	S. Korea

Japan (w/EU)



JT-60SA (also LHD)

South Korea

KSTAR

U.S.

Being planned
Fusion Nuclear Science &Technology Testing Facility (FNSF/CTF/VNS)

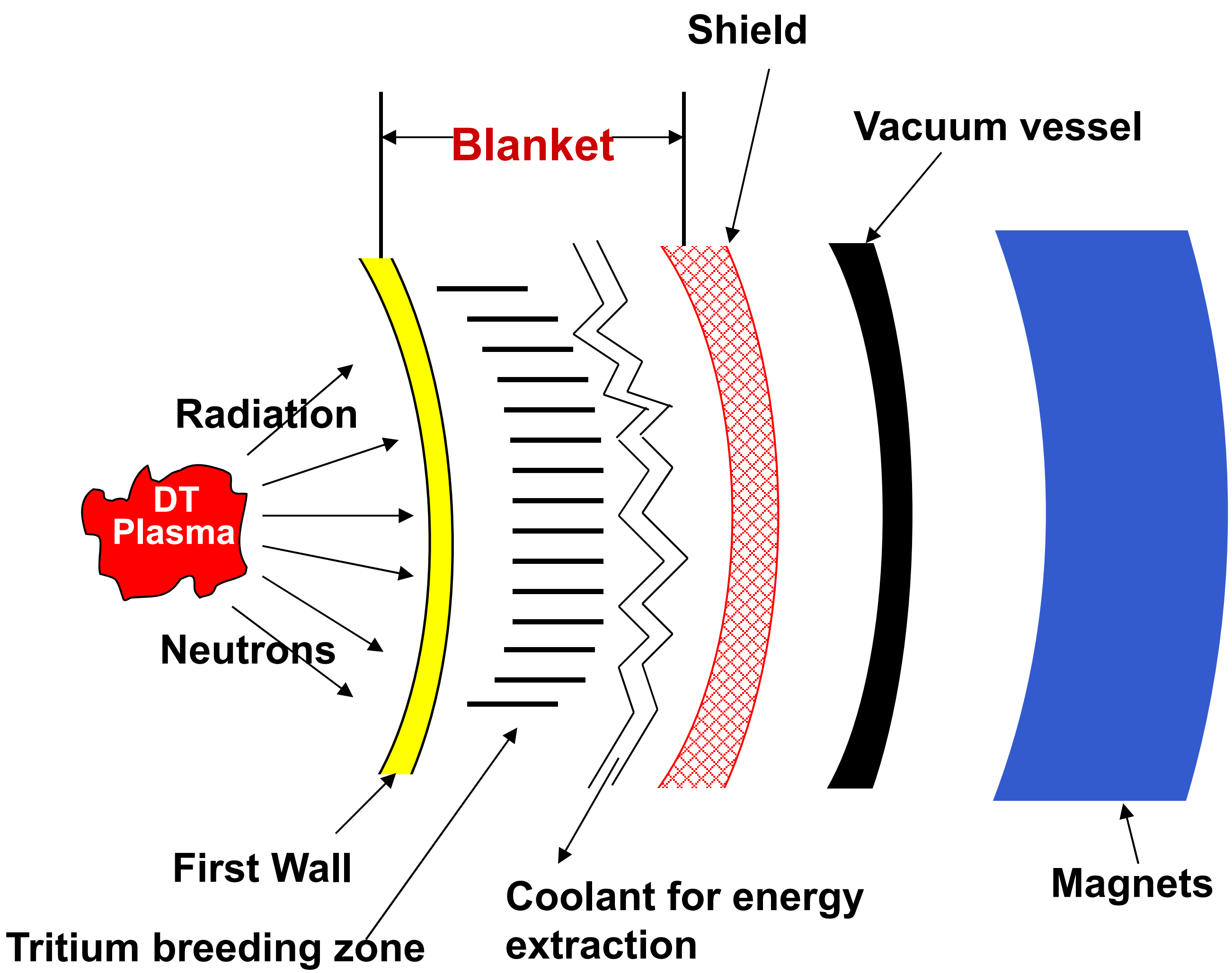
The Deuterium-Tritium (D-T) Cycle

- World Program is focused on the D-T cycle:

$$D + T \rightarrow n + \alpha + 17.58 \text{ MeV}$$

- The fusion energy (17.58 MeV per reaction) appears as kinetic energy of neutrons (14.06 MeV) and alphas (3.52 MeV)
- Tritium does not exist in nature! Decay half-life is 12.3 years
  - Tritium must be generated inside the fusion system to have a sustainable fuel cycle
  - The only possibility to adequately breed tritium is through neutron interactions with lithium. Lithium, in some form, must be used in the fusion system.
- α particles will slow down in the plasma imparting their energy to D and T and keep the plasma heated.
  - *But this "He ash" must be removed from the plasma, eg. via "Divertor"*

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.

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

Helium "ash" from the fusion reaction

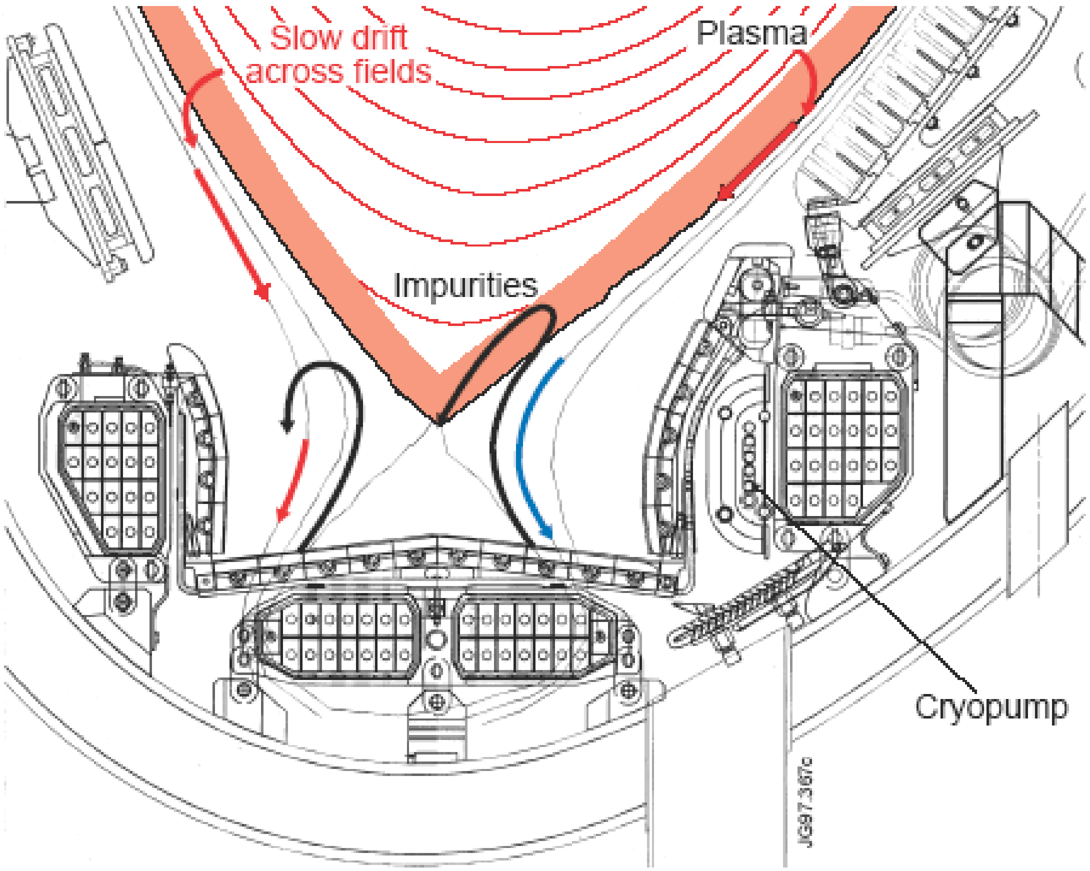
Material impurities from ***plasma-wall interactions***

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.



Fusion Nuclear Science and Technology (FNST)

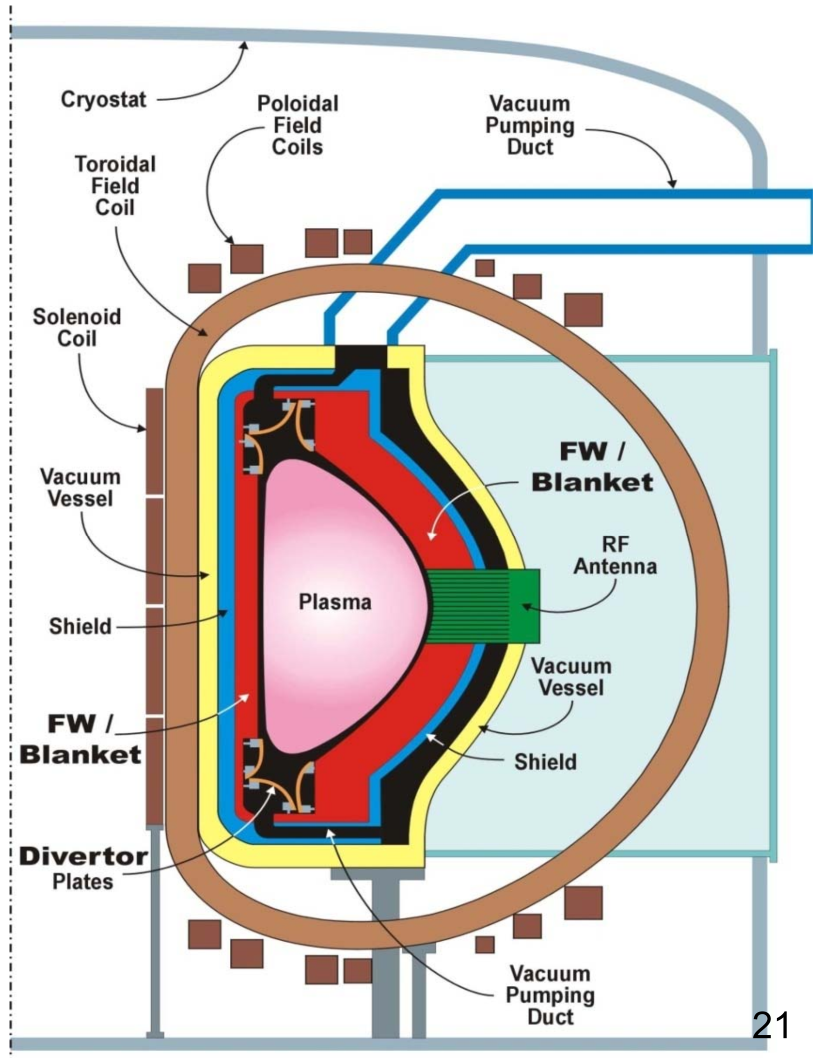
FNST is the **science**, **engineering**, **technology** and **materials** for the fusion nuclear components that generate, control and utilize neutrons, energetic particles & tritium.

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

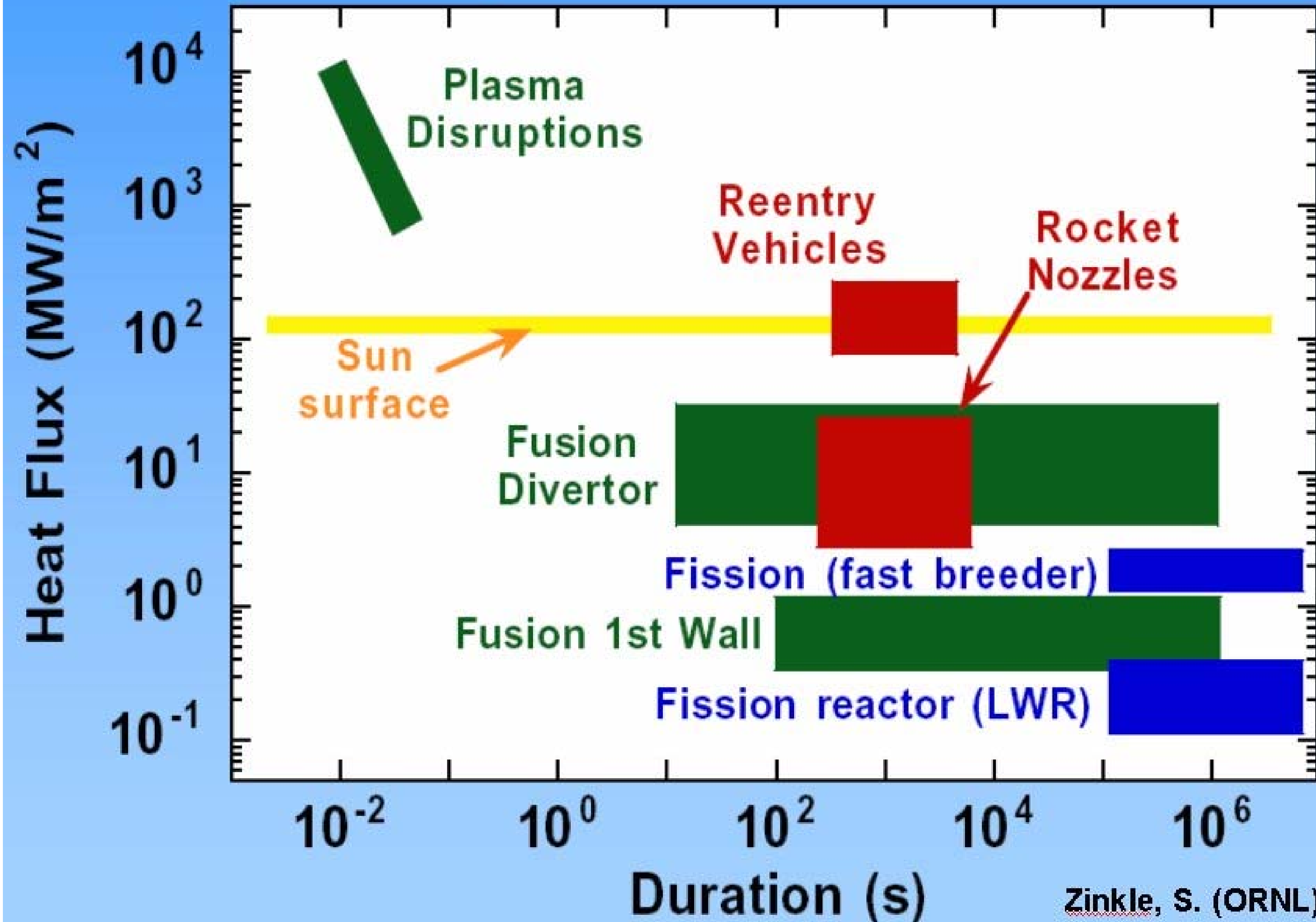


FNST research requires advancing the state-of-the-art, and developing highly integrated predictive capabilities for many cross-cutting scientific and engineering disciplines

- 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

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

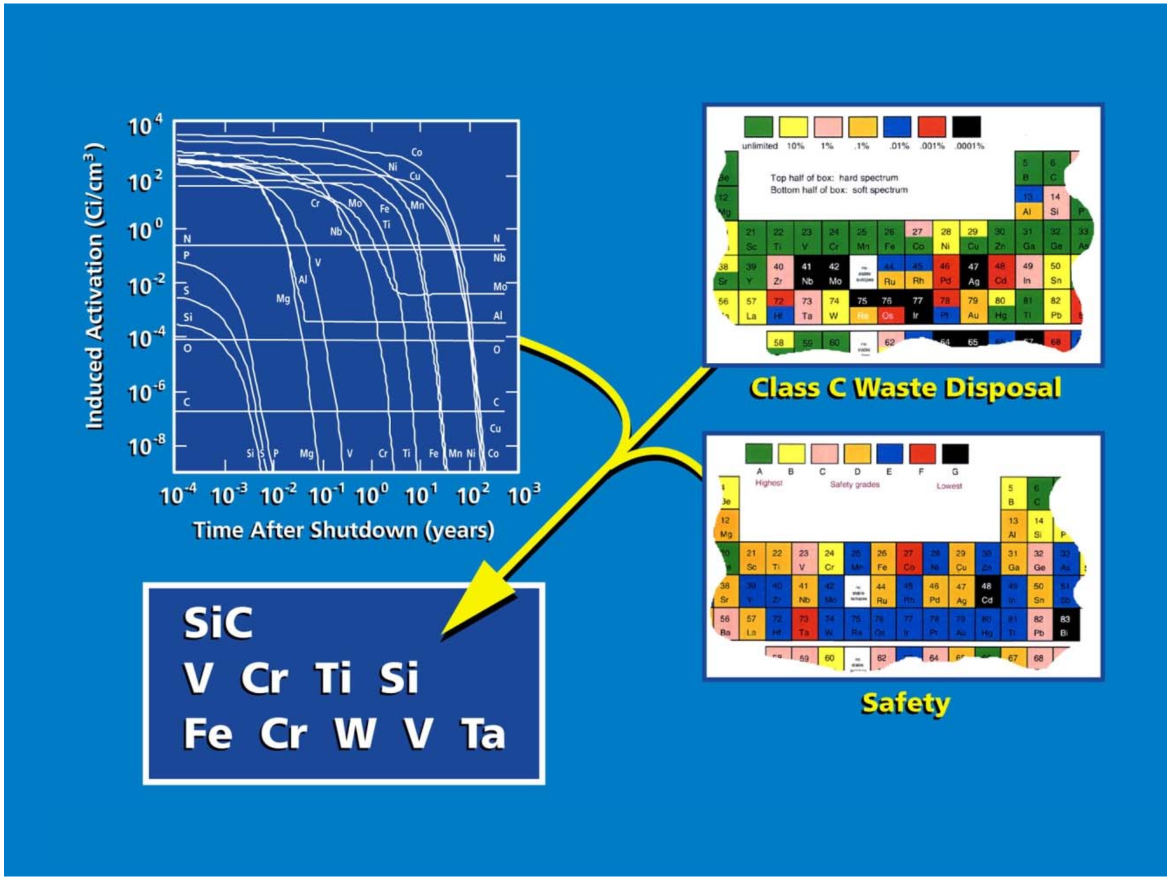
Comparison of Heat Fluxes



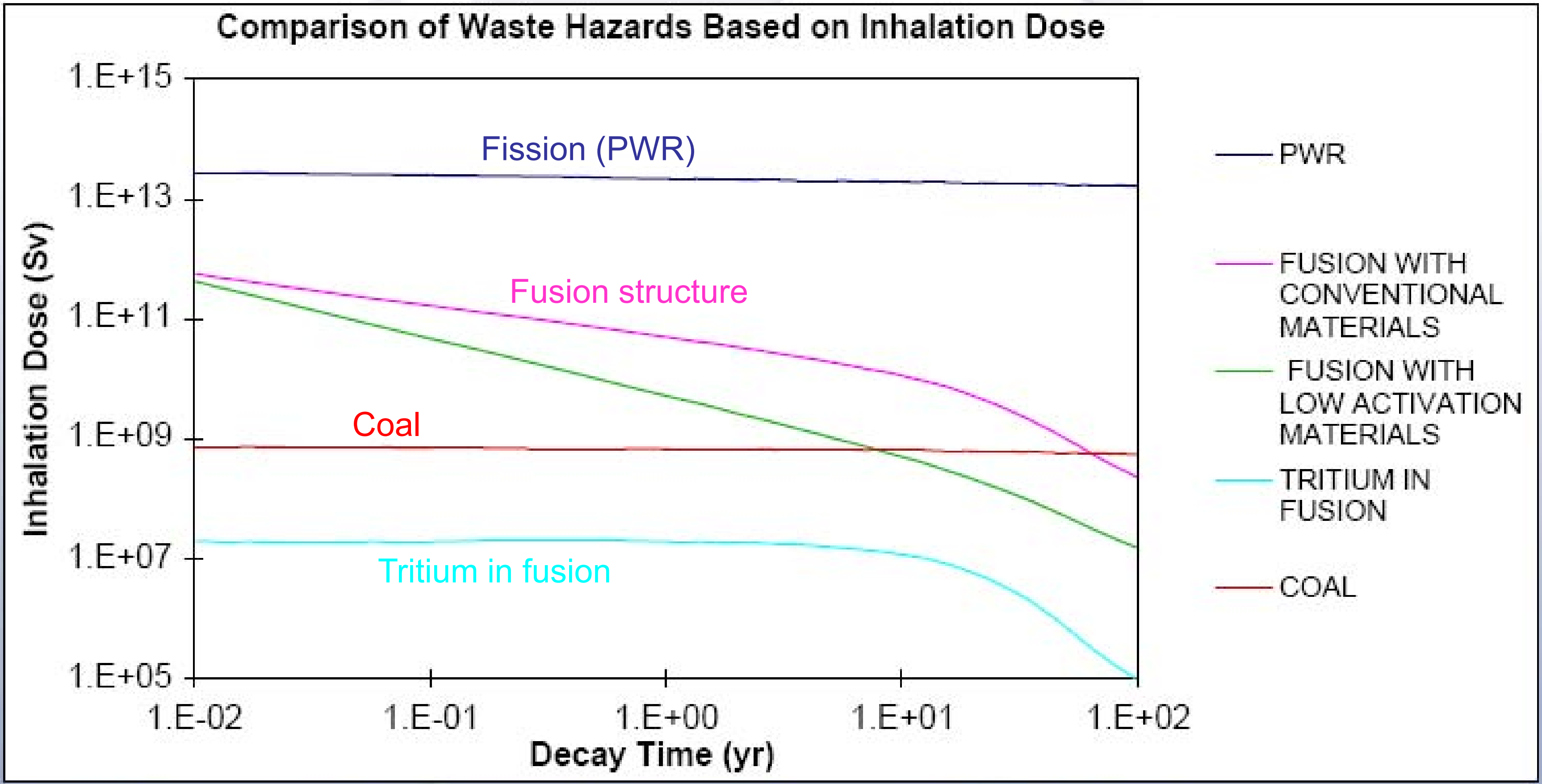
Zinkle, S. (ORNL)

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:
  - RAFM 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

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)
- Coolant: Helium or Water

B. Liquid Breeder Concepts

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

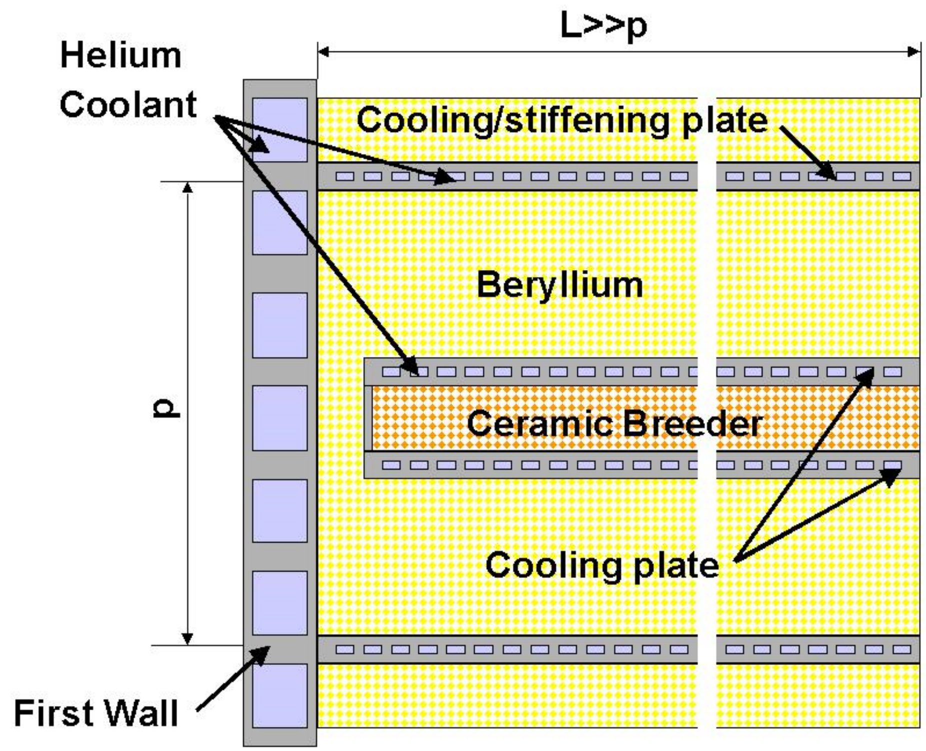
All these concepts have their own feasibility & attractiveness issues.

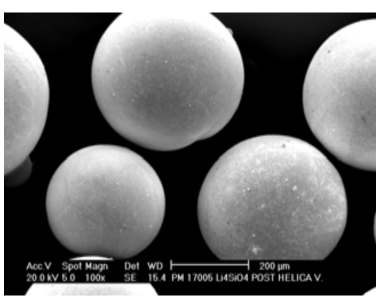
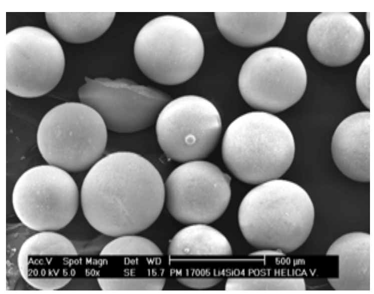
Liquid metal concepts are potentially more attractive, but feasibility issues arise because of interactions with the magnetic field.

Solid breeder blankets utilize immobile lithium ceramic breeder and Be multiplier

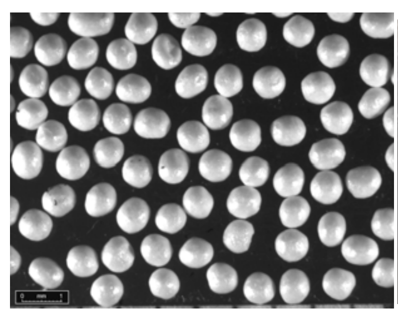
Material Functions

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

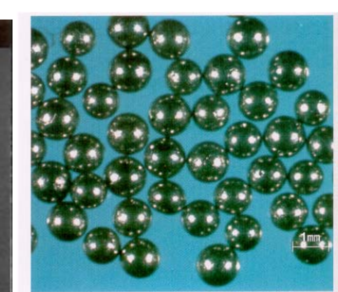


0.2- 0.4 mm Li_4SiO_4 pebbles (FZK)




0.6 – 0.8 mm Li_2TiO_3 pebbles (CEA)



NGK Be-pebble

Challenging
Fusion Nuclear Science & Technology Issues

1. Tritium Supply &
   Tritium Self-Sufficiency
2. High Power Density
3. High Temperature
4. MHD for Liquid Breeders / Coolants
5. Tritium Control (Extraction and Permeation)
6. Reliability / Maintainability / Availability
7. Testing in Fusion Facilities

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:

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

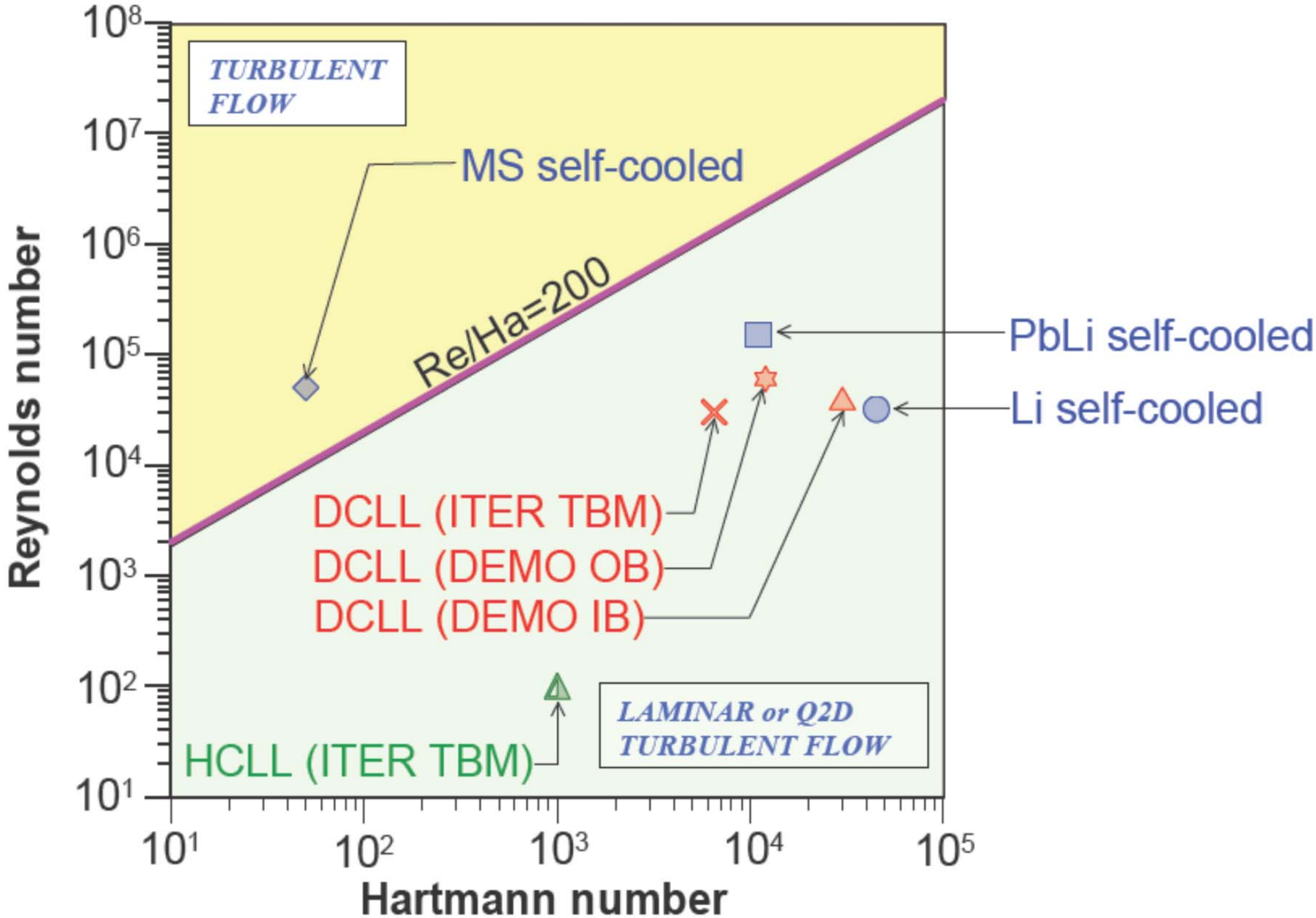
- Any induced current in the liquid results in an additional body force in the liquid that usually opposes the motion. This body force must be included in the Navier-Stokes equation of motion:

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

- 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

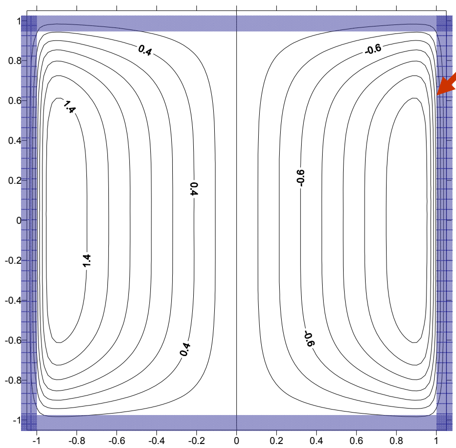
MHD Characteristics of Fusion Liquid Breeder Blanket Systems



Self-Cooled liquid metal blankets are NOT feasible now because of MHD Pressure Drop

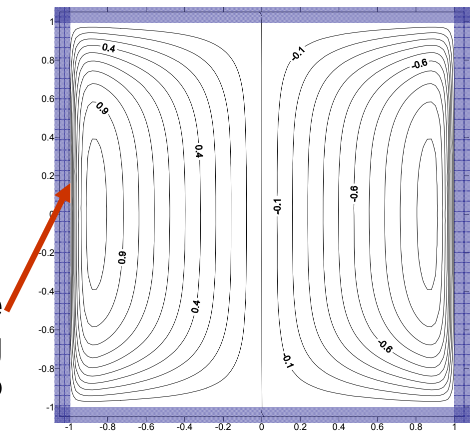
A perfectly insulated “WALL” can solve the problem, but is it practical?

Conducting walls



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

Insulated walls



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

- 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 ($\sim 10^{-7}$).
  - 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

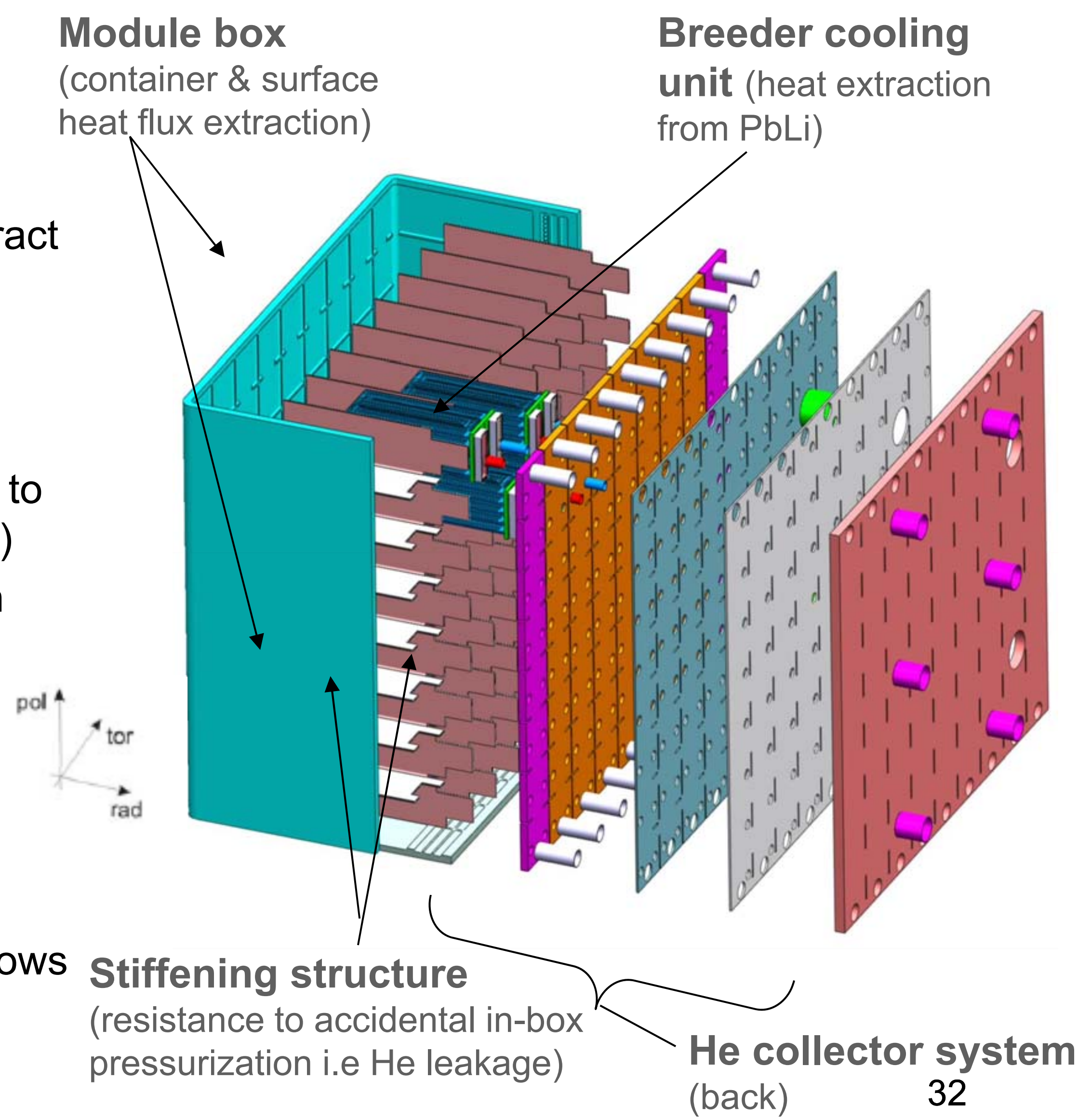
Example: PbLi Breeder/ helium Coolant with RAFM

- 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



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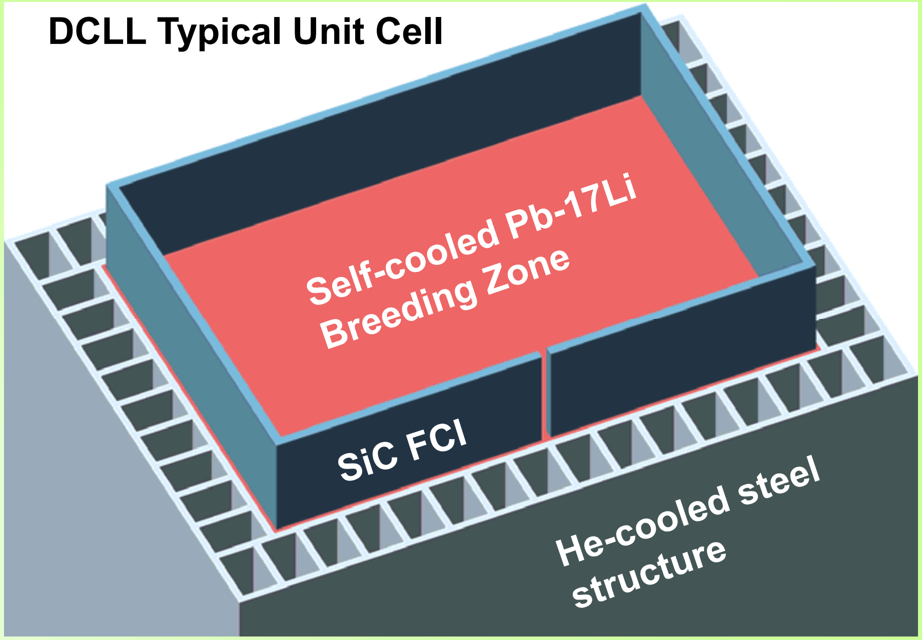
Pathway Toward Higher Temperature through Innovative Designs with Current Structural Material (Ferritic Steel): *Dual Coolant Lead-Lithium (DCLL) FW/Blanket Concept*

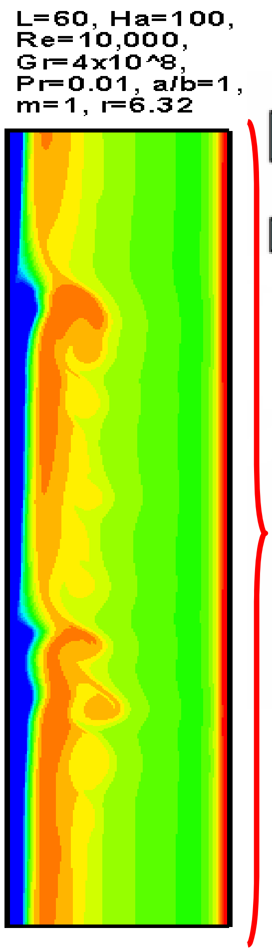
- **First wall and ferritic steel structure cooled with helium**
- **Breeding zone is self-cooled**
- **Structure and Breeding zone are separated by SiCf/SiC composite *flow channel inserts (FCIs)* that:**
  - **Provide thermal insulation to decouple PbLi bulk flow temperature from ferritic steel wall**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

FCI does not serve structural function

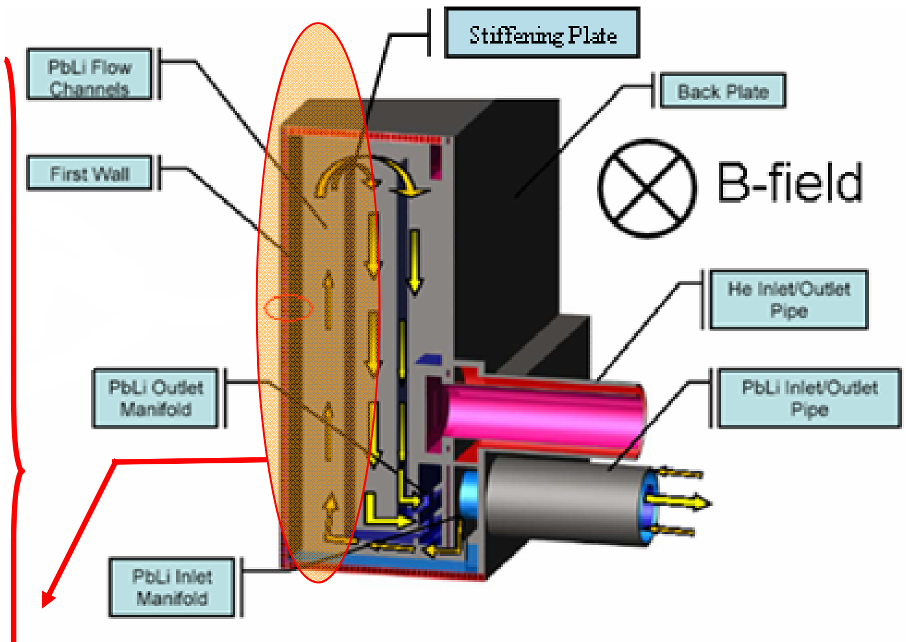


Pb-17Li exit temperature can be significantly higher than the operating temperature of the steel structure ⇒ High Efficiency

Buoyancy effects in DCLL blanket



DCLL DEMO blanket, US



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

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

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

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

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

Summary

- Fusion is the most promising long-term energy option
  - renewable fuel
  - no emission of greenhouse gases
  - inherent safety
- 7 nations started construction of **ITER** to demonstrate the scientific and technological feasibility of fusion energy
  - ITER will have first DT plasma in ~2026
  - ITER is the largest scientific/engineering project in the world
- **Fusion research has made considerable progress**
  - **But significant challenges remain ahead for fusion energy development and demonstration**
  - **Fusion research offers exciting opportunities for the next generation of bright young scientists and engineers**