Technological Challenges for Realizing Fusion Energy

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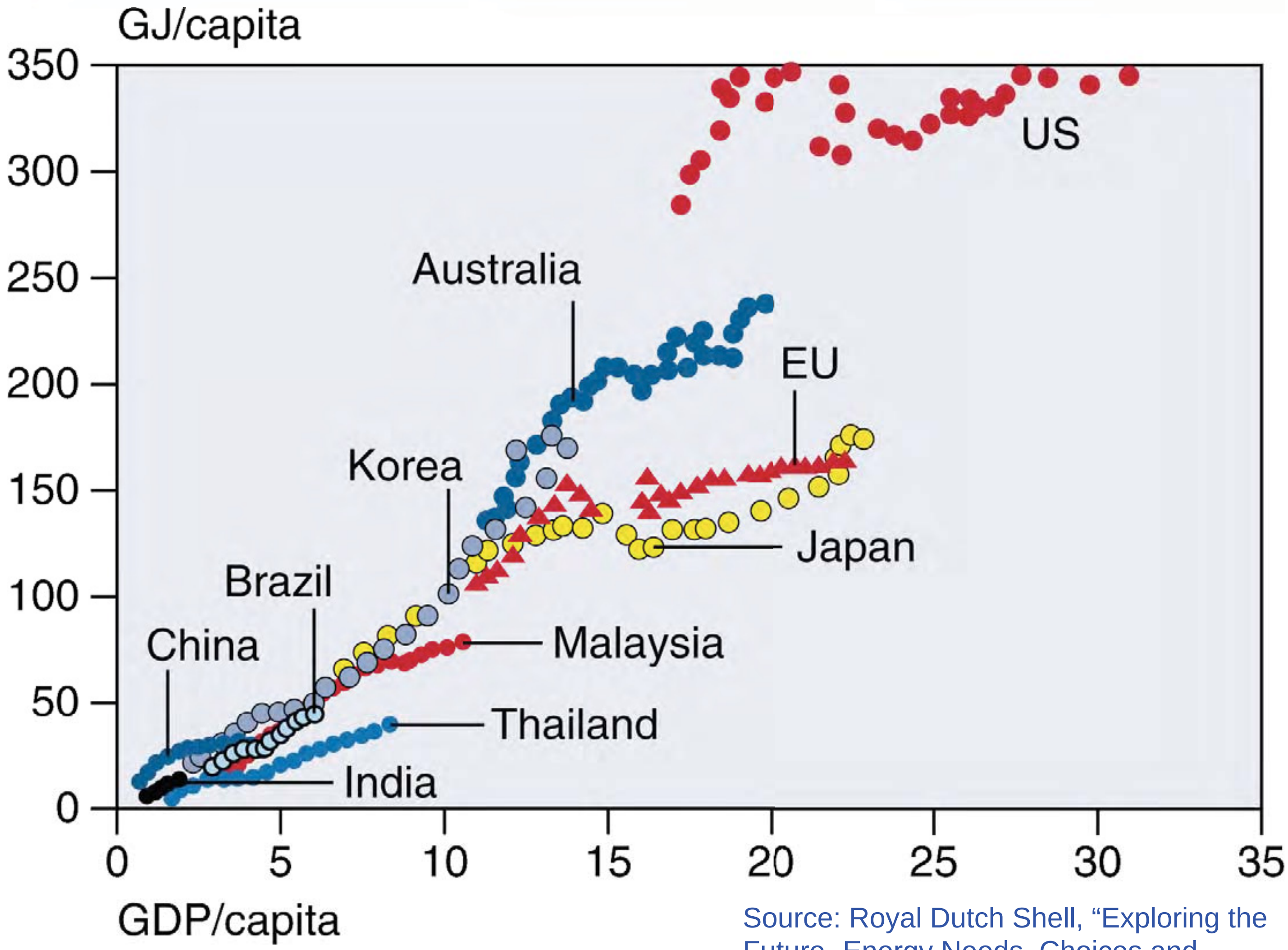
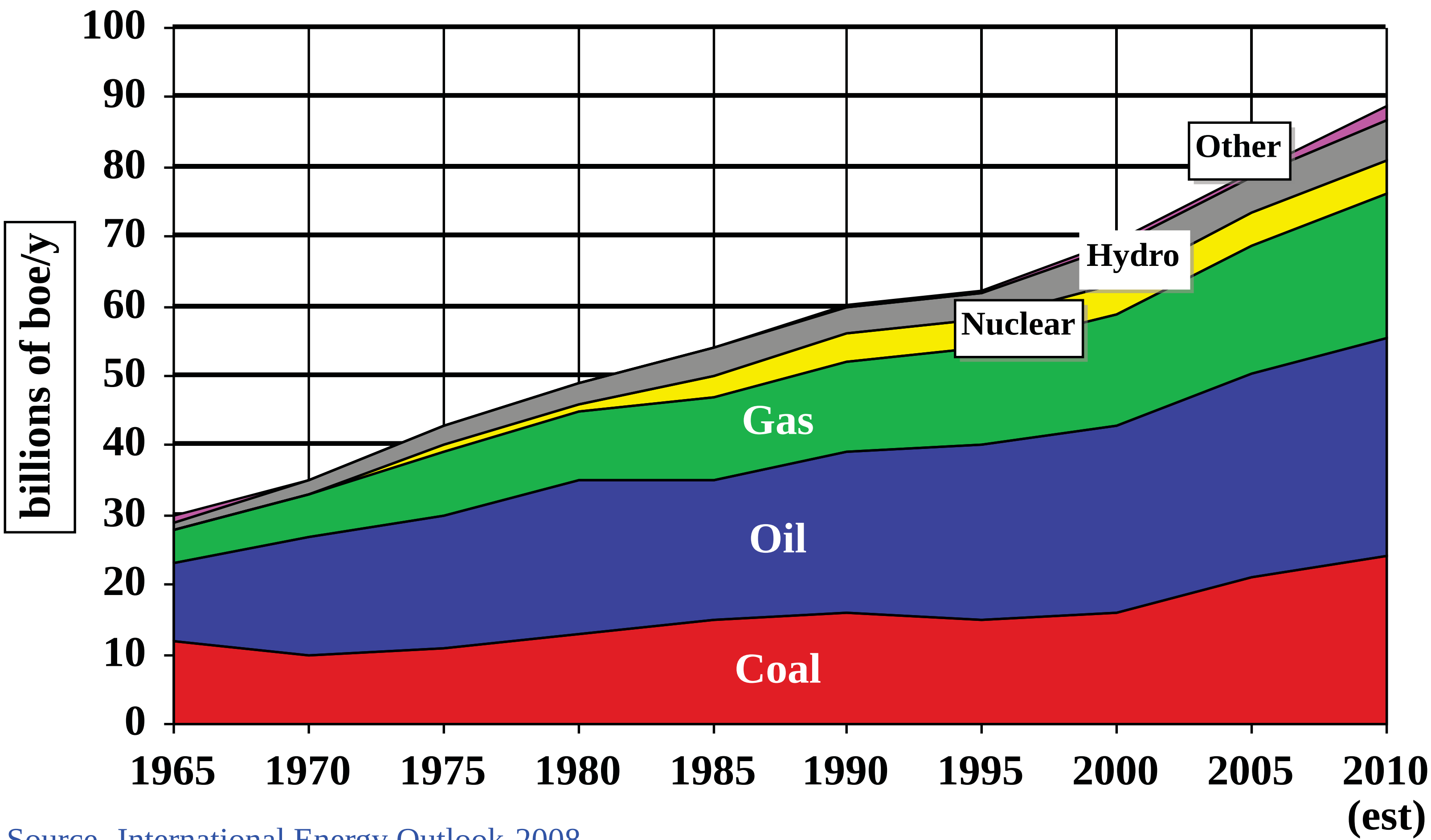
Energy is Fuel of Prosperity



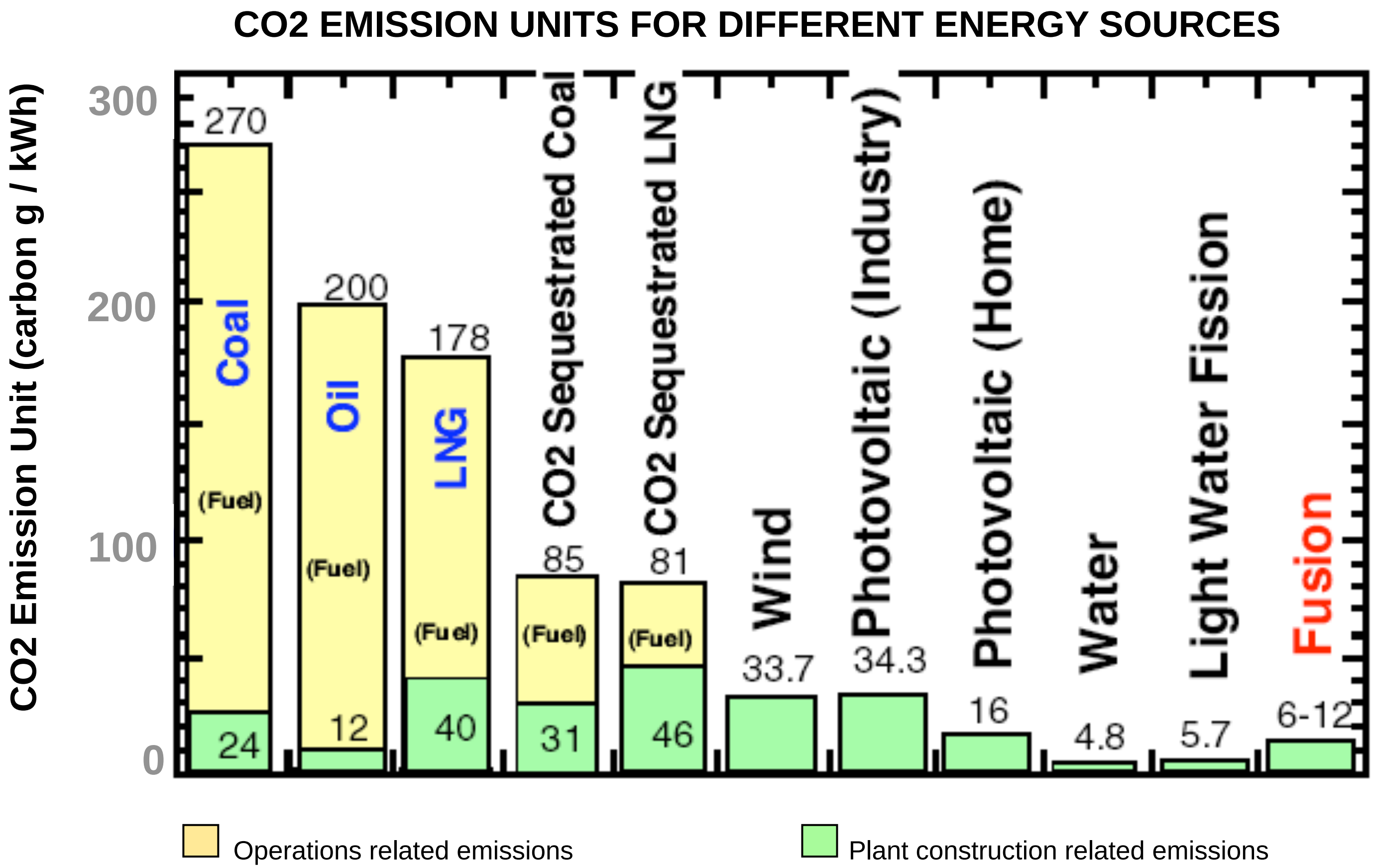
Source: Royal Dutch Shell, “Exploring the Future- Energy Needs, Choices and Possibilities”

Fossil Fuels Still Account for Over 85% of the Primary Energy Consumed in the World

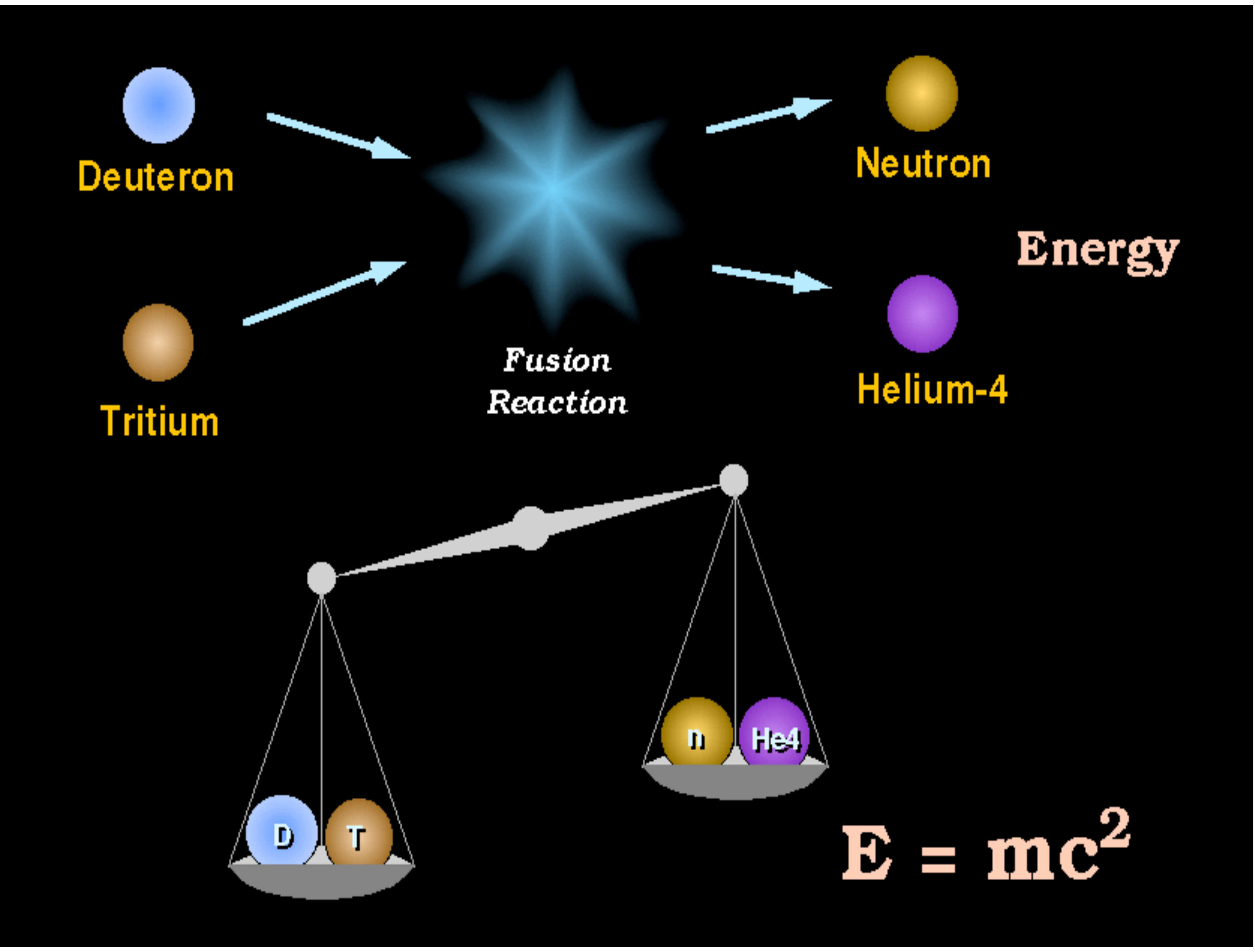


Source -International Energy Outlook-2008

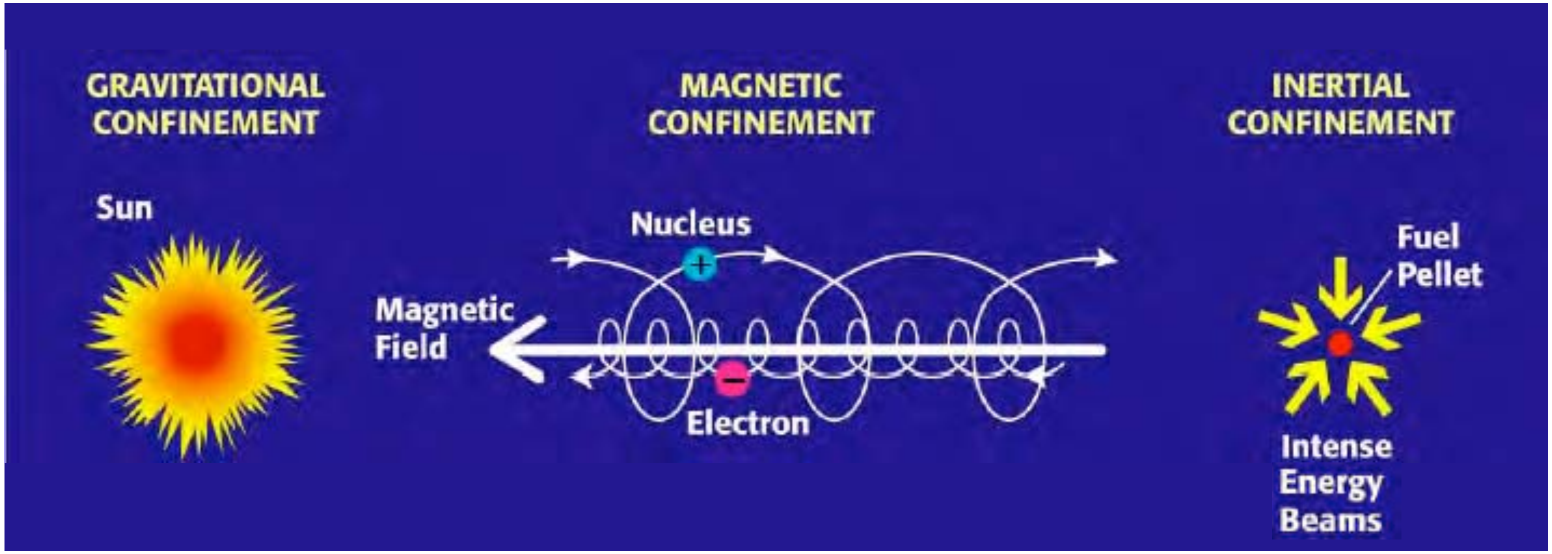
CO_2 Emission from Energy Sources



[ref. Y.Uchiyama, Report Of Central Research Institute Of Electrical Power Industry, T94009
K.Tokimatsu et al. 6th IAEA TCM on Fusion Power Plant Design & Technology]


Deuteron
Tritium
Fusion
Reaction
Neutron
Energy
Helium-4
D
T
n
He4
E = mc²

There are several ways to reach fusion conditions – all involve a plasma



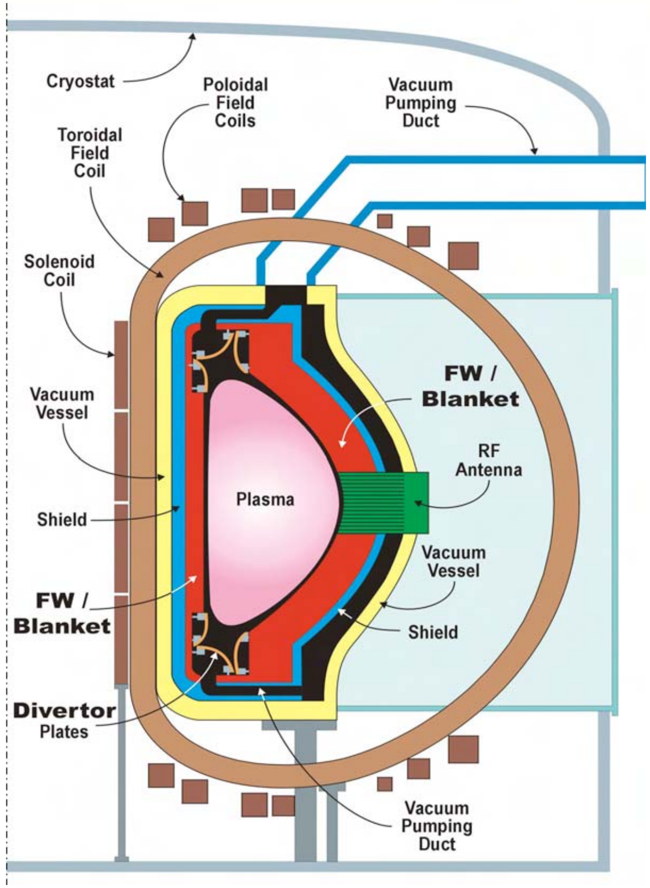
High-density, high-temperature thermonuclear plasmas must be confined long enough for efficient fusion reactions to occur:

==> Net energy gain

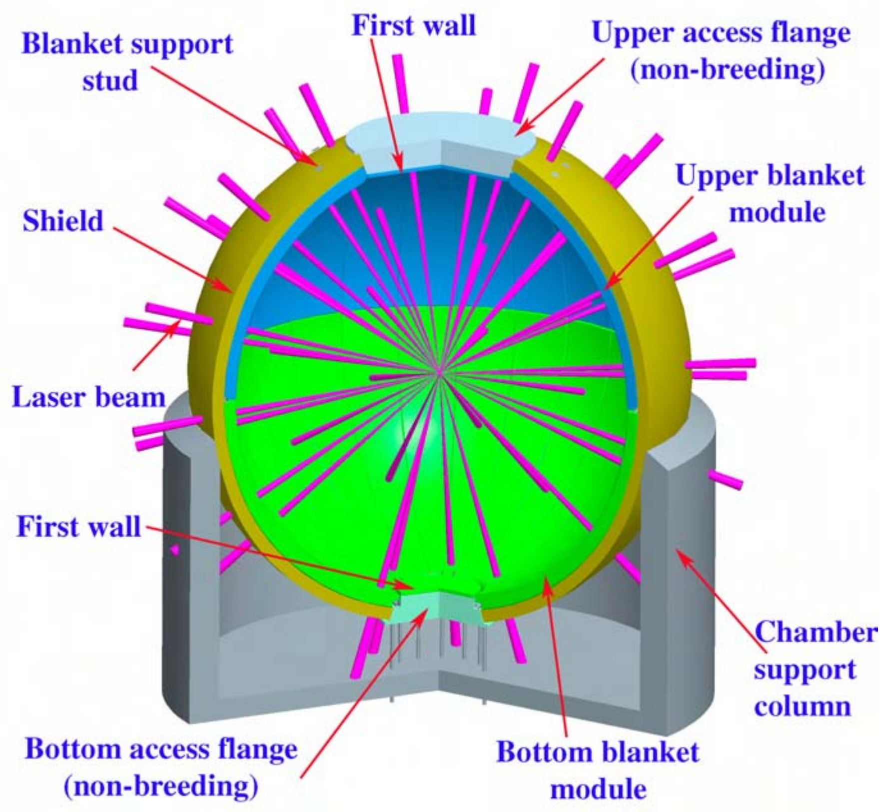
Nuclear Fusion Energy

- Unlike fission where uranium splits generating energy, fusion occurs when two hydrogen nuclei fuse together and release energy
- Two approaches:
  - Magnetic confinement
  - Inertial confinement

MFE and IFE Fusion Reactors are Complex with Many Components



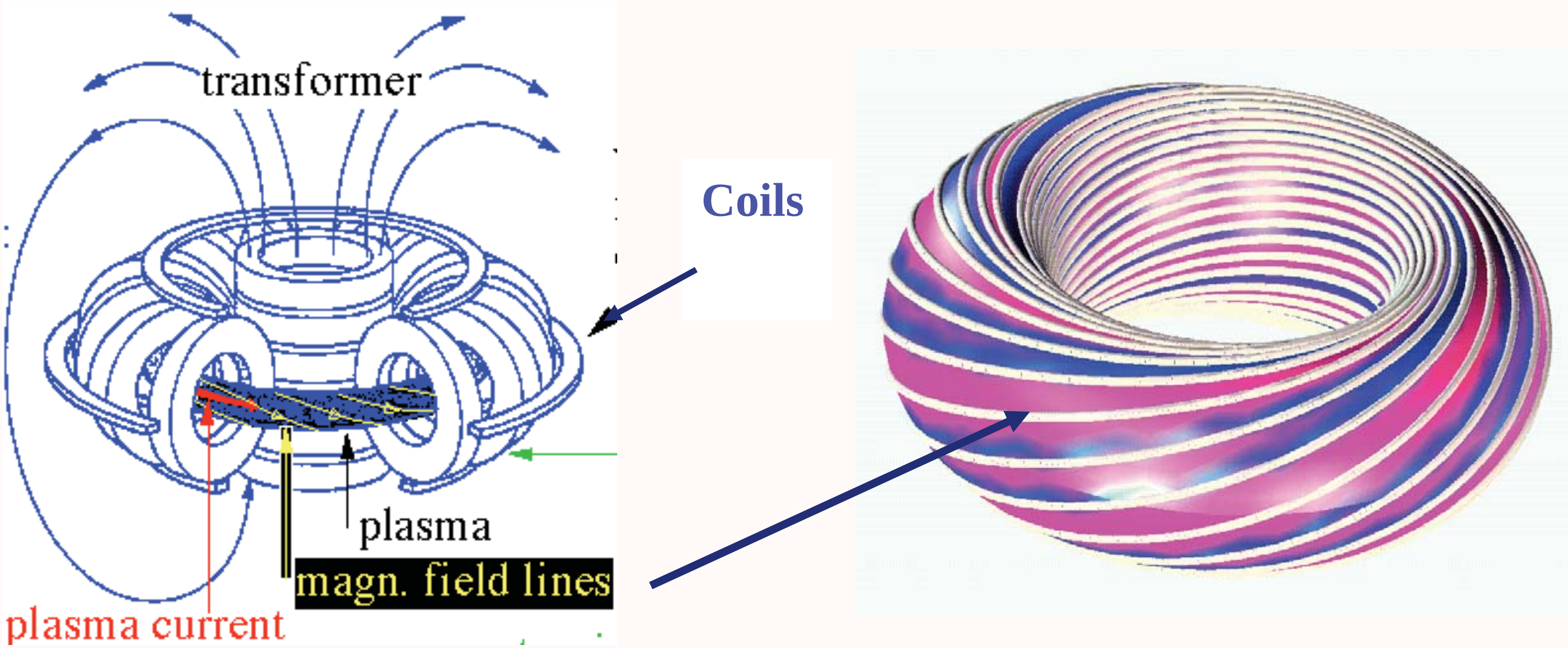
MFE



IFE

Fusion – Magnetic Confinement

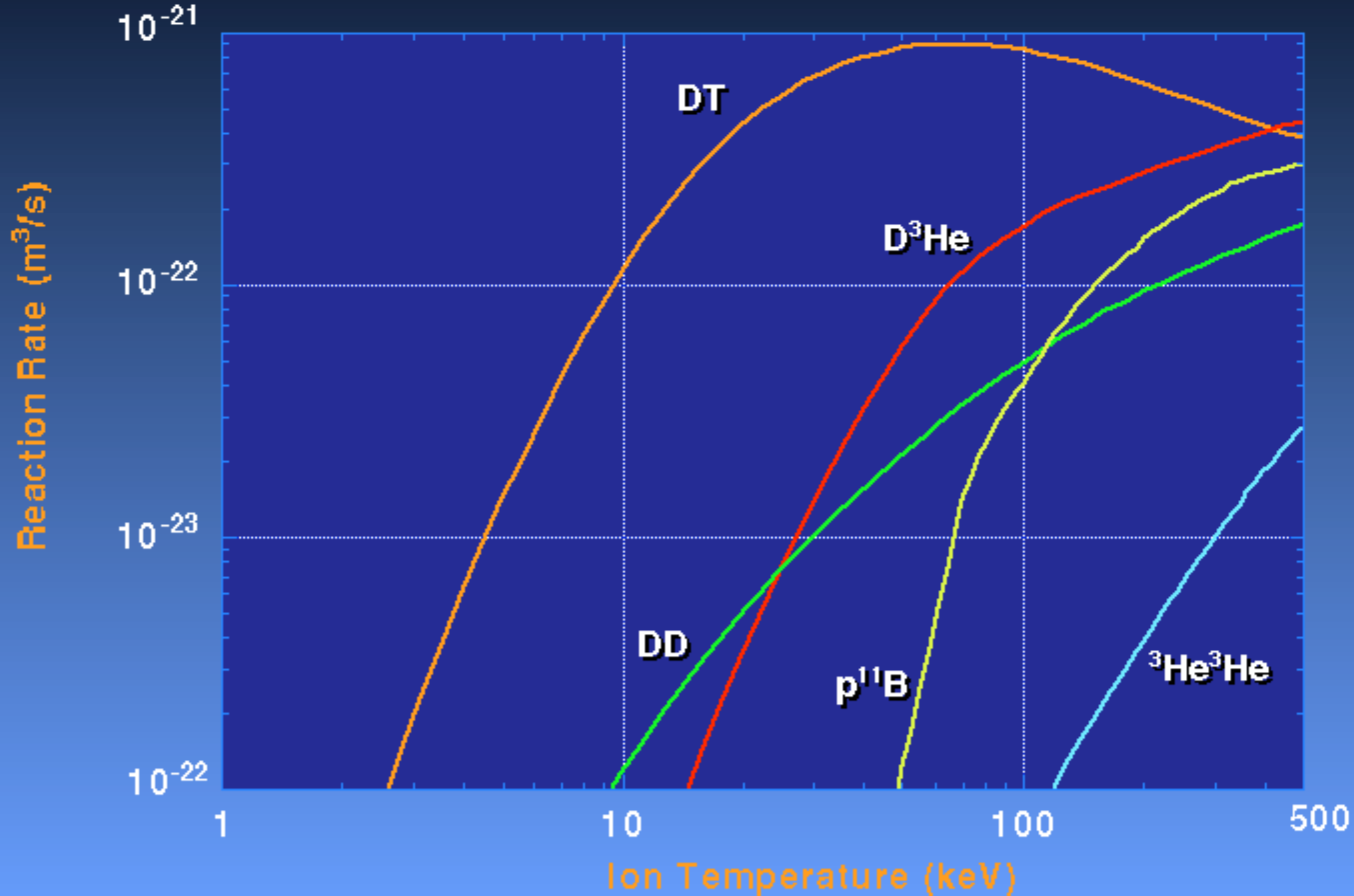
- The tokamak is the most widely studied configuration and uses a large current in the plasma to twist the magnetic fields.



- Holding the plasma with magnetic fields is sometimes likened to compressing Jell-o with rubber bands.

Illustrations from IPP and ORNL

Maxwellian Fusion Reaction Rates



D-T Fusion Represents a Nearly Inexhaustible Energy Source

Fuels: **Deuterium**: abundant in sea water

Tritium: Half-life~12 years…must be produced?

Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^4He + n	45	4	17,600

$^6Li + n \dashrightarrow T + {}^4He + 4.8\ MeV$ + others

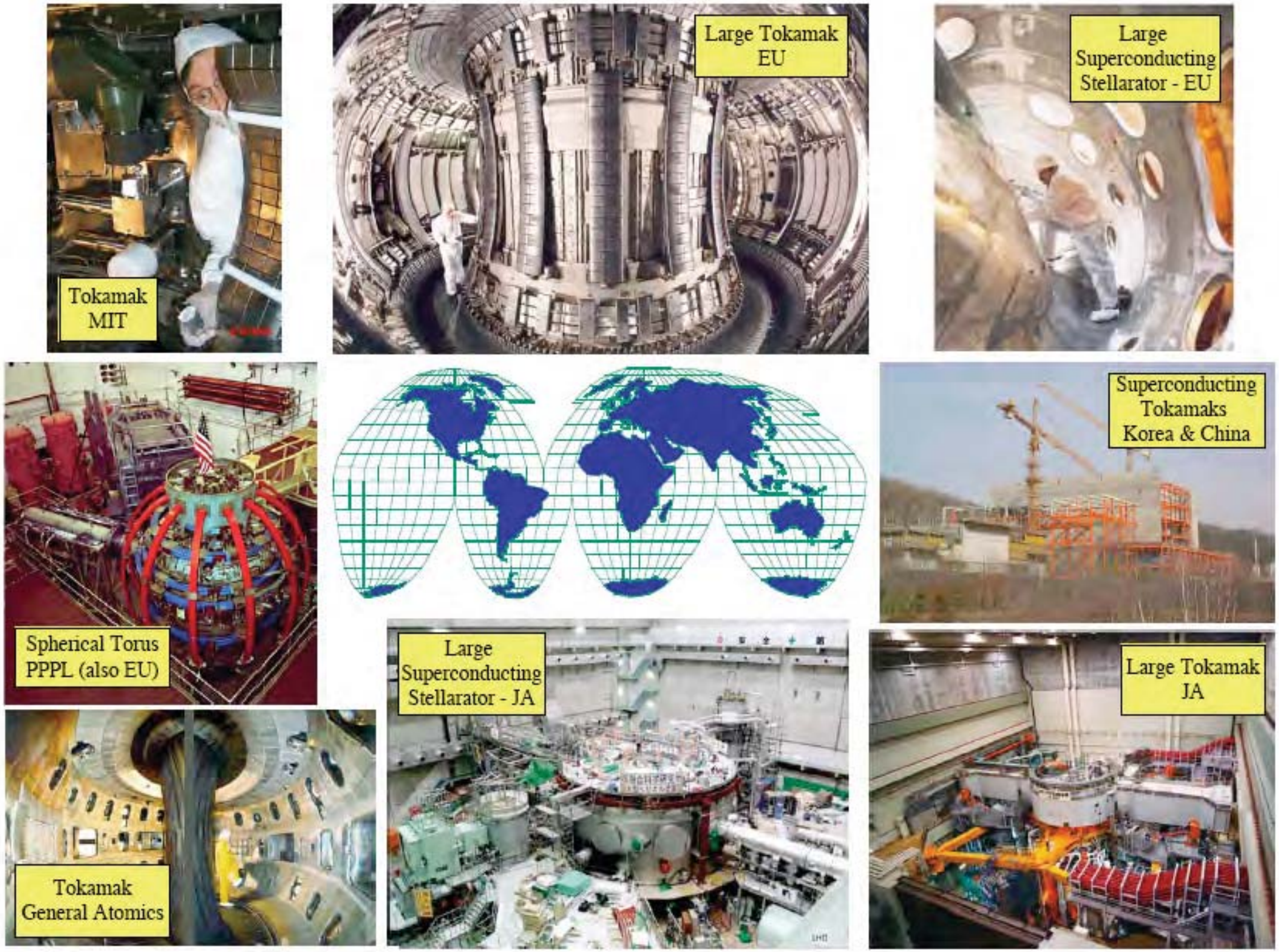
$T_{bred} / T_{burned} > 1$

"Real" fusion fuel cycle:

$^6Li + D = 2\,{}^4He + 22.4\ MeV$

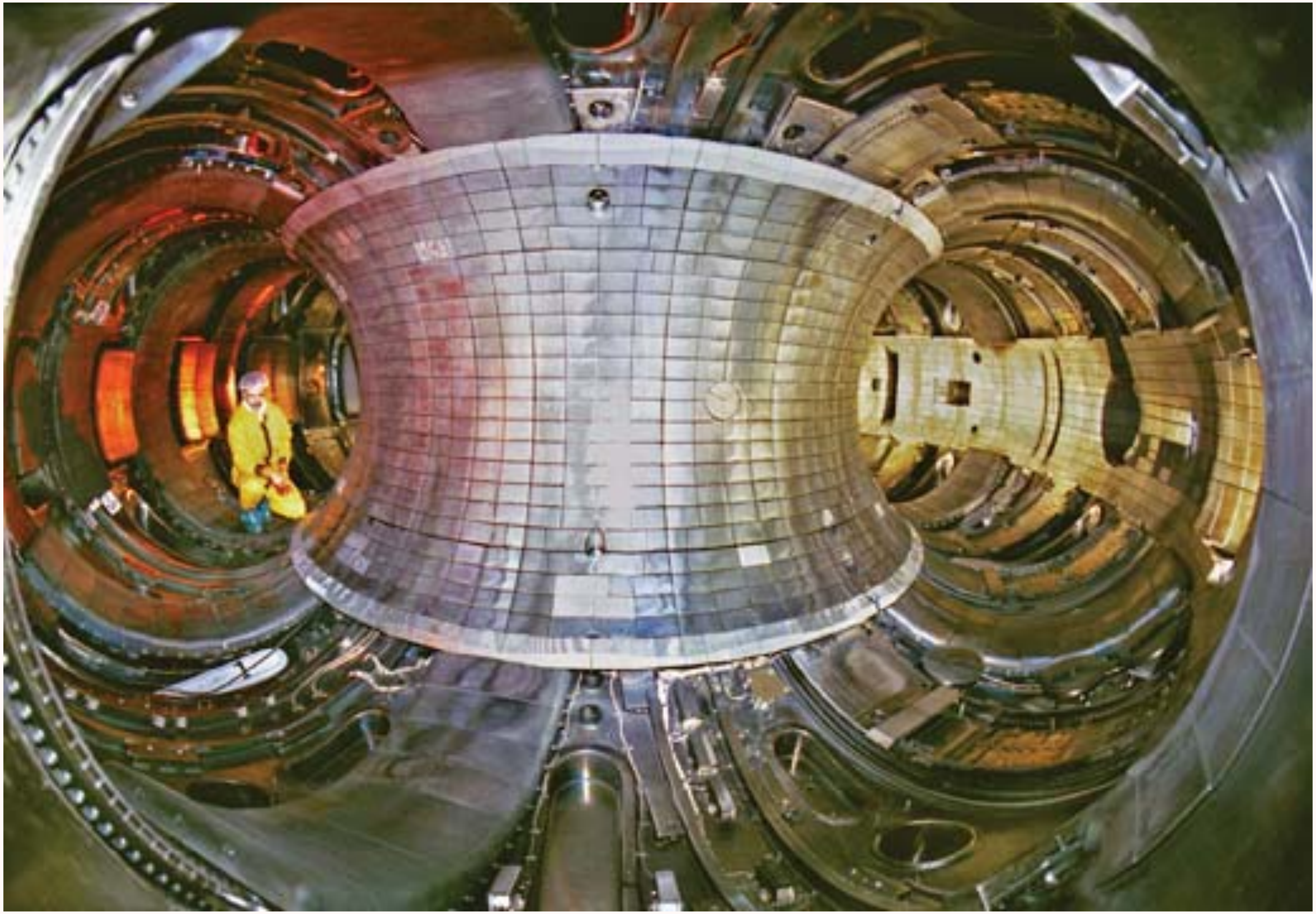
No Resource Concern

“Everybody” is running experiments in magnetic fusion

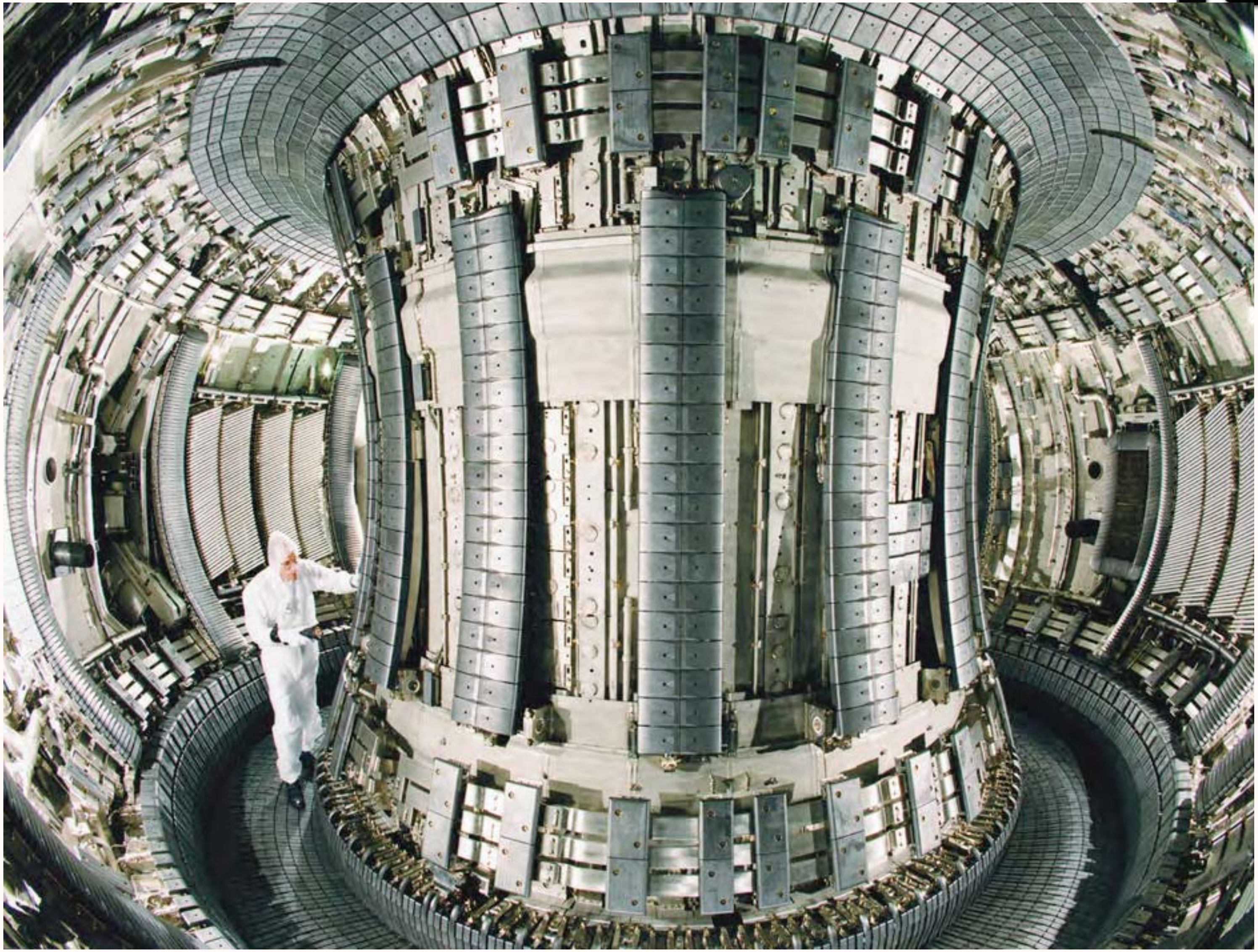


Tokamak Fusion Test Reactor (TFTR) ~ 10 MW fusion power

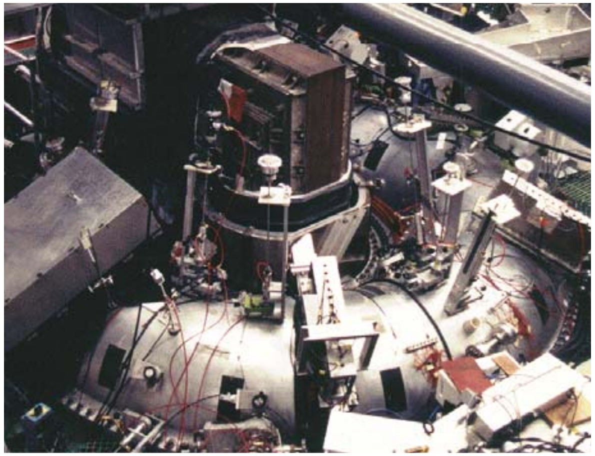
first to approach "breakeven", Q=1



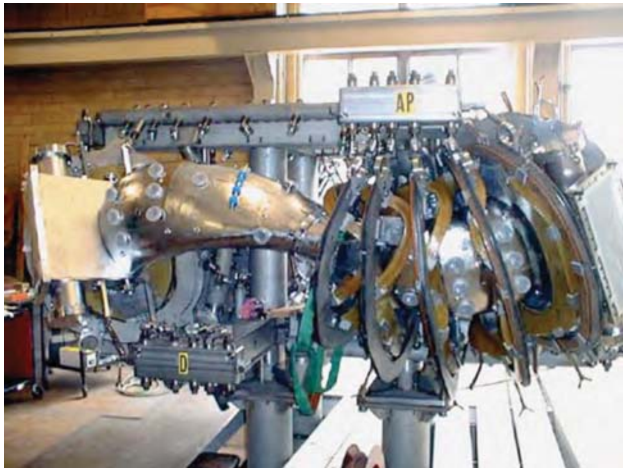
Joint European Torus (JET) is currently world's largest tokamak - 16 MW



There Are Many Experimental Fusion Devices on the University of Wisconsin Campus

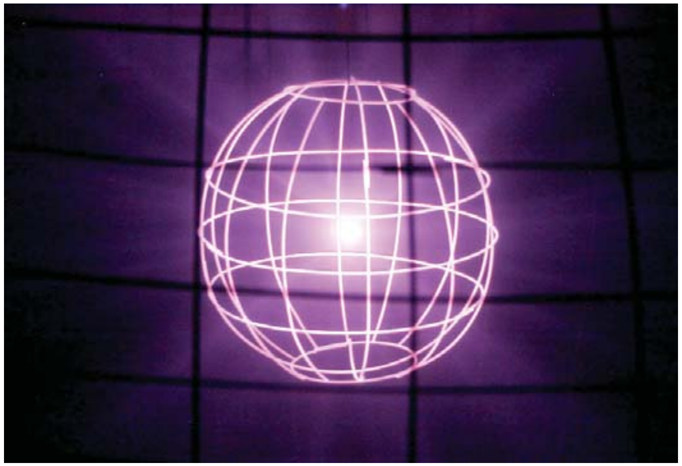


RFP – Physics



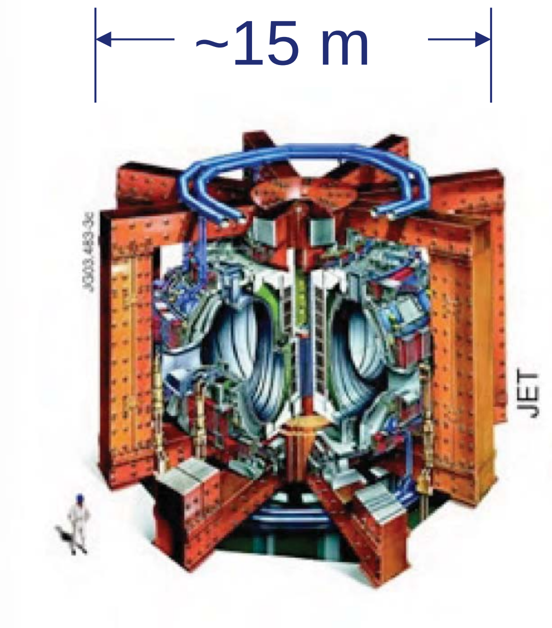
HSX - Electrical & Computer Engineering

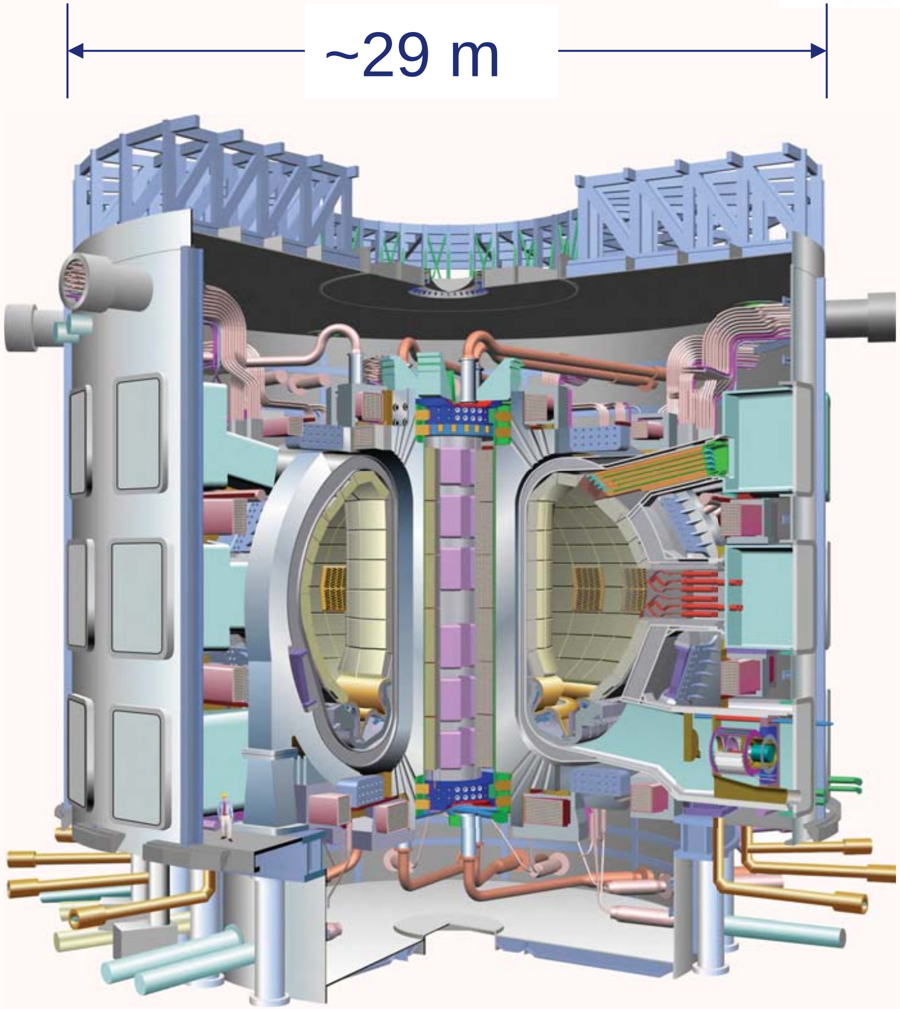
Pegasus - Engineering Physics



IEC - Engineering Physics

We are ready for the next step - ITER

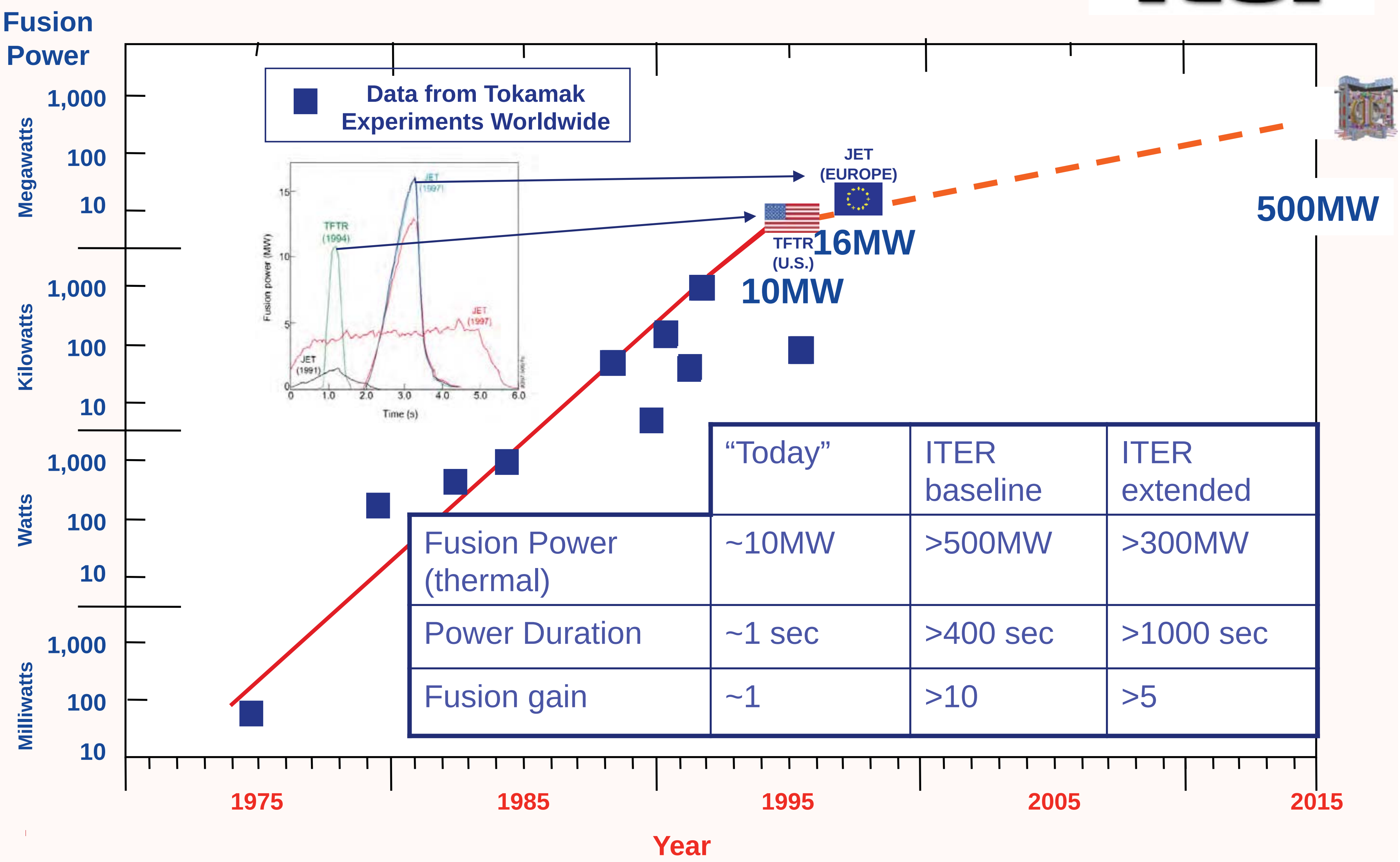




JET

ITER

ITER is major step in power & pulse length; the plasma is “burned” self-heated

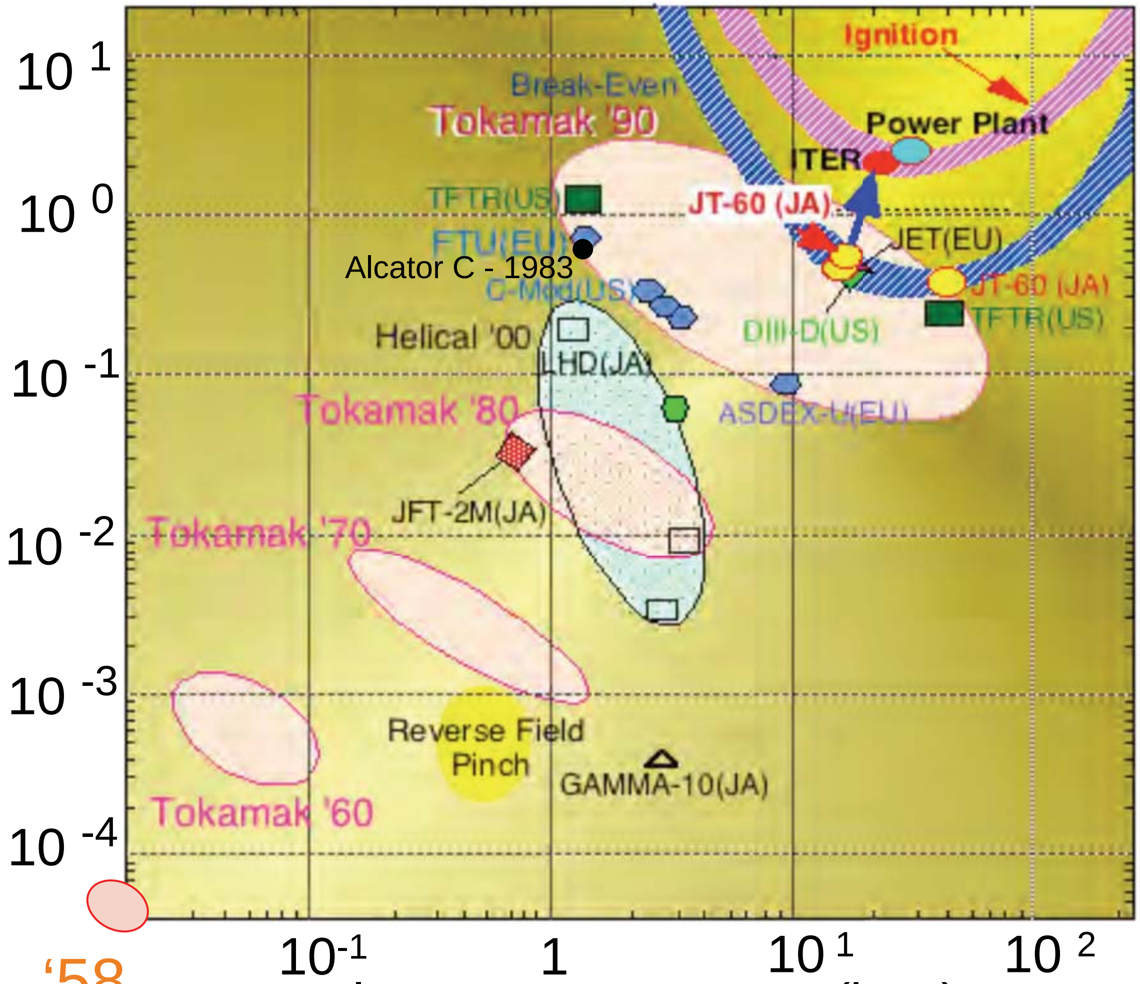


	“Today”	ITER baseline	ITER extended
Fusion Power (thermal)	~10MW	>500MW	>300MW
Power Duration	~1 sec	>400 sec	>1000 sec
Fusion gain	~1	>10	>5

Fusion Temperatures Attained, Fusion Confinement One Step Away

$n_i(0)\tau_E$

$(10^{20}\ m^{-3}\ s)$

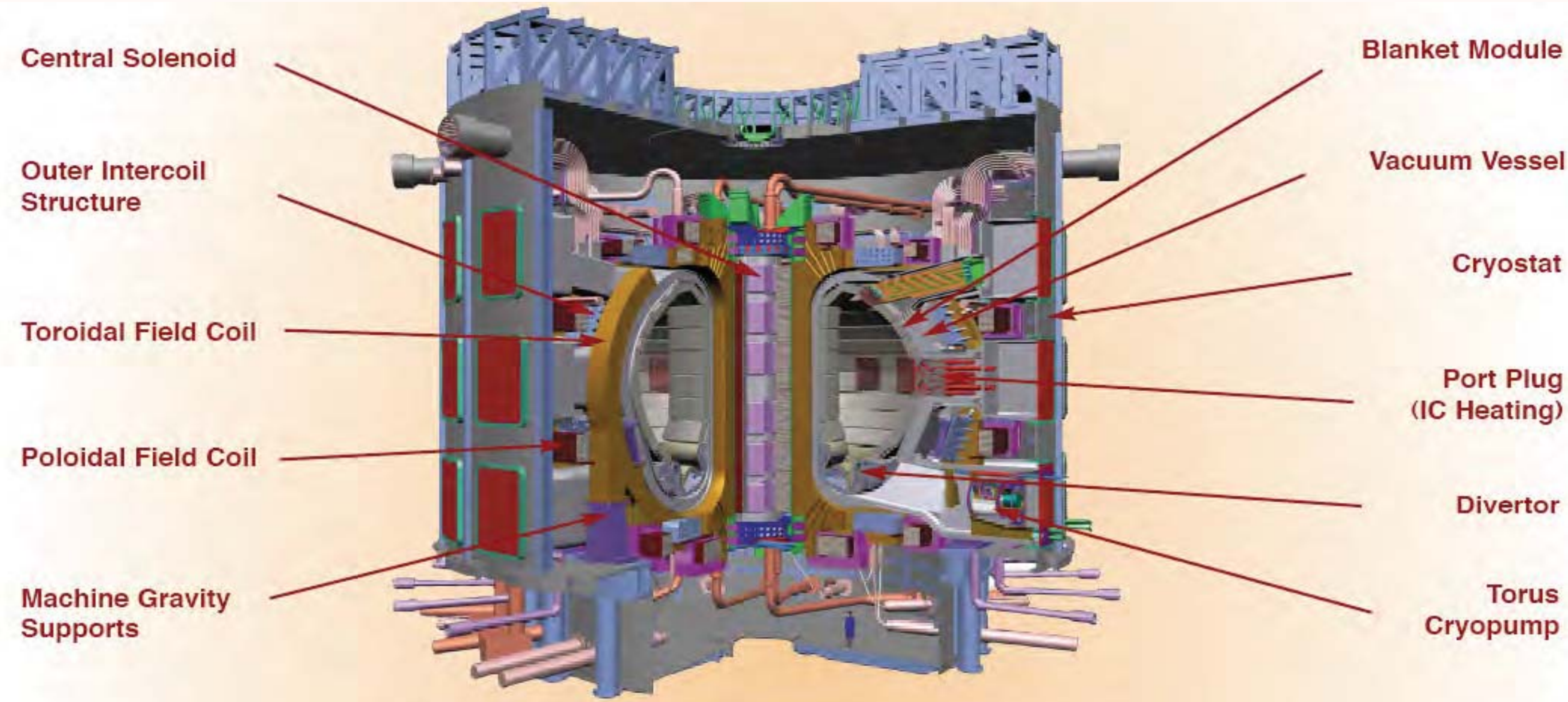


Plasma Temperature (keV)

JAEA

$n_i(0)\tau_E T_i$ increased by $\sim 10^7$ since 1958

ITER is a 500 MW Tokamak Experiment



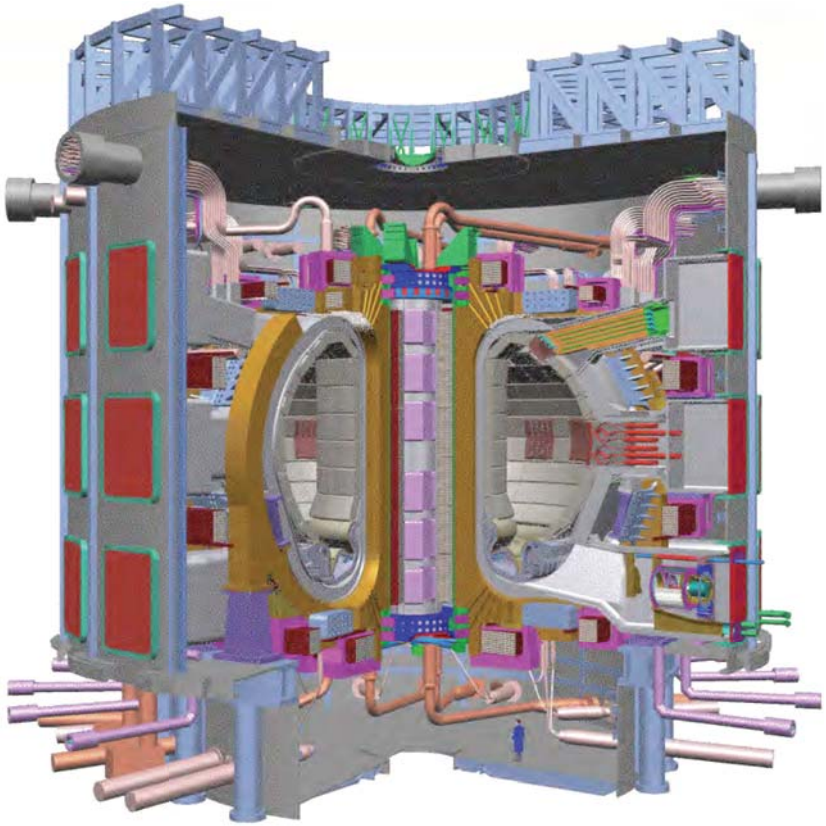
Main Plasma Parameters and Dimensions	
Total fusion power	*500 MW*
Q — Fusion power/auxiliary heating power	≥ 10
Average (14 MeV) neutron wall loading	$0.57\ MW/m^2$
Plasma major radius	*6.2 m*
Plasma minor radius	*2.0 m*
Plasma current	*15 MA*
Toroidal field @ 6.2 m radius	*5.3 T*
Plasma Volume	$837\ m^3$
Installed auxiliary heating/current drive power	*73 MW*

•Ref DOE

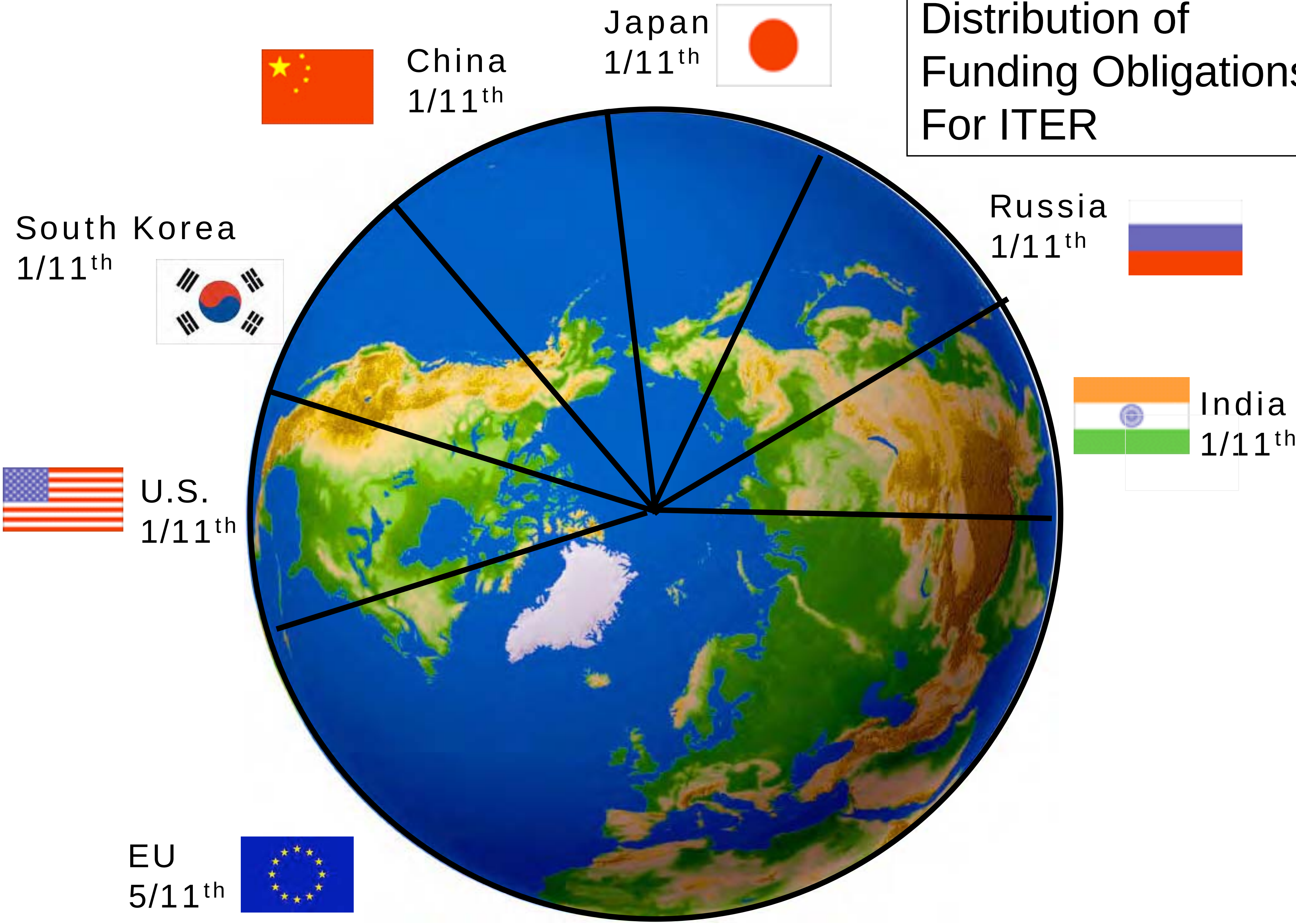
ITER

1st Integrated Fusion Test Reactor

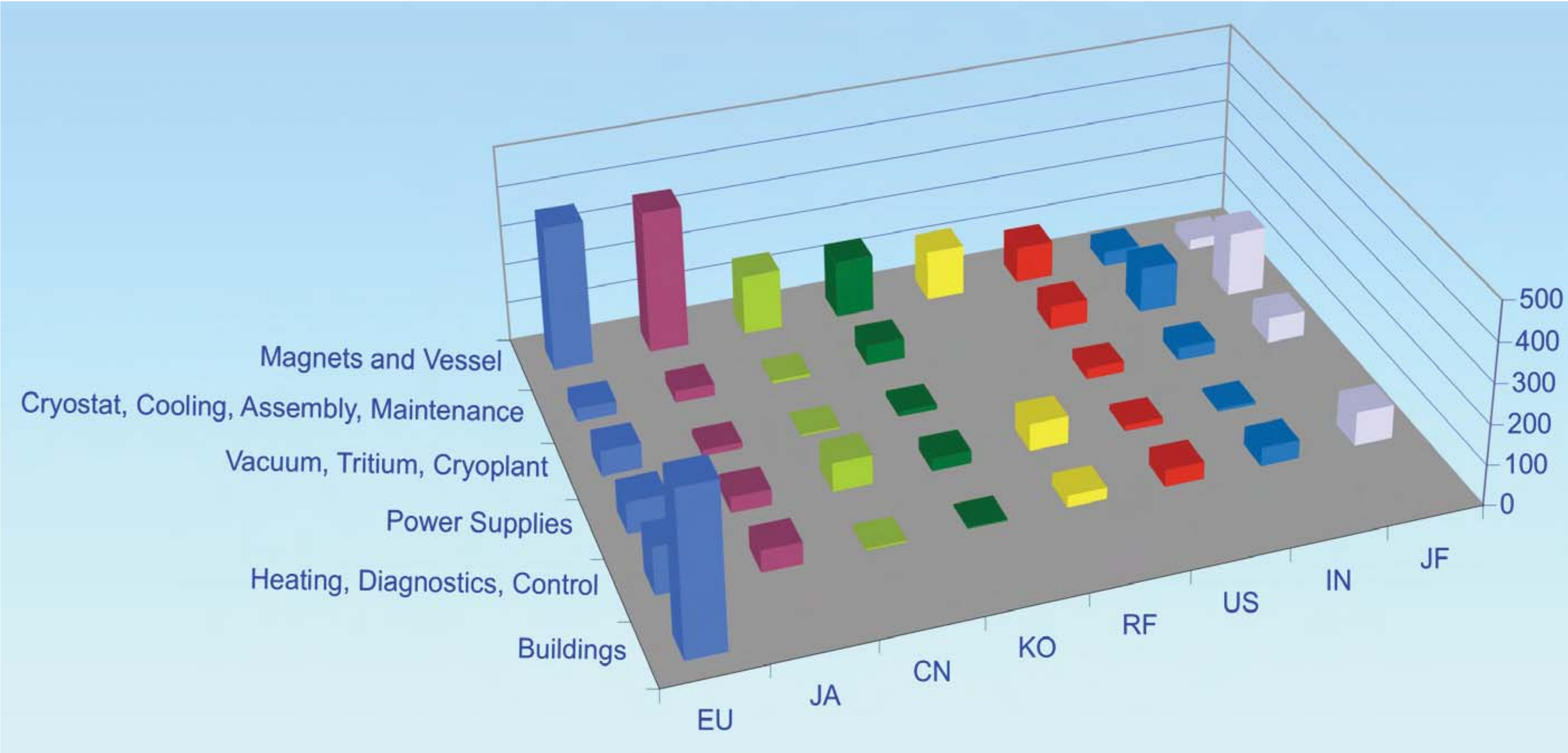
- Agreement signed on November 21, 2006
- Seven parties with more than half of the world population
- Cost ~$7B
- ITER construction started in 2008 at Cadarache, France
- First plasma in 2018 and 20 year operation



Distribution of Funding Obligations For ITER



In-kind contributions

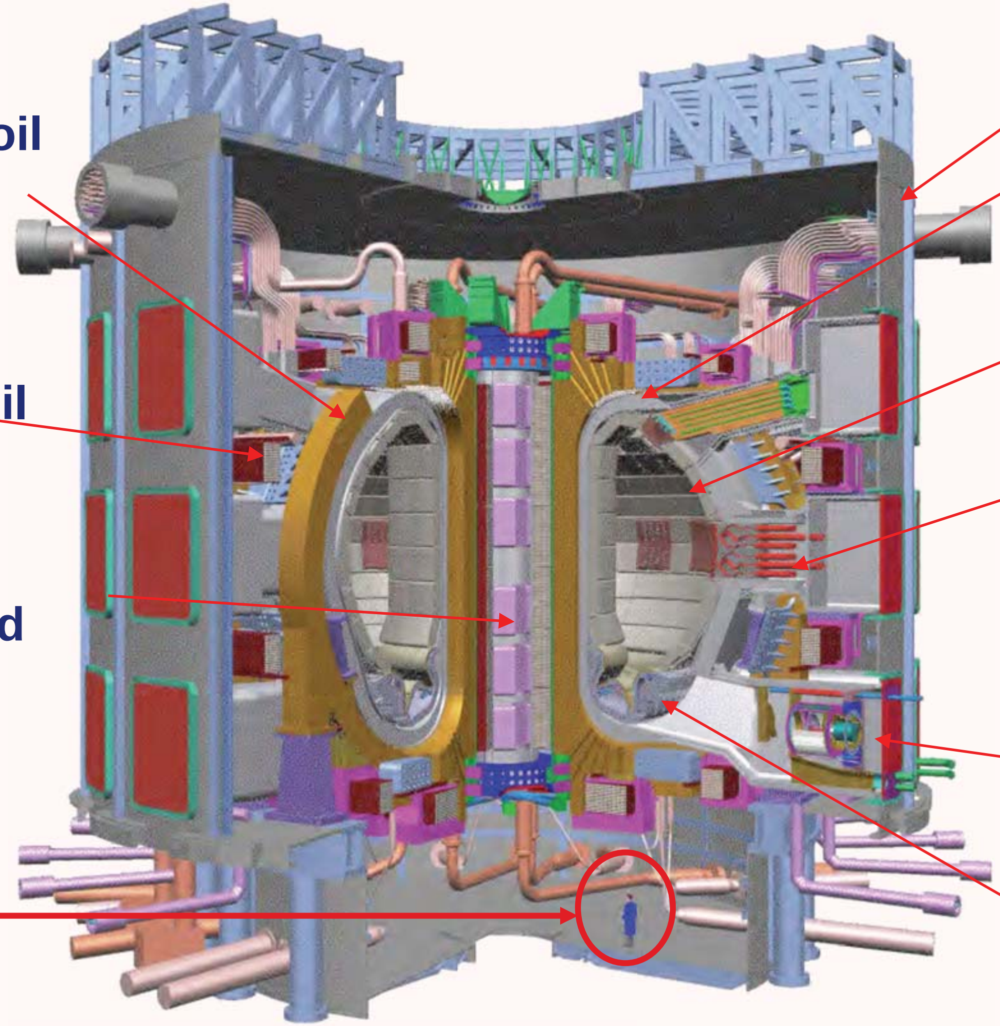


ITER has many engineering challenges

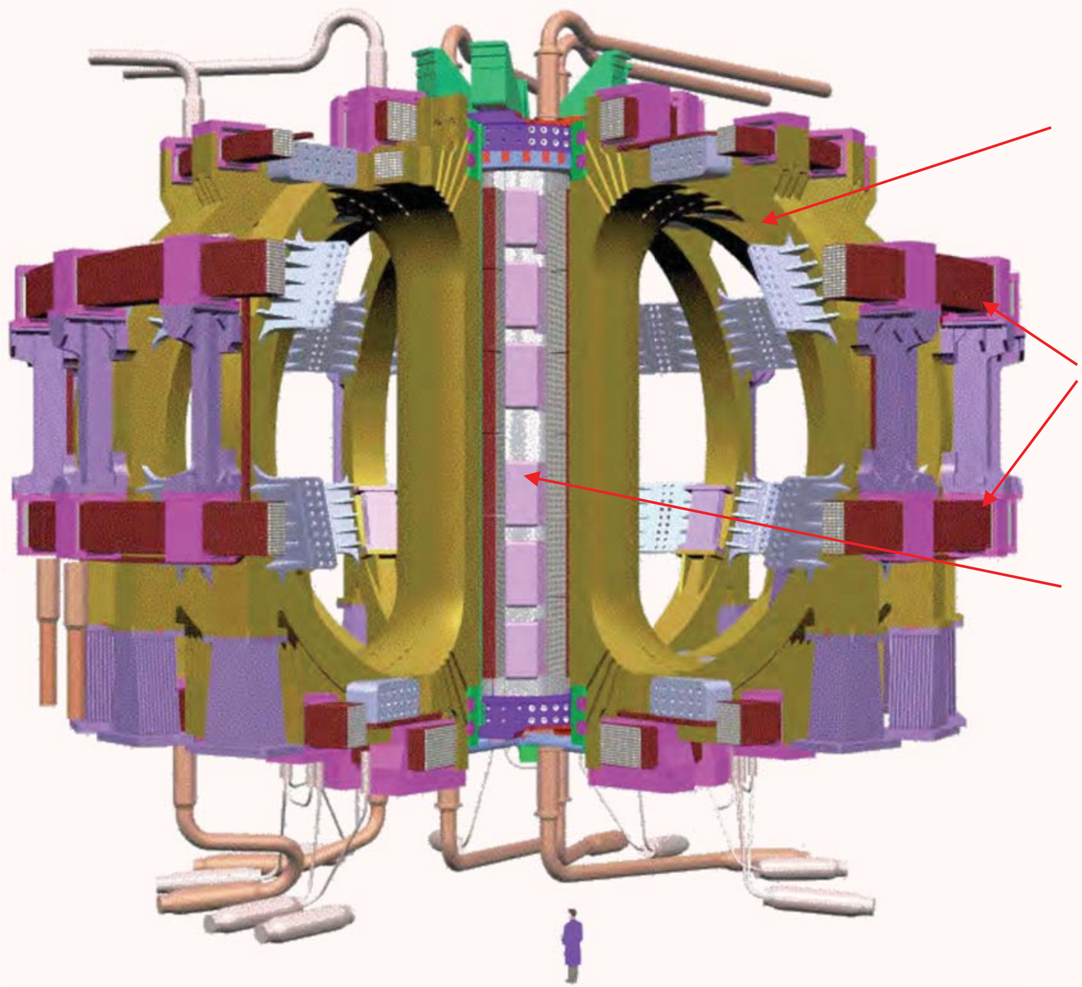
How do we:

- Provide specified magnetic field over a large volume?
- Protect the device from high heat flux and neutrons?
- Heat the plasma and drive the plasma current?
- Diagnose the plasma?
- Maintain the device over time?
- Integrate the systems into a coherent design?

ITER is complex (~10^7 parts) and big; the Core of ITER weighs 24000 tonnes

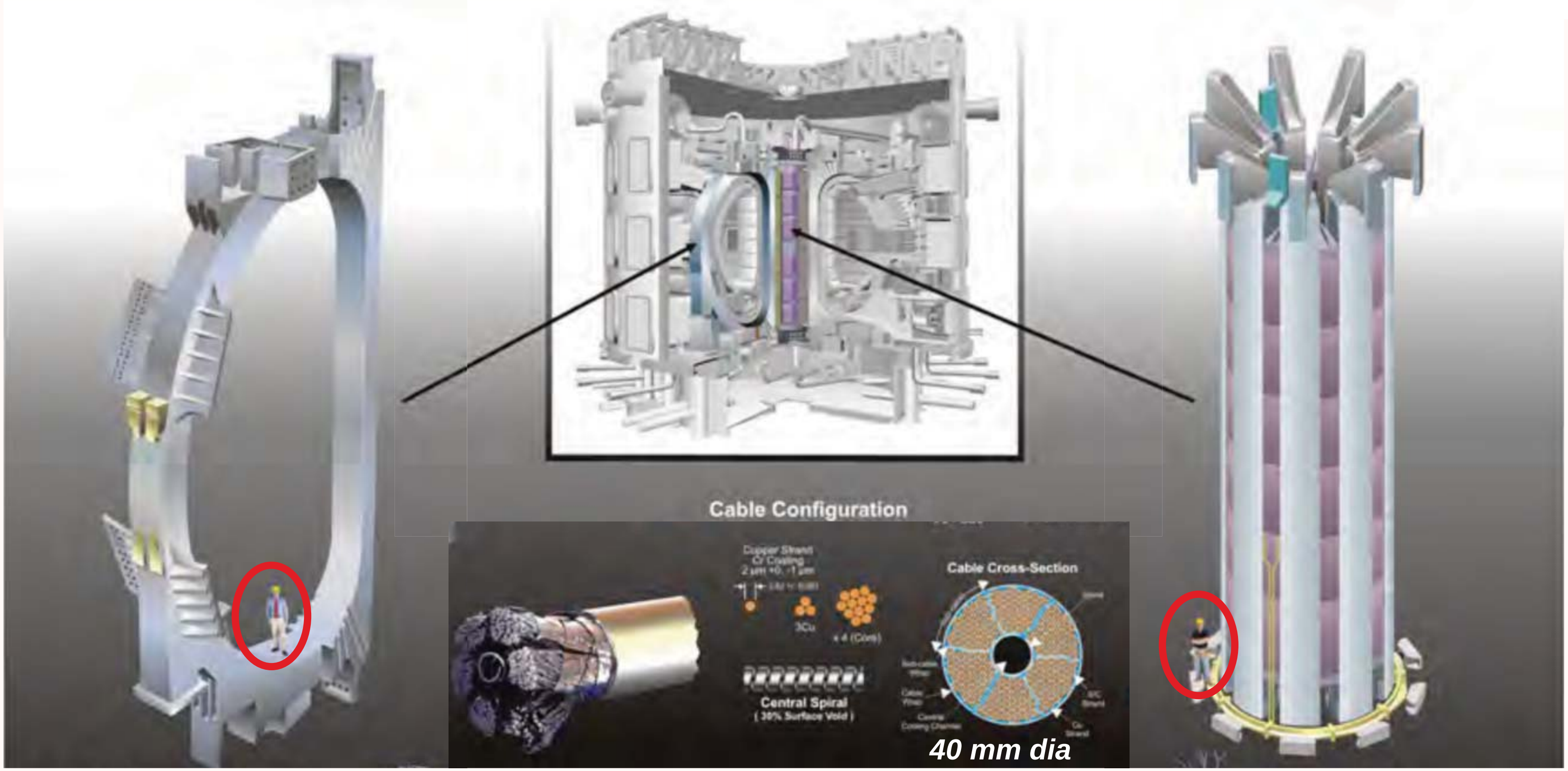


Inside the cryostat is the magnetic coil set



- **Toroidal Field Coils (18)**
  Provide primary magnetic field and support structure
- **Poloidal Field Coils (6)**
  Provide shaping and position control
- **Central Solenoid (6 seg.)**
  Drives plasma current inductively
- **Correction coils (18)**
  Compensate for field errors and stabilize MHD instabilities

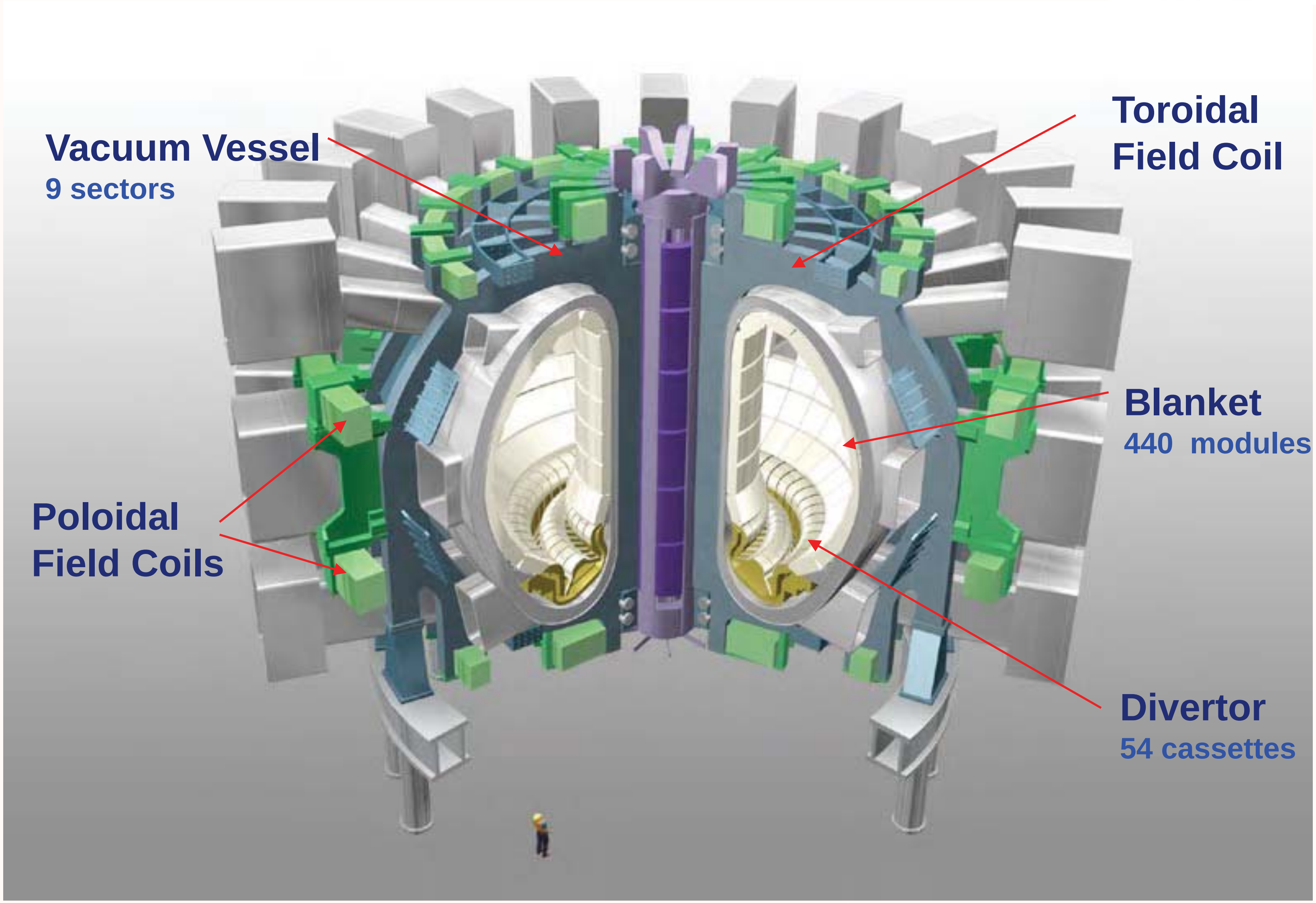
Magnets are unprecedented in size and performance for fusion systems



TF coils
11.8 Tesla, 41 GJ
400 MN centering force

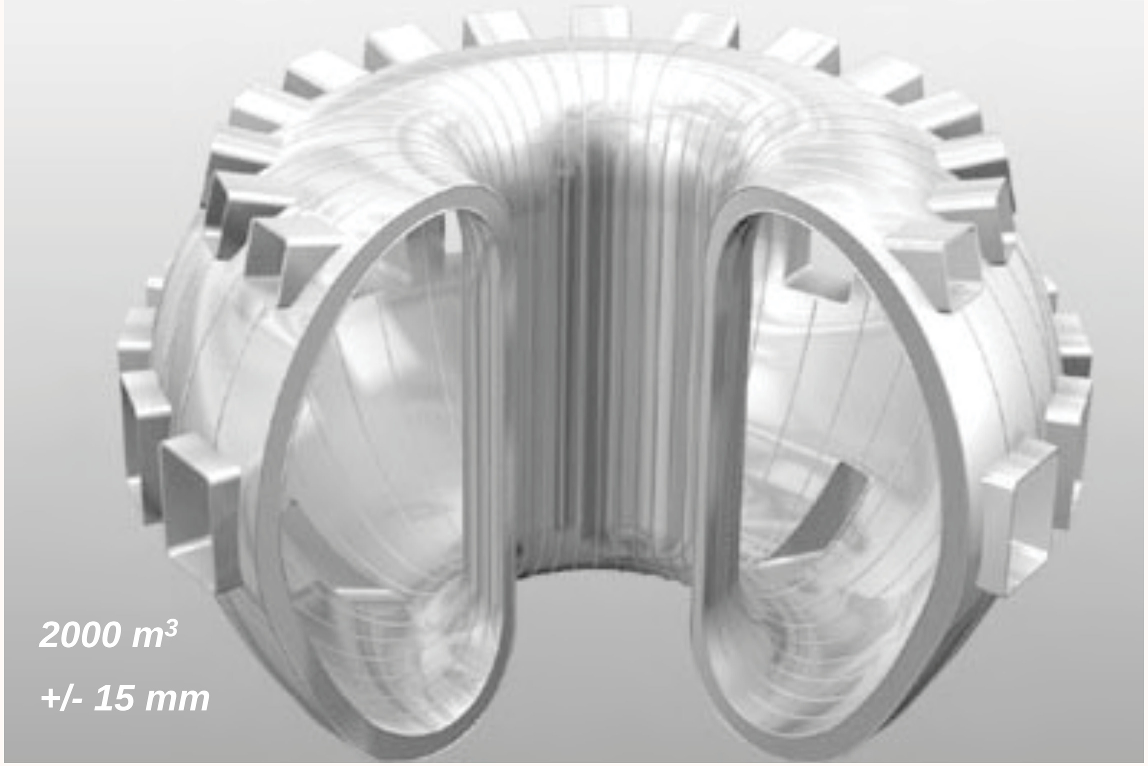
Central Solenoid
13 Tesla, 7 GJ
20 kV, 1.2 T/s

Inside the magnet set are the vacuum vessel and in-vessel components



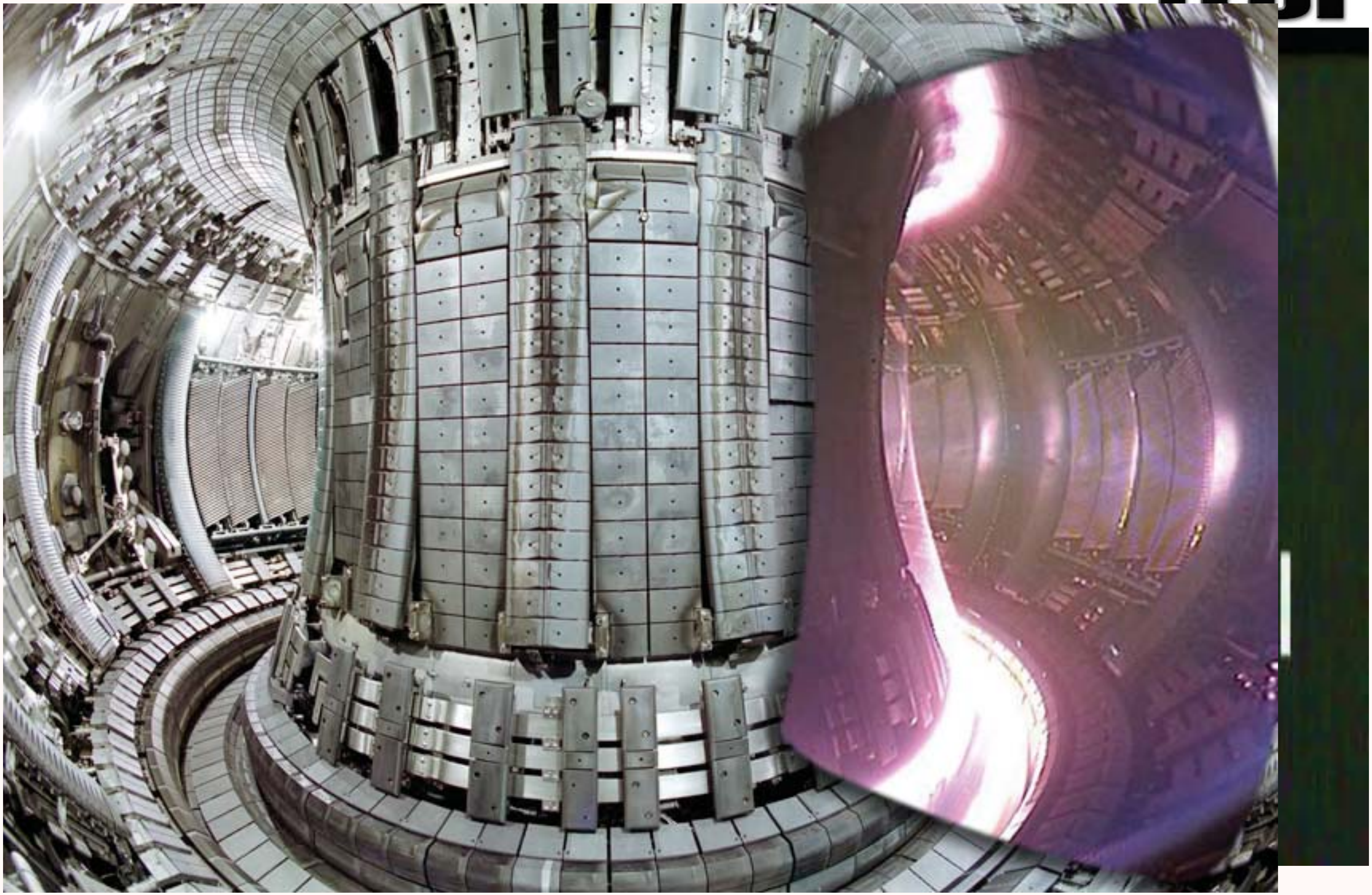
Vacuum vessel is the plasma chamber

- Double walled, water-cooled, stainless steel structure provides high quality vacuum and first confinement barrier for radioactive materials.
- Prototype constructed to prove feasibility of double wall construction with prototypic size and tolerances.



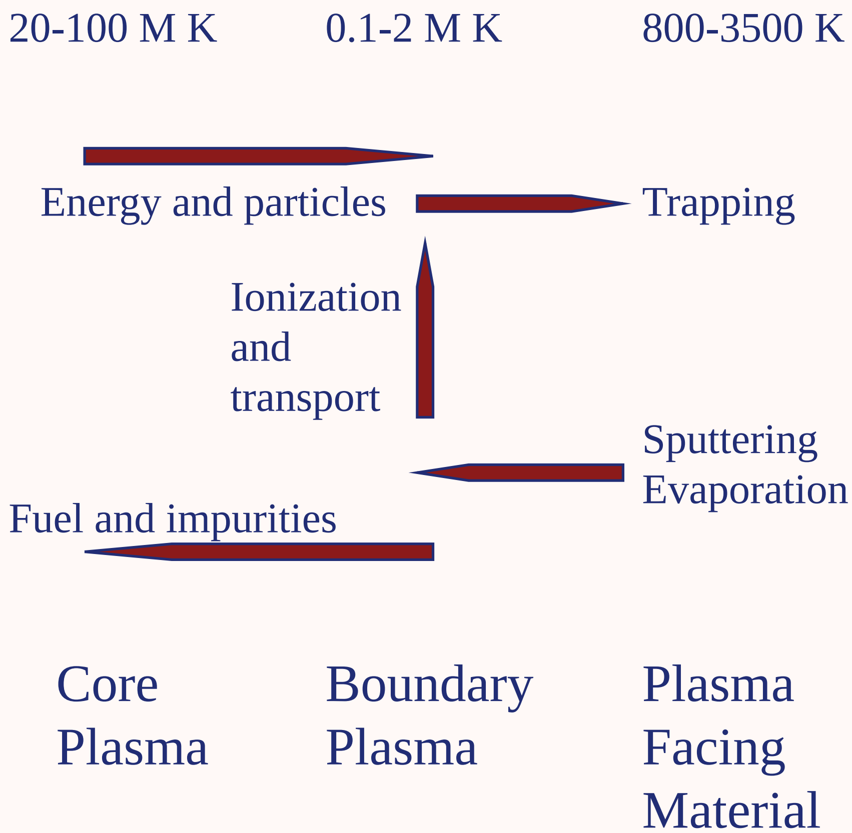
- Vessel must be protected from the plasma.

Plasma interacts with surfaces

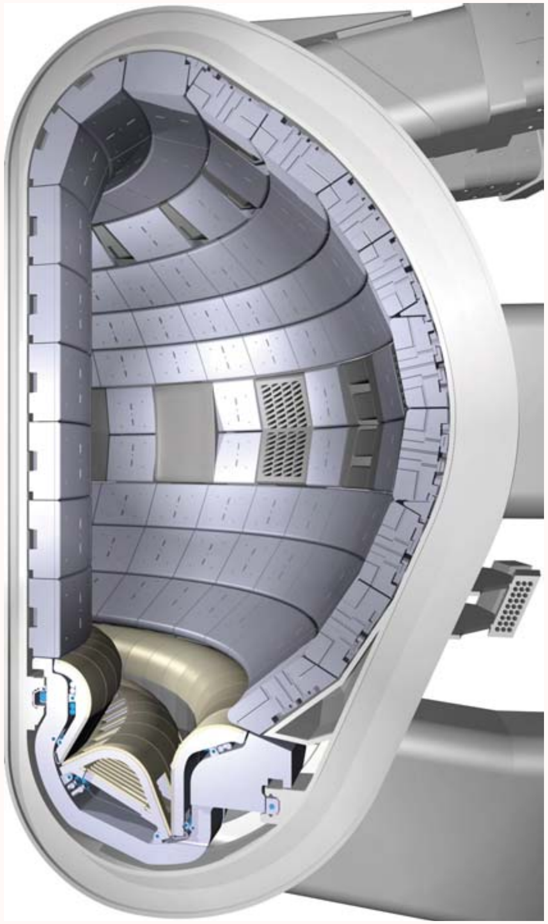


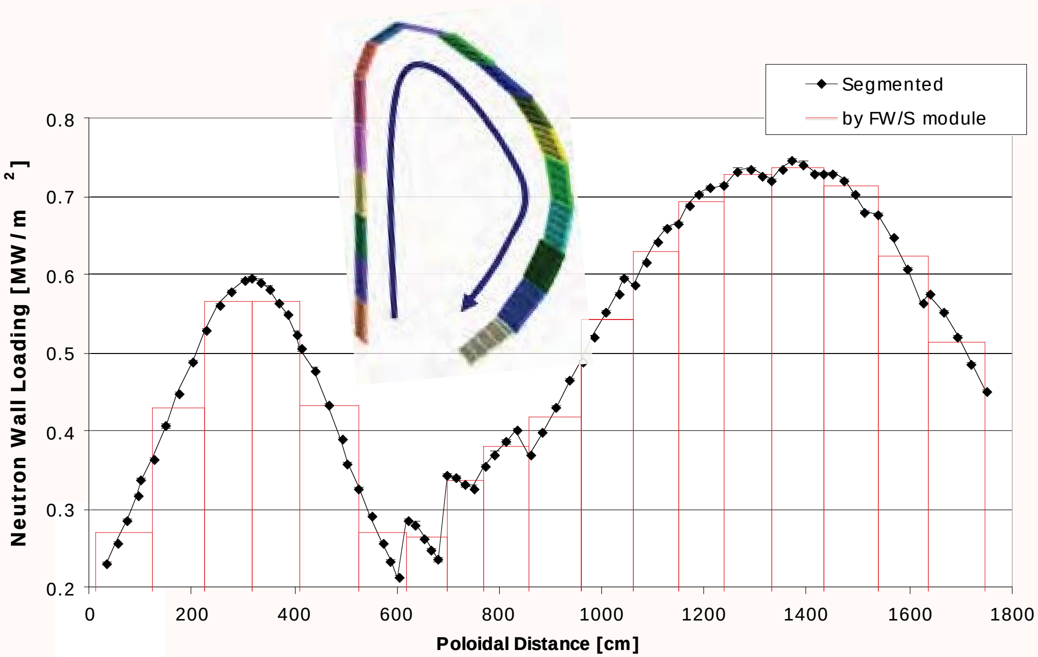
Fusion Plasma Materials Interactions

- The core plasma must be kept clean of impurities and He ash.
- The plasma facing component surface sees high density and temperature plasma.
- Heat flux on plasma facing surfaces can range above 10^4 MW/m^2 for short times and above 10 MW/m^2 continuously (reentry vehicles ~ 100 MW/m^2)
- Key issues are hydrogen trapping, erosion, and thermal fatigue.
- Spans science specialties from ionized gases to materials science.



Plasma facing components shield vessel and magnets from heat flux, neutrons

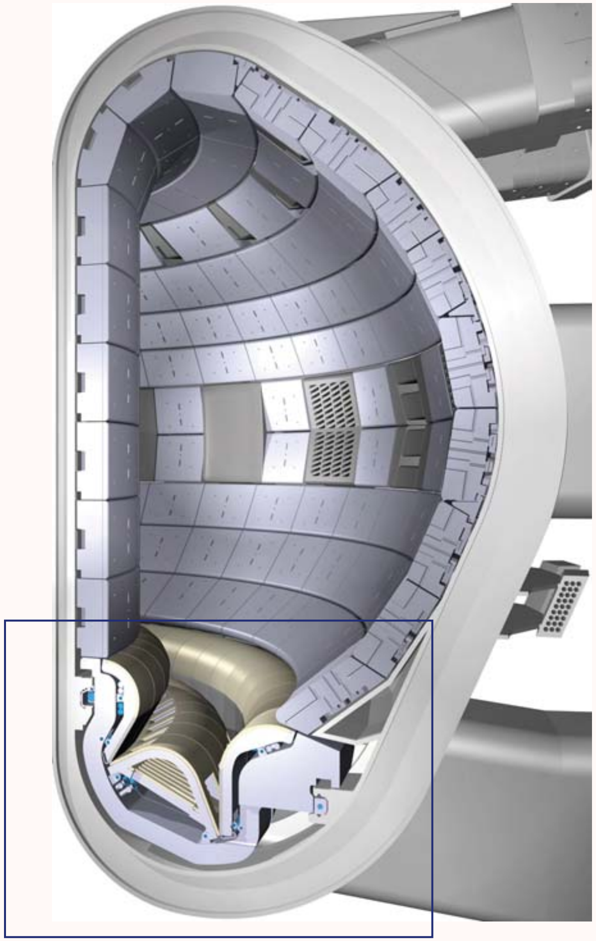


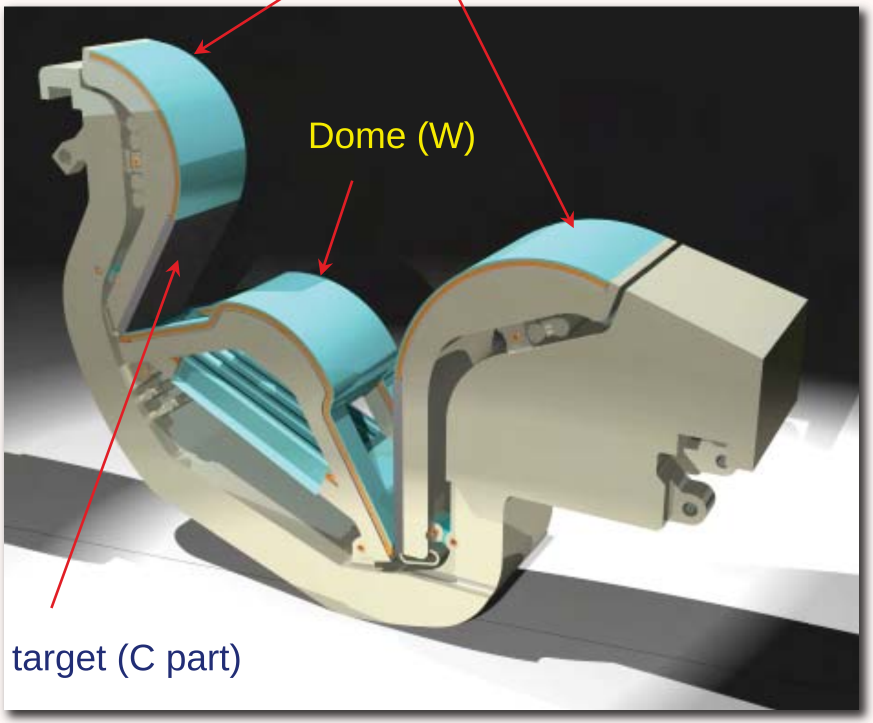


Ref. M Sawan

- **Neutron wall load peaks on midplane**
  Initial DT operation ~ 0.75 MW/m^2
- **TF heat load < 15 kw**
- **Magnet insulation dose < 10^7 Gray**
- **He production in VV < 1 appm**

Divertor exhausts a major part of plasma heating power and helium "ash"

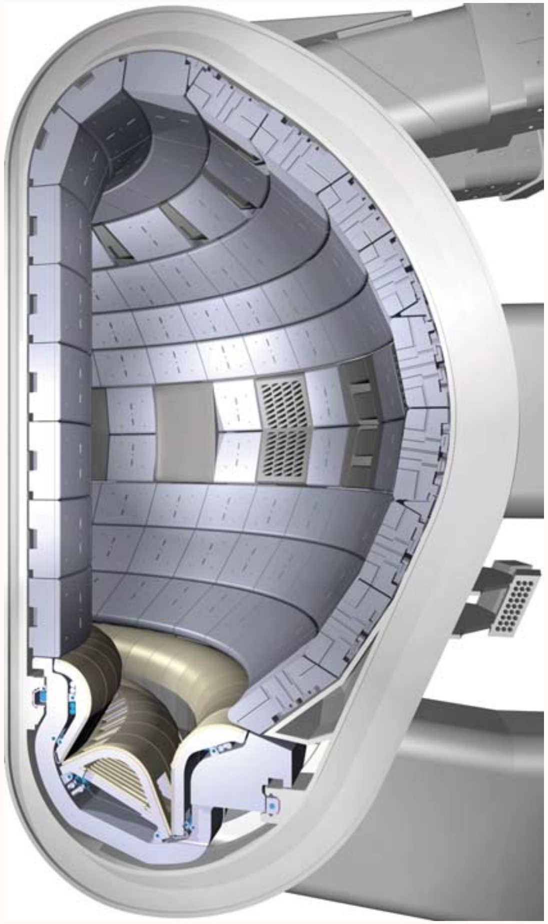


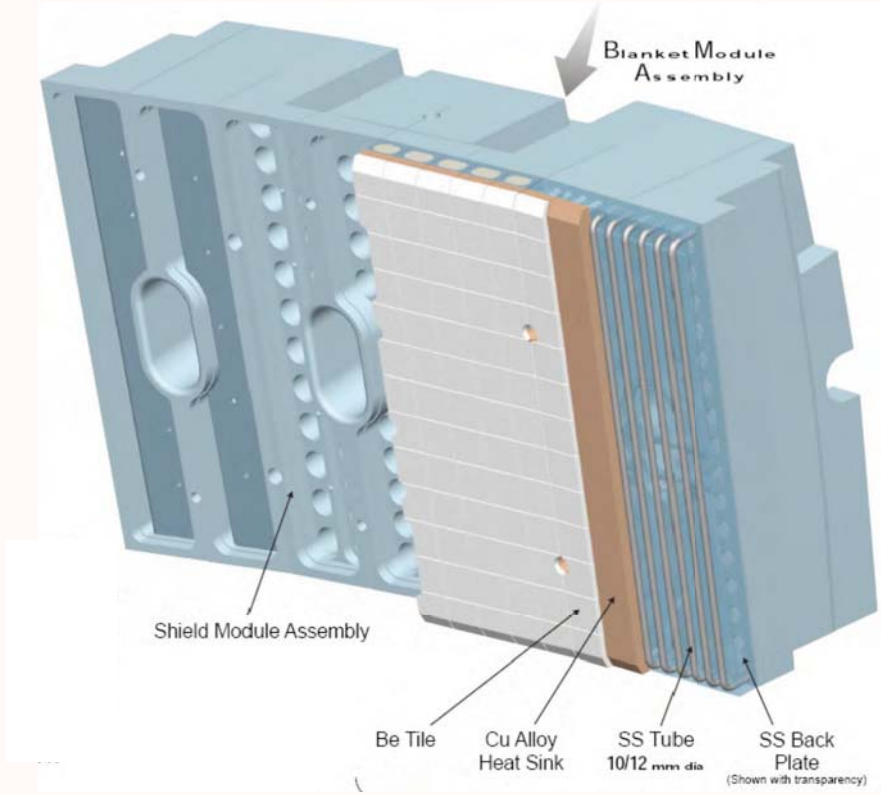


Divertor Cassette

<u>Challenge:</u> Absorb 10-20 MW/m^2 heat flux while minimizing impurity influx, tritium retention

First Wall and Blanket take balance of neutron radiation and plasma heat load



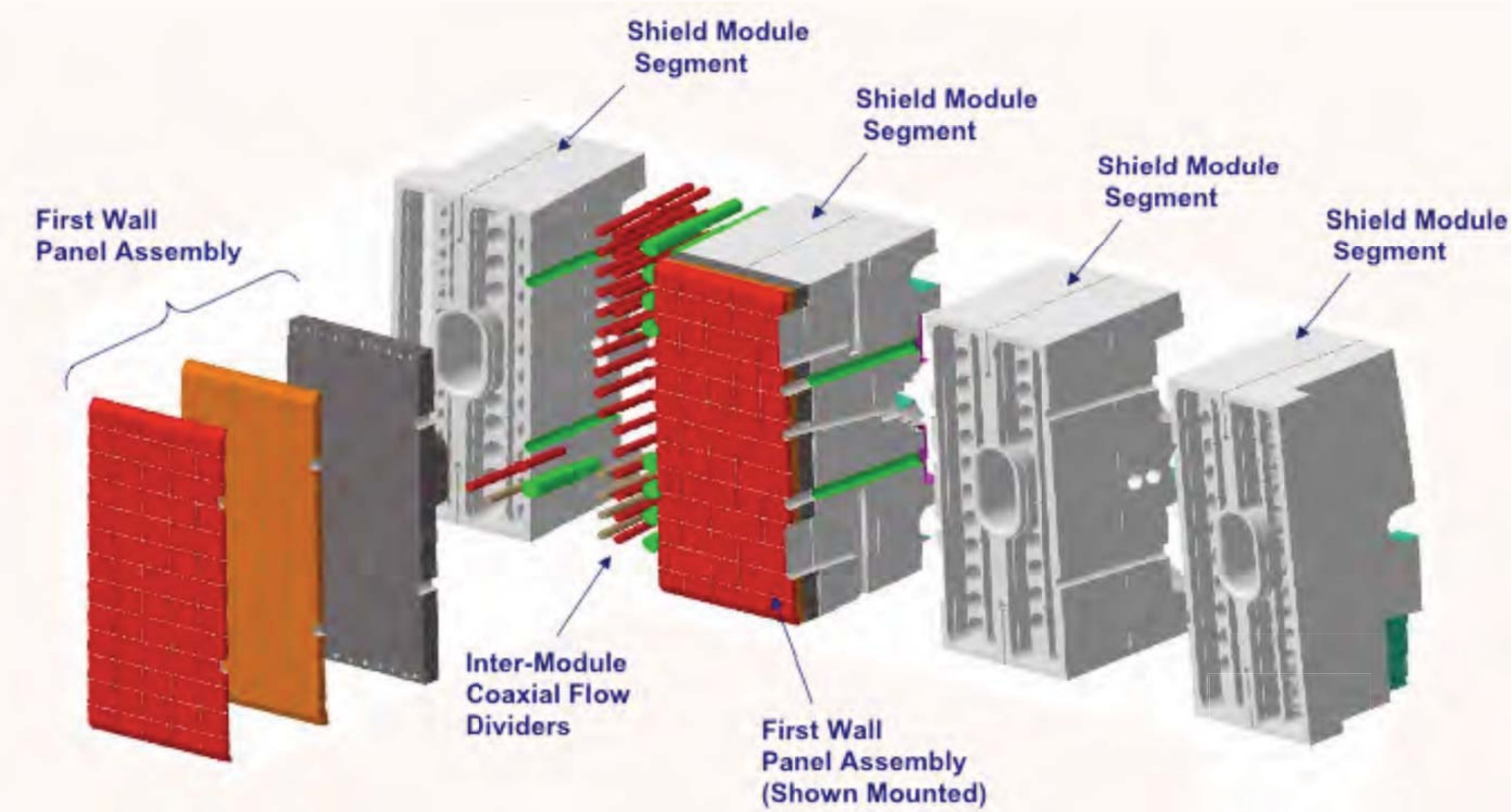


Blanket Module, 440 total

The Blanket serves three main functions:

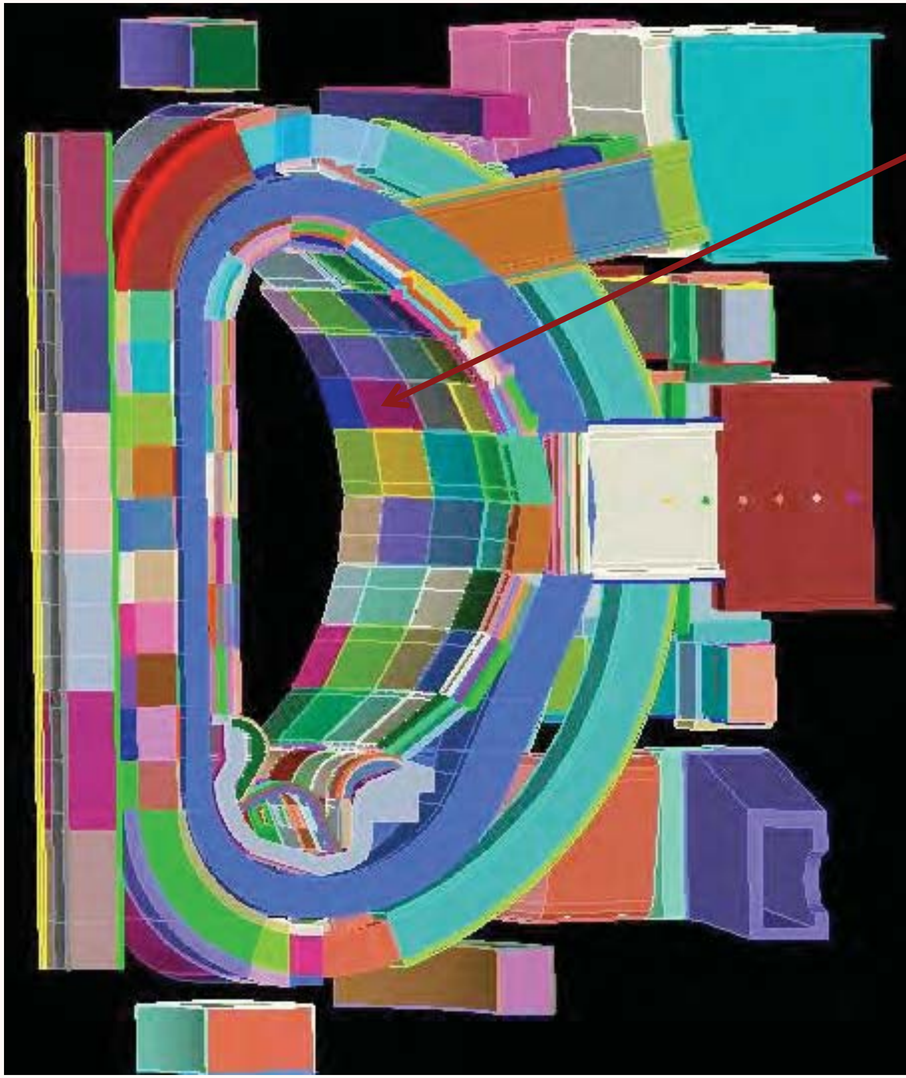
- To remove the useful neutron power and most of the particle power in the plasma
- To provide shielding of the vacuum vessel structure and S/C coils
- To help in passive stabilization of the plasma

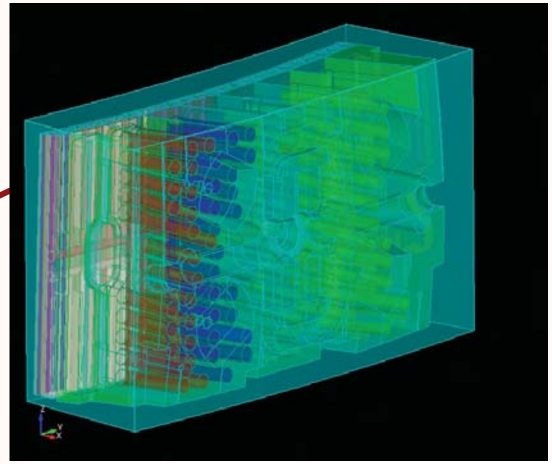
Blanket modules are high-performance heat exchangers with Be first wall

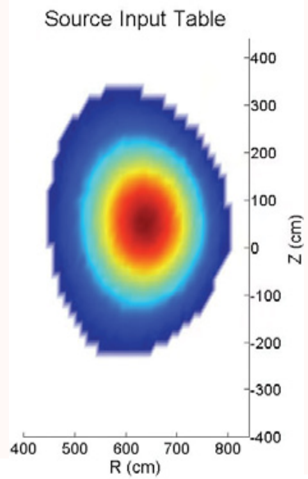


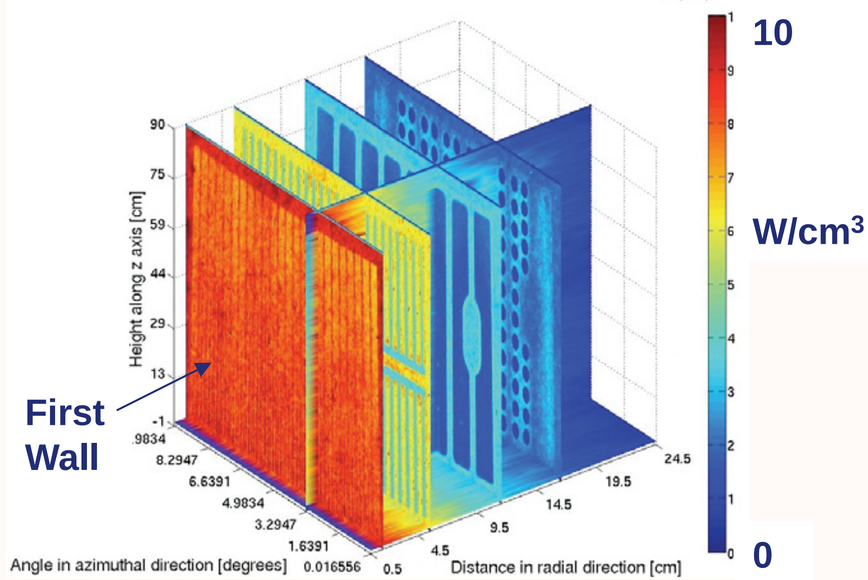
100 – 240 C,
3 - 4.4 MPa

Neutronics analyses need detailed models



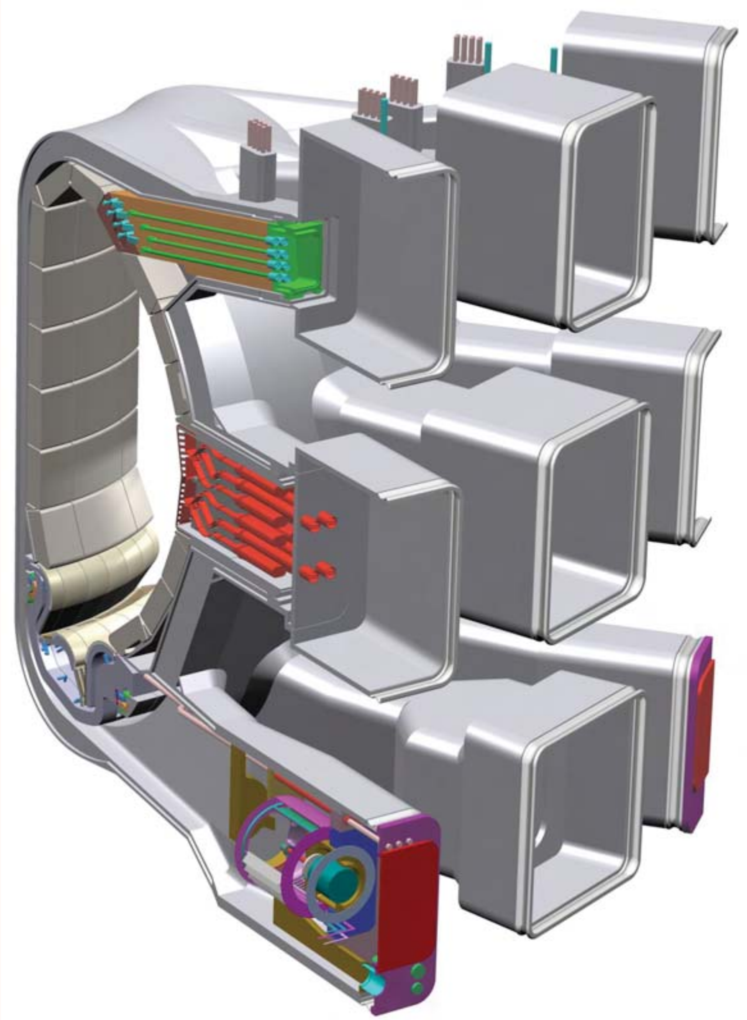


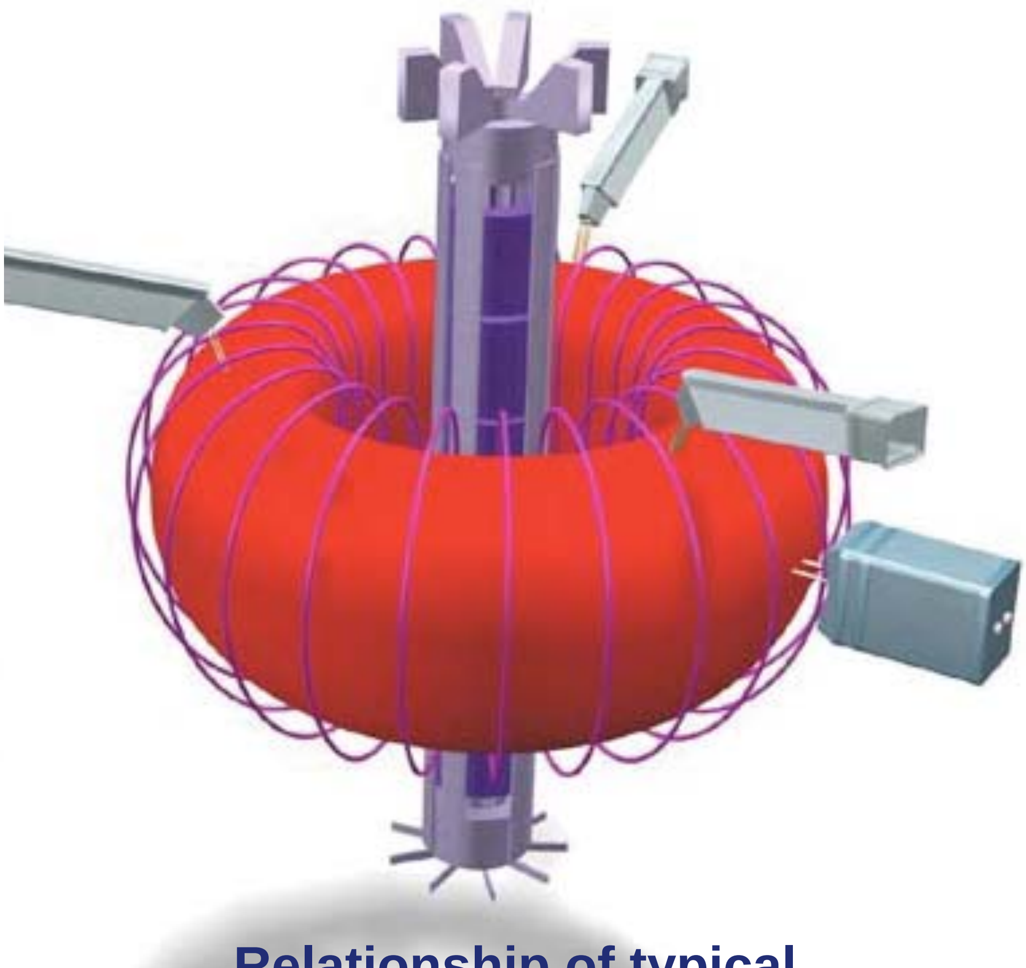




Detailed nuclear heating distr.

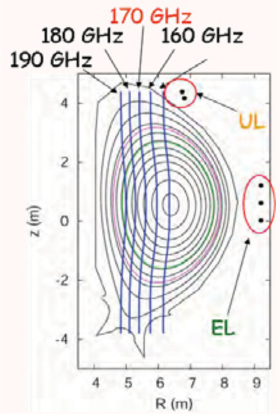
Numerous ports provide access for plasma heating, diagnostics, pumping, maintenance



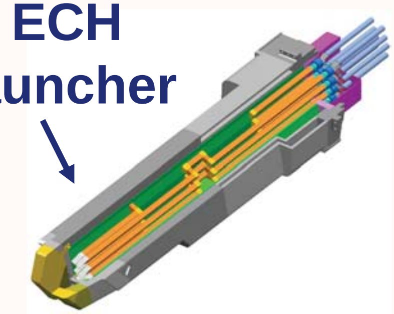


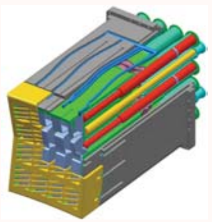
Relationship of typical port types to plasma

Plasma heating / current drive require multiple systems

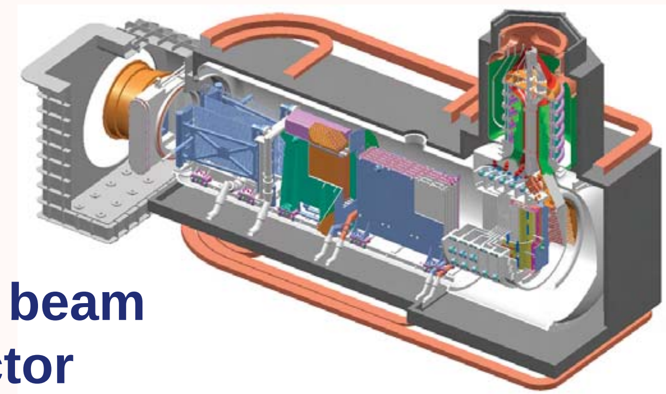


ECH launcher





ICH launcher
40-55 MHz

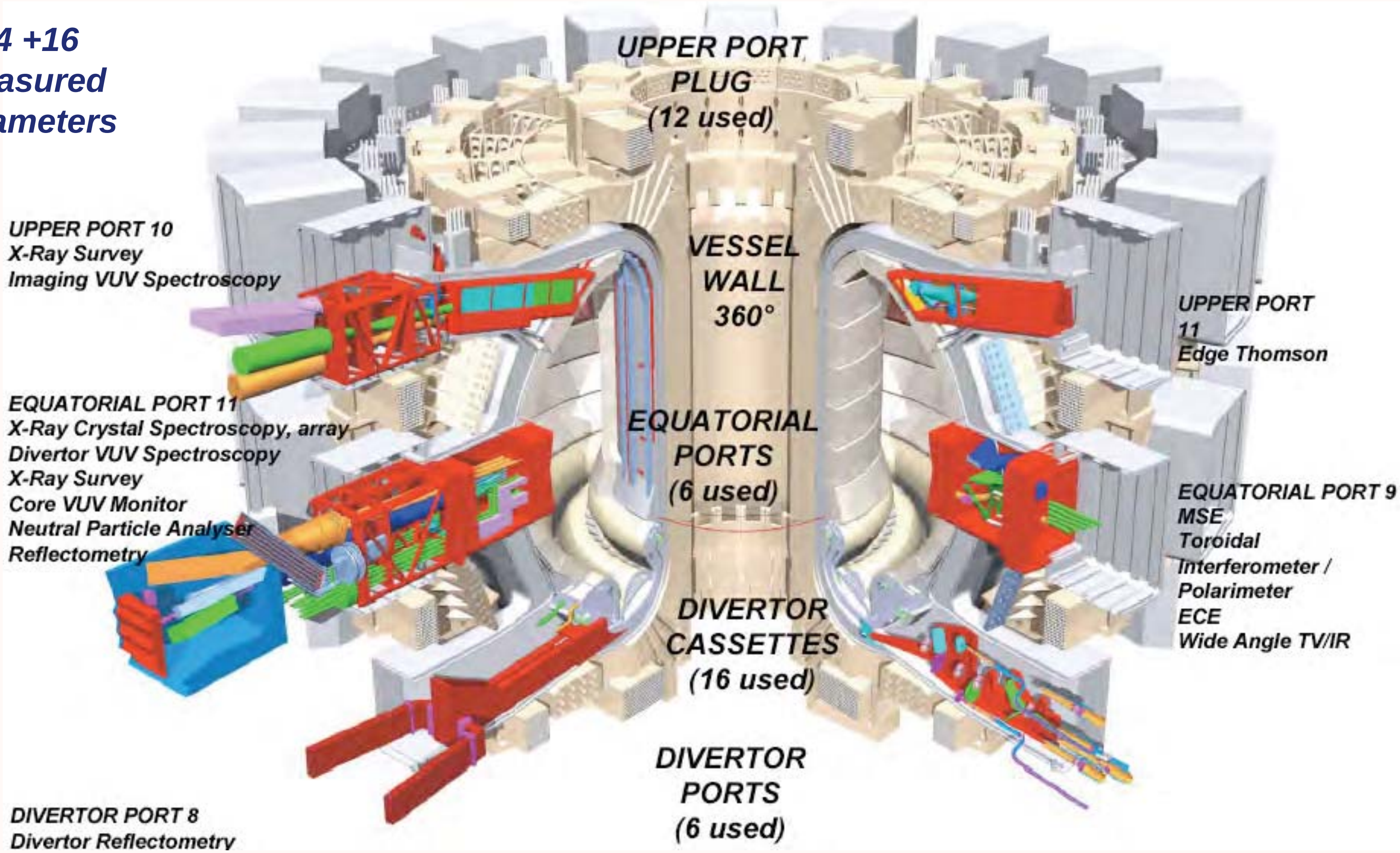


Neutral beam injector

- High energy (1 MeV D$^-$) ion beams + radio frequency heating tuned to key plasma frequencies (ion, electron cyclotron, lower hybrid).
- RF systems modular and interchangeable in equatorial ports. EC used in upper ports.
- 2 main beam-lines, with room for third.
- Initial installation 73 MW with room for expansion to 130 MW (installed).

Diagnostics monitor plasma behavior and must survive in harsh environment

44 +16 measured parameters



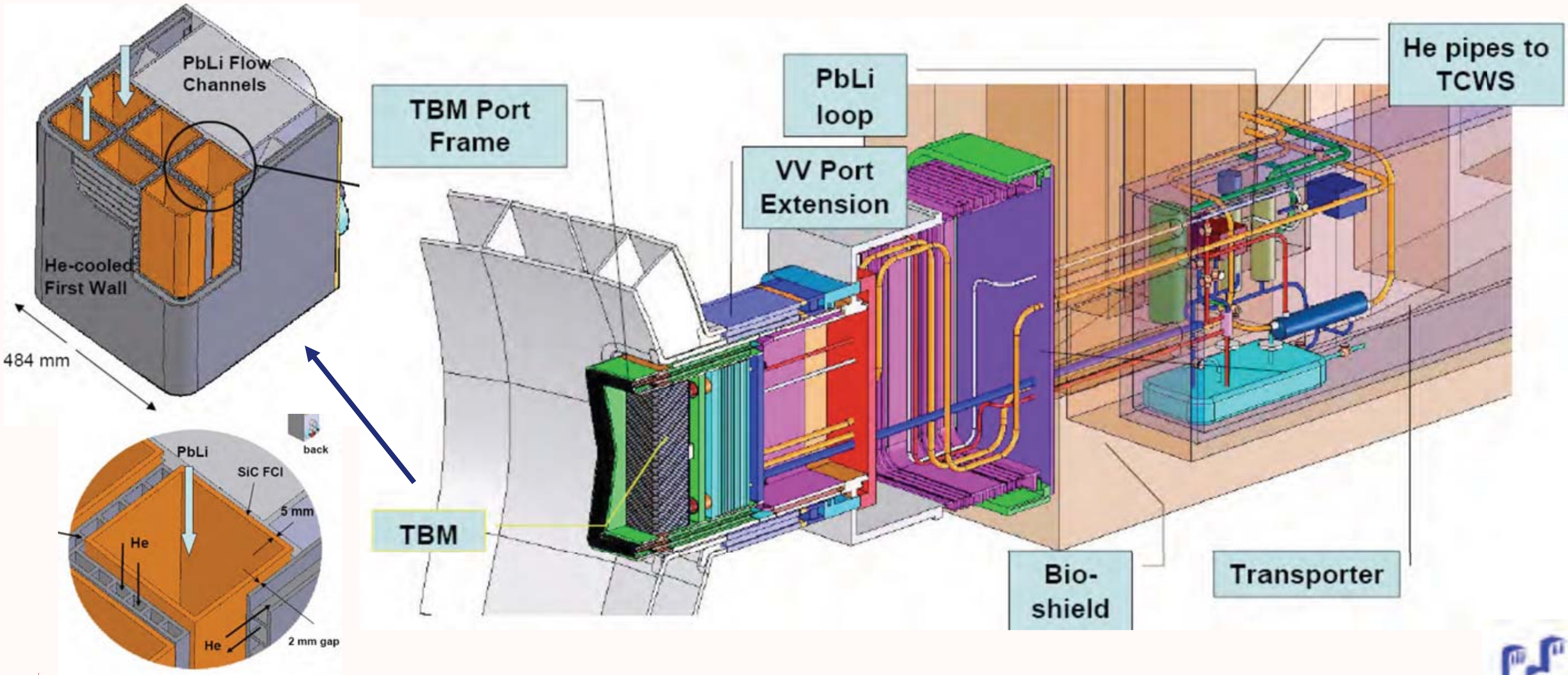
ITER environment (relative to JET)

- **High neutron and gamma fluxes** (up to x 10)
- **Neutron heating (1 MW/m^3)** (essentially zero)
- **High fluxes of energetic neutral particles from CX** (up to x5)
- **Long pulse lengths** (up to x 100)
- **High neutron fluence** (> 10^5 !)

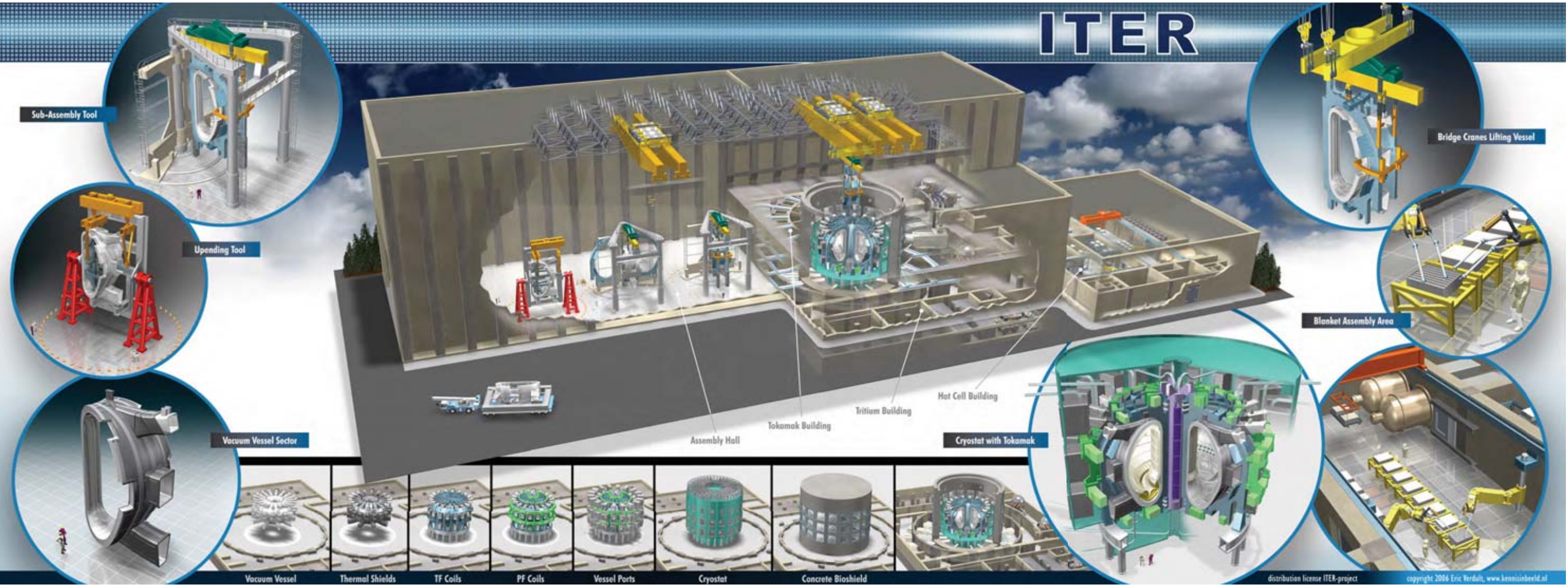
Ref Costley

Test Blanket modules demonstrate tritium breeding technology

- Tritium breeding is necessary for the fusion fuel cycle.
- Several breeding blanket concepts are under consideration.
- ITER provides three equatorial ports for test blanket modules.

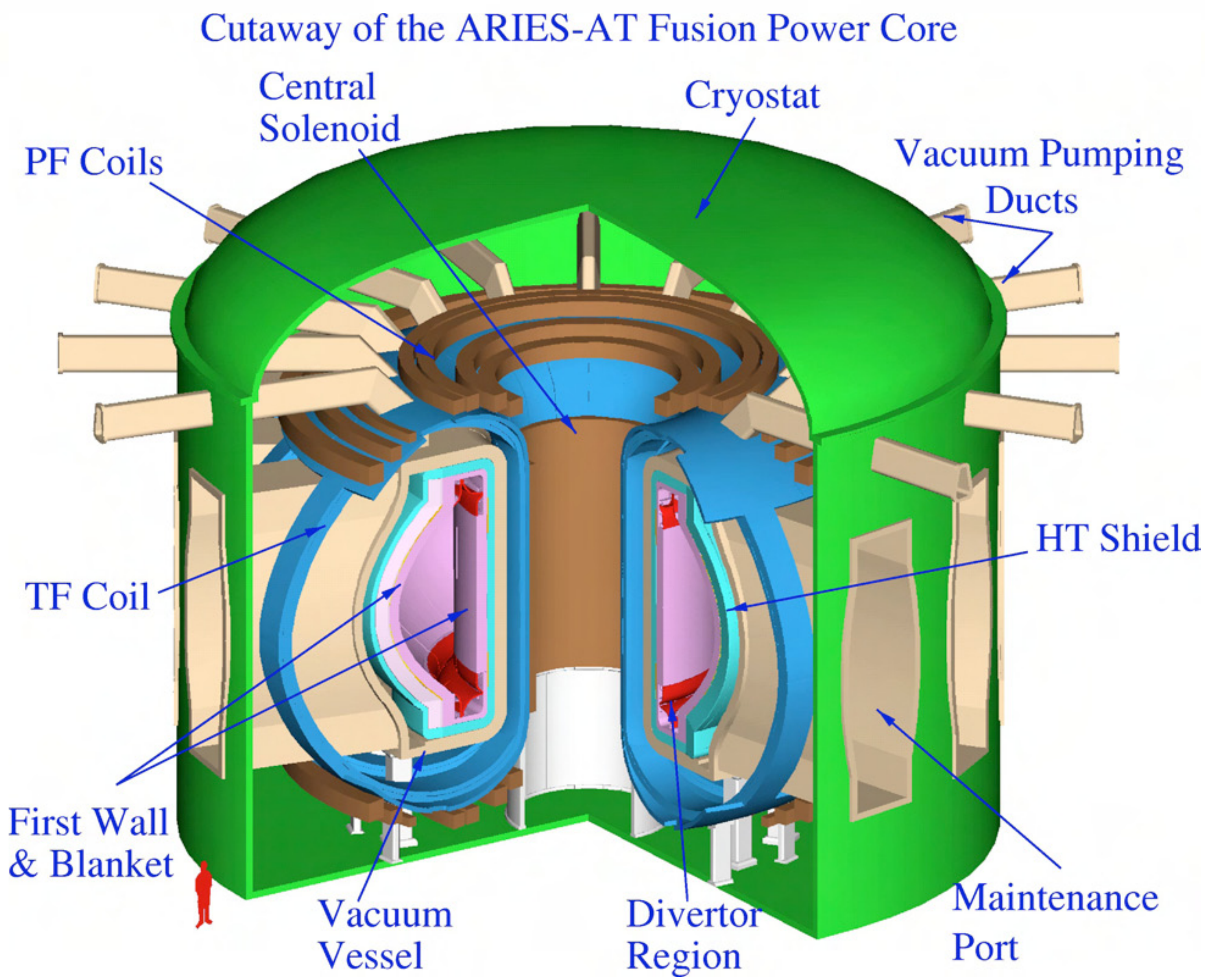


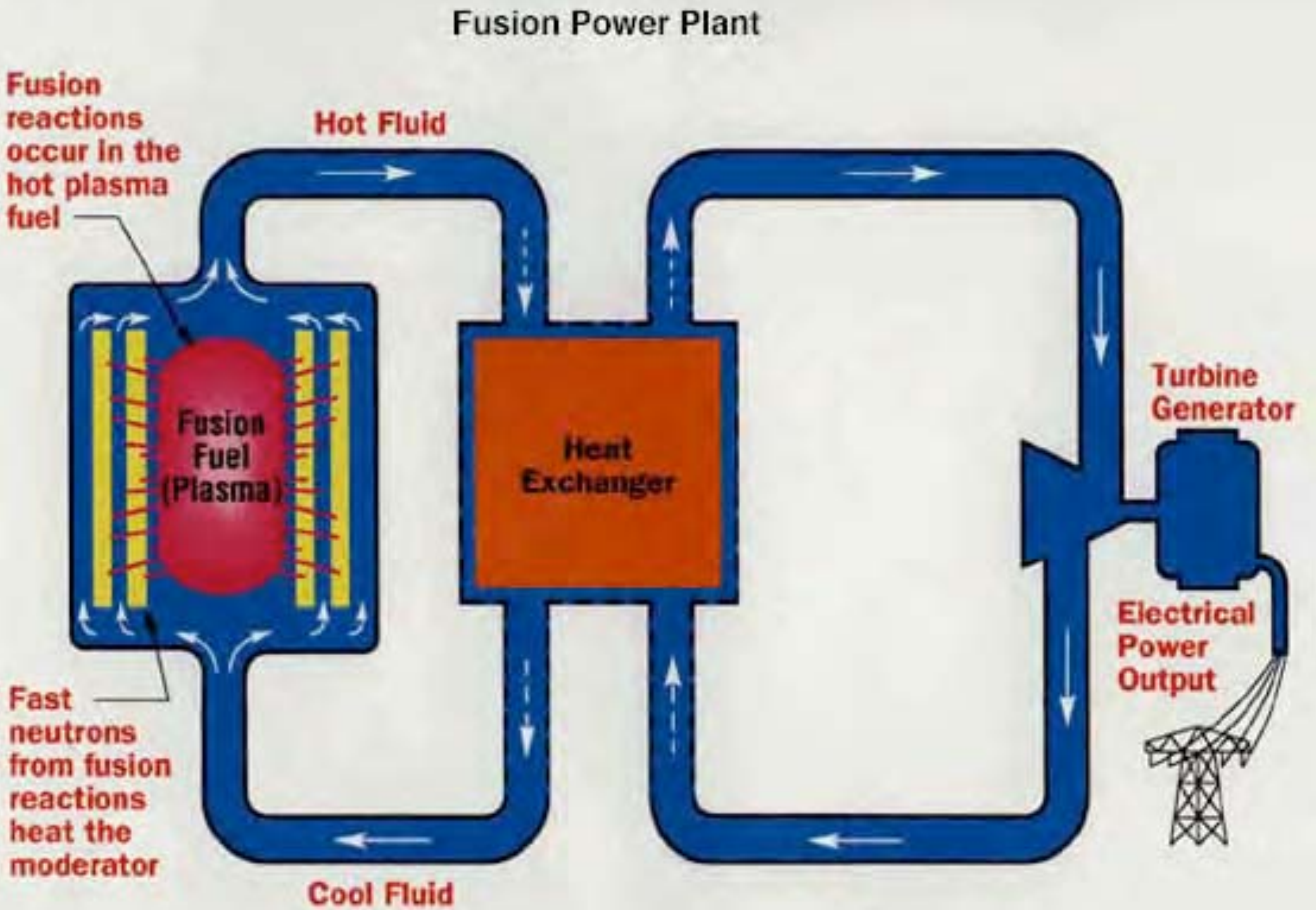
Finally, integration is key to success



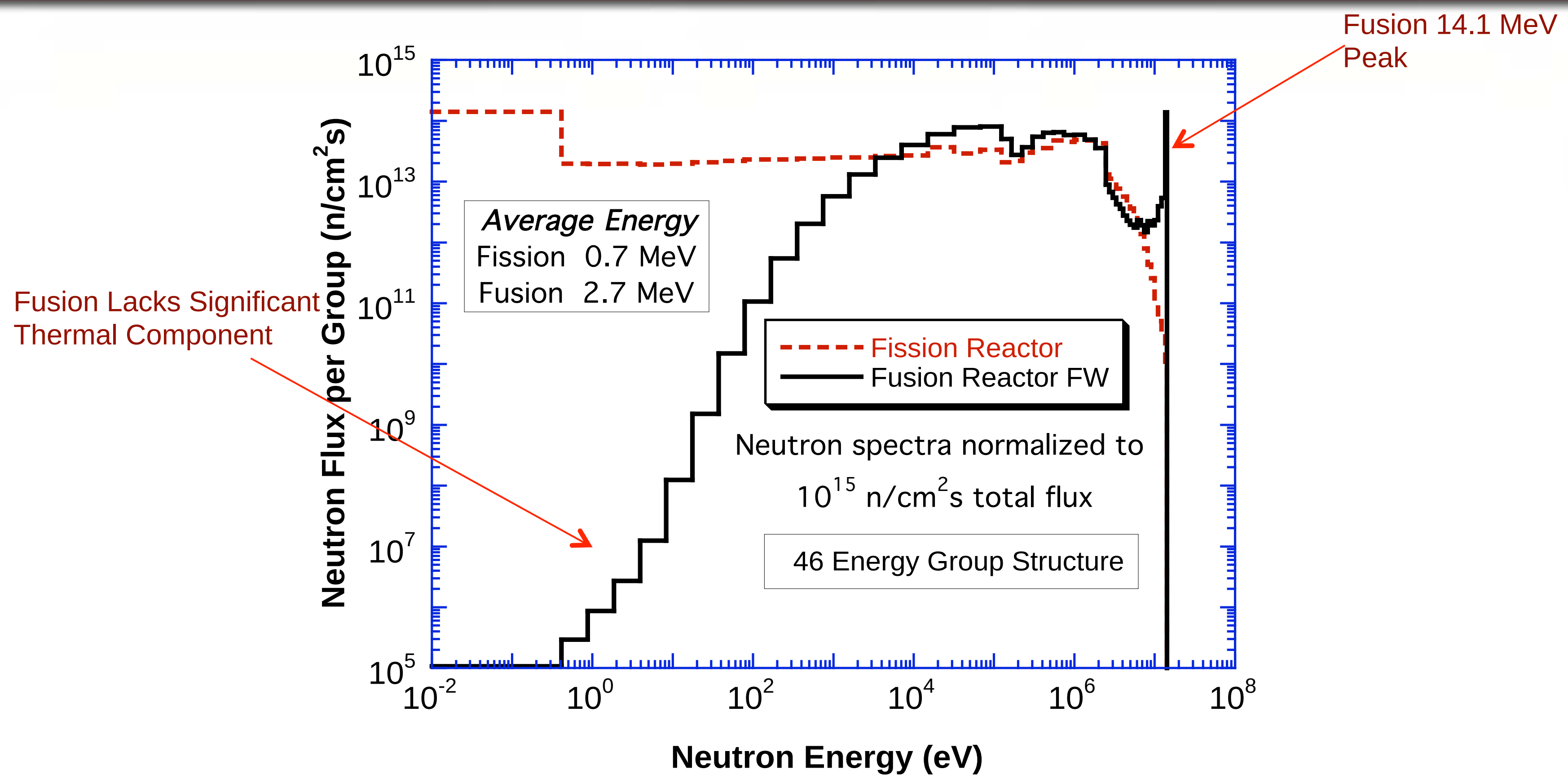
Coordination among all the team members is essential

What about Commercial Fusion Power Plants Beyond ITER?




Fusion Power Plant
Fusion reactions occur in the hot plasma fuel
Hot Fluid
Fusion Fuel (Plasma)
Heat Exchanger
Turbine Generator
Electrical Power Output
Fast neutrons from fusion reactions heat the moderator
Cool Fluid

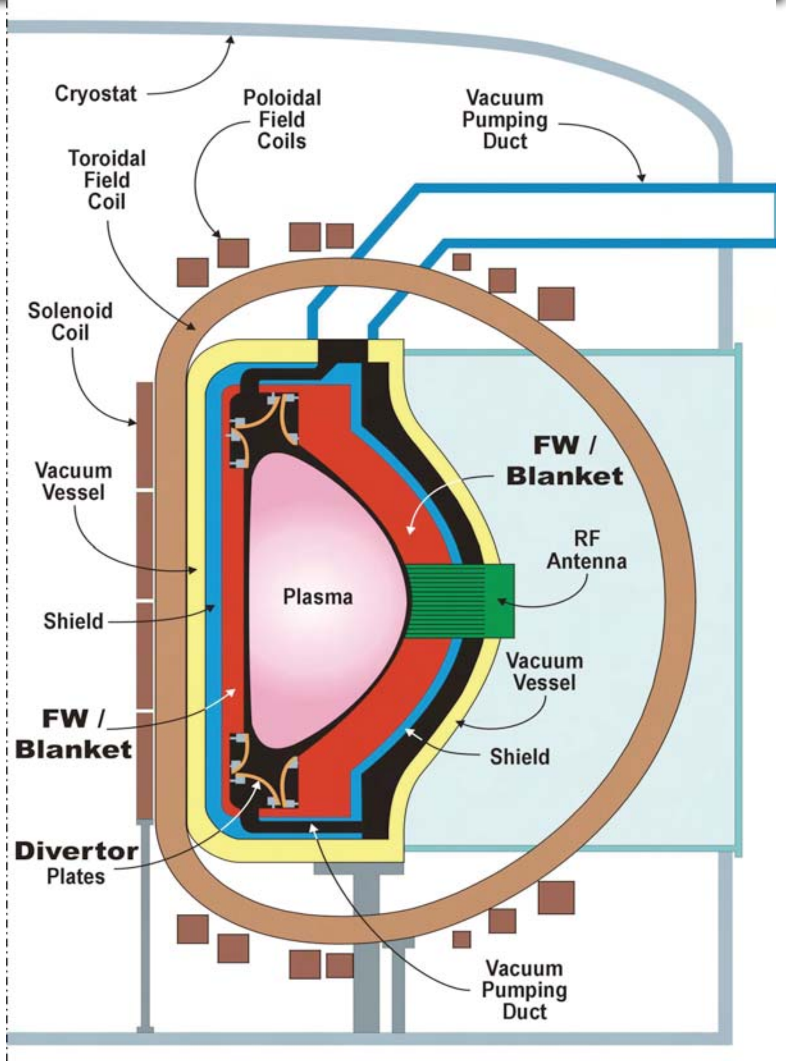
Much Harder Neutron Spectrum in Fusion Compared to Fission



- He/dpa ratio is significantly higher than in a fission reactor nuclear environment (~10 vs. ~0.3 for FS)

Do we still get radioactive waste in fusion reactors?

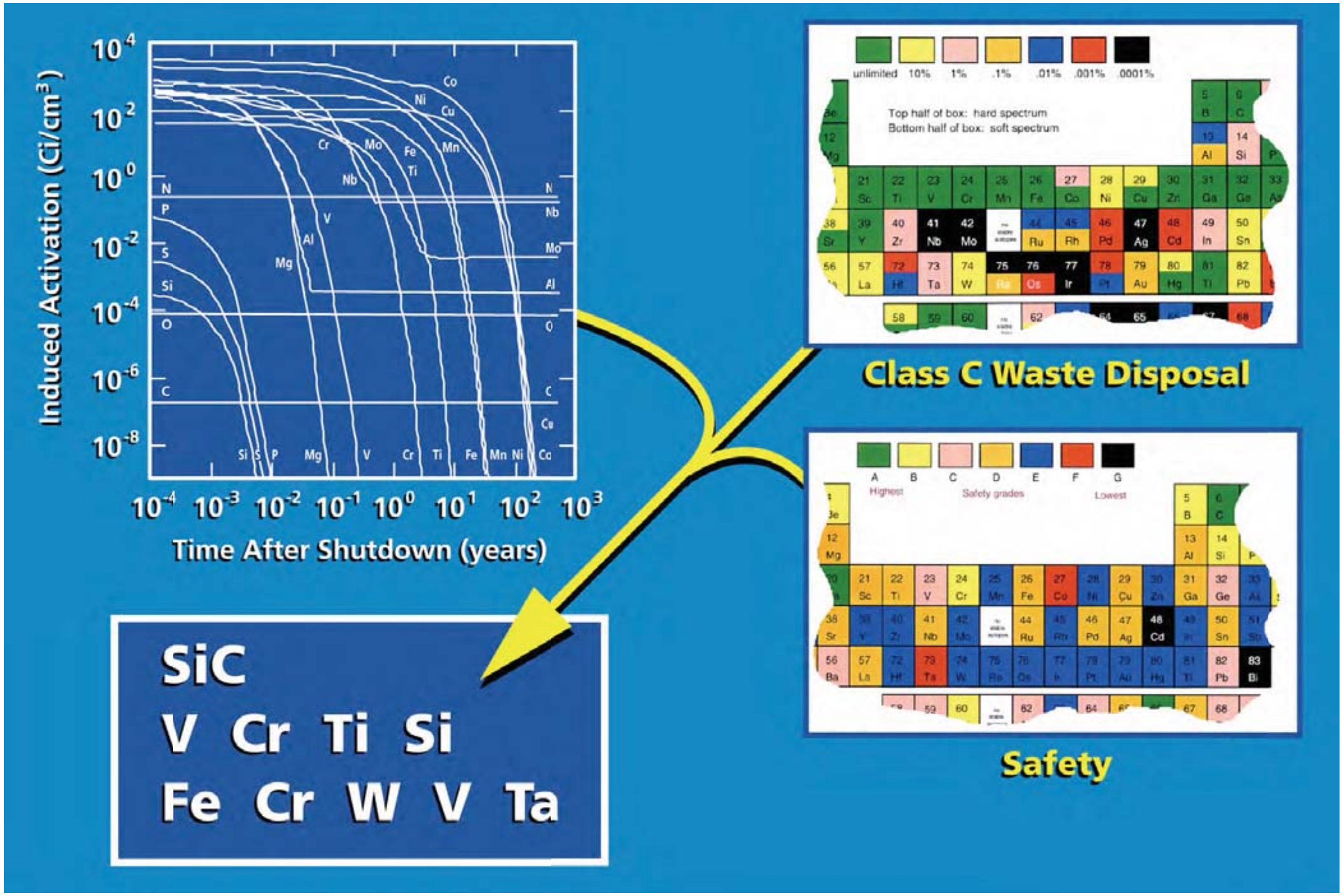
- Energetic 14 MeV neutrons are emitted in plasma and slowed down and absorbed by surrounding components
- Neutron interactions result in producing radioactive materials
- Proper choice of "low activation" materials help eliminating generation of high level long lived waste
- Most fusion waste can be either recycled or is classified as low level waste for shallow land burial



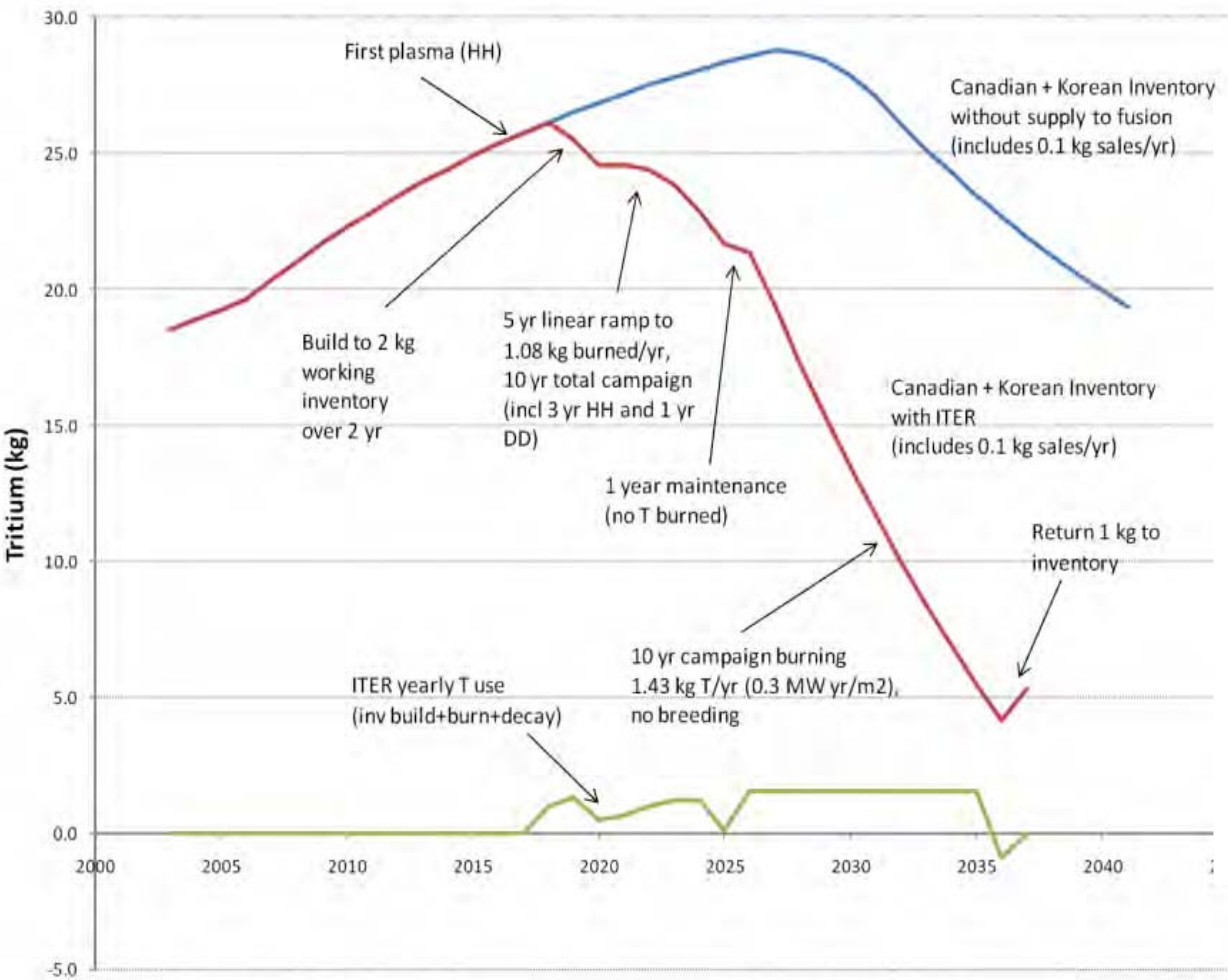
Low Activation Structural Materials for Fusion

Based on safety, waste disposal and performance considerations, the 3 leading candidates are:

Ferritic/martensitic steels
Vanadium alloy
SiC/SiC composites



All Fusion Machines Beyond ITER Must Breed Their Own Tritium



Consumption: 55.6 kg/GWy

Production from fission: 2-3 kg/yr @$84-130M/kg
CANDU reactor: 27 kg from over 40 years @ $30M/kg (current)

Tritium decays @ 5.4% per year

A successful ITER will exhaust most of the world supply of tritium

All subsequent machines must have TBR>1

From Scott Willms, LANL

Tritium Self-Sufficiency

To ensure tritium self-sufficiency, the calculated achievable tritium breeding ratio should be equal to or greater than the required TBR

Required tritium breeding ratio

Is dependent on many system physics and technology parameters:

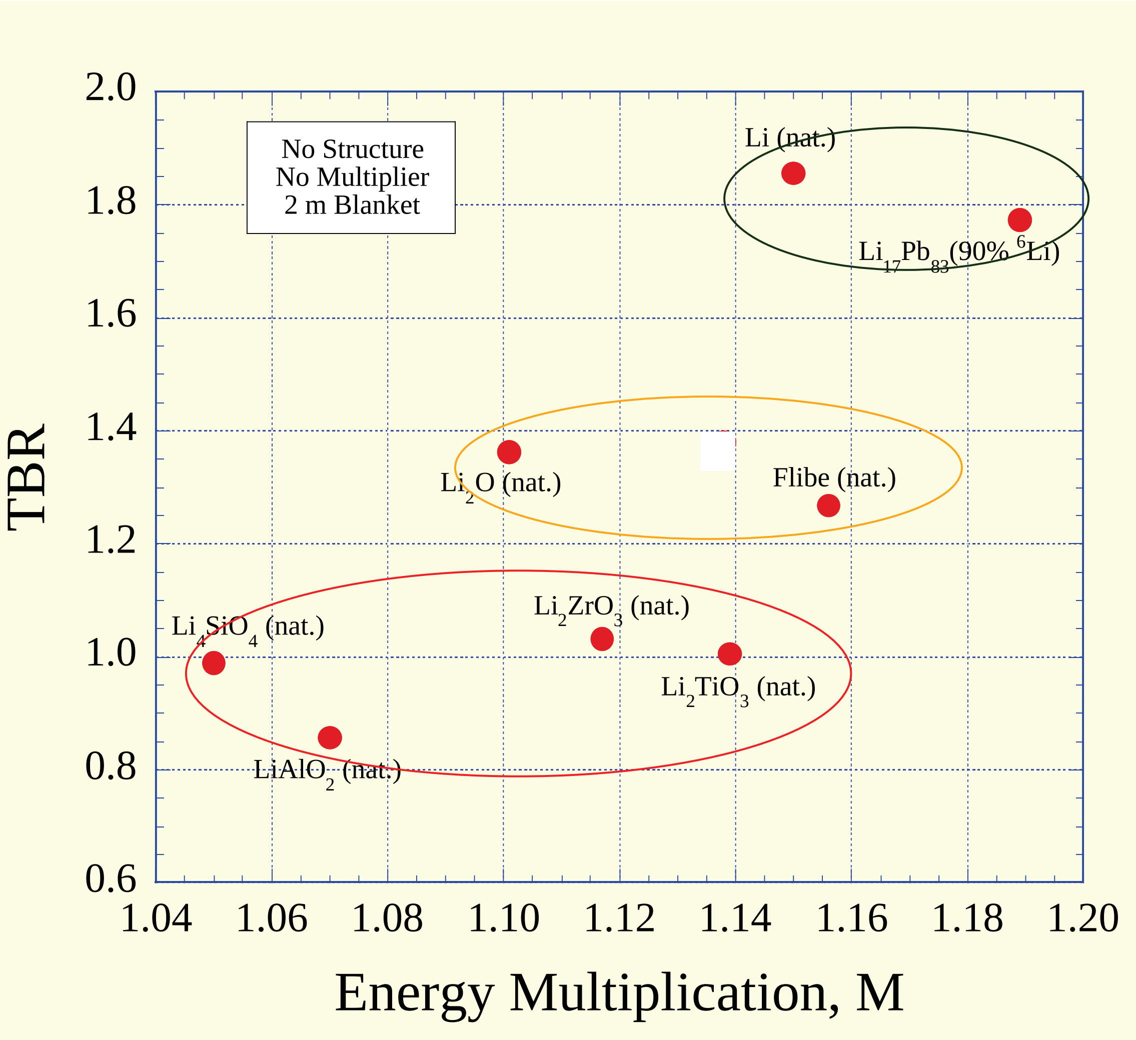
- plasma edge recycling, tritium fractional burn-up in the plasma
- tritium inventories (release/retention) in components
- efficiency/capacity/reliability of the tritium processing system

Achievable tritium breeding ratio

Is a function of technology, material and physics:

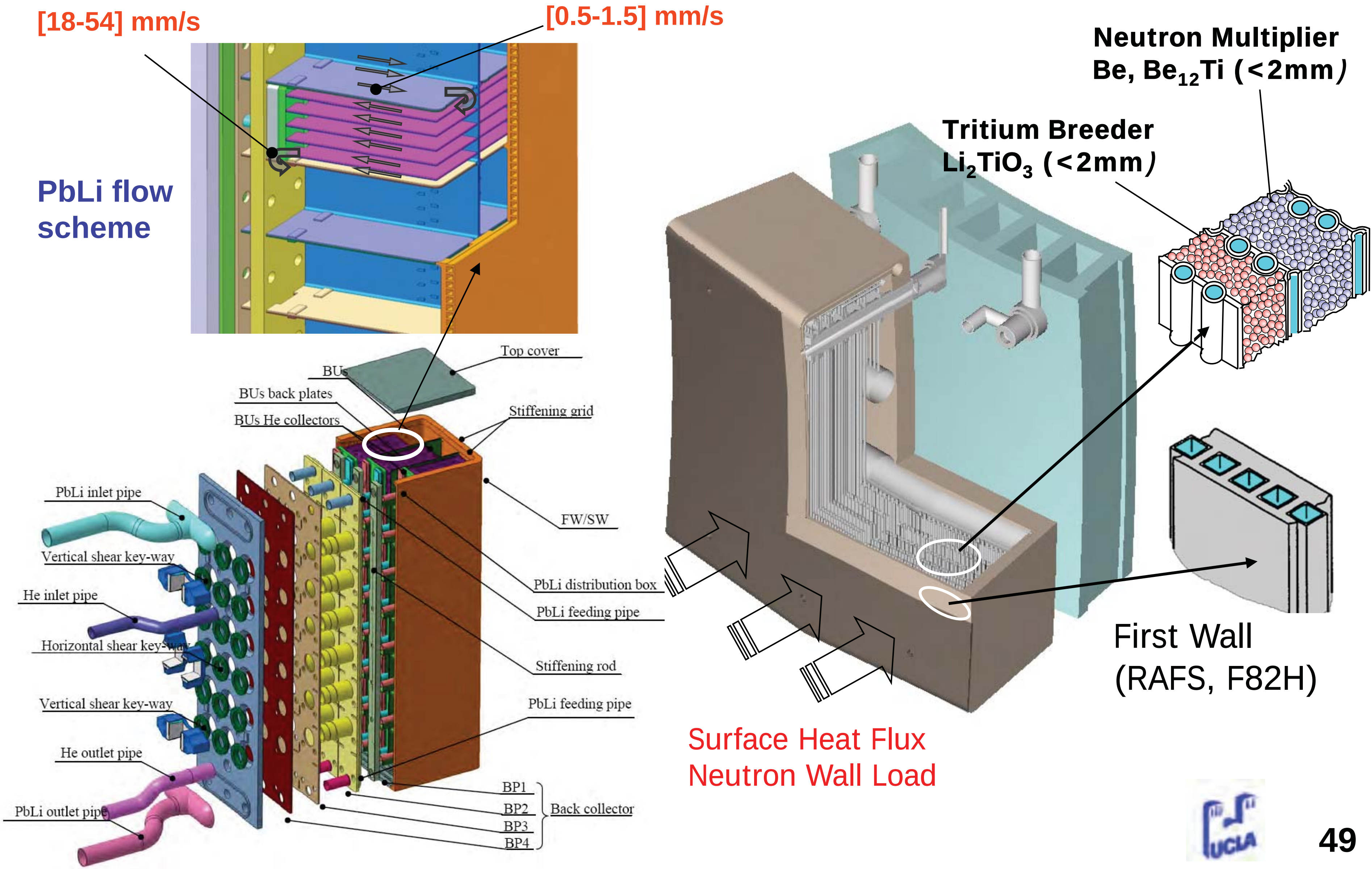
- FW thickness, amount of structure in the blanket, blanket concept
- Presence of stabilizing/conducting shell materials/coils for plasma control and attaining advanced plasma physics modes
- Plasma heating/fueling/exhaust, PFC coating/materials/geometry
- Plasma configuration (tokamak, stellerator, etc.)
- Uncertainties in nuclear data required for accurate determination of TBR

Tritium Breeding Potential of Candidate Breeders



- Li and LiPb have highest breeding potential
- Breeders with moderate breeding potential (Li_2O, Flibe) require moderate amount of multiplier
- Ceramic breeders have poor breeding potential and require significant amount of multiplier and minimal structure content
- In realistic designs, the structure, configuration, and penetrations will degrade the achievable overall TBR below the values shown

Blankets systems are complex and have many integrated functions, materials, and interfaces



One Example of Innovation

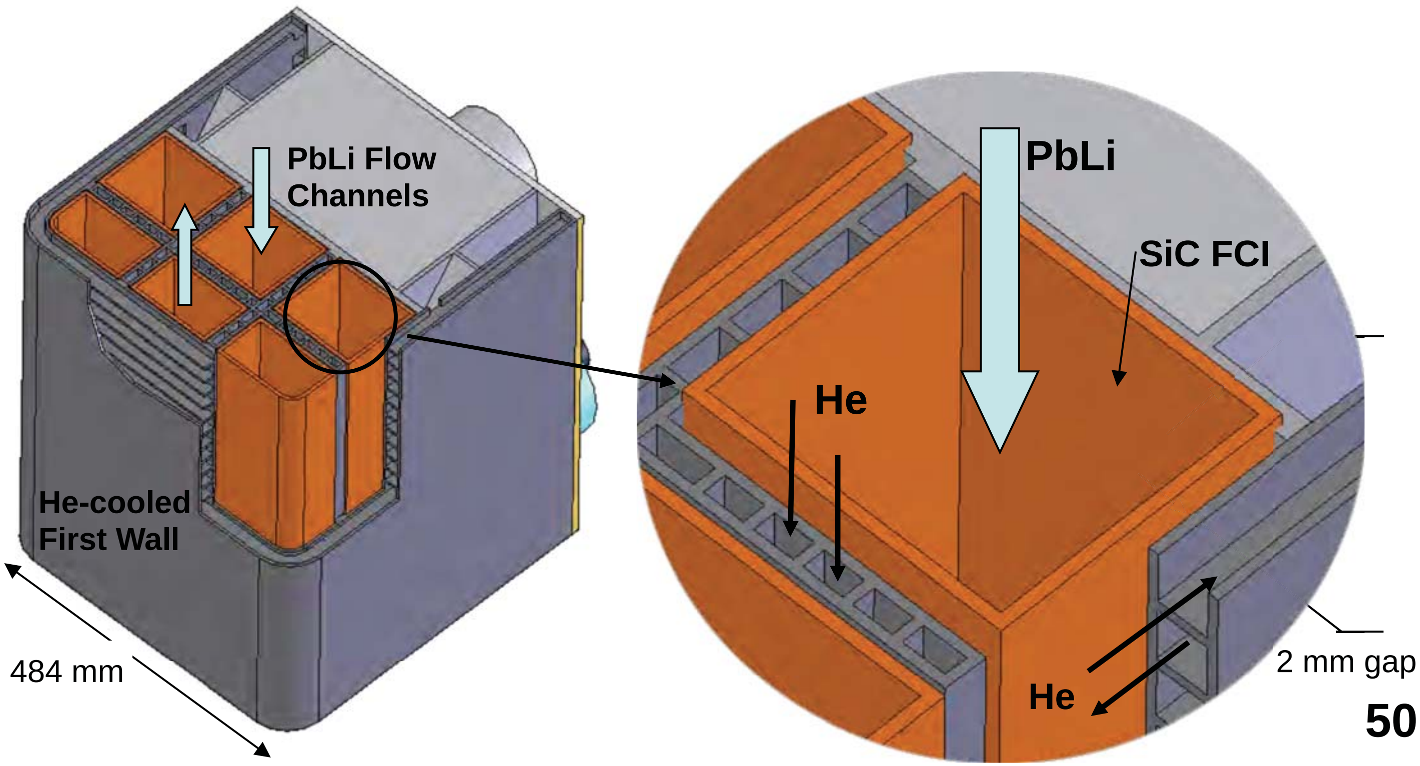
The US-Selected Dual Coolant Lead Lithium (DCLL) TBM Concept provides a pathway to high outlet temperature with current generation structural materials :

- Use RAFS with He cooling for structure, but SiC Flow Channel Inserts (FCI) to thermally and electrically isolate PbLi breeder/coolant
- Result is High outlet temperature PbLi flow for improved thermal efficiency, while making best use of both RAFS and SiC

DCLL Evolution:

- ***Developed in ARIES-ST ,US-APEX and in the EU-PPS***
- ***Adopted for ARIES-CS***
- ***Similar concept considered in US-IFE-HAPL program***

General to tokamak, stellarator and IFE

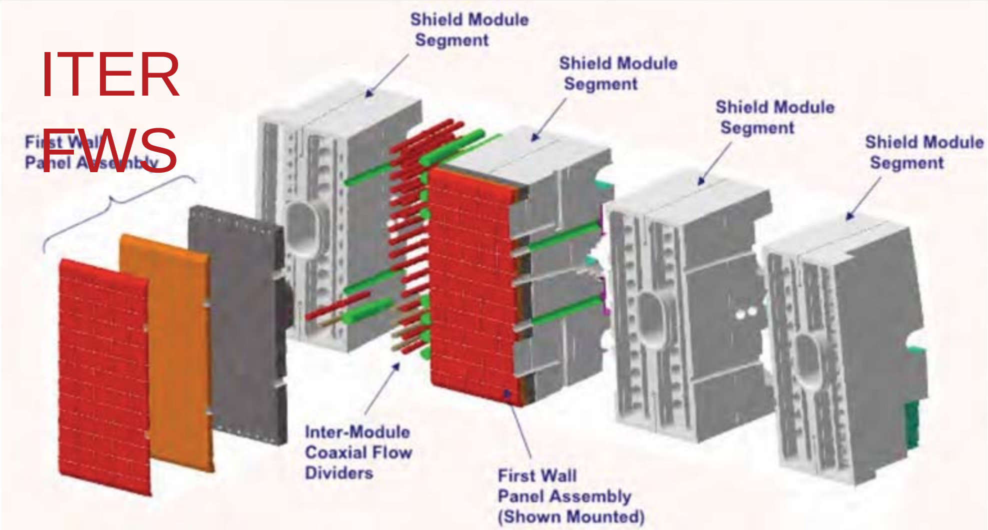


Nuclear Analysis is Essential Part of Fusion System Design

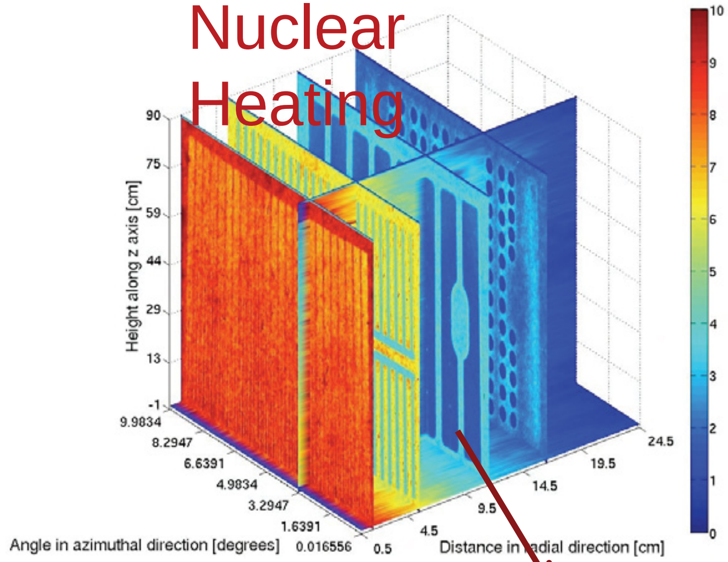
- Energetic 14 MeV neutrons are emitted in plasma and slowed down and absorbed by surrounding components
- Nuclear analysis for components surrounding the plasma is essential element of fusion nuclear technology
  - Tritium production in breeding blankets to ensure tritium self-sufficiency
  - Nuclear 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 essential to perform required nuclear analyses

DAG-MCNP Allows Generating High-Fidelity and High-Resolution Nuclear parameters

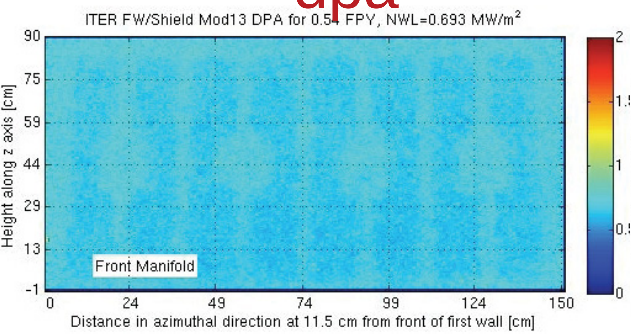
ITER FWS



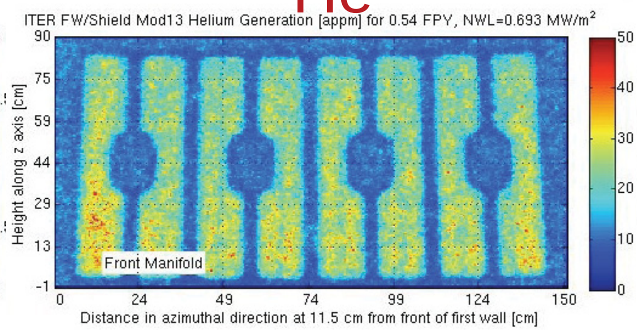
Nuclear Heating

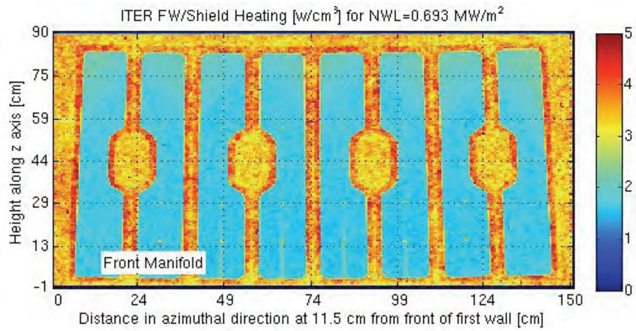


dpa



He

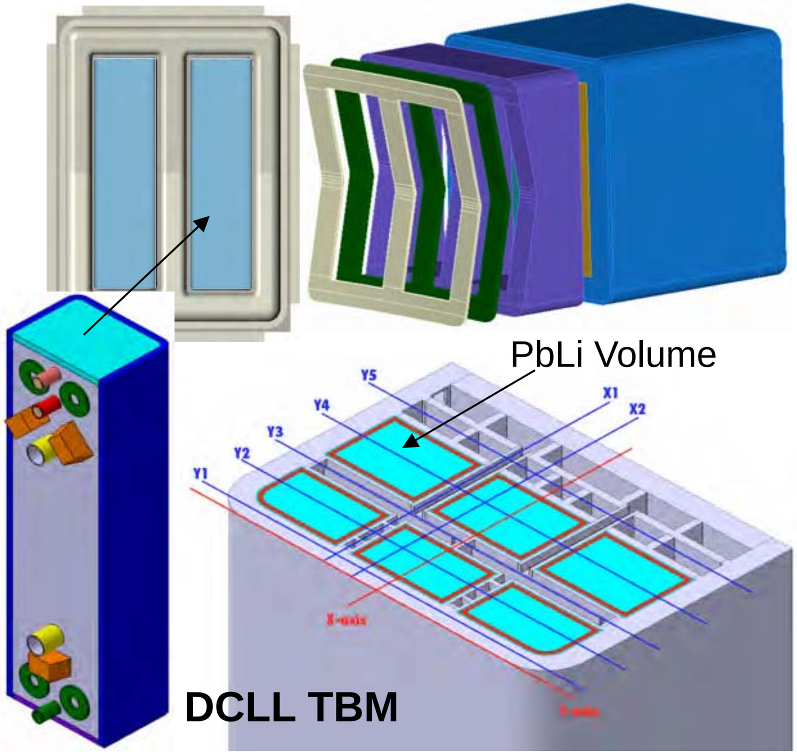




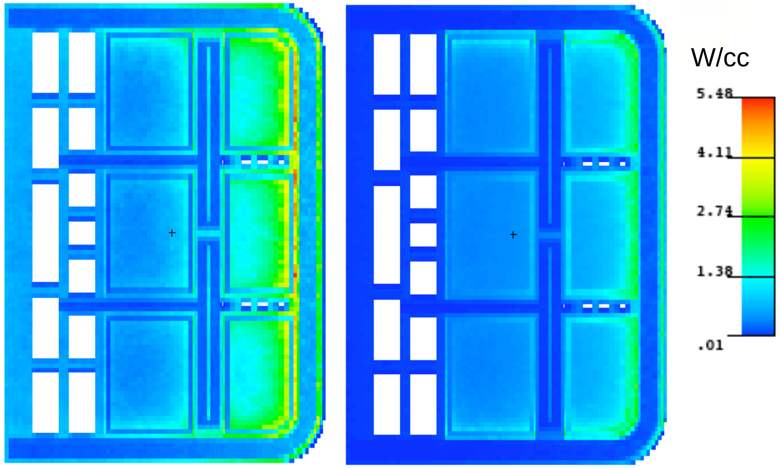
DAG-MCNP allows predicting truthful performance for the geometrically complex fusion systems

Example: Detailed DAG-MCNP 3-D neutronics analysis of TBM integrated with the surrounding water cooled frame and representation of exact source and other in-vessel components:

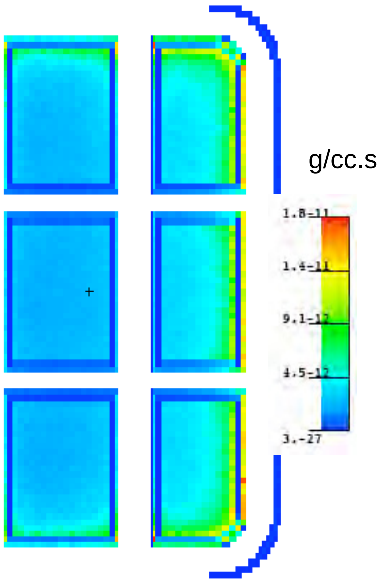
- yields total tritium production in the TBM that is 45% lower than the 1-D estimate
- yields total nuclear heating in the TBM that is 35% lower than the 1-D estimate of 0.574 MW



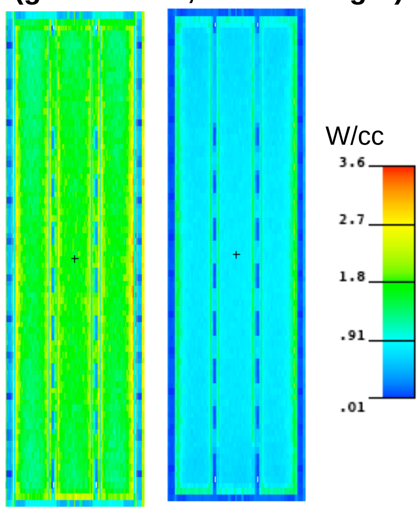
Mid-plane nuclear heating (gamma: left; neutron: right)



Mid-plane tritium production rate



Y2 plane nuclear heating (gamma: left; neutron: right)



Summary

- Fusion has the potential to be an attractive energy source, and research is under way in many countries around the world
- The ITER project combines the expertise from around the world to build the first fusion reactor – China, EU, India, Japan, Korea, Russian Federation and the U.S.
- An international organization has been established at Cadarache, France, where ITER will be built
- There are many engineering challenges, but each can be met
- ITER is proceeding toward a first plasma in 2018
- Additional technological challenges should be overcome to realize fusion as an attractive source of sustainable and environmentally friendly source of energy