# ITER

# der entscheidende Schritt zum Fusionsreaktor

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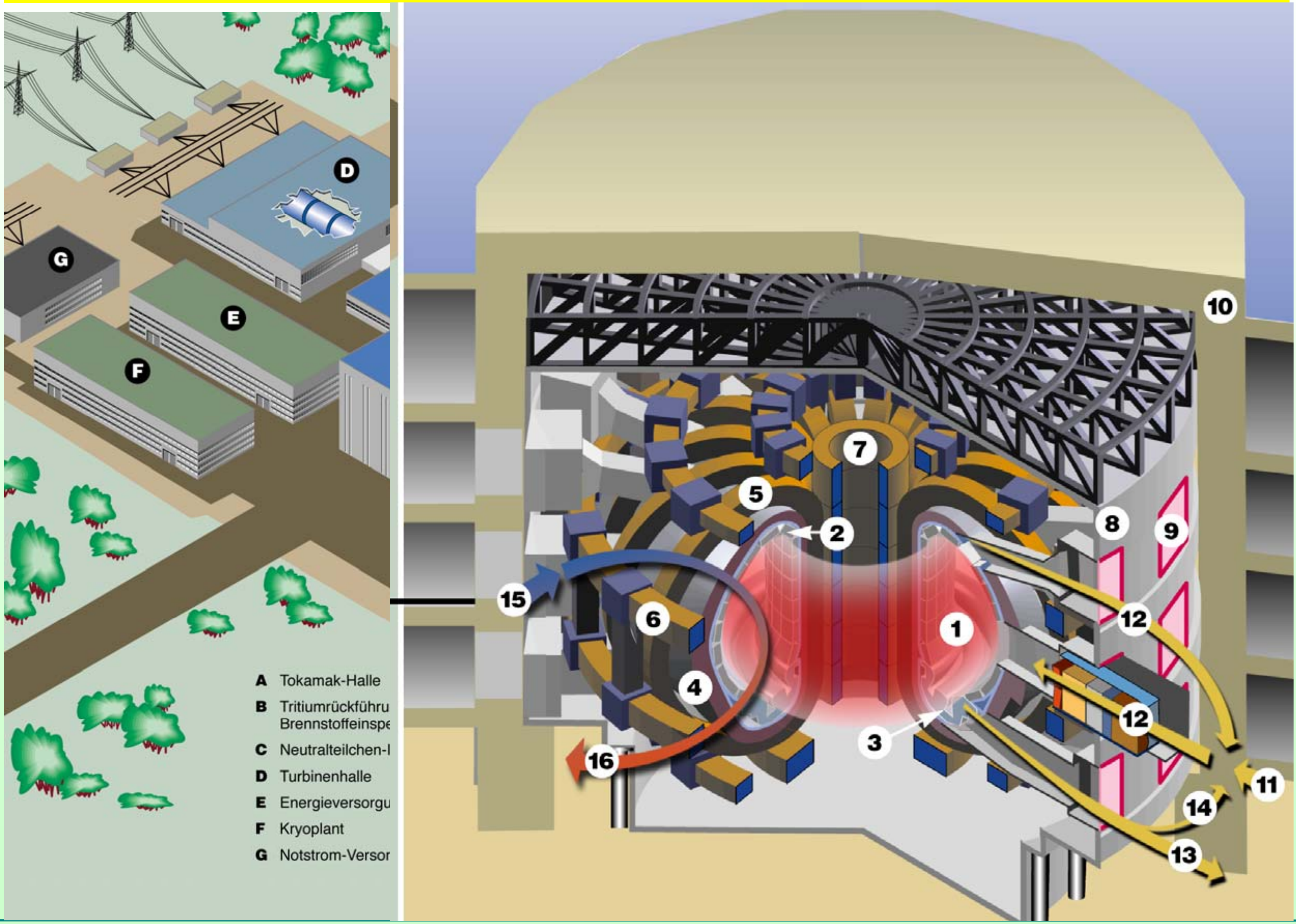
Fusion
die Energiequelle der Sonne
muss auf der Erde nutzbar
gemacht werden

# Schematic View of a Fusion Power Reactor



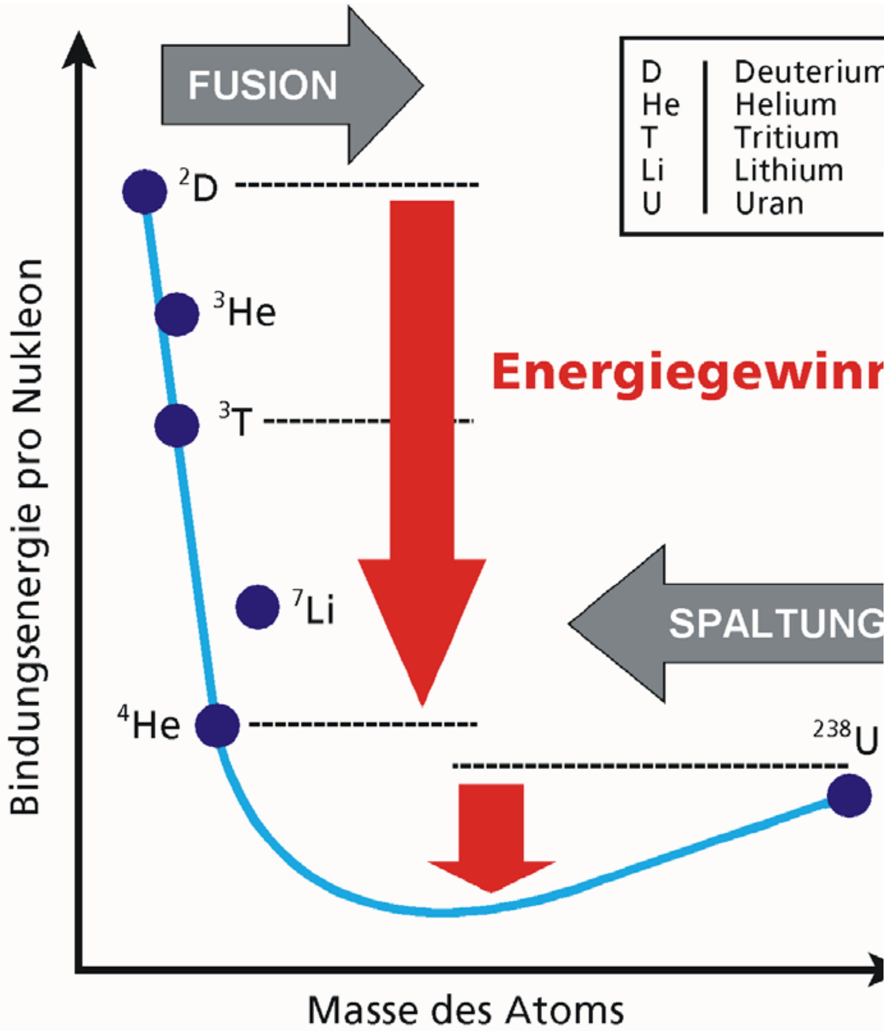
# ITER is not a reactor
# but it is an experiment with a reactor plasma

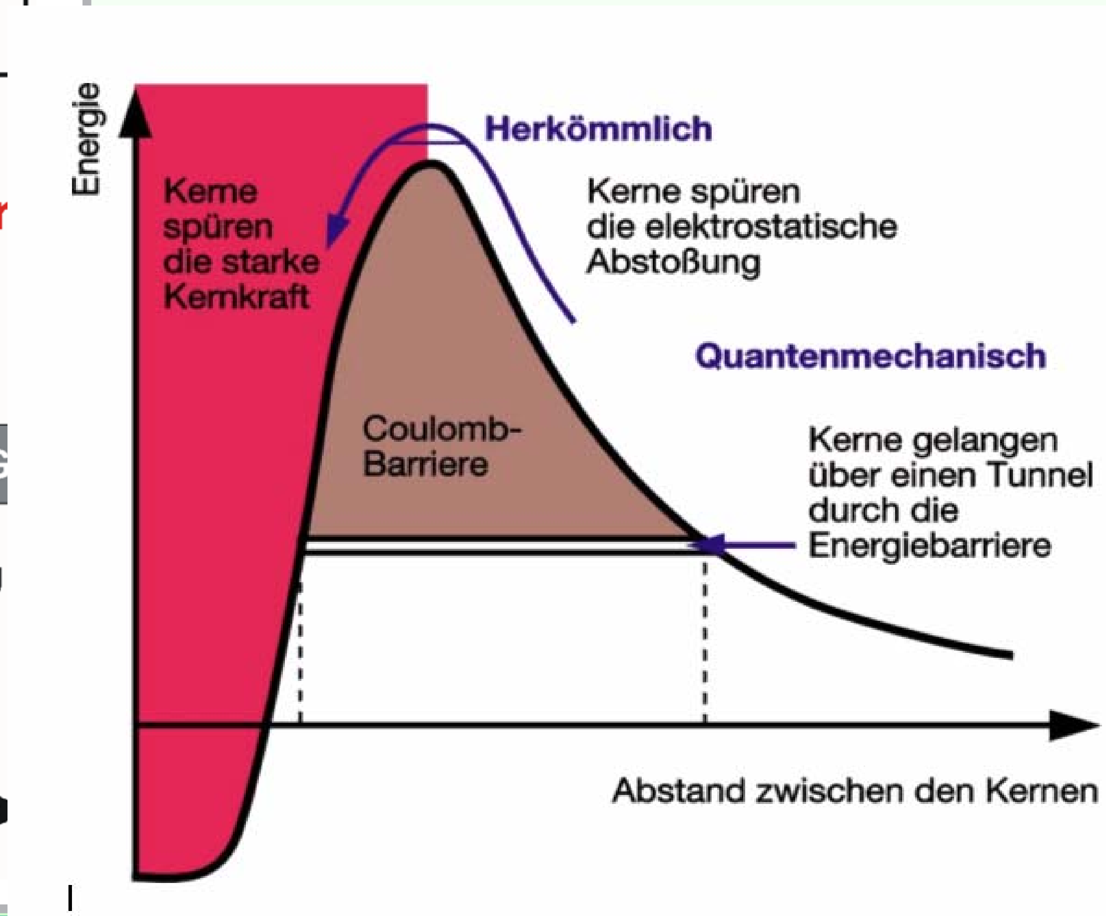
## Outline

- **Fusion Basics**
- **How to size a reactor class machine**
- **ITER history and objectives**
- **ITERs design, technology and R&D**
- **The Challenges ahead and conclusions**

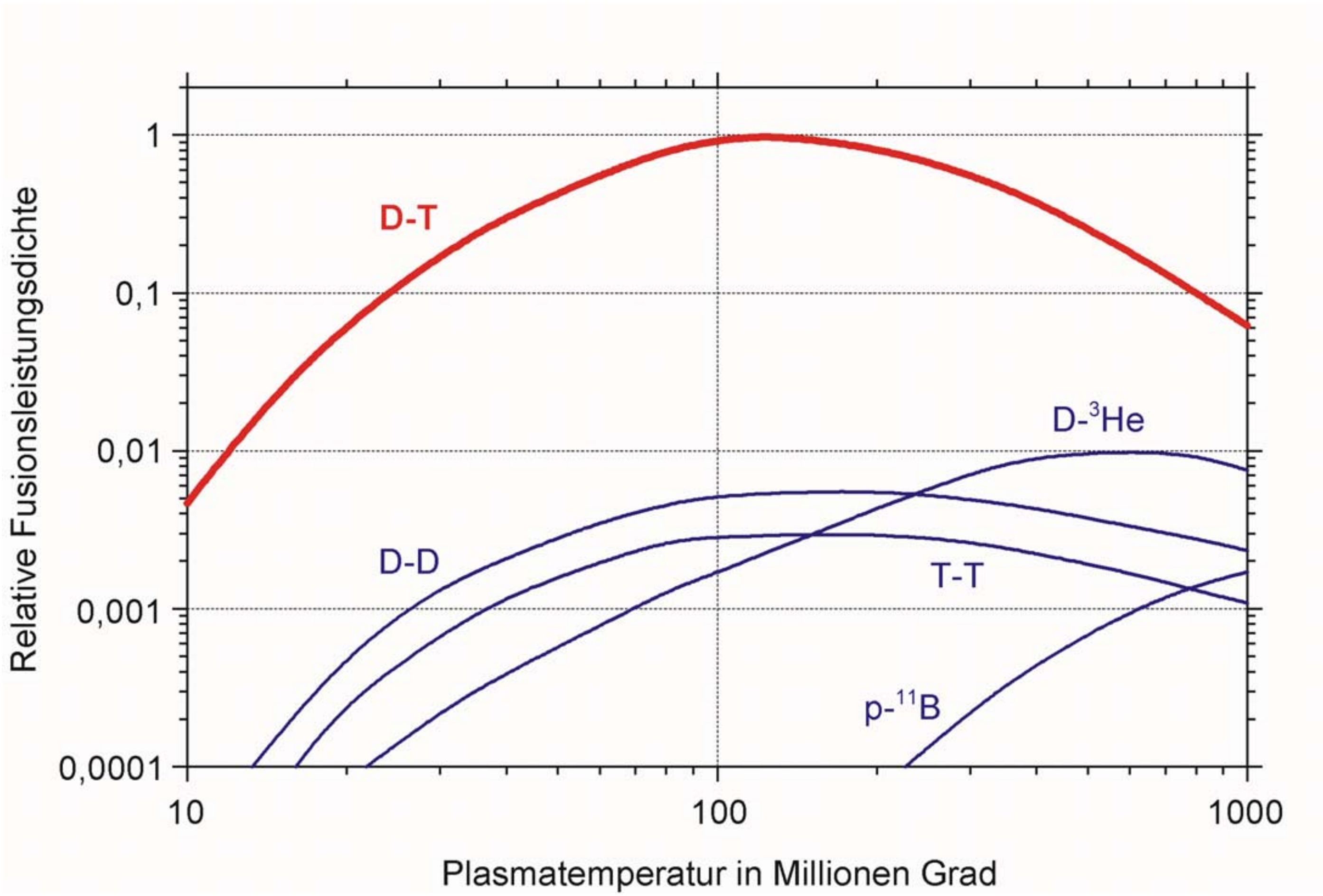
# For Fusion to happen the Coulomb Barrier has to be overcome

- Needs kinetic energy
- Could be provided by temperature



# Die wichtigsten Fusionsreaktionen




**Abkürzungen**

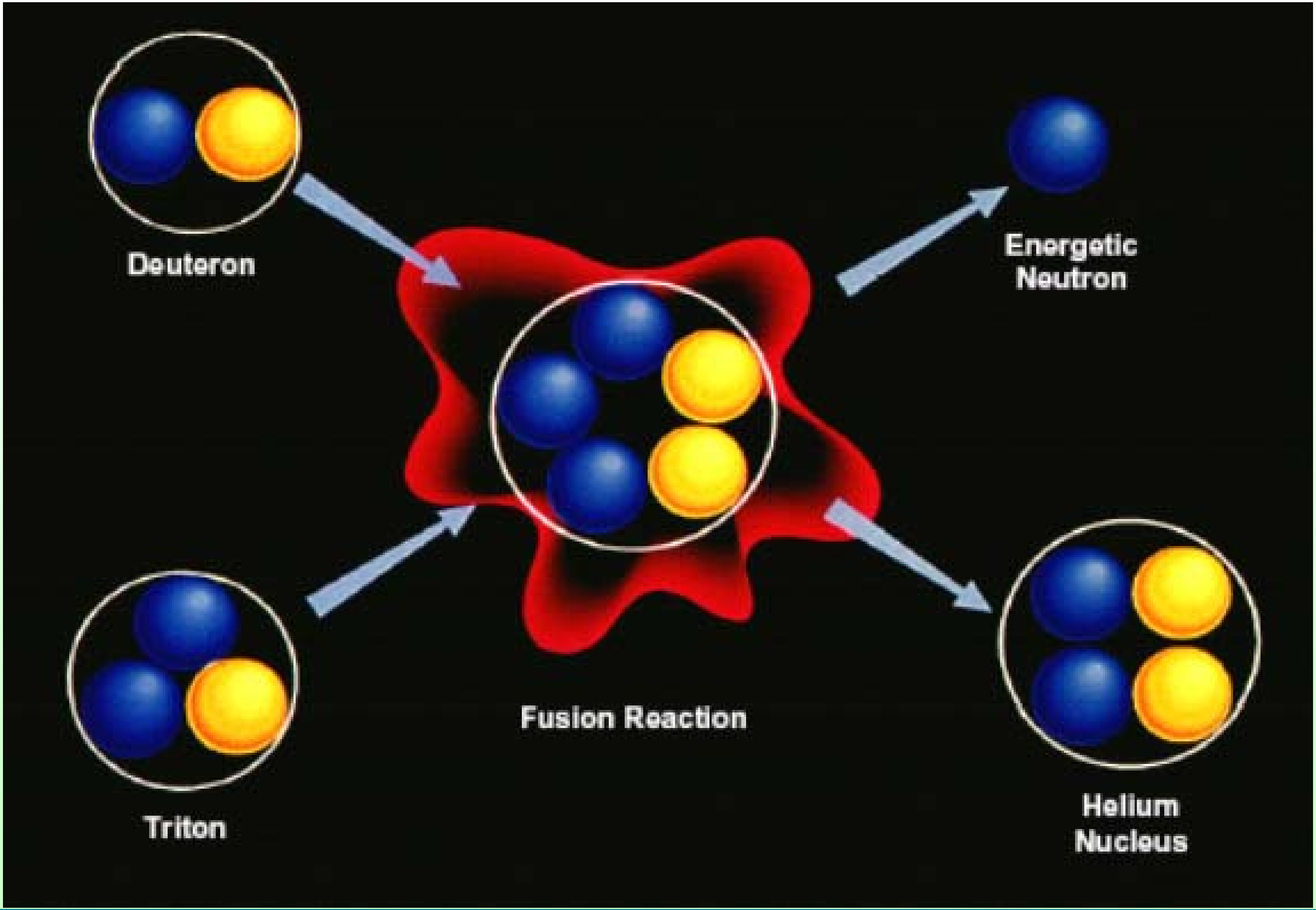
| | |
|---|---|
| D | Deuterium |
| T | Tritium |
| He | Helium |
| B | Bor |
| p | Proton |

**Reaktionen**

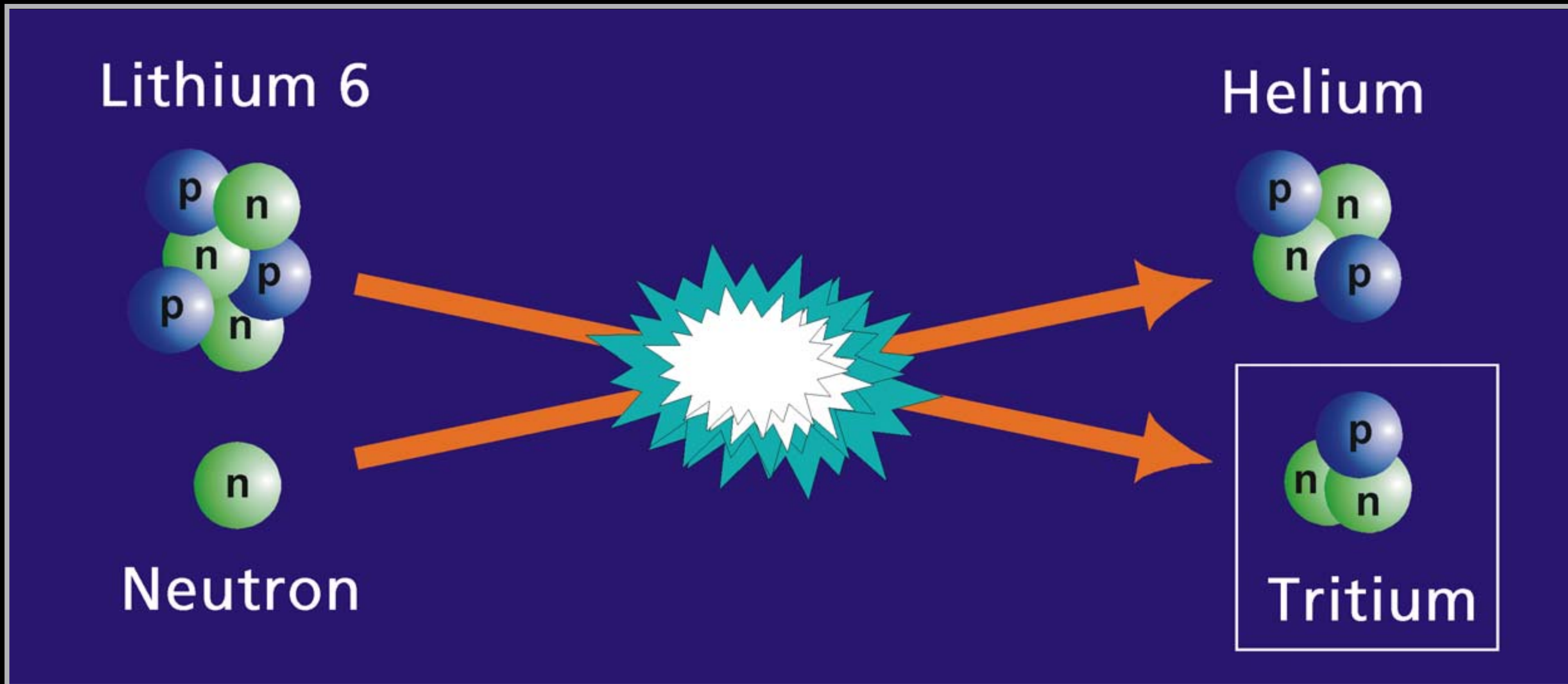
**D + T → $^4$He + n**

D + D → $^3$He + n
→ T + p
D + $^3$He → $^4$He + p
T + T → $^4$He + 2n
p + $^{11}$B → 3 $^4$He

**Optimal ist die Deuterium/Tritium-Reaktion bei etwa 100 Millionen Grad Plasmatemperatur**


Deuteron
Energetic Neutron
Fusion Reaction
Triton
Helium Nucleus

# Tritium muss erbrütet werden




Tritium ist radioaktiv. Wegen der Halbwertszeit von nur 12 Jahren ist es in der Natur nicht ausreichend vorhanden. Tritium muss deshalb künstlich aus Lithium hergestellt („erbrütet") werden.

**Die Rohstoffe der Fusion sind Deuterium und Lithium**

# Fusion ist eine sichere abfallarme nukleare Energiequelle

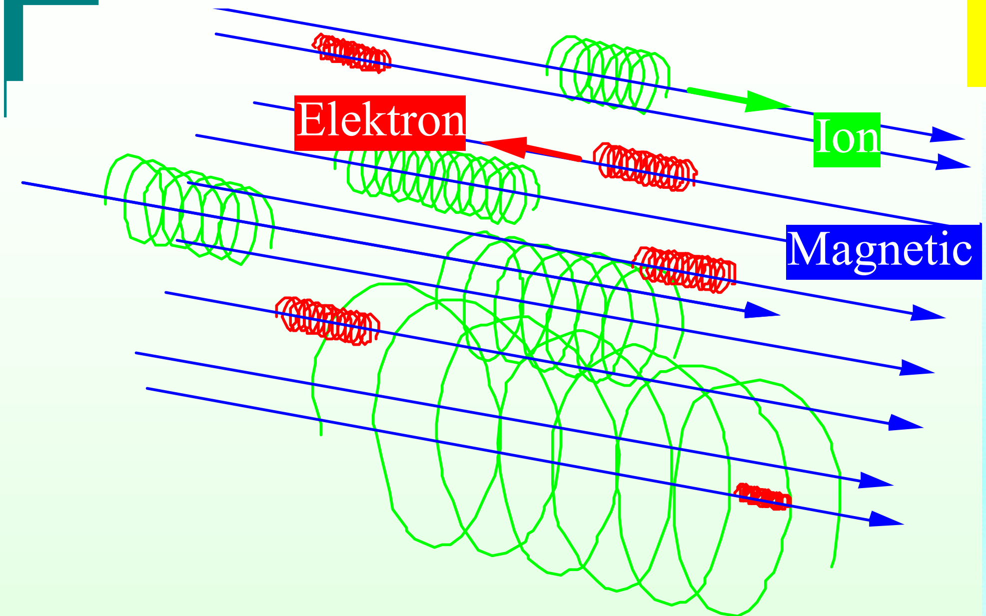
- Bei derzeitigem Weltenergieverbrauch hat die Fusion eine Reichweite von etwa 30 Millionen Jahren => praktisch unbegrenzte Energieversorgung

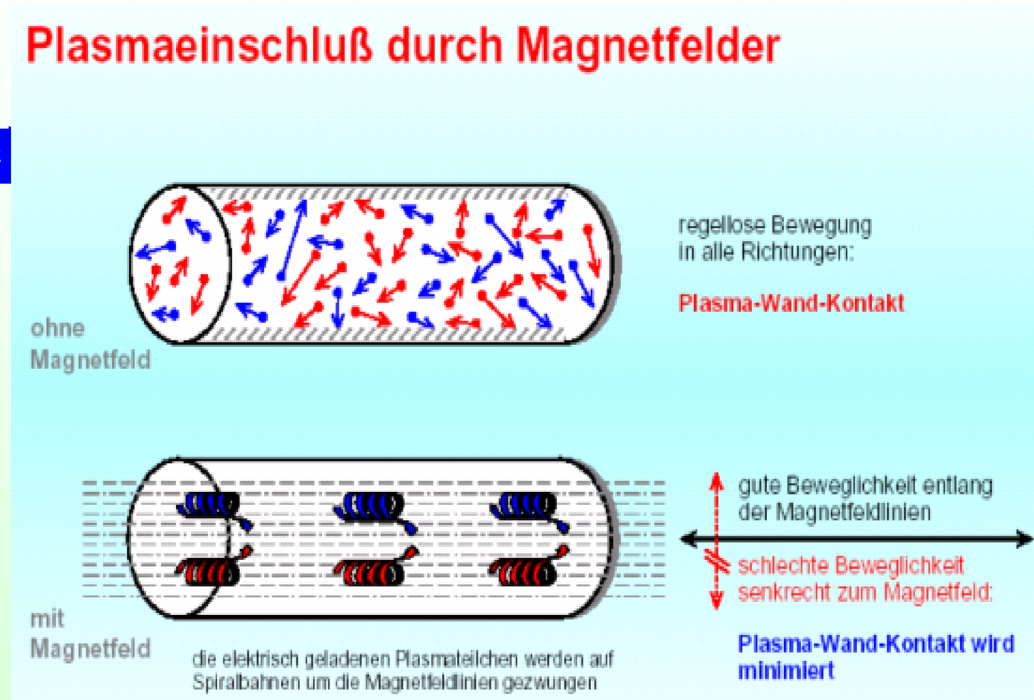
- Deuterium und Lithium (Brennstoff) sind aus den Weltmeeren zu gewinnen (Lithium auch aus Sanden) und daher für Jedermann zugänglich

- Fusionsreaktoren werden mit He Gas gekühlt (Austrittstemperaturen von 550 - 900 °C) und somit auch geeignet für die Herstellung von Wasserstoff

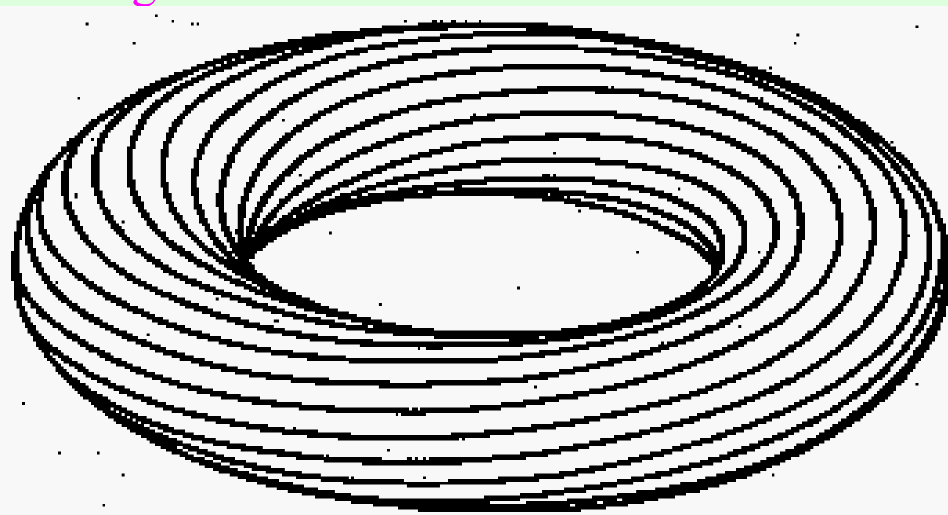
- Da das Fusionsprodukt He ist, fällt primär kein radioaktiver Abfall an
  - Allerdings wird durch die bei der Fusion entstehenden Neutronen die Struktur des Reaktors radioaktiv
  - Materialien mit kurzen Abklingzeiten ~ 200 Jahre vermeiden Endlager

# Magnetic Confinement



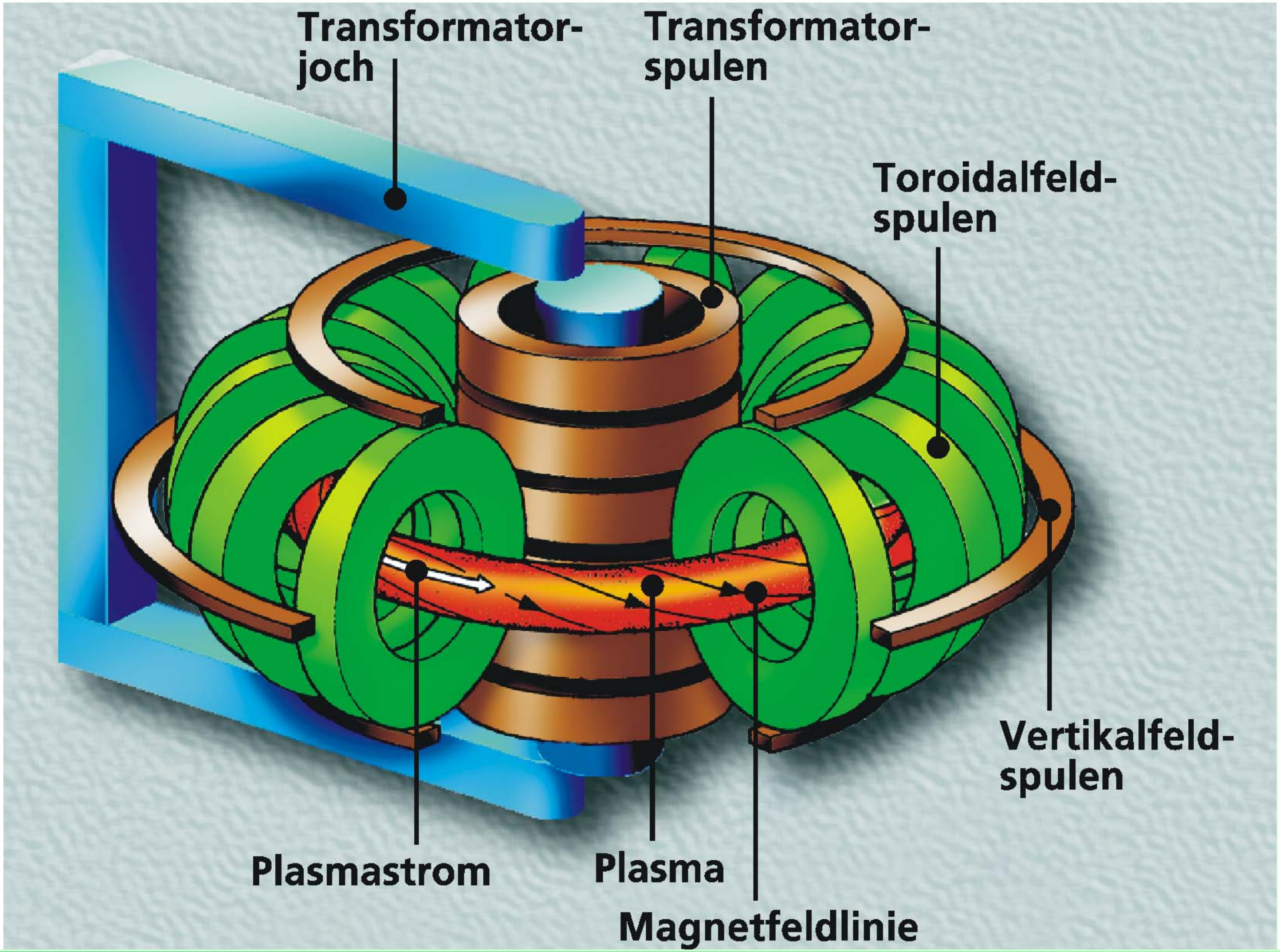




Lorenz force attaches charged particles to fieldlines
-> magnetic Confinement

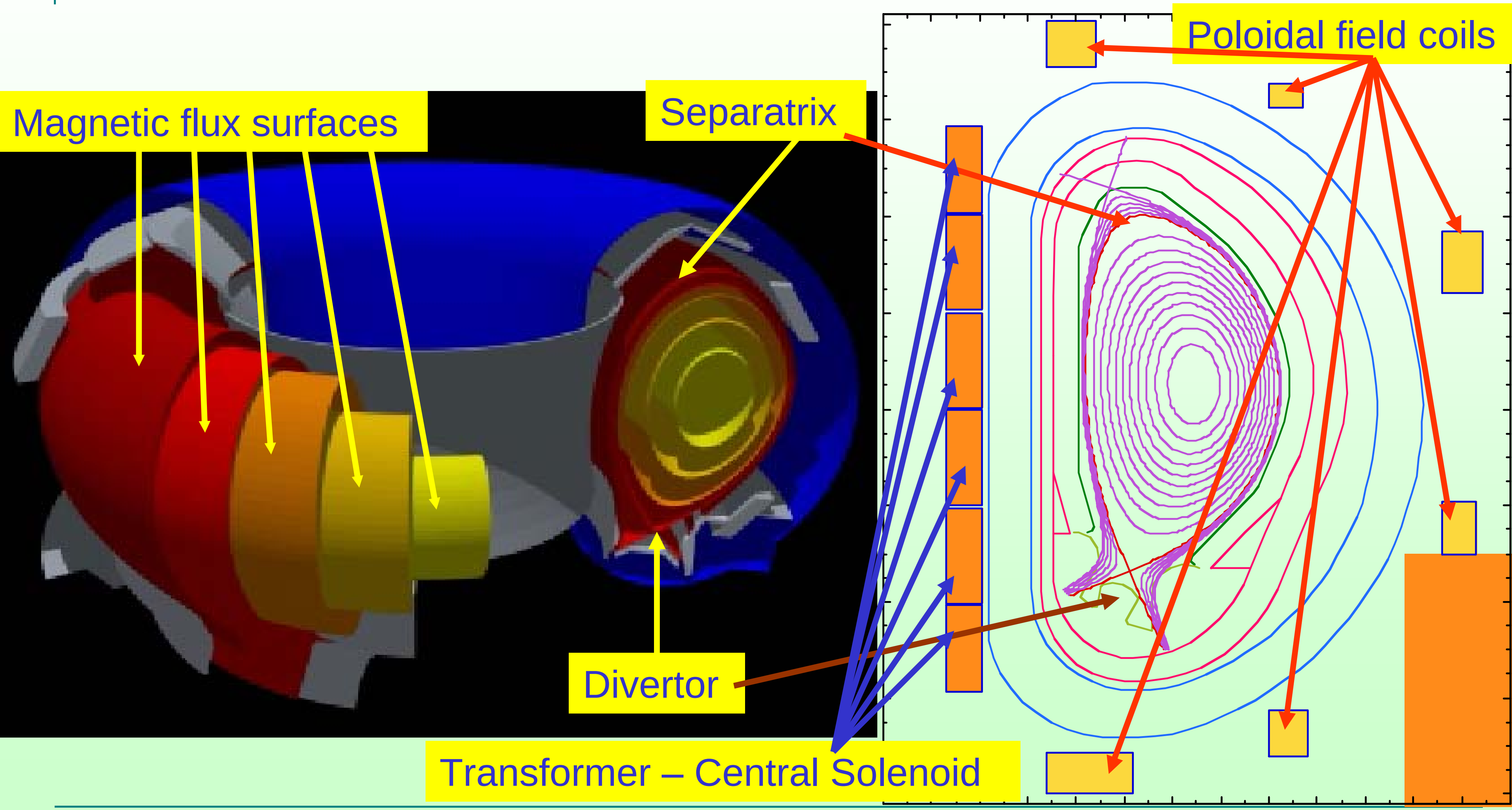


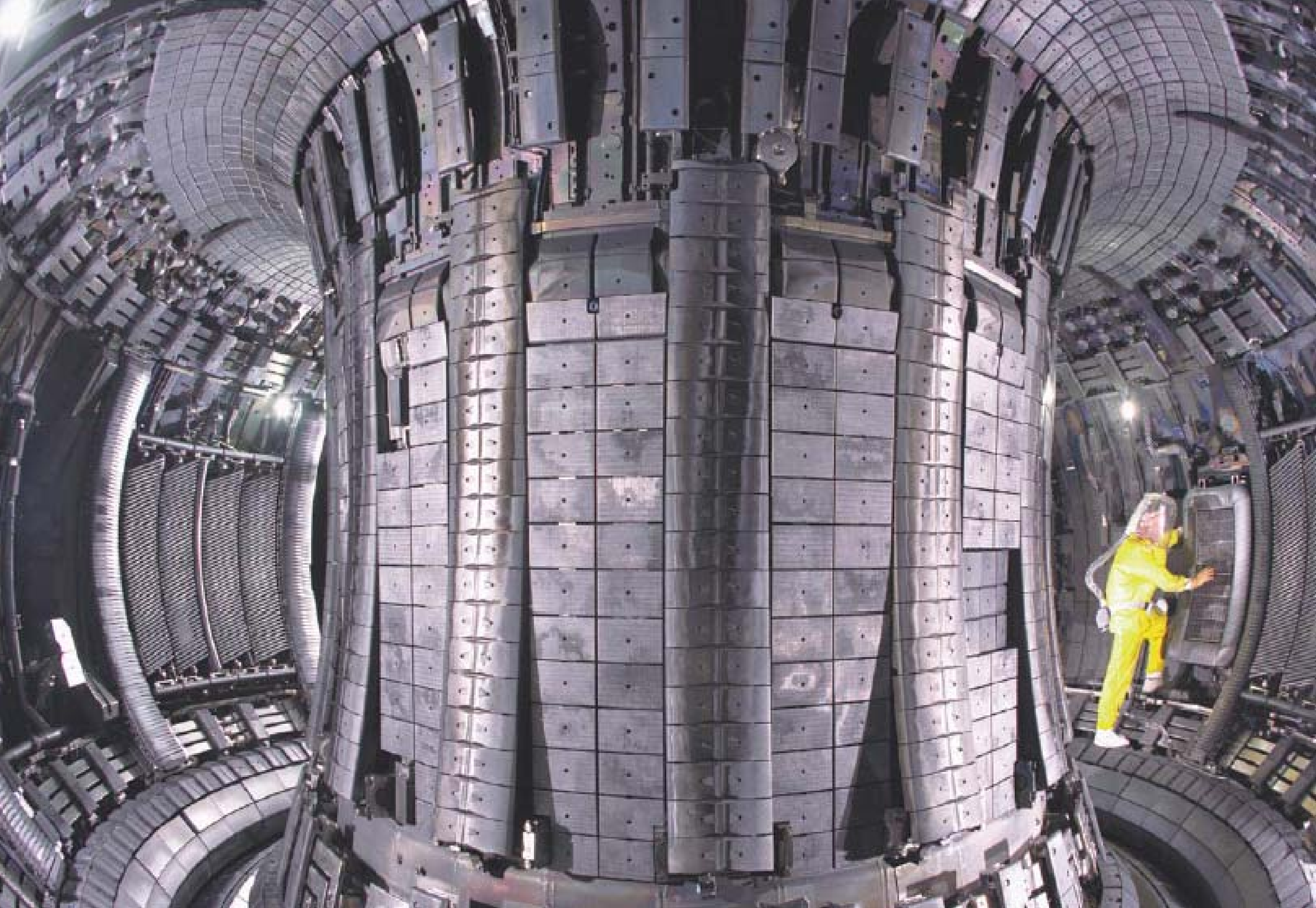
Toroidal magnetic Confinement Configuration requires Helical Fieldlines

# Magnetic Confinement, The Tokamak Principle



# The Plasma of a modern Divertor Tokamak

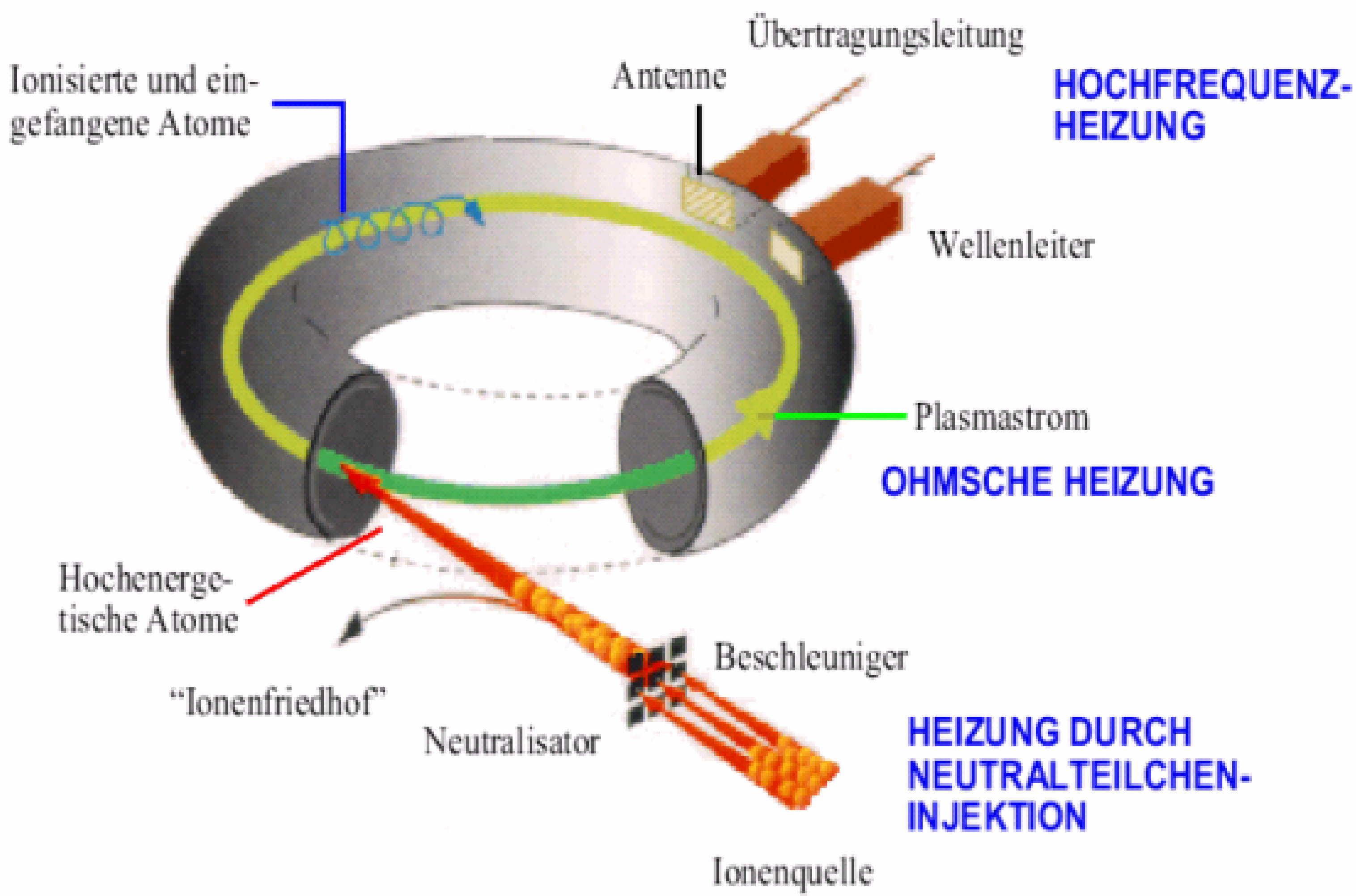




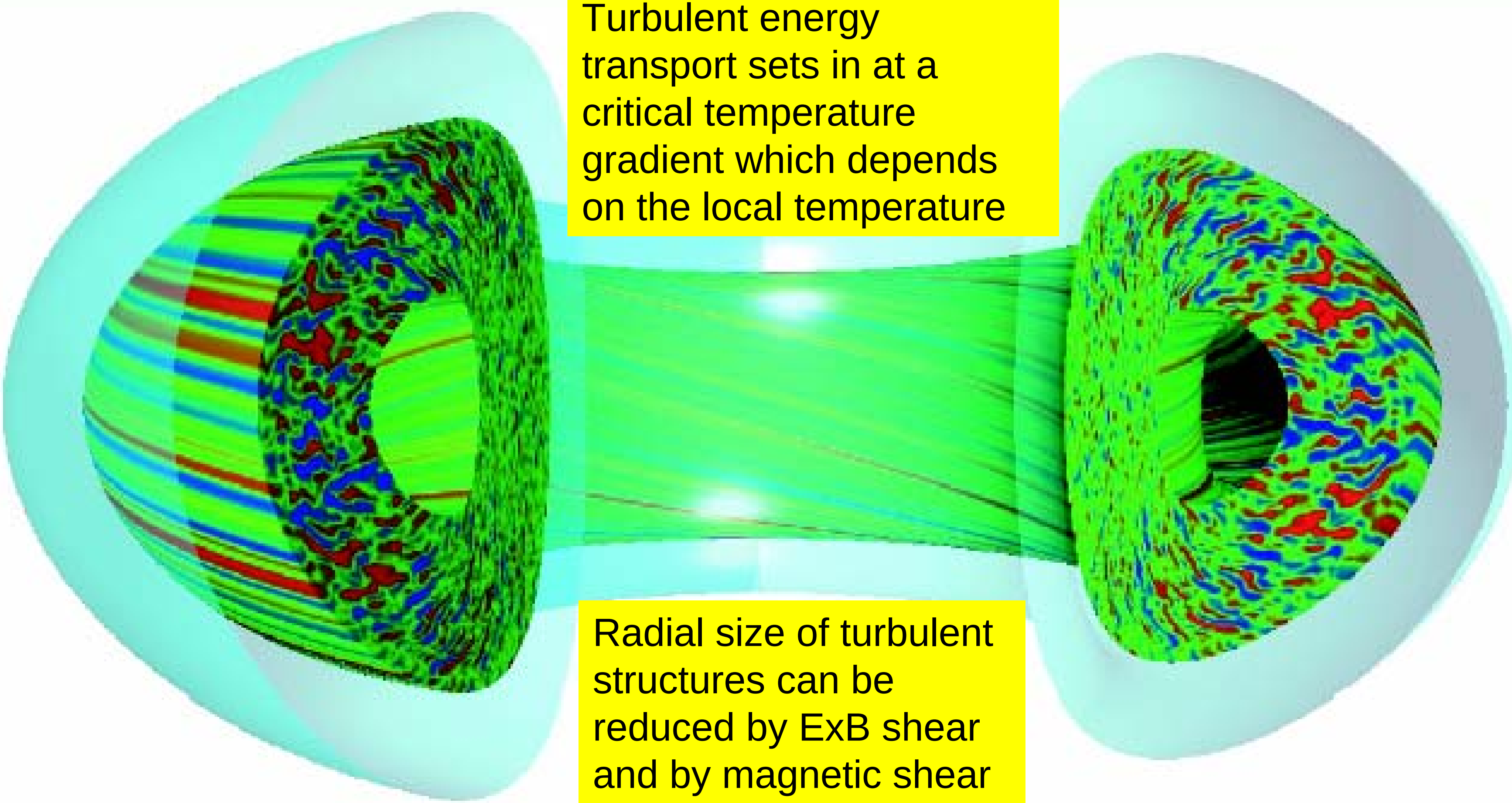
## Plasma Operation in JET

## Remote Handling in JET

# Verfahren zum Aufheizen eines Tokamakplasmas



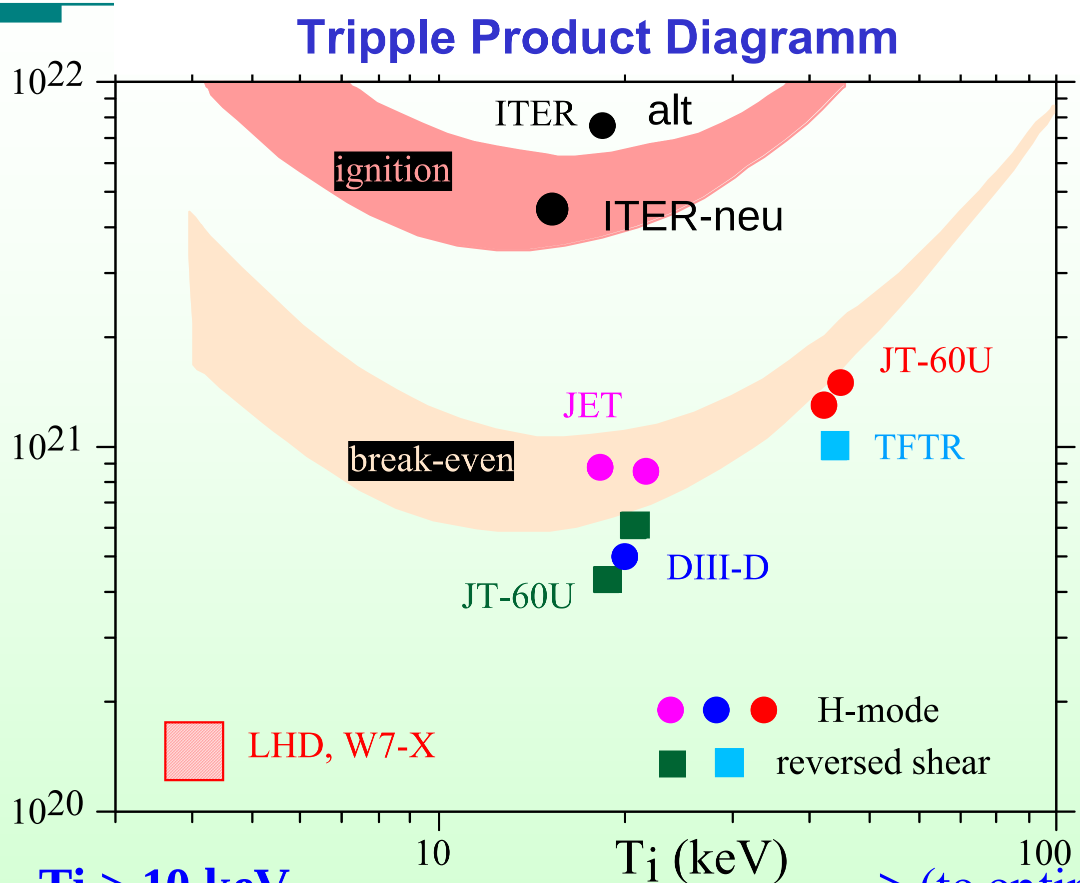
# Turbulence driven Energy Loss



Turbulent energy transport sets in at a critical temperature gradient which depends on the local temperature

Radial size of turbulent structures can be reduced by ExB shear and by magnetic shear

# How do we size a Reactor class Fusion machine (1)




- **Ti > 10 keV** -> (to optimise D-T reaction rate)
  - **=> $n_e \times \tau_E \sim 6.0\ 10^{20}\ m^{-3}s$**
  - **=> $n_e \sim 1.0\ 10^{20}\ m^{-3}$** -> (close to Density Limit: $n_L \sim I/a^2\pi$)
  - **=> $\tau_E \sim 6.0\ s$** -> (defines more or less machine size)

H-mode Confinement Scaling Relation:

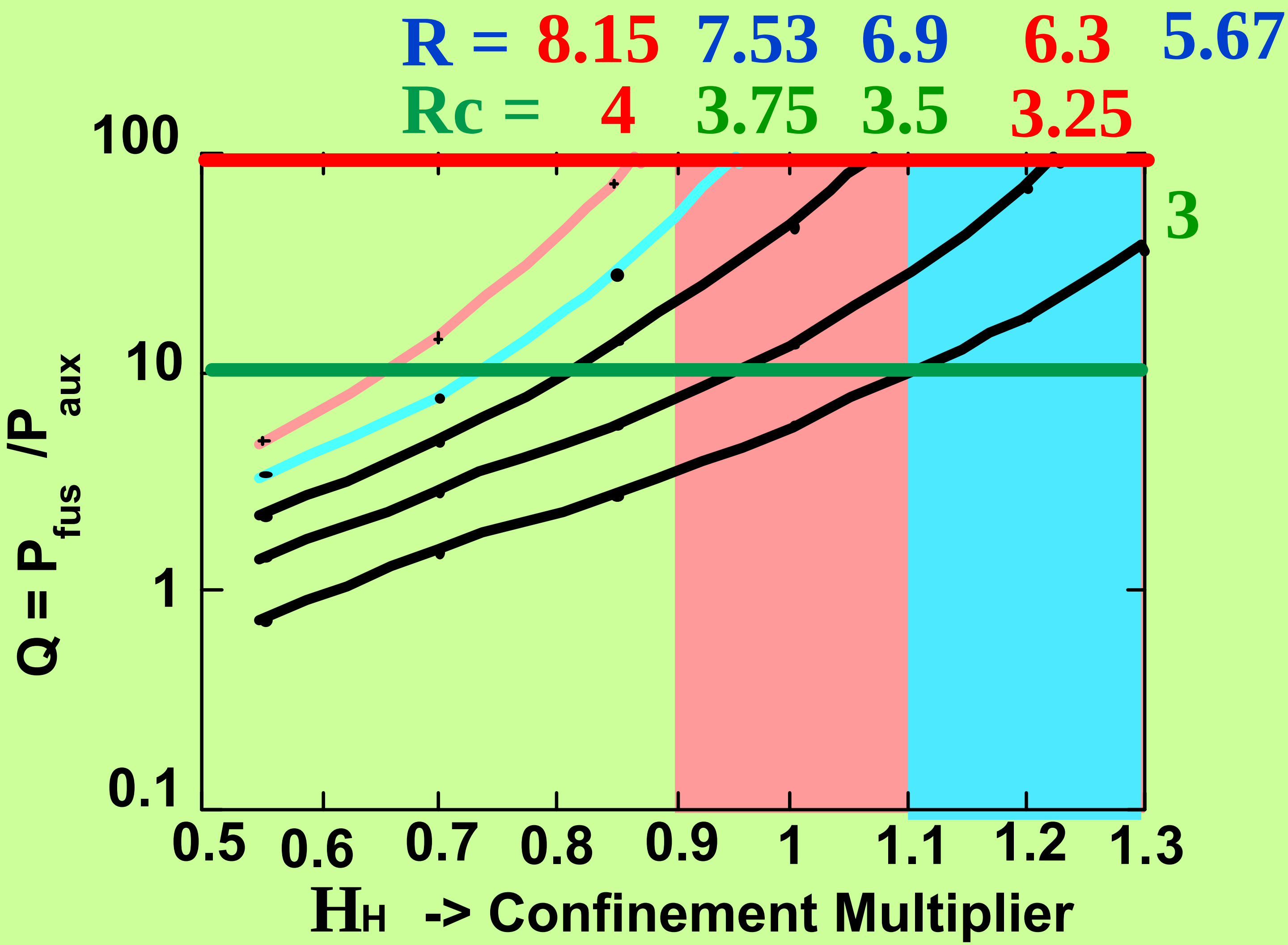
$$\tau_{E,th}^{ELMy} = 0.0562 \times I^{0.93} B^{0.15} P^{-0.69} n_{e,19}^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.78}$$

# How do we size a Reactor class Fusion machine (2)

All of the above mentioned physics and engineering constraints are combined in a

**"System Code"**

which is able to calculate a consistent parameter set.



# The ITER Machine

## Doughnut-Shaped Plasma

- V: 840m$^3$

R/a: 6.2m /2m

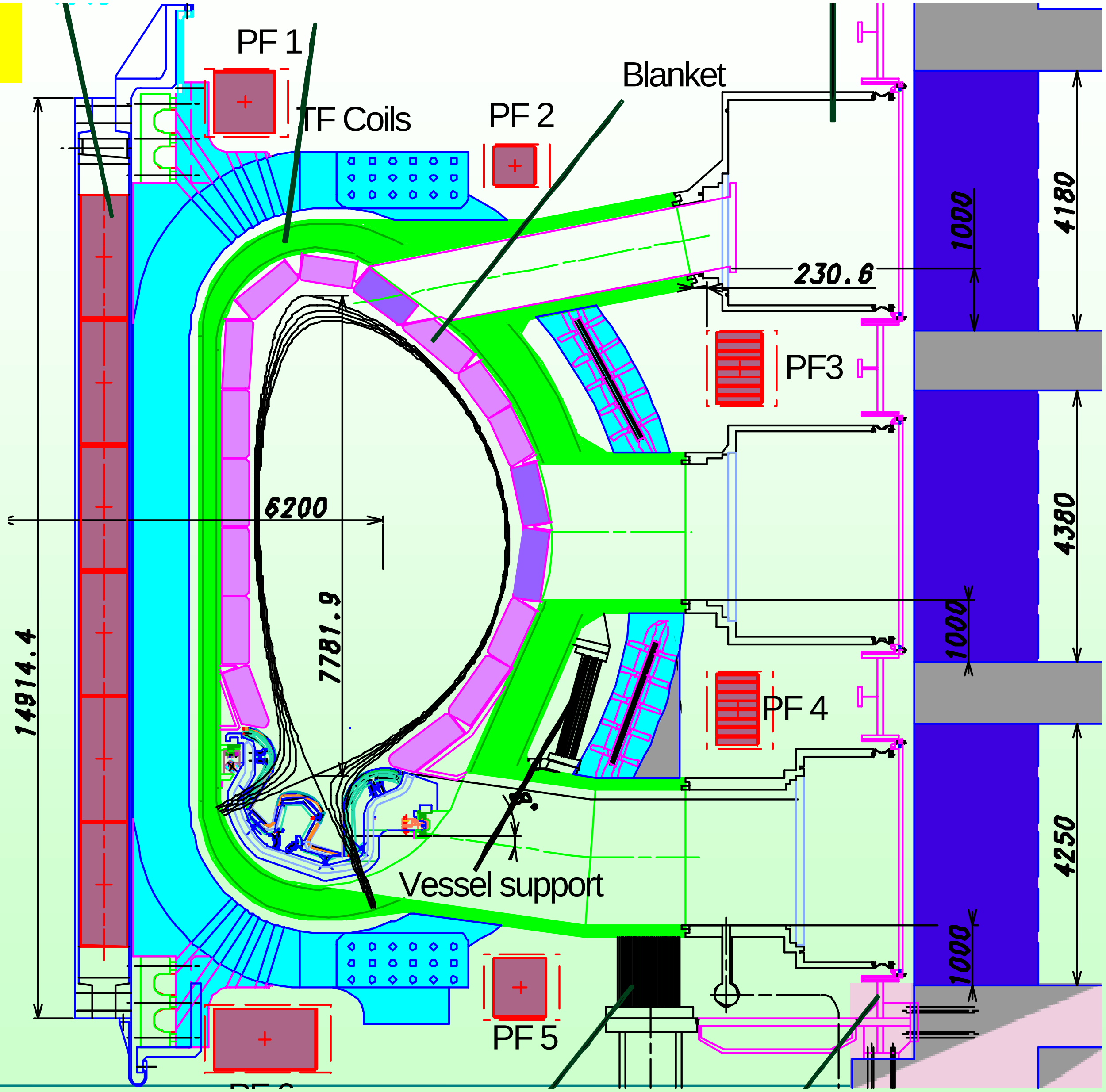
Vertical elongation: 1.85
Triangularity: 0.45

- Density: $10^{20}m^{-3}$
- PeakTemperature:17keV

- Fusion Power: 500MW

- Plasma Current : 15MA

- Toroidal field: 5.4T



# ITER History

- **1988-1991 - (CDA) Conceptual Design Phase**
  - Start of common activities among EU,RF, USA and JA
  - Selection of machine parameters and objectives

- **1992-1998 - (EDA) Engineering Design Phase**
  - Developed design capable of ignition - large and expensive
  - The Parties (EU, JA, RF, US) endorsed design but could not afford to build it

- **1999 – 2001 – (EDA continues)**
  - US withdraws from project
  - Remaining Parties searched for less ambitious goal
  - New design: moderate plasma power amplification at about half the cost.

- **2001 - now (CTA and ITA)**
  - End of EDA and start of negotiations on construction and operation
  - 4 site offers. In 2003 US re-joins, China & South Korea are accepted as full partners.
  - **Cadarache selected as ITER site in June 2005**
  - India Joins in Dec 2005

# ITERs Technical Objectives

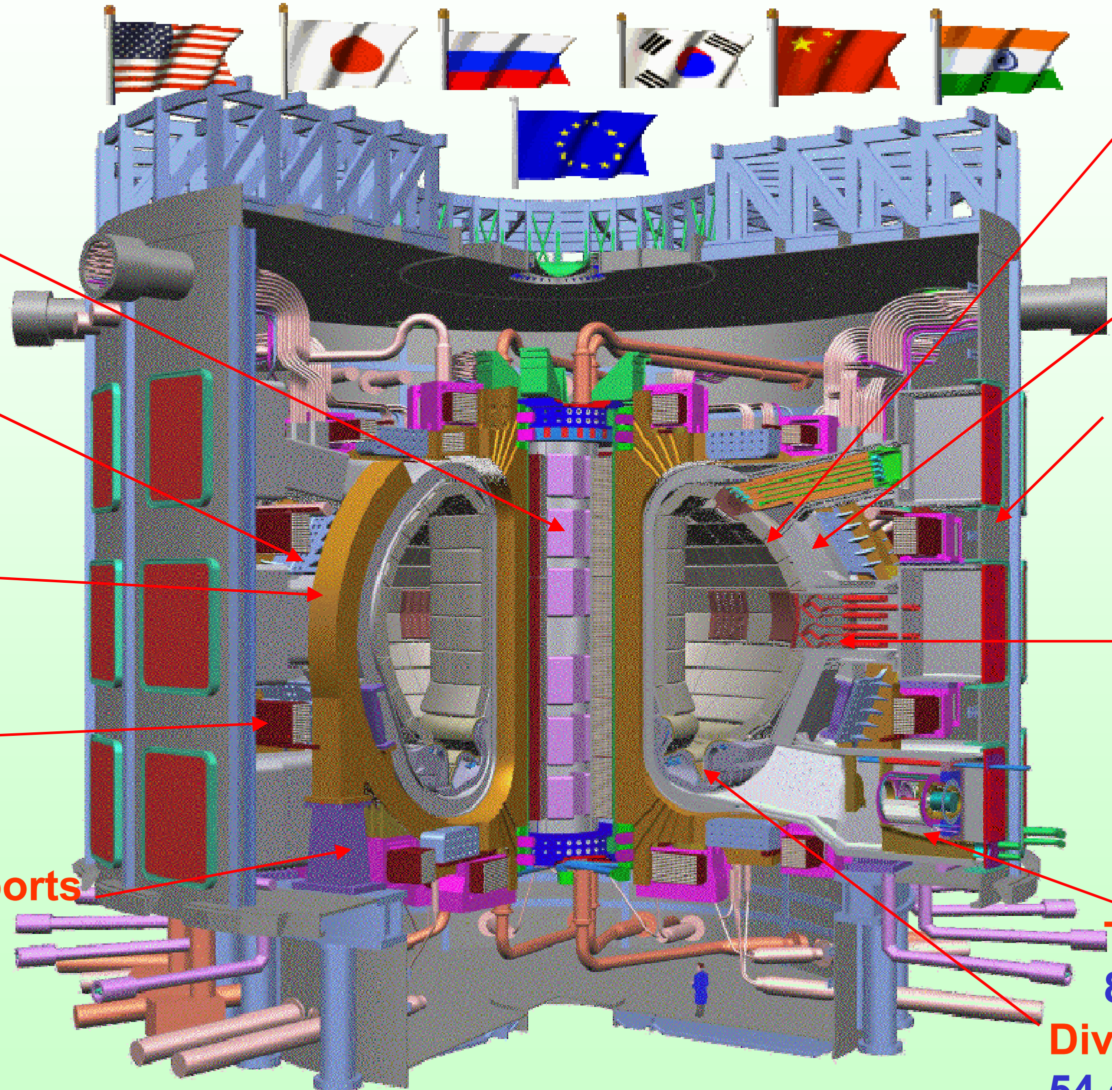
- **Q (ratio of fusion power to auxiliary heating power) ≥10 (>5 in steady state). Possibility of controlled ignition.**
- **Power flat top 300 s up to steady state.**
- **Flexible operation range, with access to advanced modes.**
- Integrate the technologies essential for a fusion reactor (e.g. superconducting magnets, remote maintenance);
- Test components for a future reactor (e.g. divertor and torus vacuum pumps, tritium breeding blanket modules).
- Average neutron flux > 0.5 $MW/m^2$, fluence > 0.3 $MWa/m^2$
- Possible later installation of tritium breeding blanket.
- **Operate for ~ 20 years, using externally supplied tritium.**

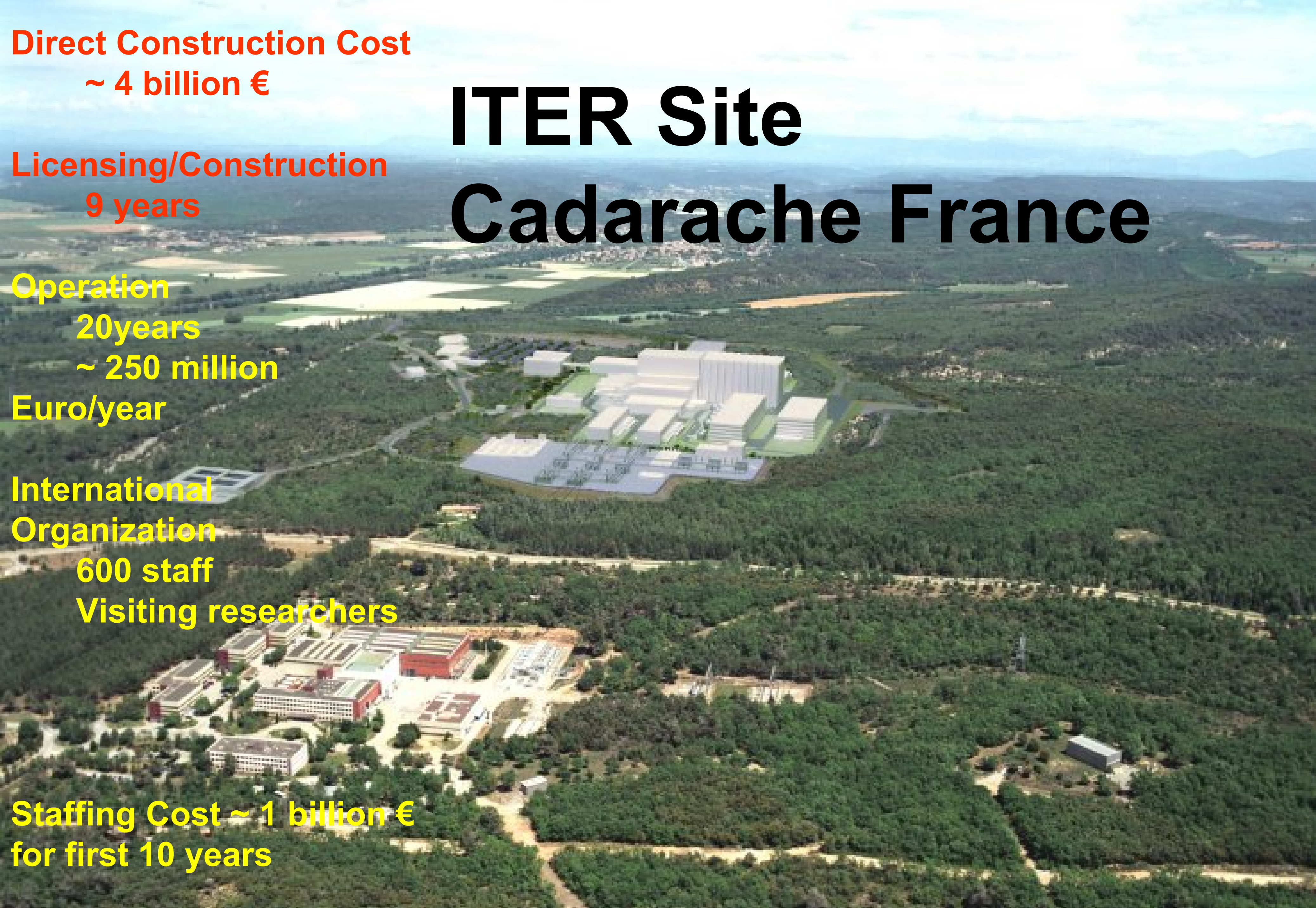
➔ **ITER is the first Reactor Plasma – its performance will determine the fate of fusion as an energy source**

➔ **ITER has to exceed its nominal performance by > 50% in order to warrant the construction of a DEMO reactor**

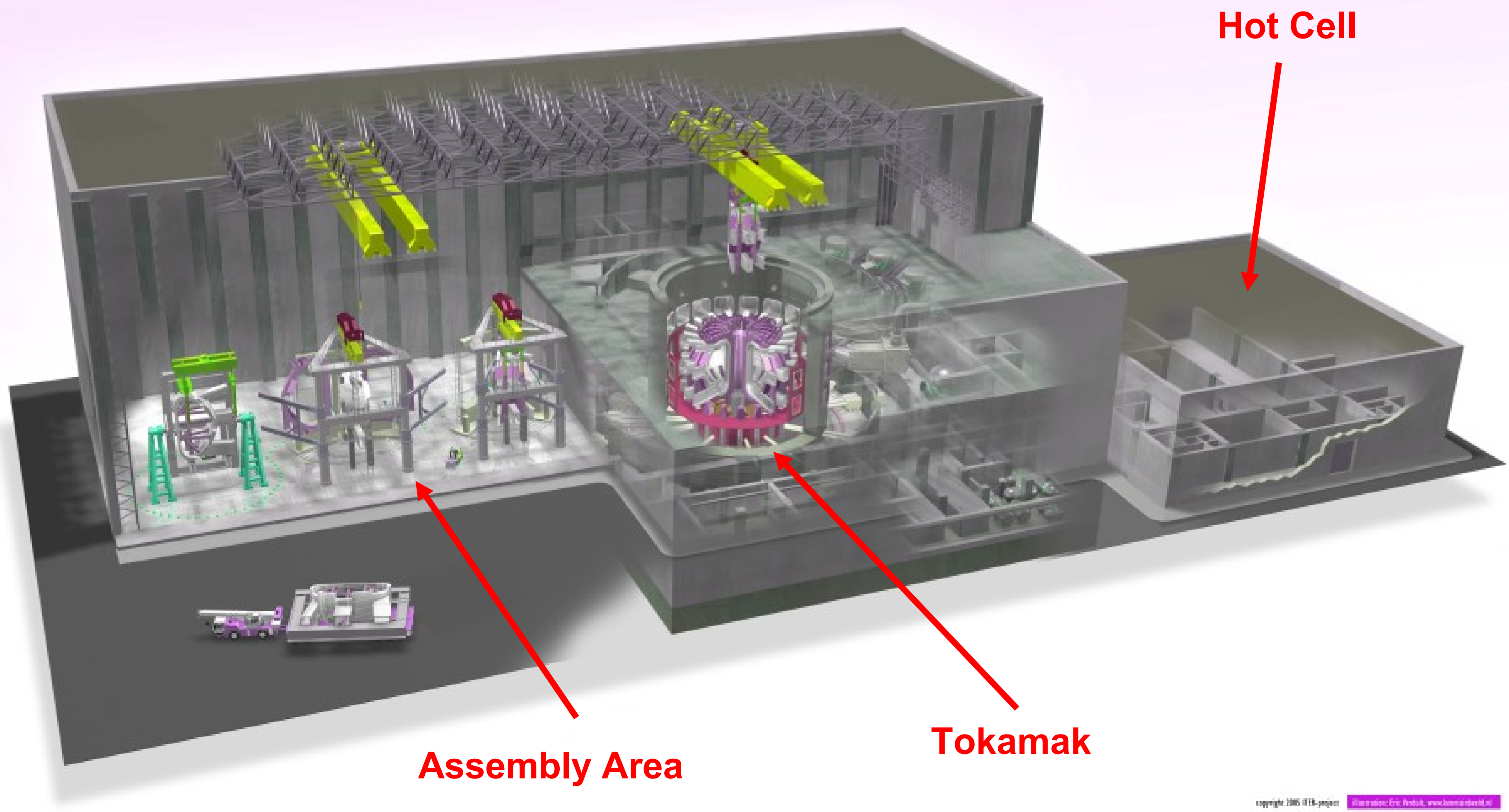
➔ **See also talk of Prof Wolf today !!**

# Main Features of the ITER Design



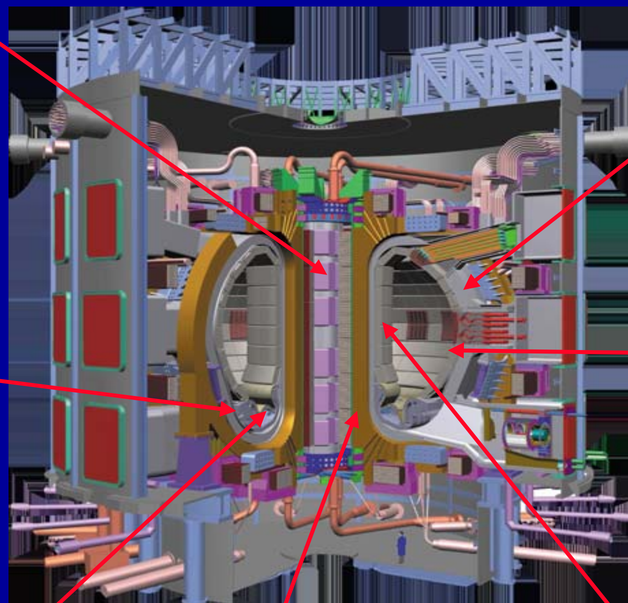

ITER Site
Cadarache France
Direct Construction Cost
~ 4 billion €
Licensing/Construction
9 years
Operation
20years
~ 250 million
Euro/year
International
Organization
600 staff
Visiting researchers
Staffing Cost ~ 1 billion €
for first 10 years

# Tokamak Building Complex



# The ITER Design and Technology has been underpinned by R&D

Completed R&D Activities by July 2001.



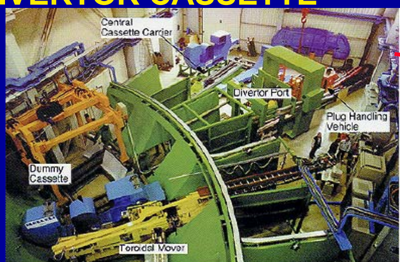
## CENTRAL SOLENOID MODEL COIL

Radius 3.5 m
Height 2.8m
$B_{max}$=13 T
W = 640 MJ
0.6 T/sec

## VACUUM VESSEL SECTOR

Double-Wall, Tolerance ±5 mm

## REMOTE MAINTENANCE OF DIVERTOR CASSETTE




Attachment Tolerance ± 2 mm

## BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

## DIVERTOR CASSETTE

Heat Flux >15 MW/m², CFC/W

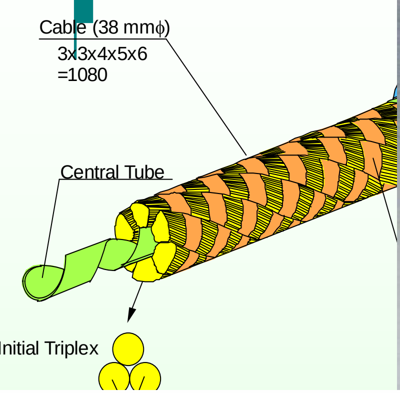
## TOROIDAL FIELD MODEL COIL

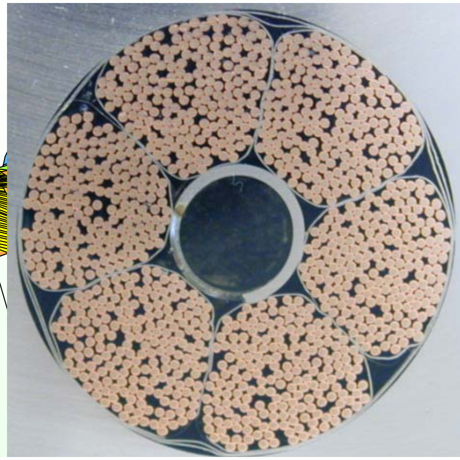
Height 4 m
Width 3 m
$B_{max}$=7.8 T
$I_{max}$ = 80kA

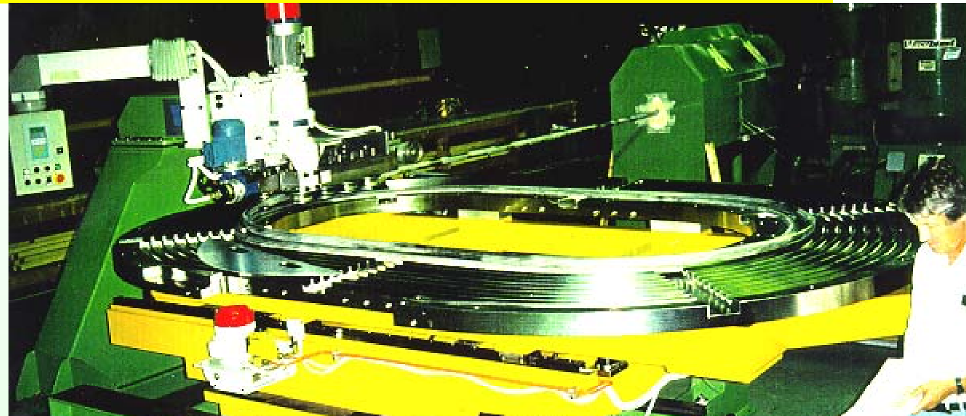
## REMOTE MAINTENANCE OF BLANKET

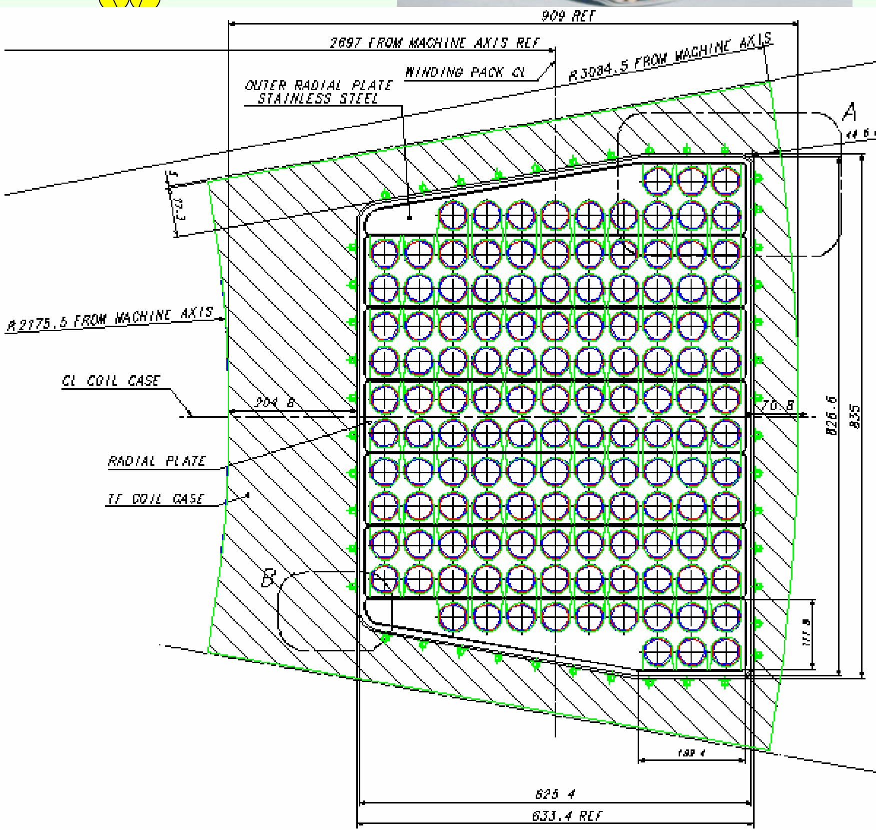
4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

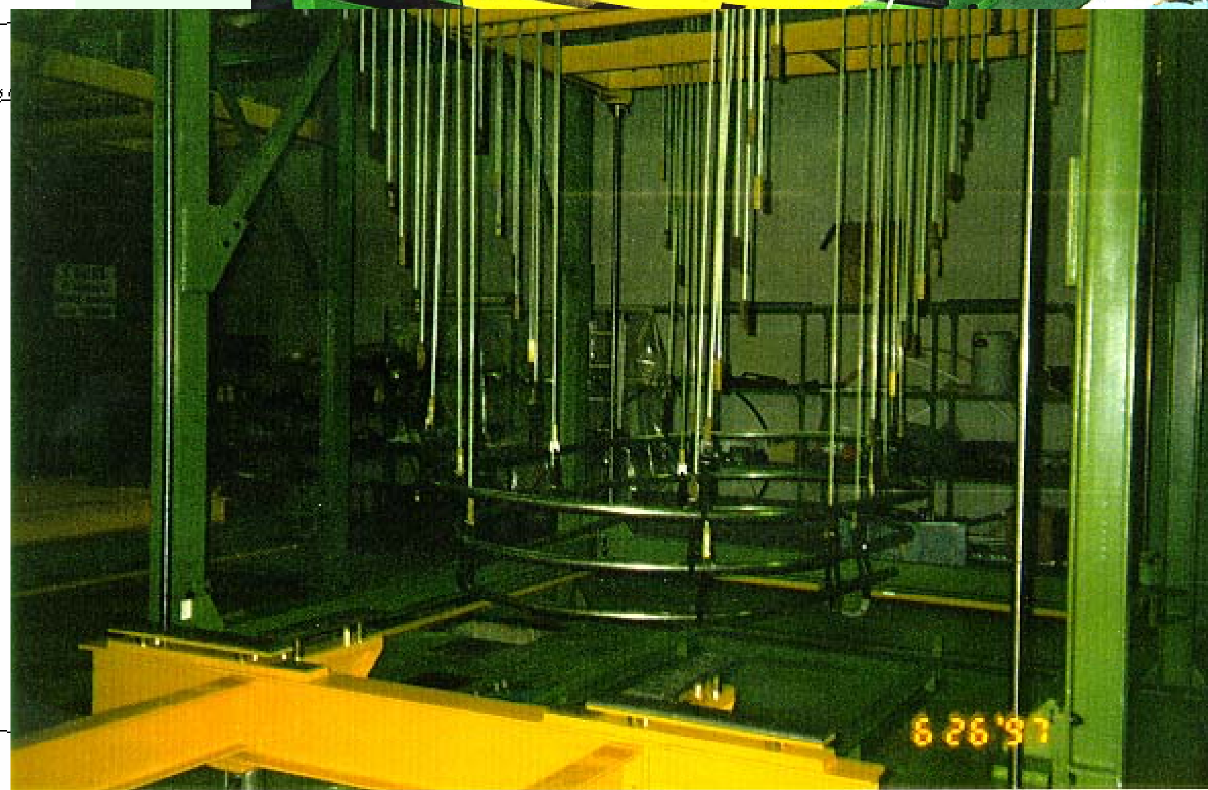
# ITER Toroidal Field Magnets



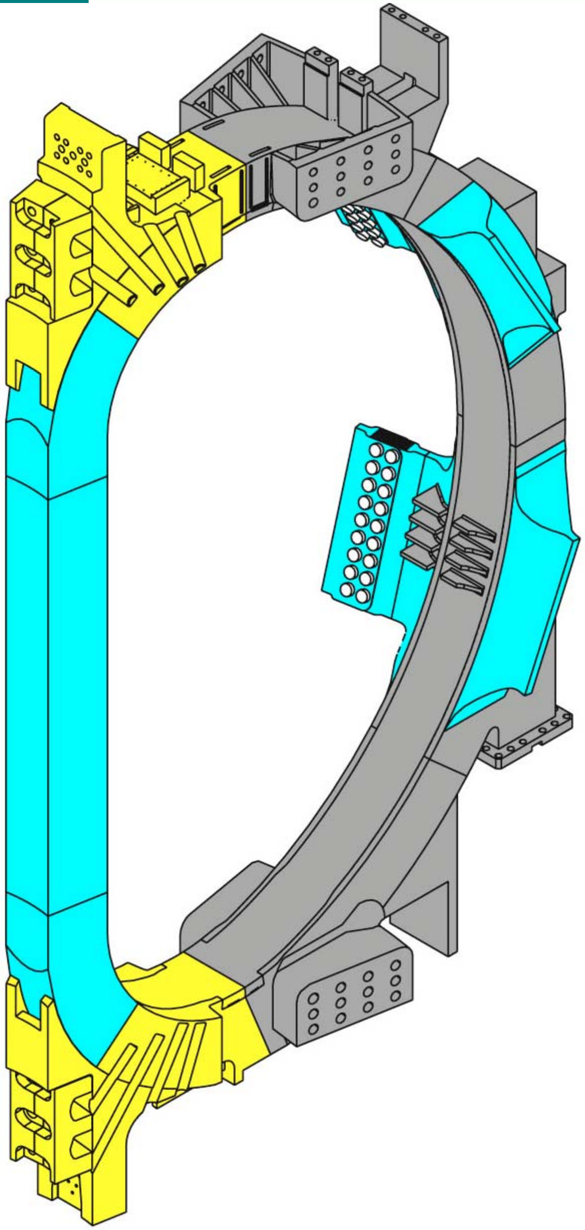



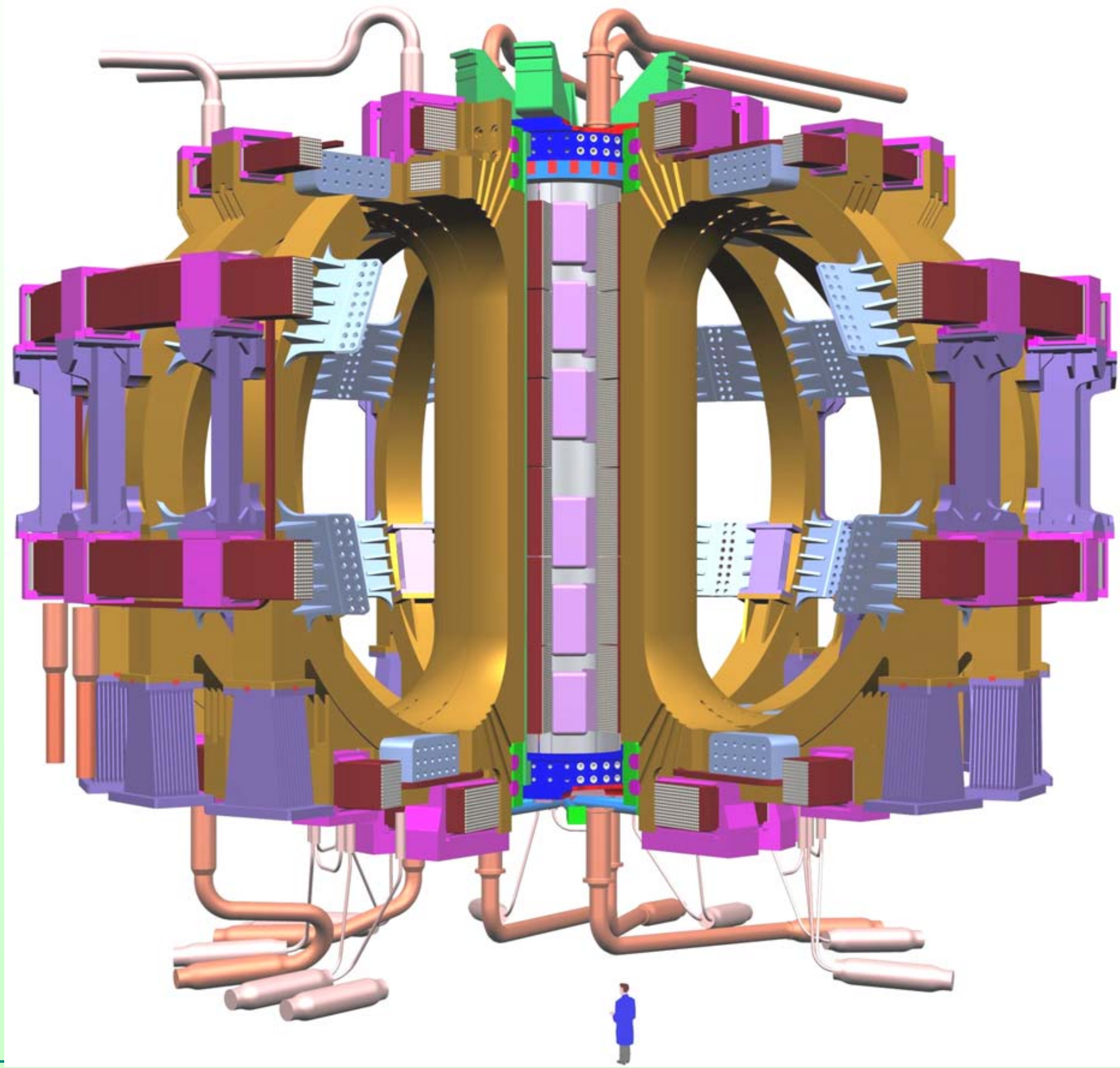




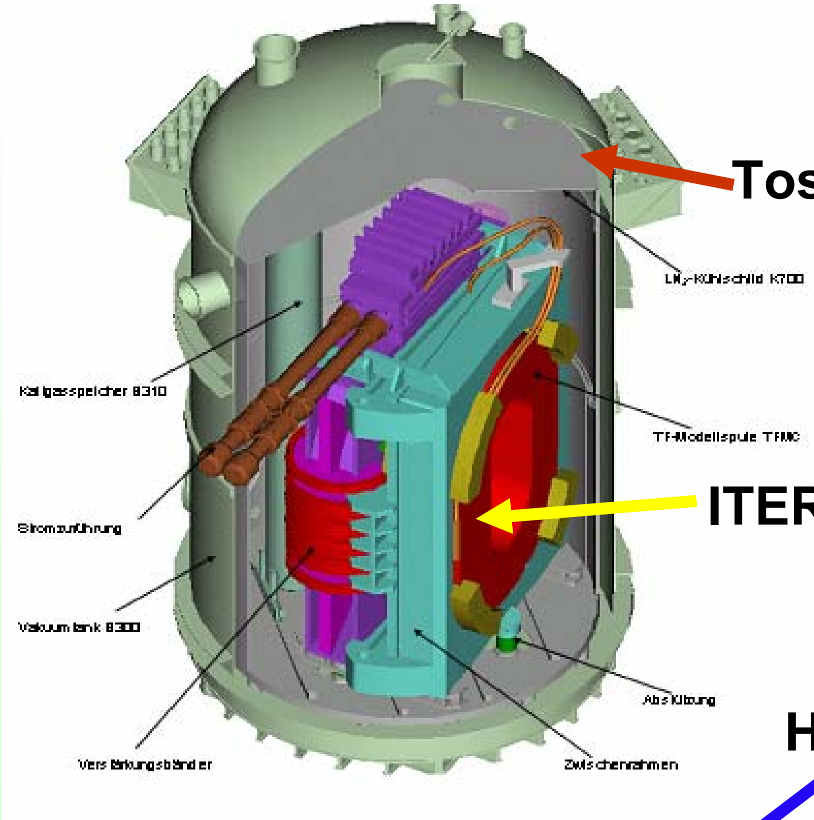



# ITER-FEAT coil assembly





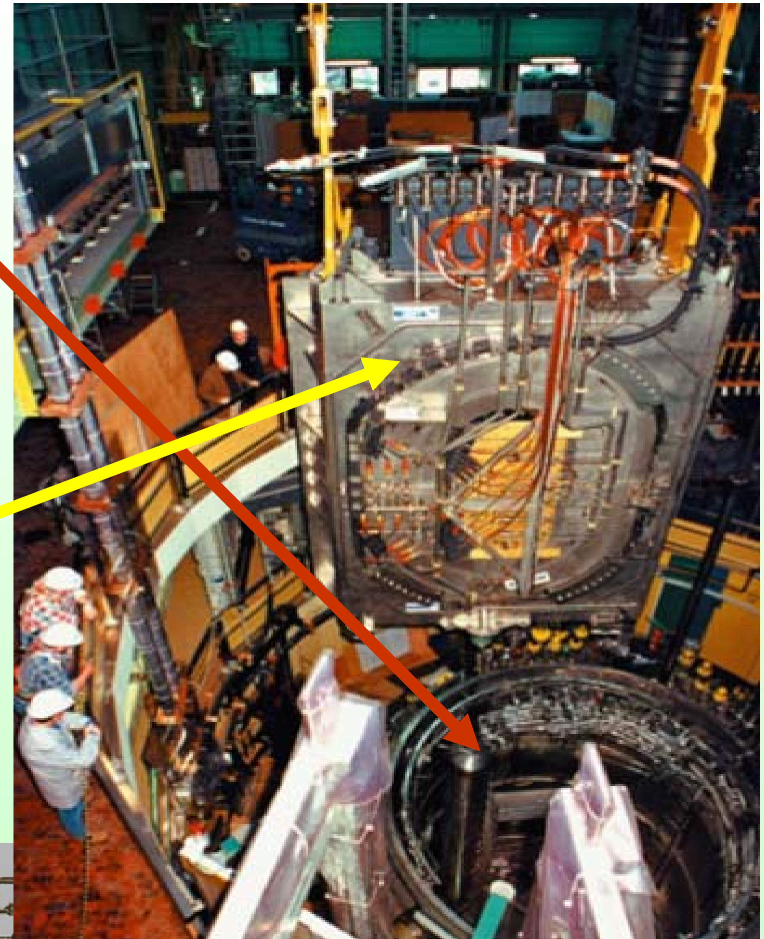
# ITER Model Coil, High Temperatur SC Current Leads

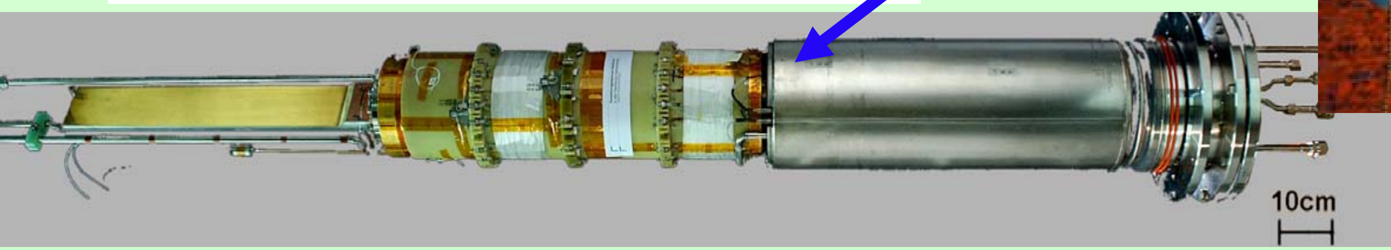



**Toska Facility**

**ITER Model Coil**

**HTS Current Lead**





FUSION

**Forschungszentrum Karlsruhe**
in der Helmholtz-Gemeinschaft

FZK - EURATOM ASSOCIATION

HELMHOLTZ GEMEINSCHAFT

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Completed R&D Activities by July 2001.

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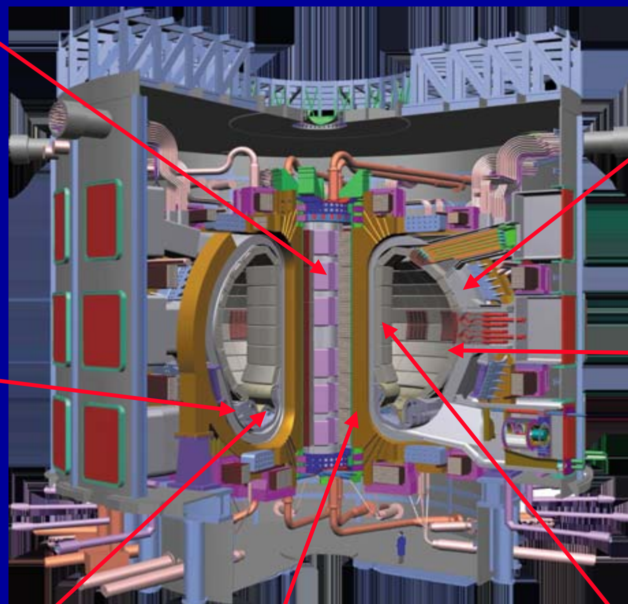
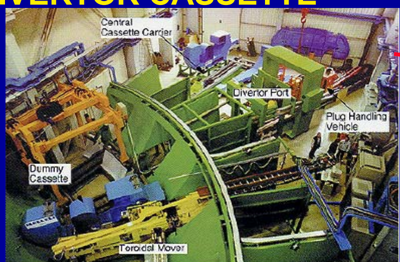


## VACUUM VESSEL SECTOR

Double-Wall, Tolerance ±5 mm

## REMOTE MAINTENANCE OF DIVERTOR CASSETTE




Attachment Tolerance ± 2 mm

## BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

## REMOTE MAINTENANCE OF BLANKET

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

## DIVERTOR CASSETTE

Heat Flux >15 $MW/m^2$, CFC/W

## TOROIDAL FIELD MODEL COIL

Height 4 m
Width 3 m
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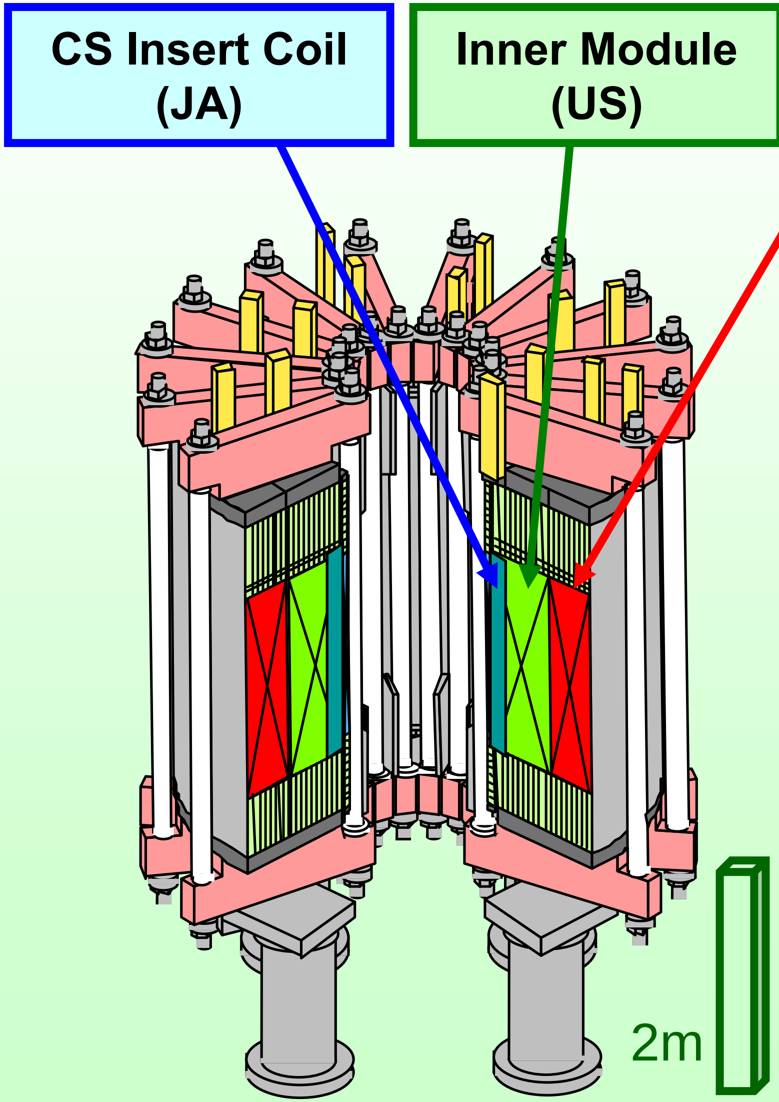
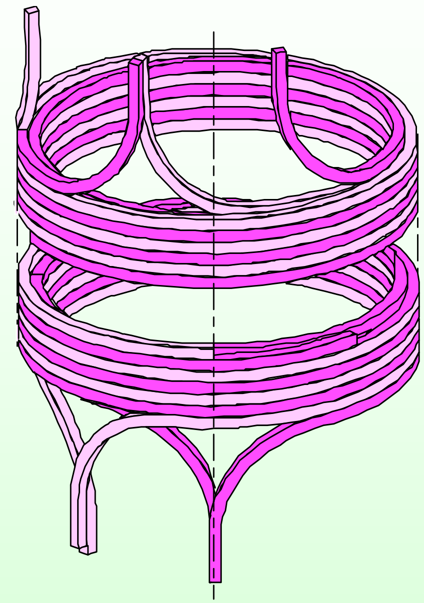
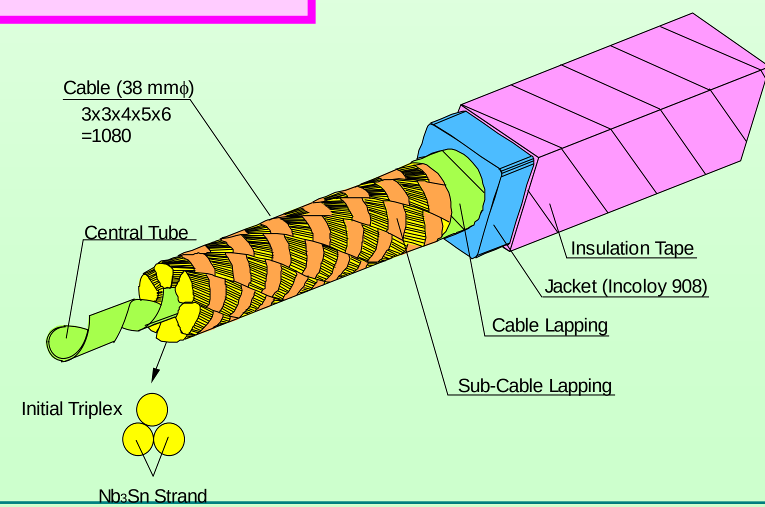
$I_{max}$ = 80kA

# Structure of the CS Model Coil



# CS Model Coil R&D

**Max. field 13.5T, max. current 46kA, stored energy 640MJ (max. in $Nb_3Sn$)**

**Ramp-up 1.2T/s (goal 0.4) and rampdown rates of -1.5T/s (goal -1.2) in insert coils, and 10,000 cycle test.**

**CS Insert Coil (JA)**

**Inner Module (US)**

**Outer Module (JA)**

# CS Model Coil R&D

# Closing of the Test Cryostat (JA)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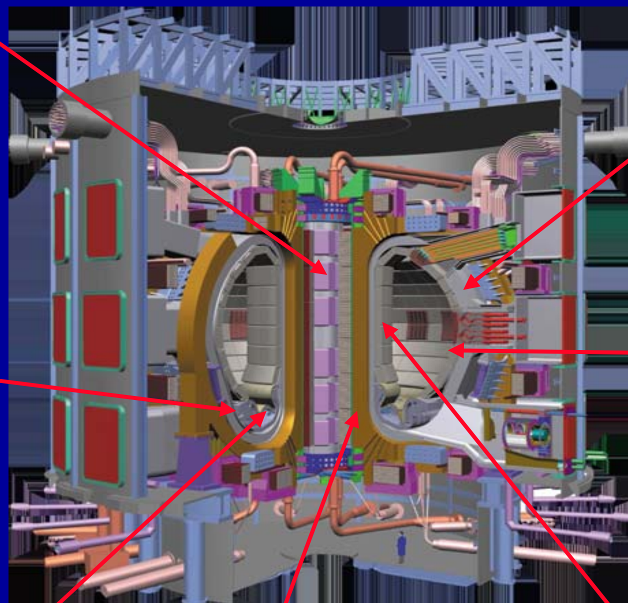
**Completed R&D Activities by July 2001.**



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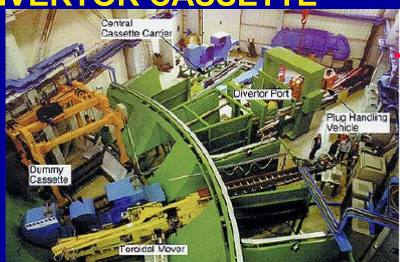


Attachment Tolerance ± 2 mm

**BLANKET MODULE**

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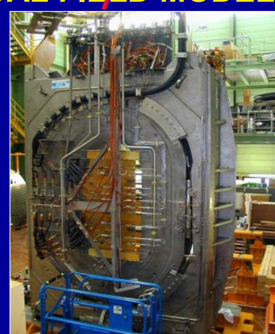
**TOROIDAL FIELD MODEL COIL**



Height 4 m
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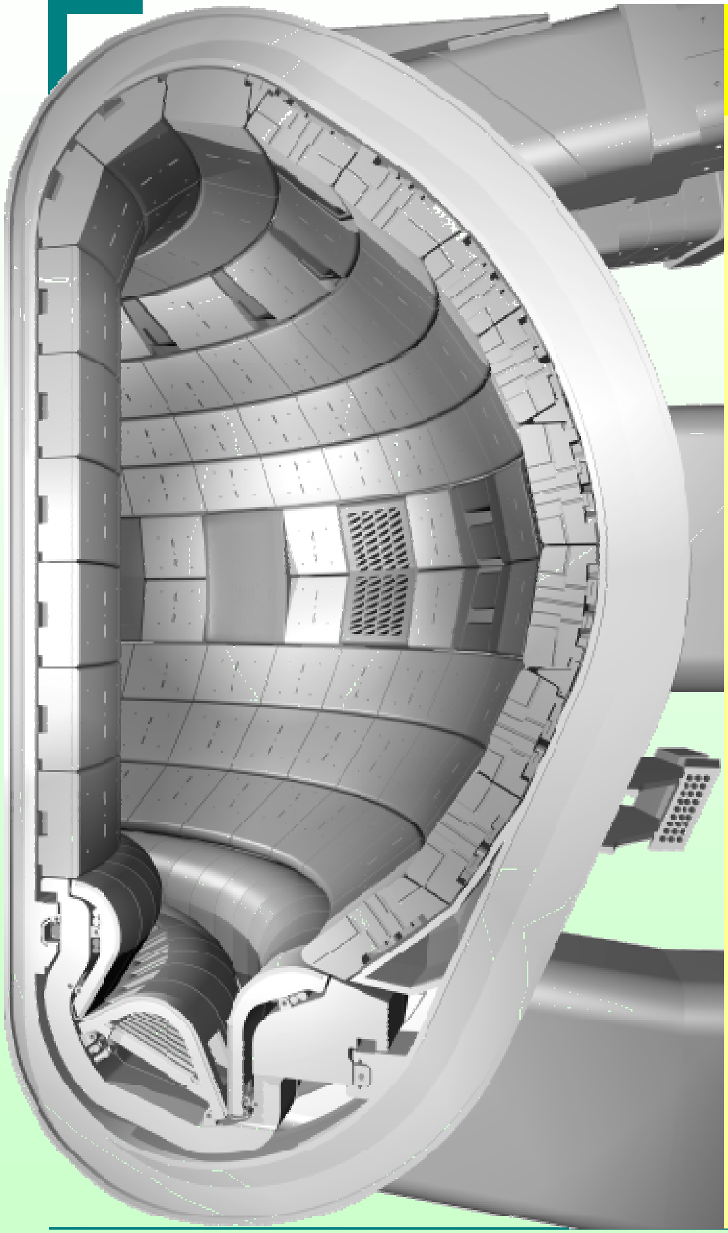
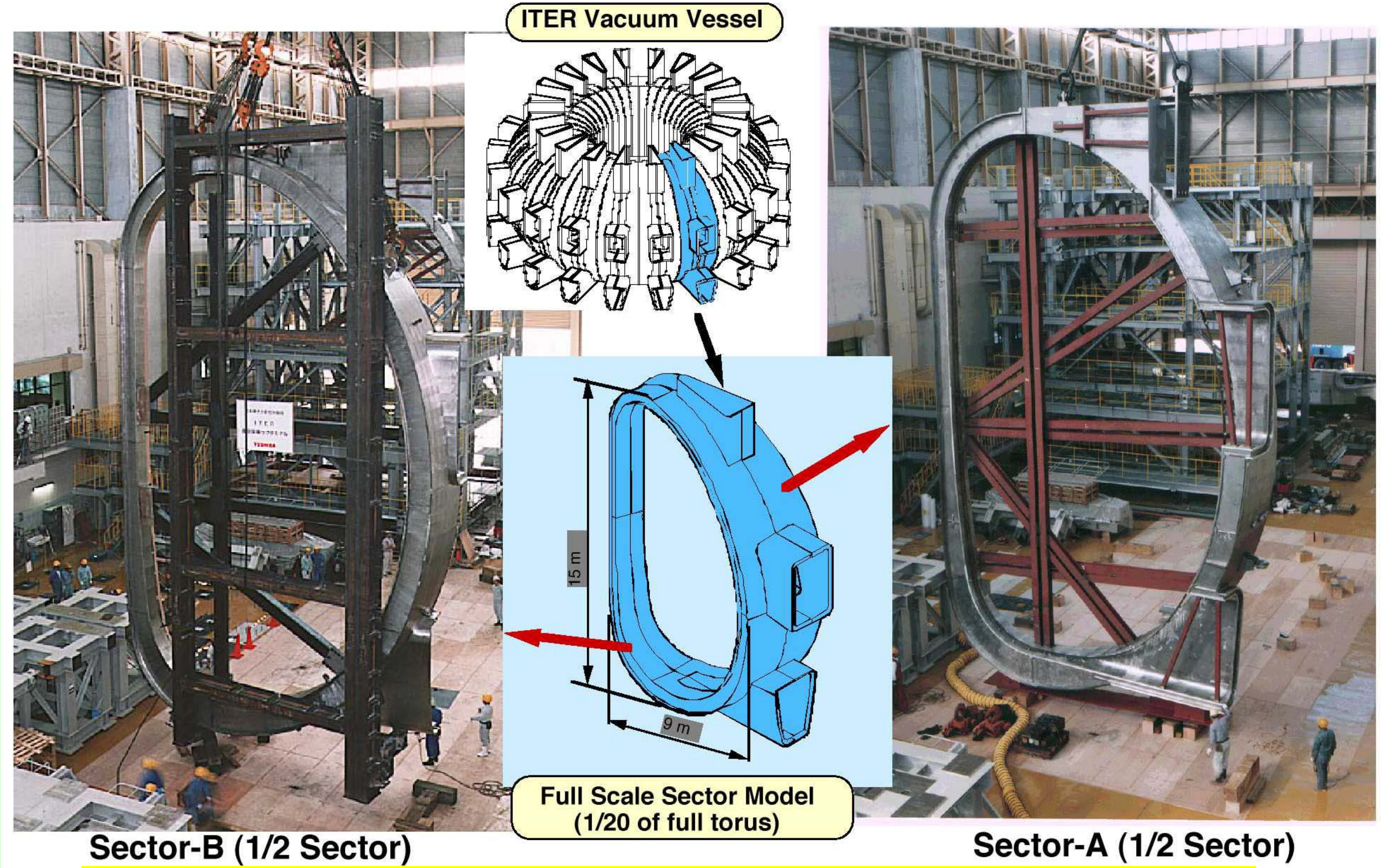
**REMOTE MAINTENANCE OF BLANKET**

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm



# Vacuum Vessel & In-Vessel Components

- Double-walled vacuum vessel lined by modular removable components,
- blanket modules, divertor cassettes, and diagnostics sensors, as well as port plugs for limiters, heating antennae, diagnostics and test blanket modules.
- The total vessel/in-vessel mass is ~10,000 t.
- Components absorb most of the radiated heat from the plasma and protect the magnet coils from excessive nuclear radiation.
- The VV is able to remove the decay heat from all in Vessel components in case of coolant failure
- A tight fitting configuration of the VV to the plasma aids passive plasma vertical stability
- ferromagnetic material “inserts” in the VV reduce toroidal field ripple and its associated particle losses.




**Dimensional accuracy after welding sector halves ± 3 mm**

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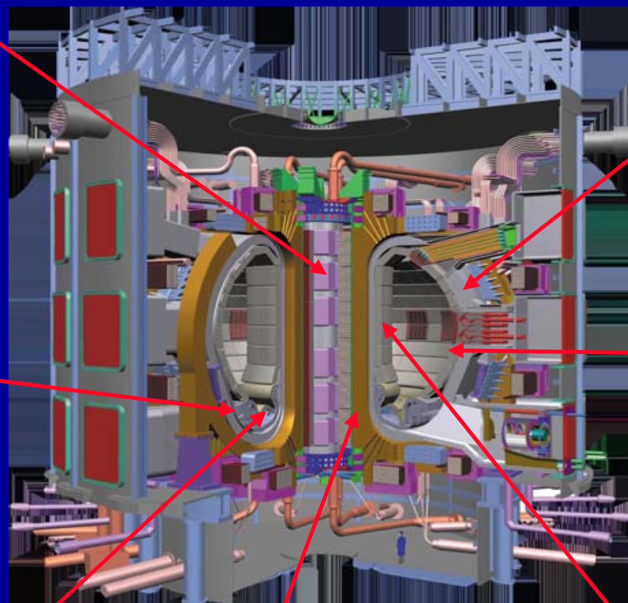

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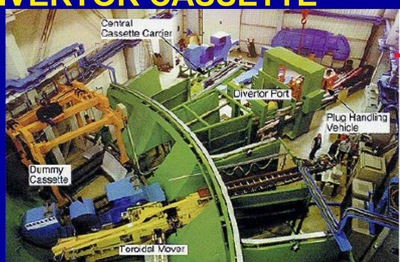
Double-Wall, Tolerance ±5 mm

## REMOTE MAINTENANCE OF DIVERTOR CASSETTE




Attachment Tolerance ± 2 mm

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Height 4 m
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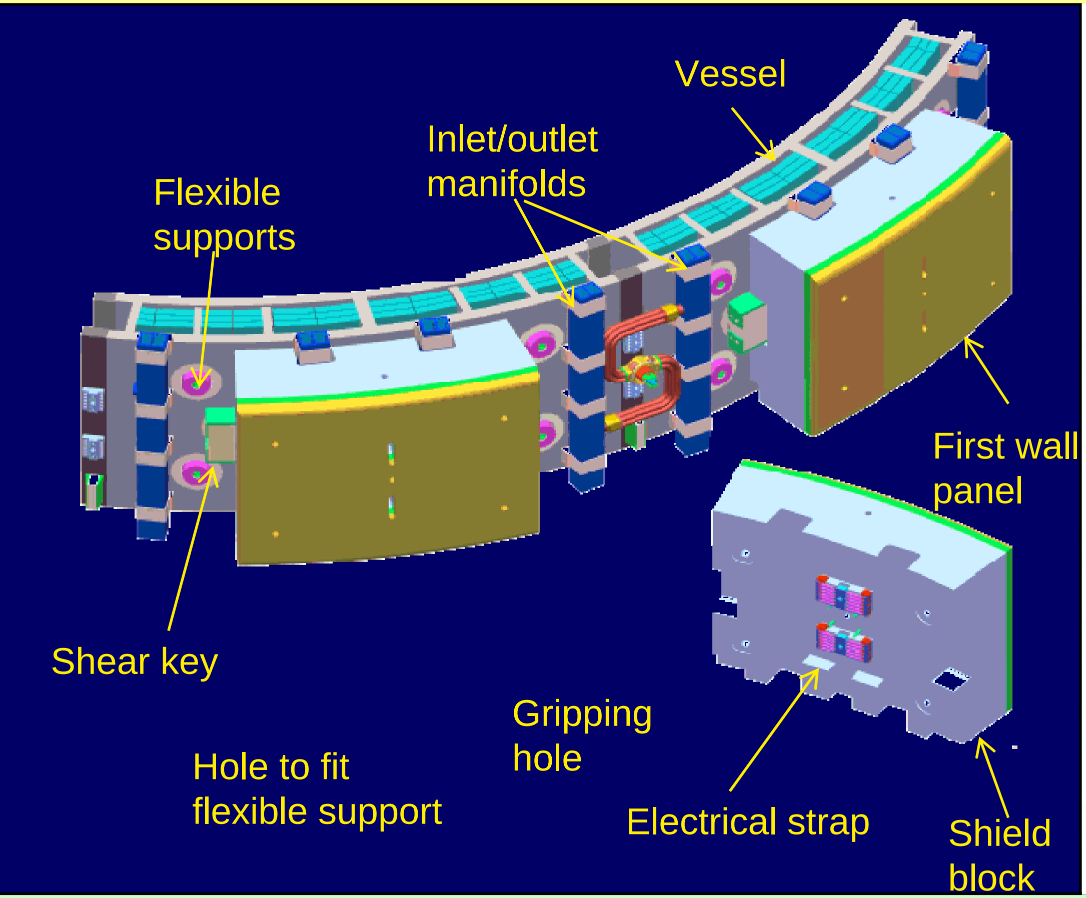
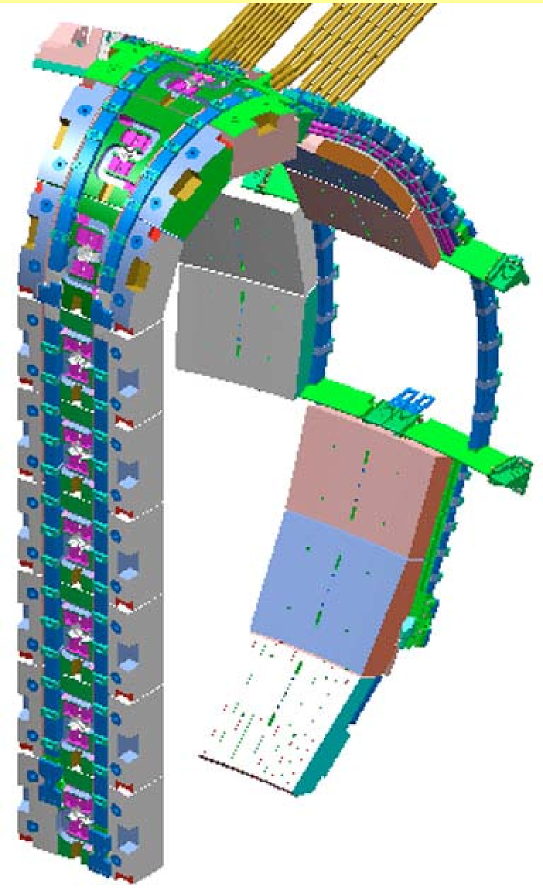
# Blanket Attachment and Manifold

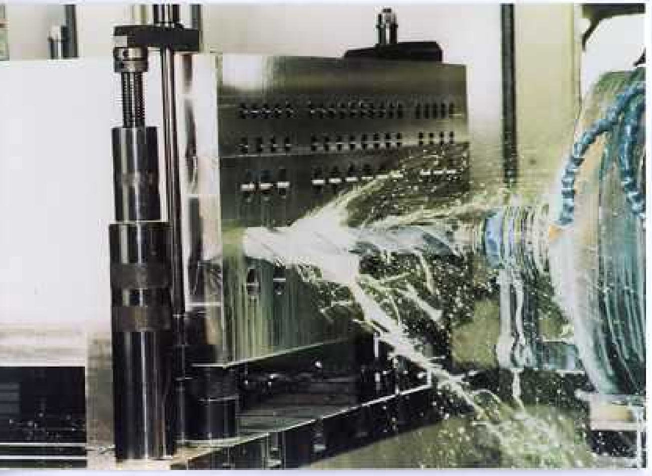
- 421 blanket modules with detachable faceted first wall (FW) with Be armour on a water-cooled copper substrate, attached to a SS shielding block - minimises radioactive waste and allows testing of alternative wall materials.



- Initial blanket acts solely as a neutron shield,
- tritium breeding experiments are carried out on test blanket modules inserted and withdrawn at radial equatorial ports.
- About 4t per module.

# Blanket Module R&D


Drilling of forged steel block
(Shield block cooling channels)


Bending of ice-plugged steel block
(10,000 ton press machine)


Steel block after solution heat treatment
(1010-1054 °C)

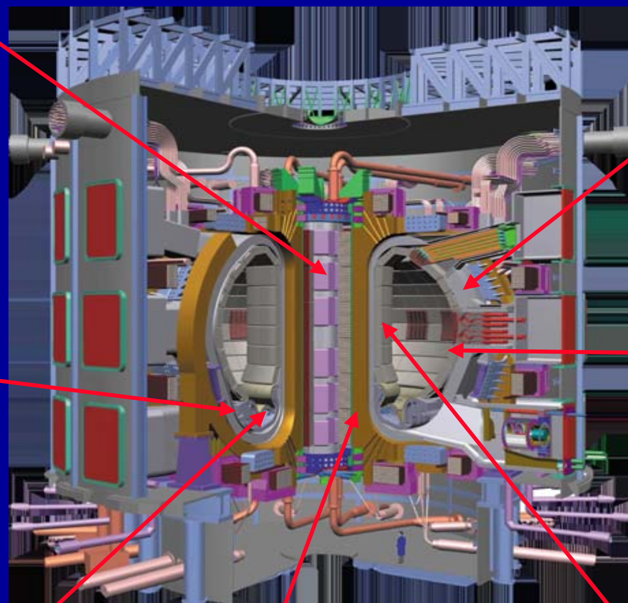

Assembly of steel tubes and DS Cu plates


Final assembly of FW and shield block


Canning for HIPing

# The ITER Design and Technology has been underpinned by R&D

Completed R&D Activities by July 2001.



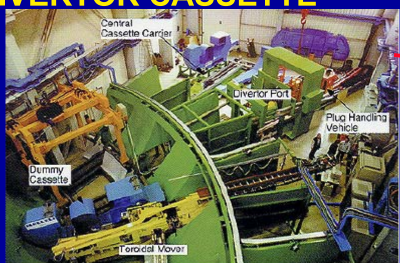
## CENTRAL SOLENOID MODEL COIL

Radius 3.5 m
Height 2.8m
$B_{max}$=13 T
W = 640 MJ
0.6 T/sec

## VACUUM VESSEL SECTOR

Double-Wall, Tolerance ±5 mm

## REMOTE MAINTENANCE OF DIVERTOR CASSETTE




Attachment Tolerance ± 2 mm

## BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

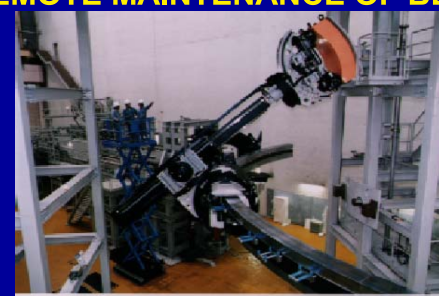
## DIVERTOR CASSETTE

Heat Flux >15 MW/m$^2$, CFC/W

## TOROIDAL FIELD MODEL COIL

Height 4 m
Width 3 m
$B_{max}$=7.8 T
$I_{max}$ = 80kA

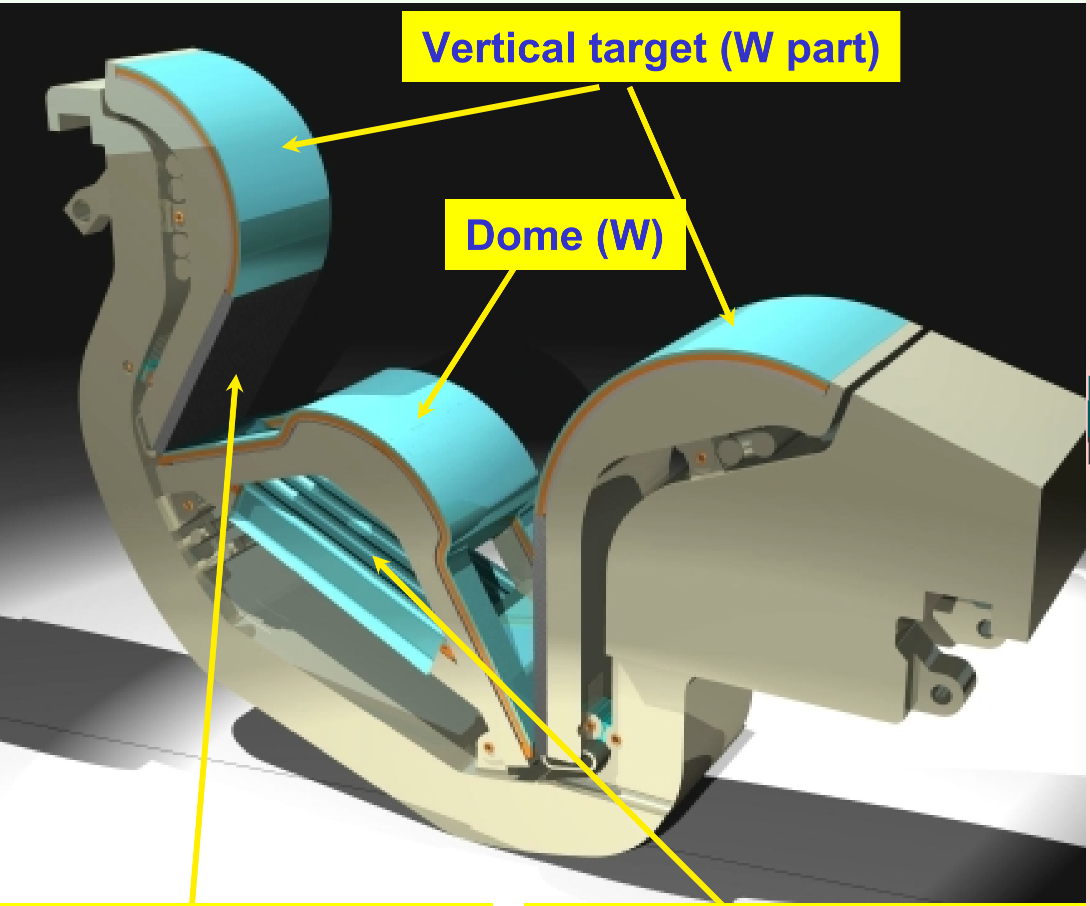
## REMOTE MAINTENANCE OF BLANKET

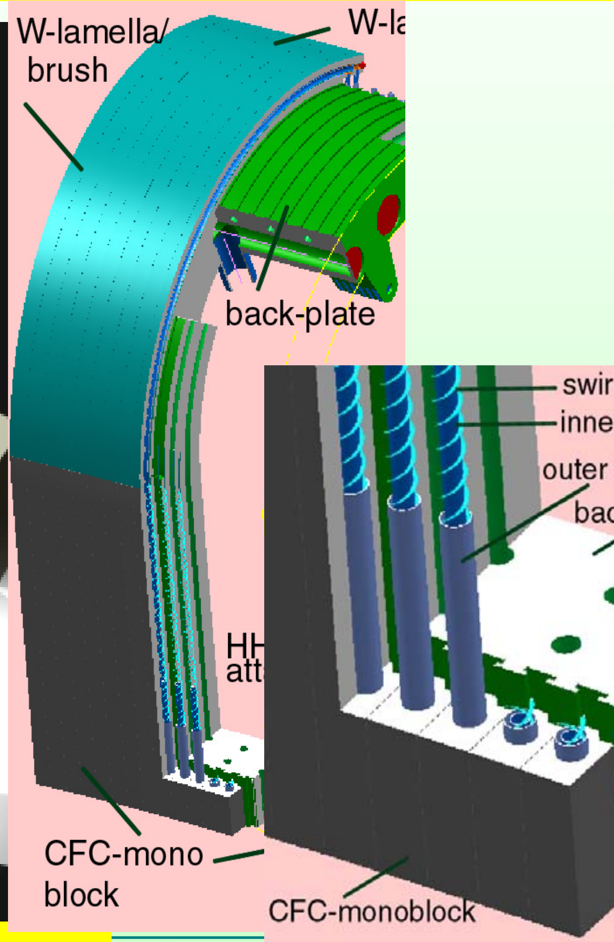


4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

# Divertor - Design

- 54 cassettes.
- Large openings between the inner and outer divertor balance heat loads in the inboard and outboard channels.

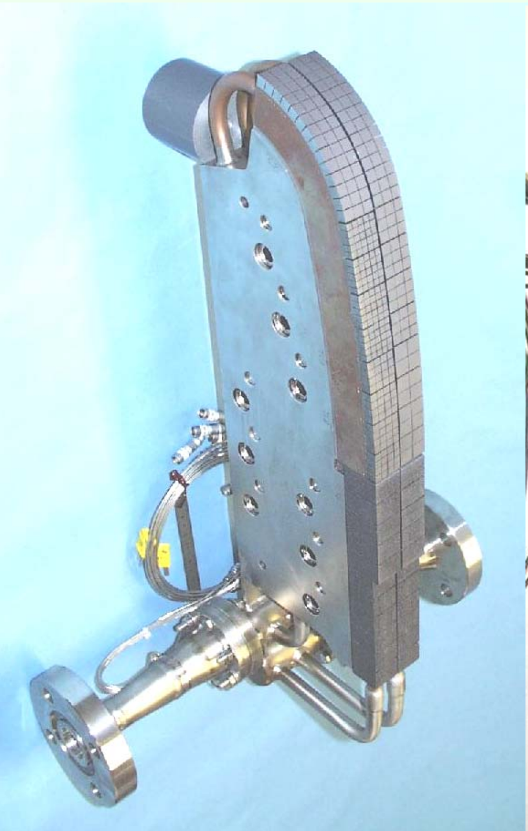


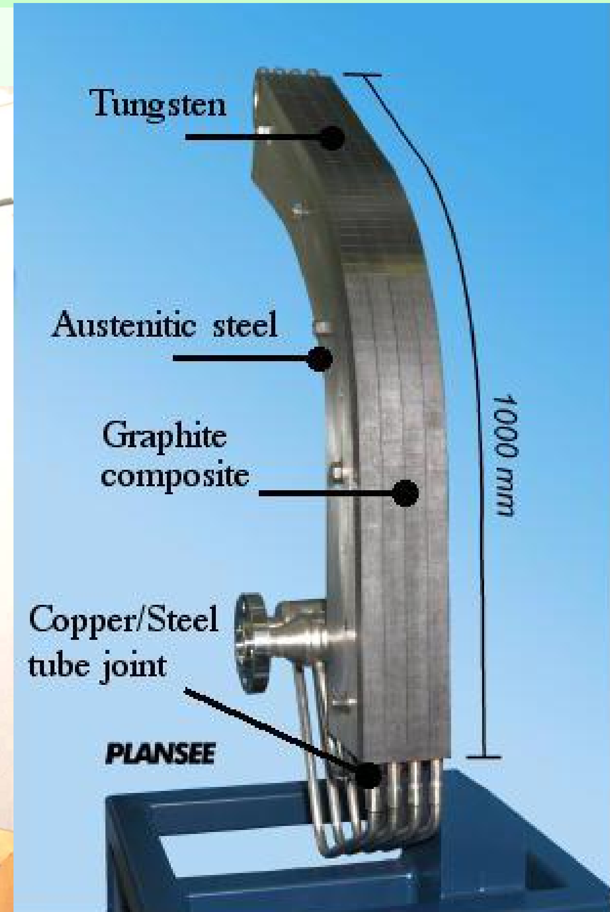




- Design uses C at the vertical target strike points.
- W is the backup.
- The targets are replaceable in the Hot Cell.

# Divertor Prototypical Vertical Target and cassette Mock-ups

- Under high heat flux testing in the Le Creusot e-beam facility, it sustained:
- **1000 cycles at 18 MW.m$^{-2}$ on the W macro-brush armour**
- **2000 cycles at 20 MW.m$^{-2}$ on the CfC armour.**
- **Finally, the CfC armour was shown to survive > 30 MW.m$^{-2}$ in a CHF test.**





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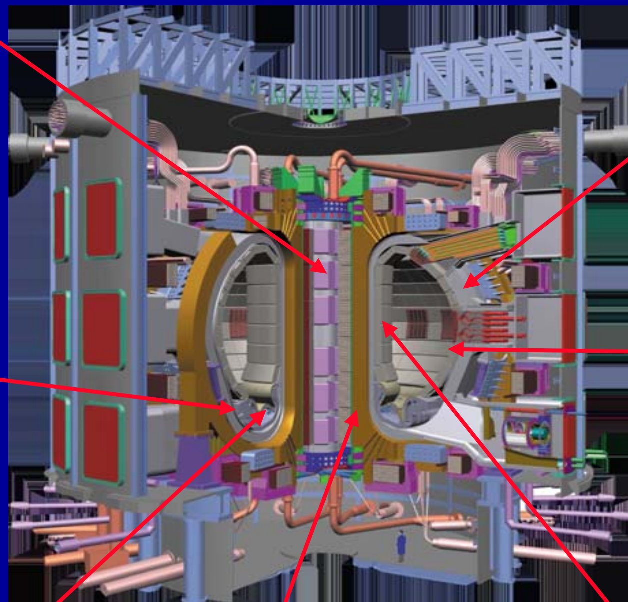

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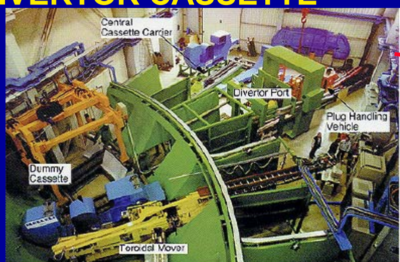


Attachment Tolerance ± 2 mm

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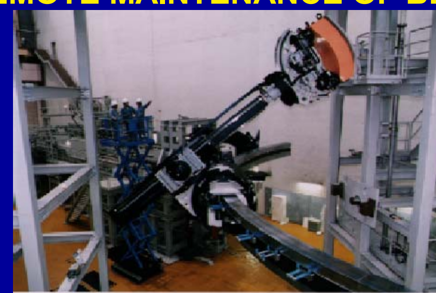
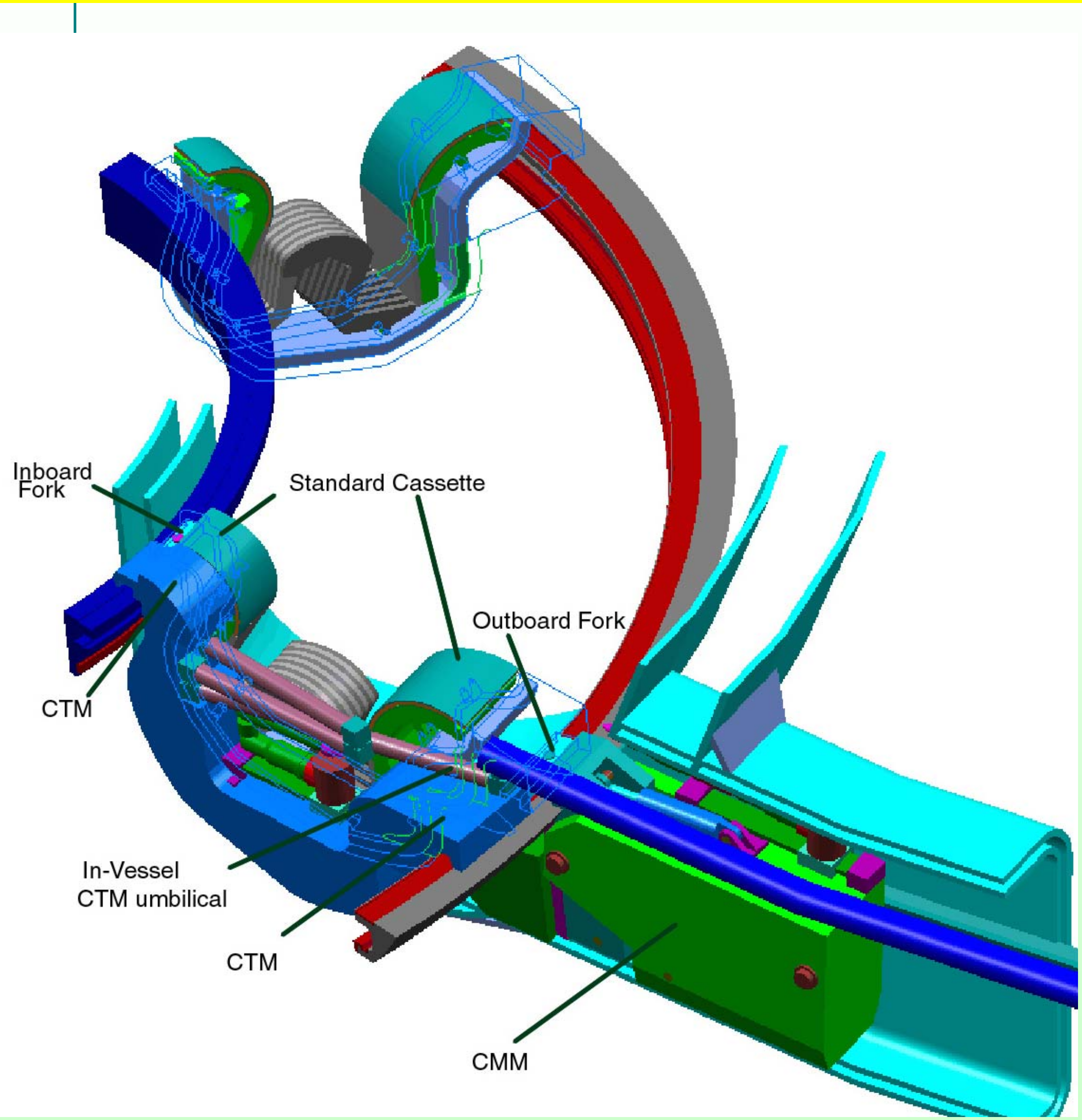
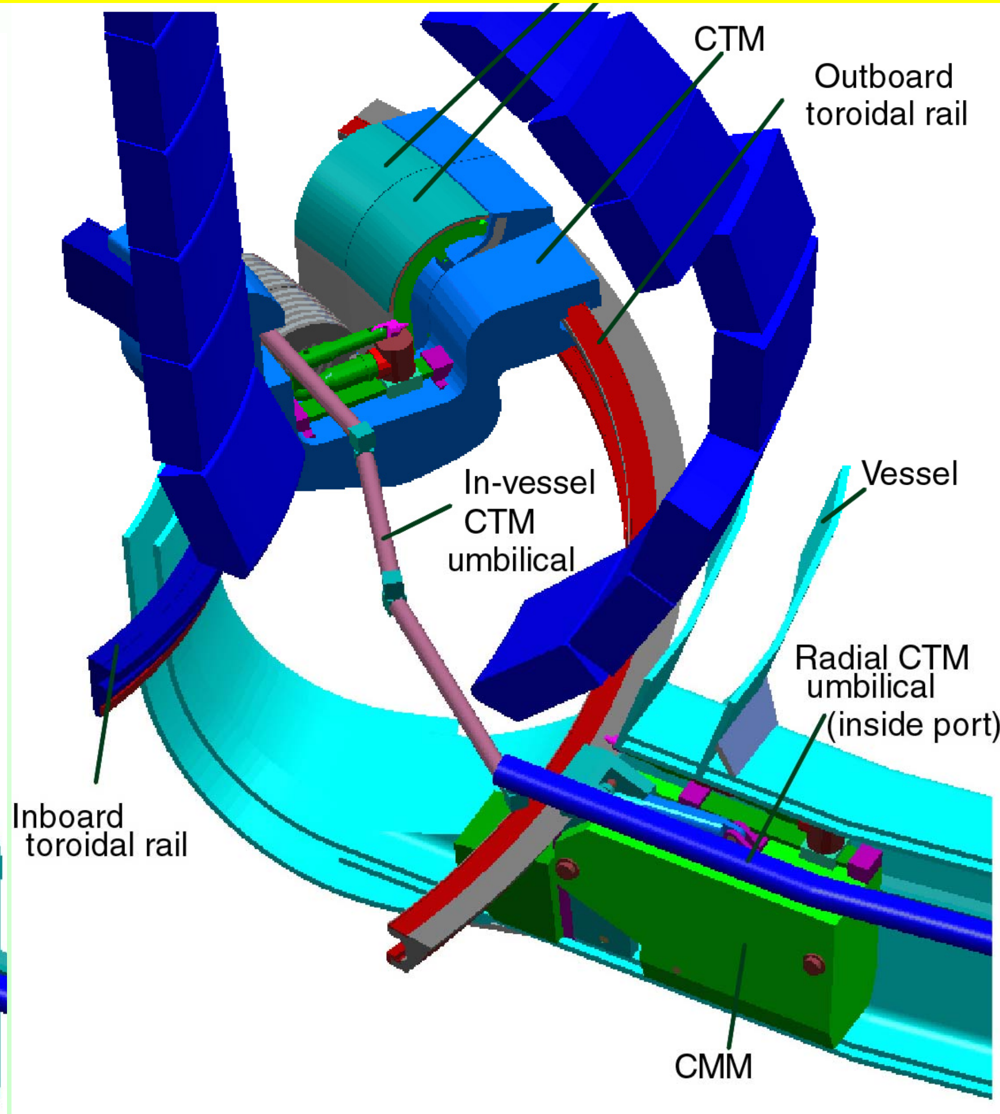


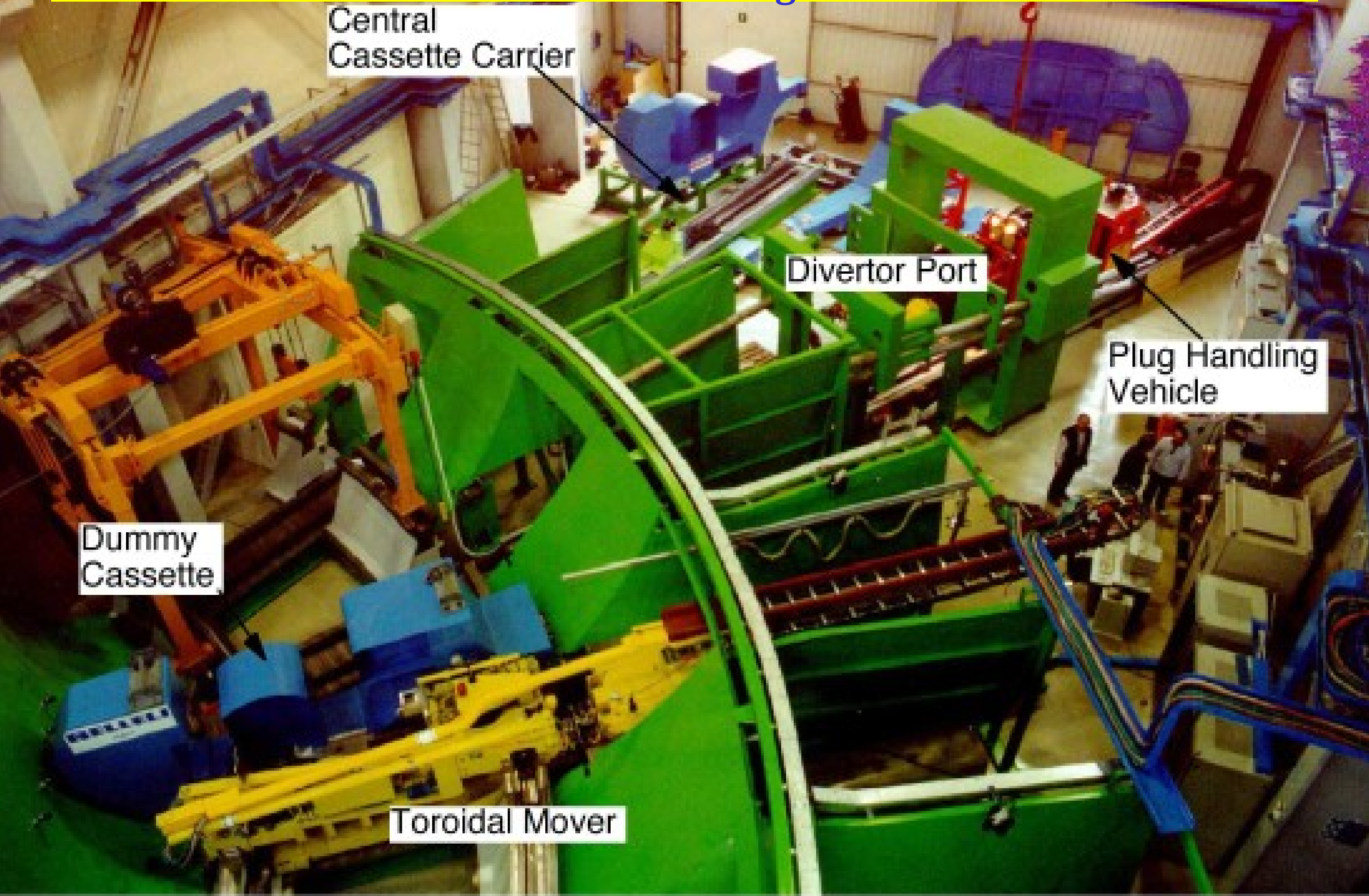
4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

# Remote Maintenance of the Divertor - cassette toroidal and radial mover



# Divertor Remote Handling Test Platform



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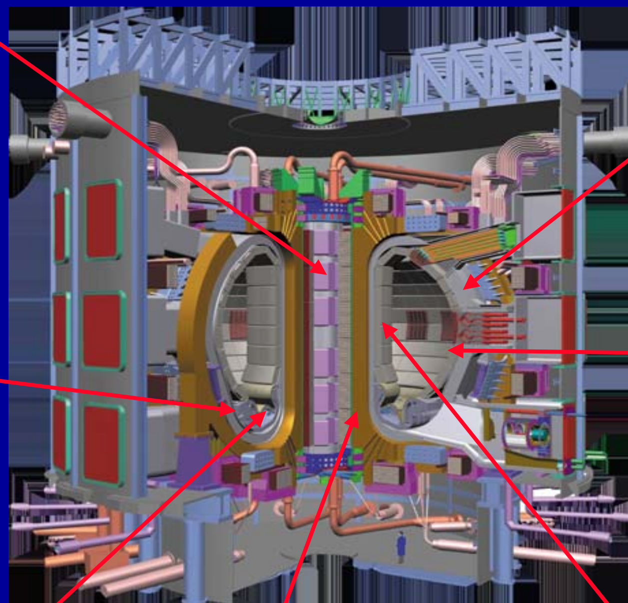
**Completed R&D Activities by July 2001.**



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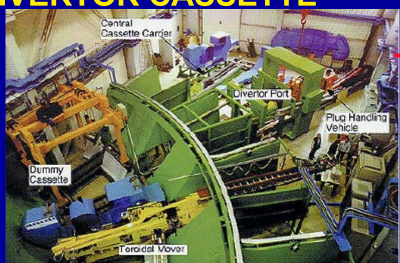


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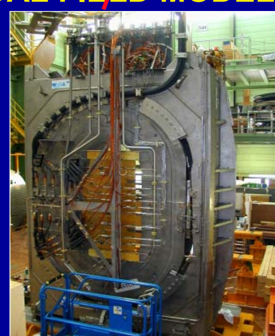

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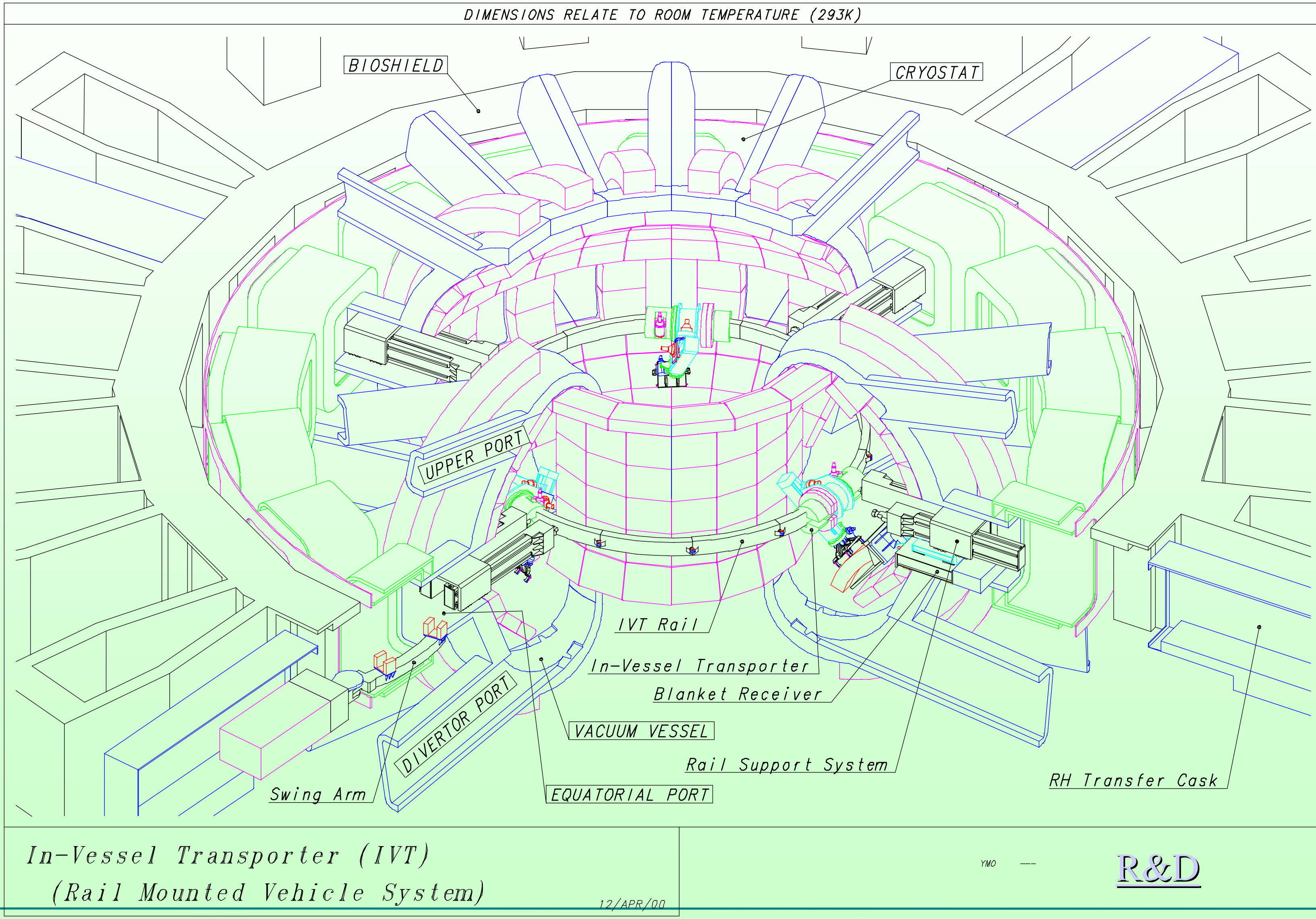
$I_{max}$ = 80kA

## REMOTE MAINTENANCE OF BLANKET

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

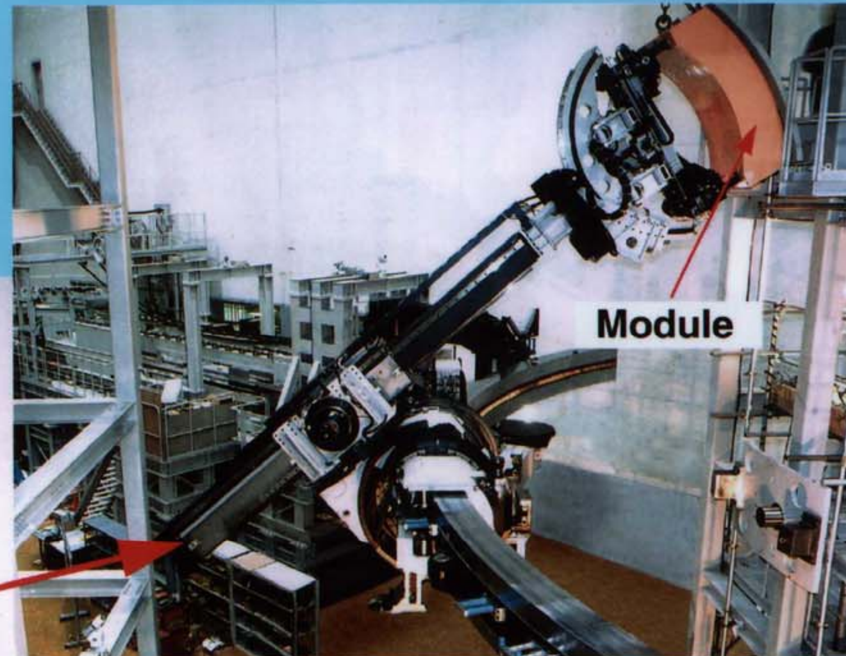
# In Vessel Transporter for Blanket Maintenance

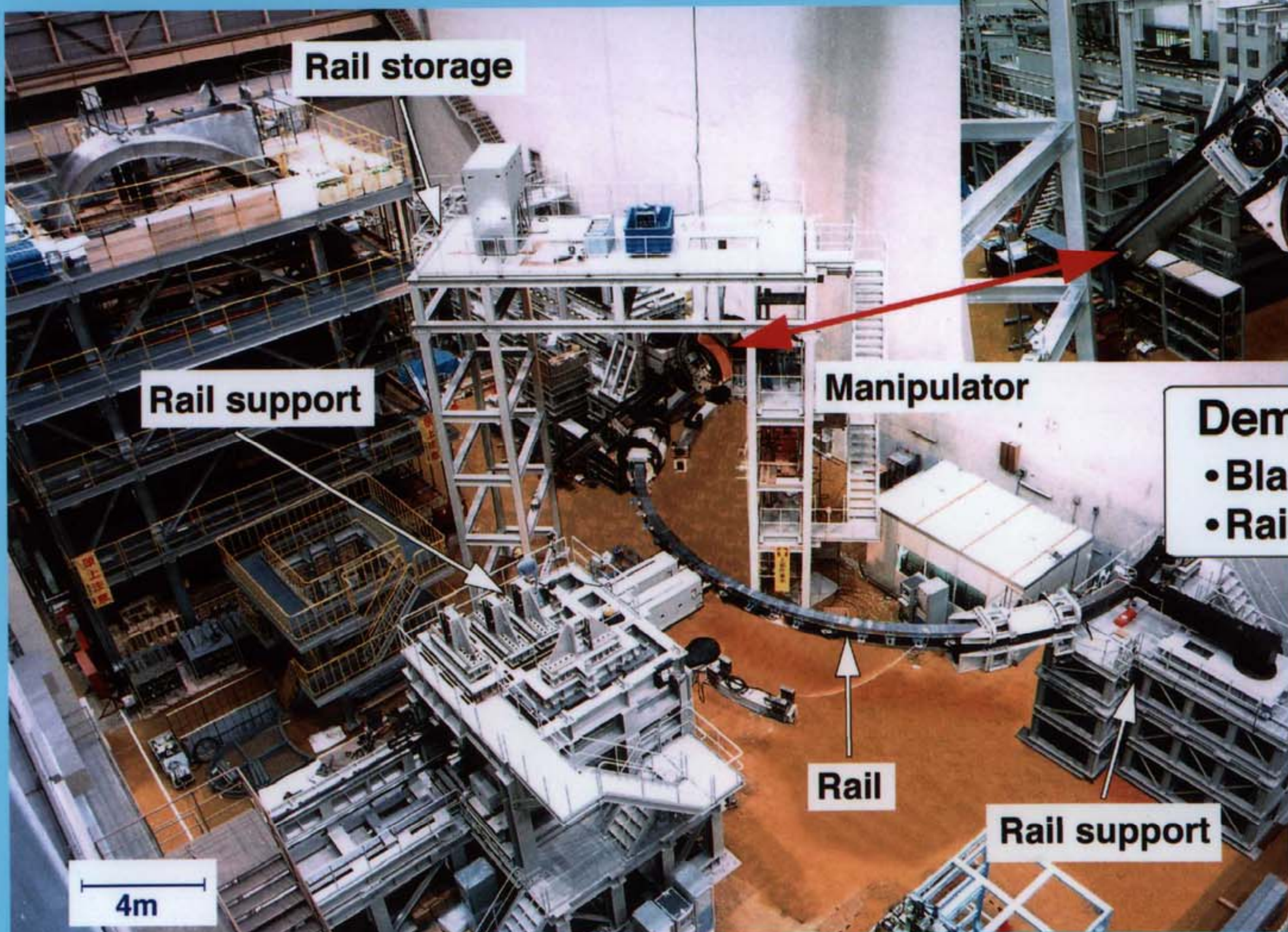



R&D

# Vehicle Manipulator System for Blanket Maintenance

**Payload~4 ton,Arm length~6m**




**Demonstration of**

- Blanket module handling
- Rail deployment

**Positioning 0.5 mm and 0.1°, rail deployed 90° around torus in ~ 30 min..**

# Engineering/Technology Challenges ahead

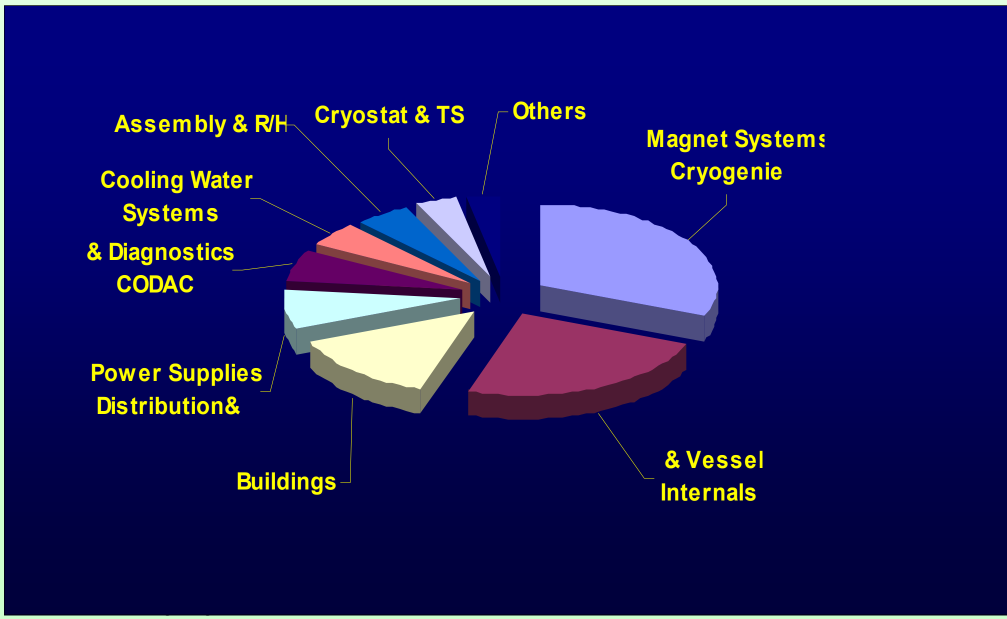
**The above R&D performed during the EDA has shown the feasibility to built ITER, but now reliable functioning components have to be built !!**

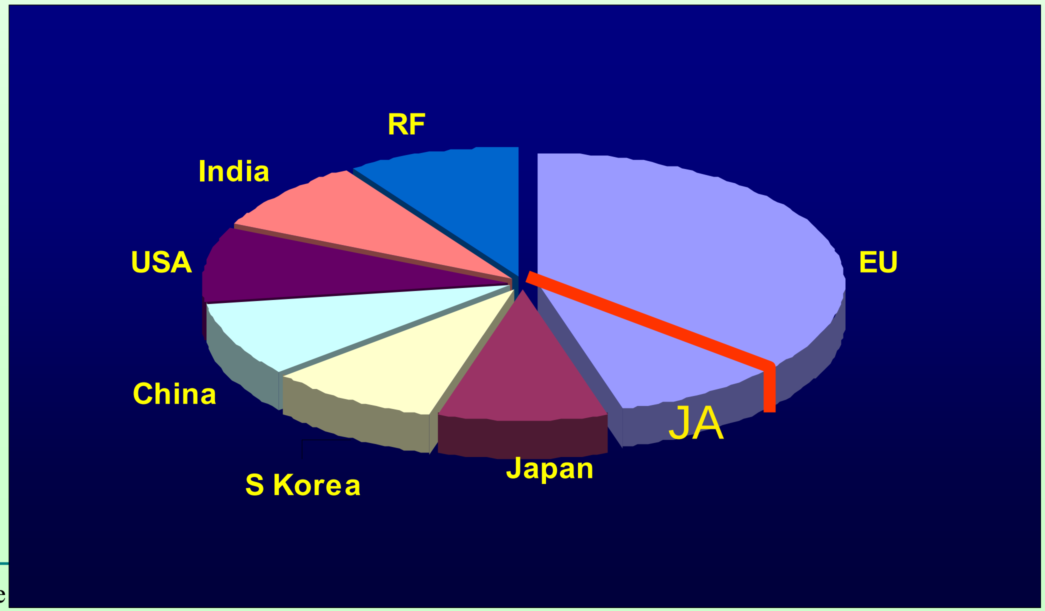
- **ITER has millions of parts with very complex interfaces and ensuing knock-on effects**
- **Unprecedented size of the super-conducting magnet and structures.**
- **All in vessel components (Divertor, Blanket) are subject to large heat fluxes and electromagnetic forces**
- **All maintenance operations inside the ITER machine and the refurbishment of components in the Hot Cell has to be performed remotely**

**➔ A difficult engineering and contract follow-up job lies in front of the future ITER International Team**

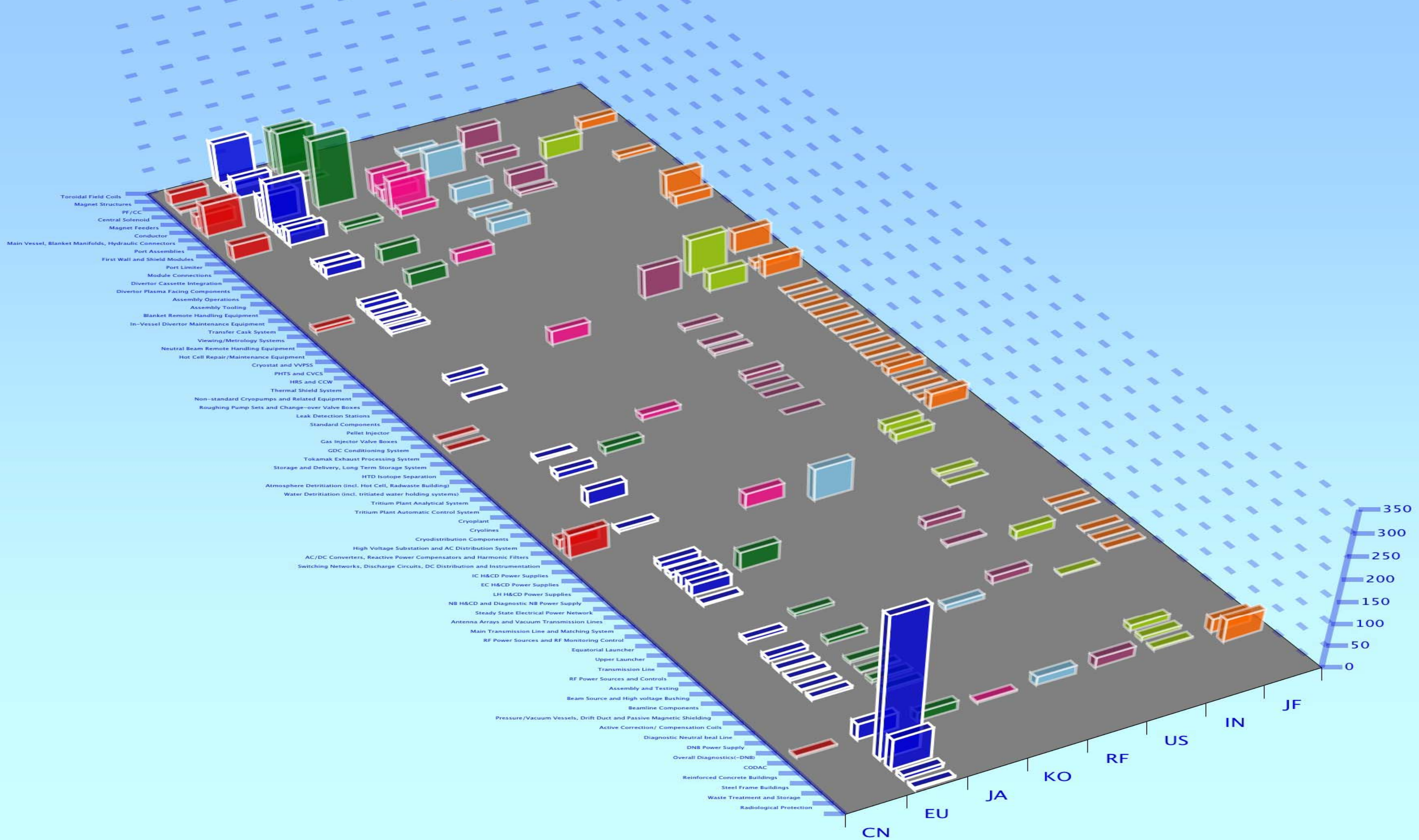
# Organisation Challenges (1)

- The Parties contribute components "In-Kind"
  - Involve all the Parties in key fusion technology areas.
  - Share the cost of the device by 'value' and not by currency.
  - Automatically ensure fair return
- Sharing: 5/11 EU (1/11 procured in Japan), 1/11 Others. (of which 10% centrally funded and 90% in-kind)



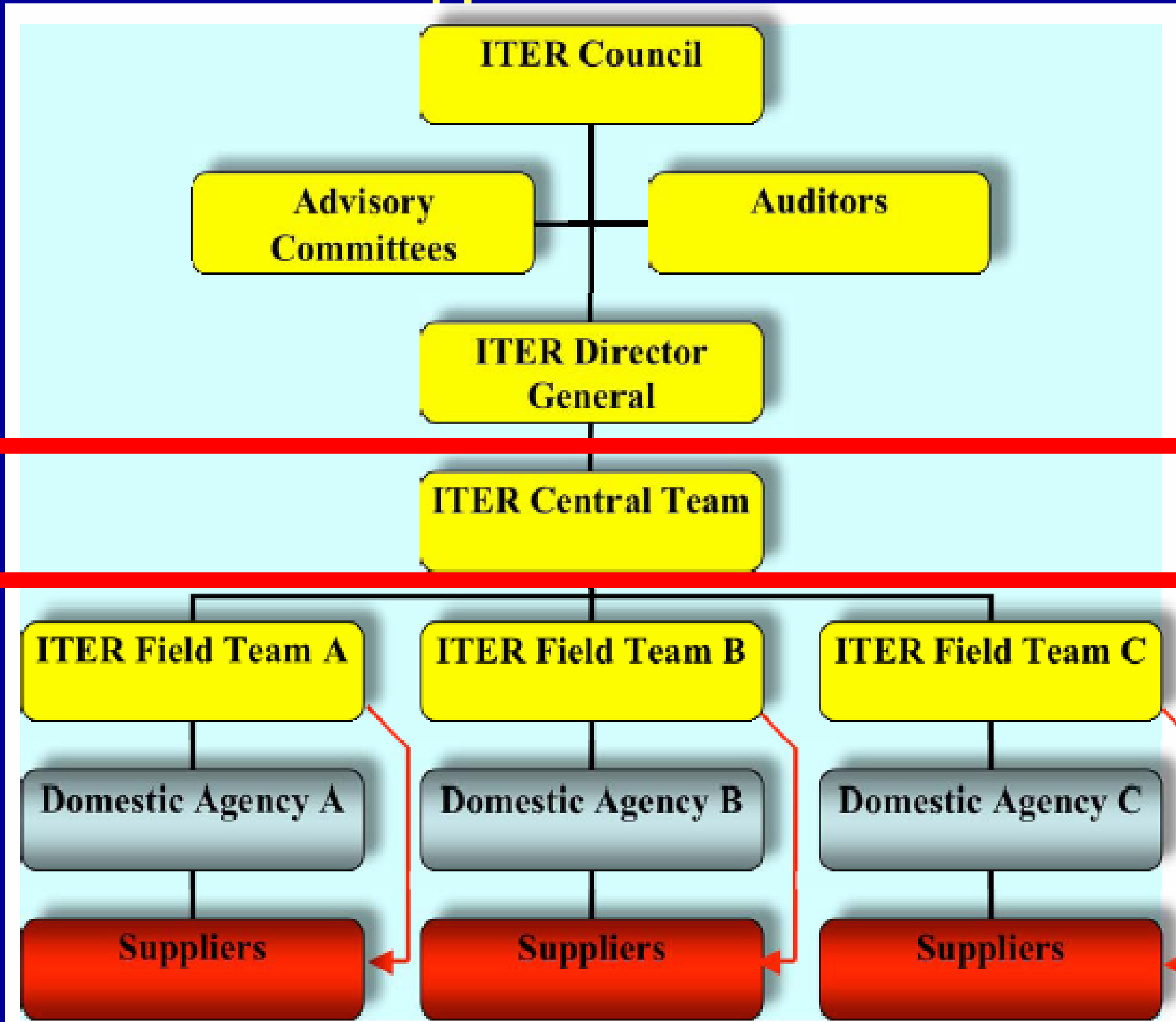



# Procurement Sharing



# Organisation Challenges (2)

- **Forging one coherent project team across multiple cultures (and time zones) with industrial support.**



# Negotiation Status

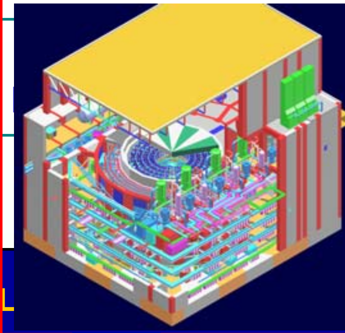
- **ITER Parties are now in the process of finalising the Joint Implementation Agreement and its main instruments.**
  - **Main Agreement Text**
  - **Staffing regulations**
  - **Procurement and cost sharing**
  - **Intellectual Property Rights**
  - **Principles of Operation Programme**
  - **Resource Management**
  - **Principles on management**

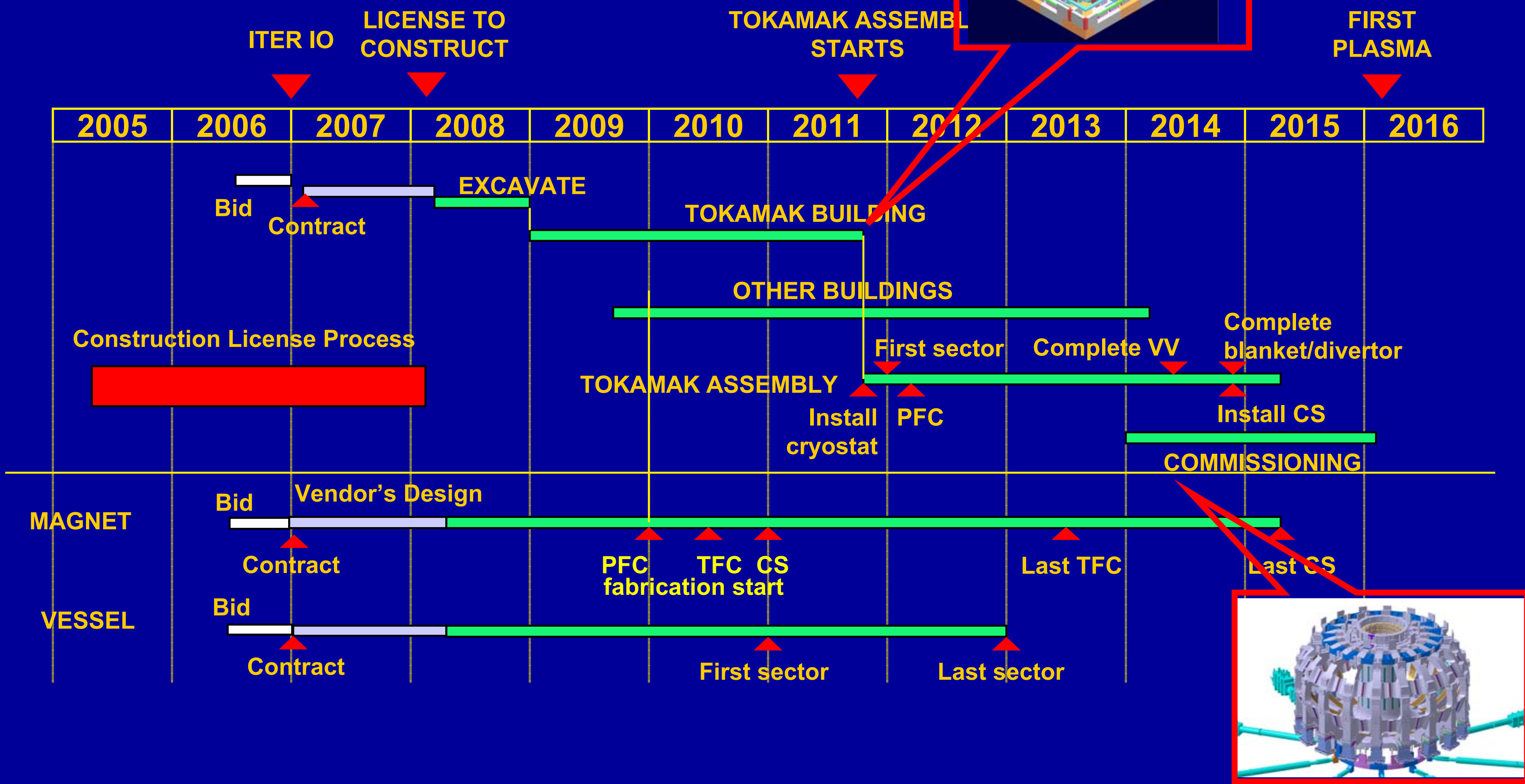
- **The negotiations are successfully finished !**

**<u>To be performed in the near future:</u>**

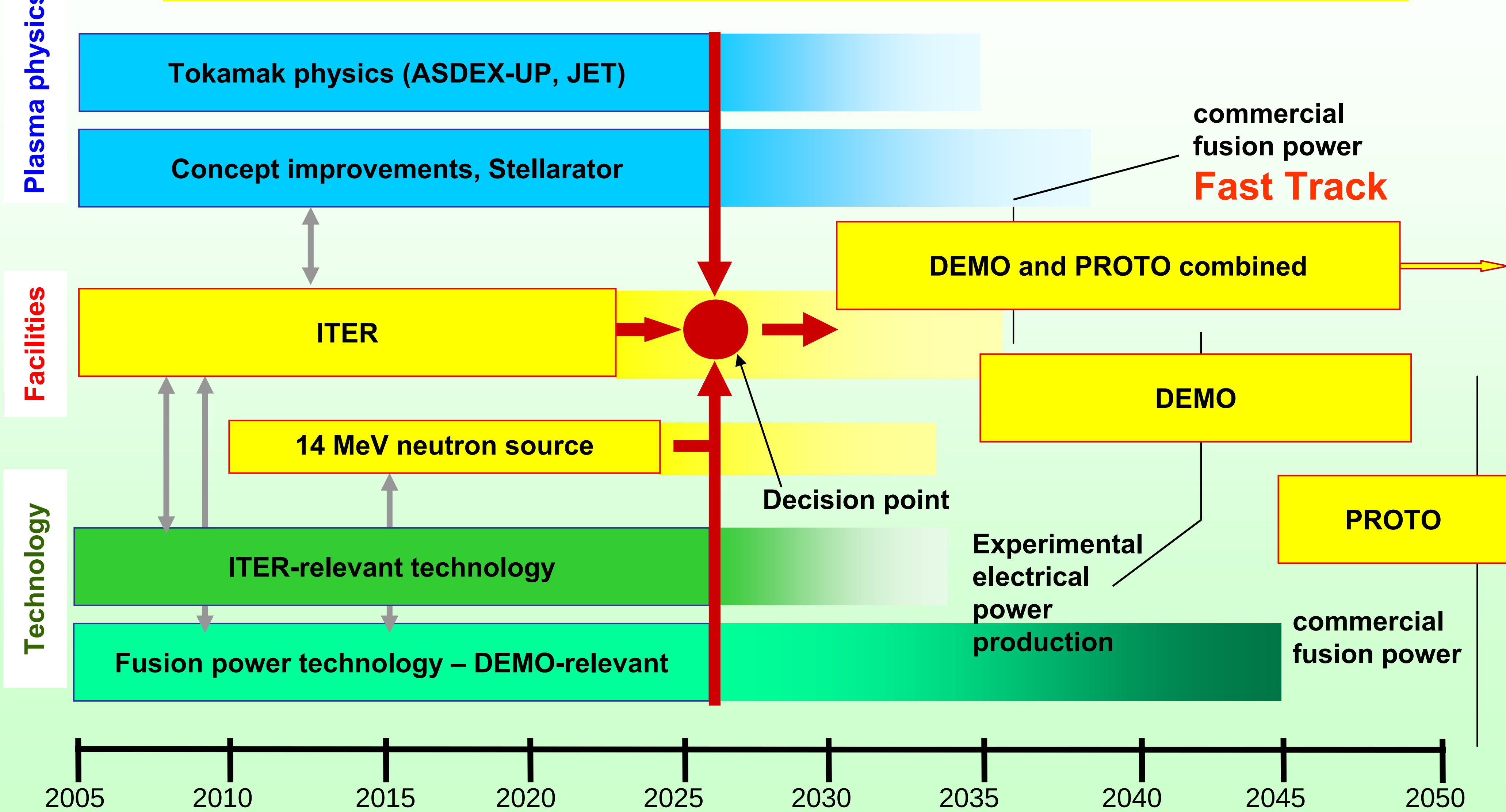
→ **Spring 2006: Ministerial Meeting to “initial” Agreement**
→ **Jun-Jul 2006: Agreement Formal Signature**
→ **End 2006: Agreement enters into force**

# Schedule




ITER IO
LICENSE TO CONSTRUCT
TOKAMAK ASSEMBL... STARTS
FIRST PLASMA
2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016
Bid
Contract
EXCAVATE
TOKAMAK BUILDING
OTHER BUILDINGS
Construction License Process
TOKAMAK ASSEMBLY
First sector
Complete VV
Complete blanket/divertor
Install cryostat
PFC
Install CS
COMMISSIONING
MAGNET
Bid
Vendor's Design
Contract
PFC
TFC
CS
fabrication start
Last TFC
Last CS
VESSEL
Bid
Contract
First sector
Last sector

# Strategy for achieving commercial fusion power, The Fast Track



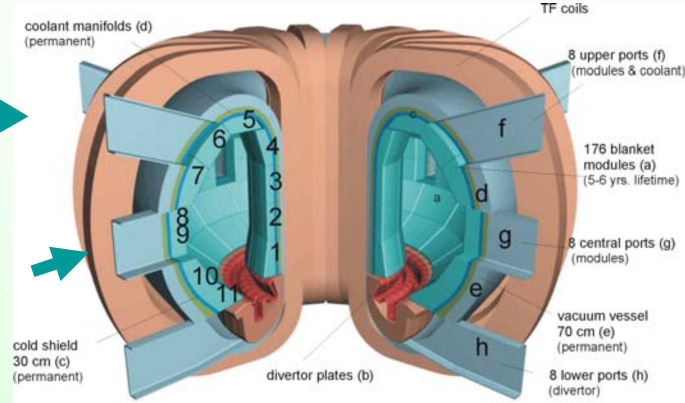
# Conclusions

- ITER is one of the most technologically, organisationally and politically challenging projects being undertaken today.
- Nevertheless, a convincing design has been and continues to be developed able to meet its objectives, and the international infrastructure and the organisation necessary to build it on the expected timescale is (imminently) ready to be set up.
- ITER will be the proving ground for the key technologies necessary to make magnetic fusion into a viable energy source.
- The design phase has demonstrated the desirability of jointly implementing ITER in a broad-based international collaborative frame with the strong involvement of Industry.
- Procurement is split among the ITER Parties, but Europe provides 36% of the hardware.  This allows considerable opportunities for European manufacturers and service providers.
- In its host role, Europe is well-placed to gain essential know-how from its involvement  in most systems, via installation and plant licensing.

Energy Conversion Technology

$H_2$ Production ?

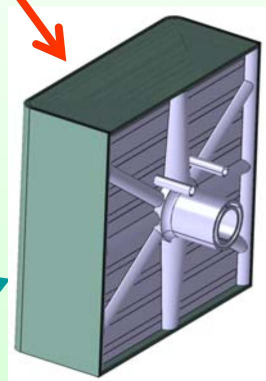
IFMIF

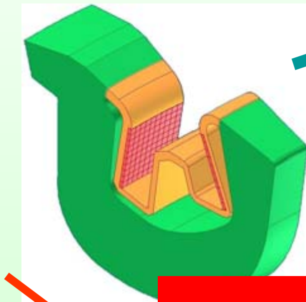



EU DEMO 2035

Materials

Technology

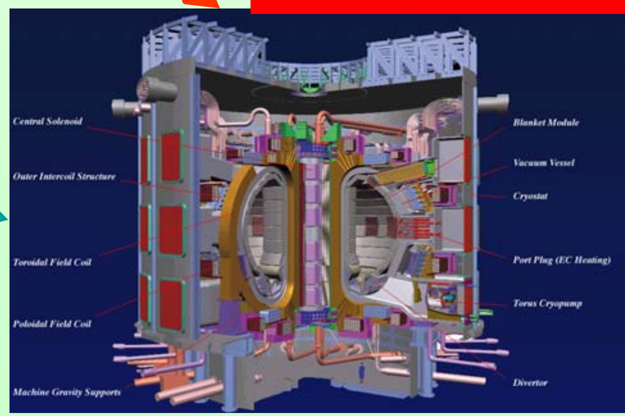




TBM, TDM

now

Physics & Technology




ITER 2016

# What can ITER show about fusion safety?

- **Fusion offers a safe, long term source of energy with abundant resources and major environmental advantages. Magnetic fusion has favourable safety characteristics:**
  - **The nuclear fusion reaction is self-limiting, bounded by the plasma pressure of the burning plasma, thus runaway does not exist.**
  - **Fusion power density and radioactive decay heat densities are moderate, and fast-acting emergency cooling systems are not required.**
  - **The ultimate performance of fusion reactor confinement barriers needs to provide about a factor 10 reduction for tritium. By comparison, fission reactors need to provide a factor $10^6$-$10^7$ reduction for iodine and rare gases.**
  - **Structural materials are activated by fusion neutrons. With the successful development of appropriate materials, the wastes would not require isolation beyond a few hundred years.**

- **ITER has the main characteristics of a fusion power plant (size, power, radioactive inventories).**
- **Safe operation of ITER will demonstrate fusion's safety and environmental potential.**