The Development of Commercial Fusion Energy in the EU
"ITER", "Fast Track", "Ultra Fast Track"

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Forschungszentrum Karlsruhe
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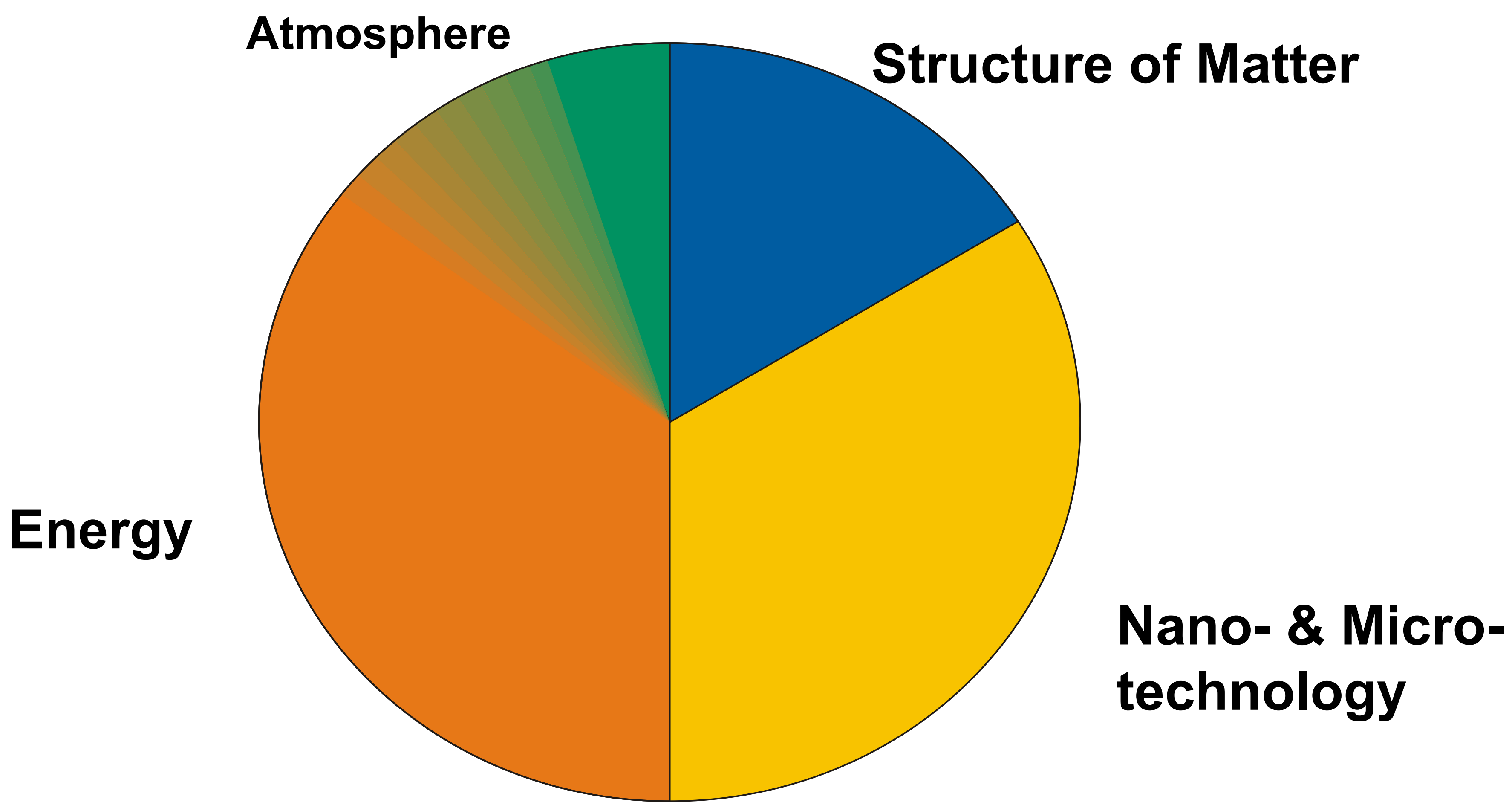
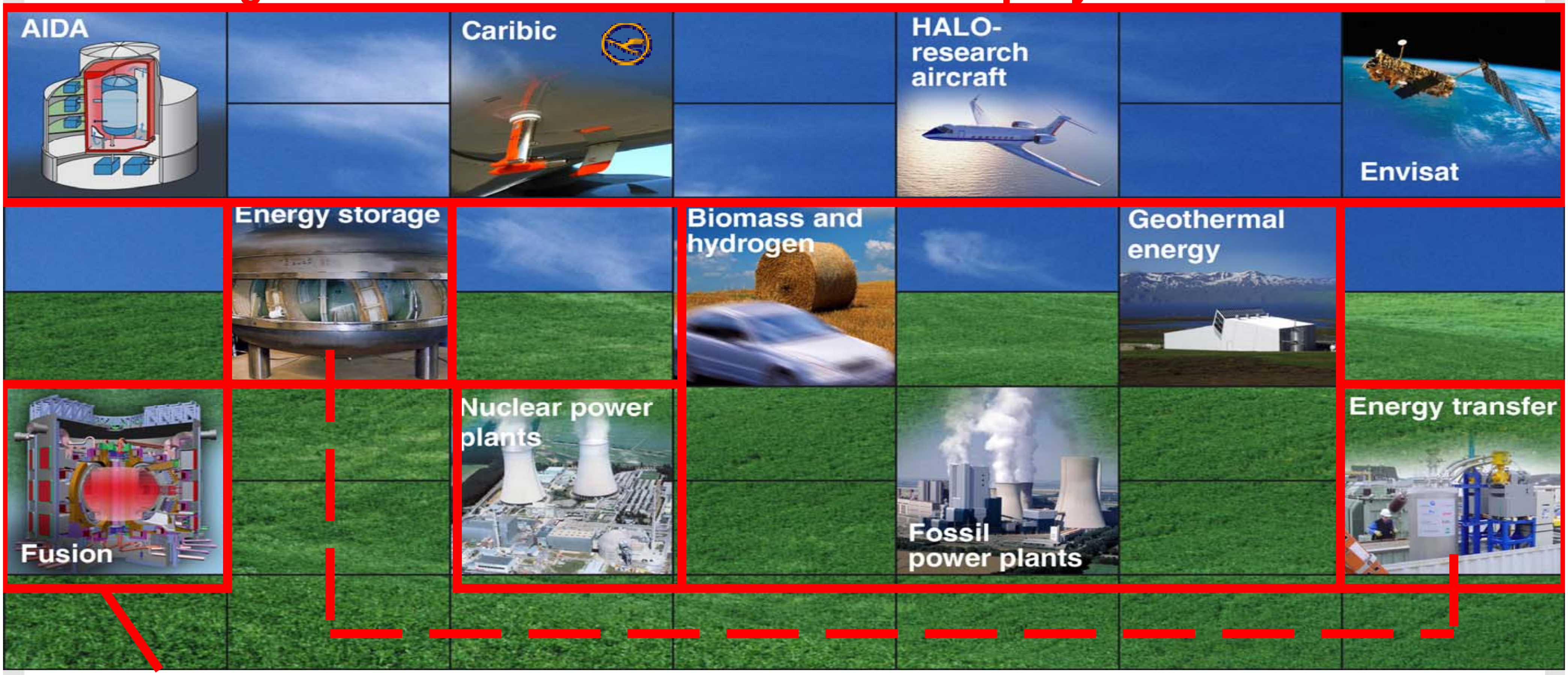
Research Centre Karlsruhe – KIT Campus North
KIT has ~ 8000 employees – half in Campus North
KIT = Karlsruhe Institute of Technology
KIT Campus South is the former University

Program topics in KIT-CN (Campus North)



Program Topic “Energy”

Programs in KIT-CN ~ 200 to 400 employees



Fusion Program has 230 employees and ~ 31 M€ budget per year

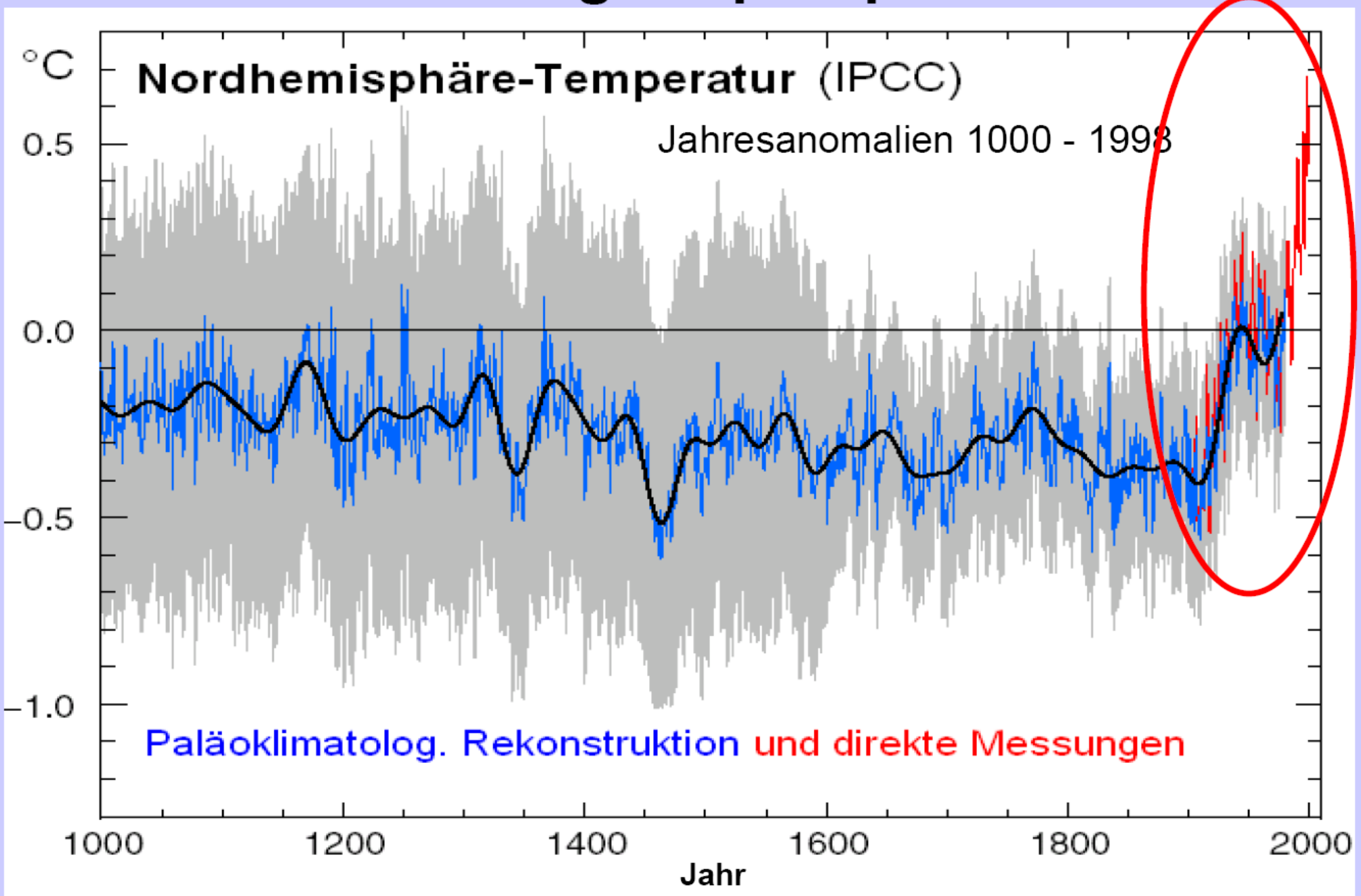
Outline

- **What are the problems concerning the worldwide energy production and use**
  - Climate change, finite Oil and Natural Gas resources
- **Possible solutions for these problems and their potential**
  - Renewals, Nuclear Fission, Fusion, Transport – electric (battery, fuel cells)
- **Fusion as mid- to long-term solution for part of the problem**
  - ITER and its mission
  - The Fast Track to Fusion Energy (DEMO)
  - The Ultra Fast Track
- **Summary and Conclusions**

The Climate Change Problem

KIT Karlsruhe Institute of Technology

Die Langfristperspektive



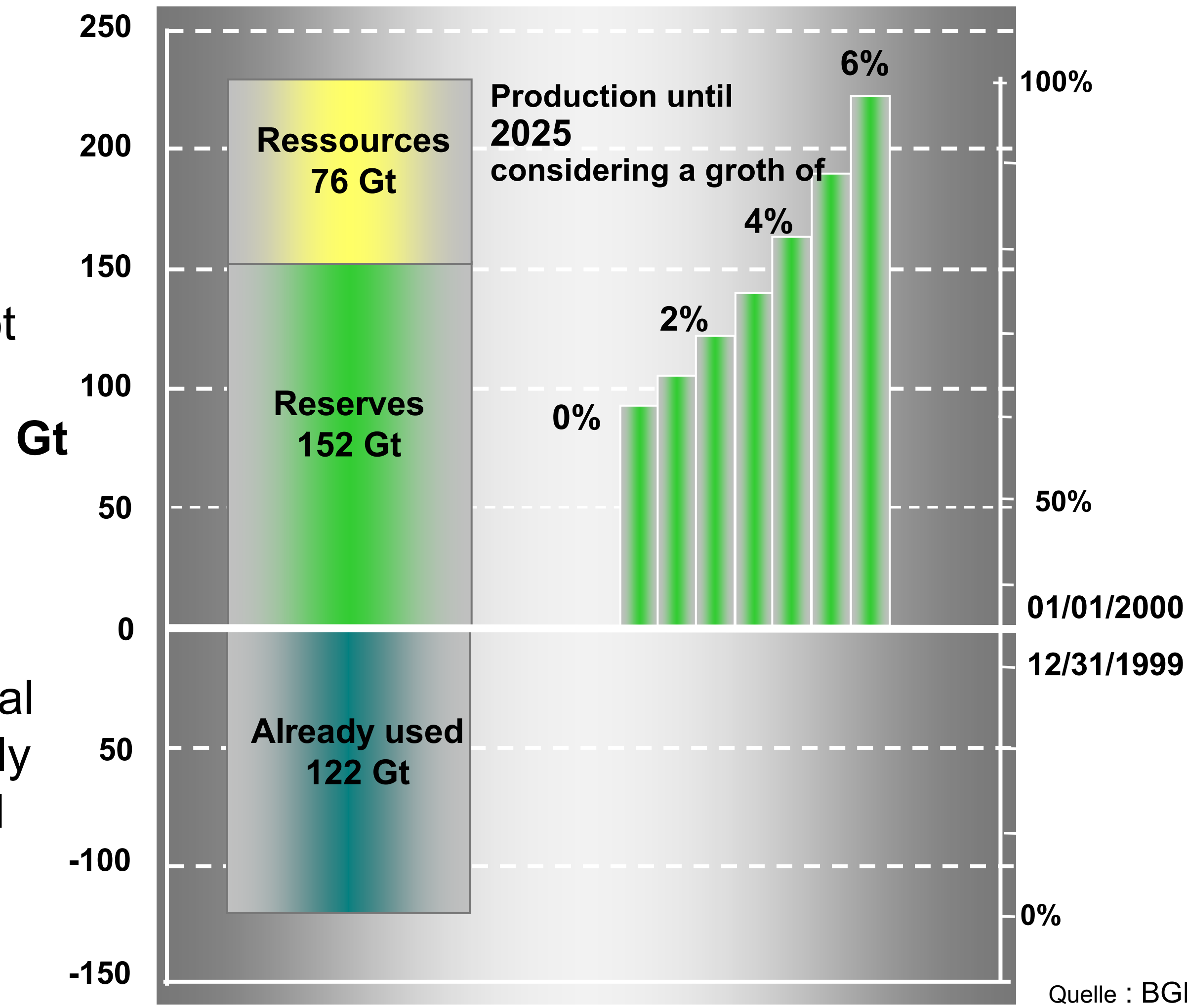
Mann et al., 1999; IPCC, 2001

The Problem of limited Oil Resources

- Total World Potential and available Reserves

Ressources: Part of the total resources which has been either discovered but is not yet economically accessible, or geologically indicated, estimated in situ amount or for other reasons not part of the oil reserves

Reserves: This is the part of the total resources which has been accurately measured and which can be utilised within today's technical and economical boundary conditions.

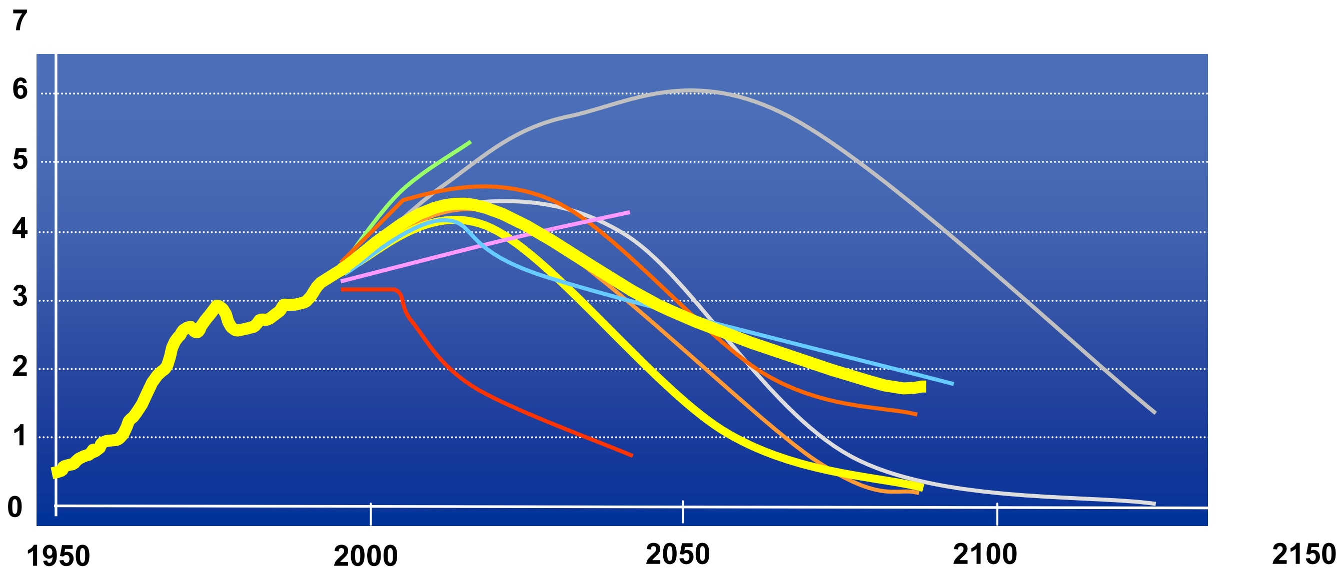


Quelle : BGR

A selection of different prognosis for conventional and non conventional oil production

- US-DOE 1999
- Odell 1998, conv. + non-conv., EUR > 800 Mrd. t
- Odell 1998, only conv., EUR ca. 540 Mrd. t
- Campbell 1997, only conv., EUR ca. 250 Mrd. t
- Edwards 1997, conv + non-conv., EUR > 500 Mrd. t
- Edwards 1997, only. Without NGL, EUR 385 Mrd. t
- WEC 1999, conv. + non-conv.
- Shell 1995, conv. + non-conv., EUR ca. 600 Mrd. t
- Hiller 1999, only conv., EUR ca. 350 Mrd. t
- Hiller 1999, conv. + non-conv., EUR ca. 580 Mrd. t

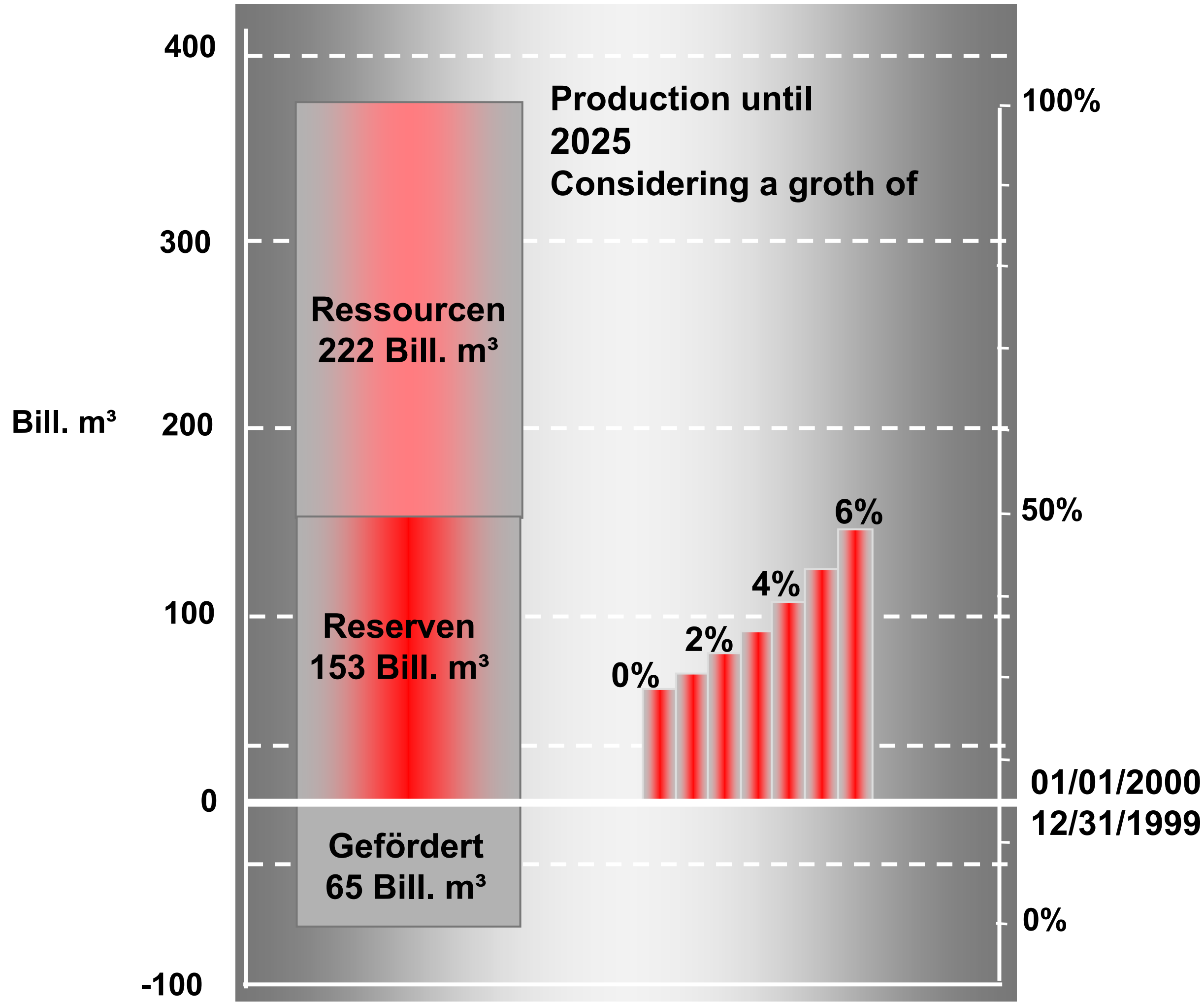
EUR estimatad ultimate recovery



Quelle: BGR

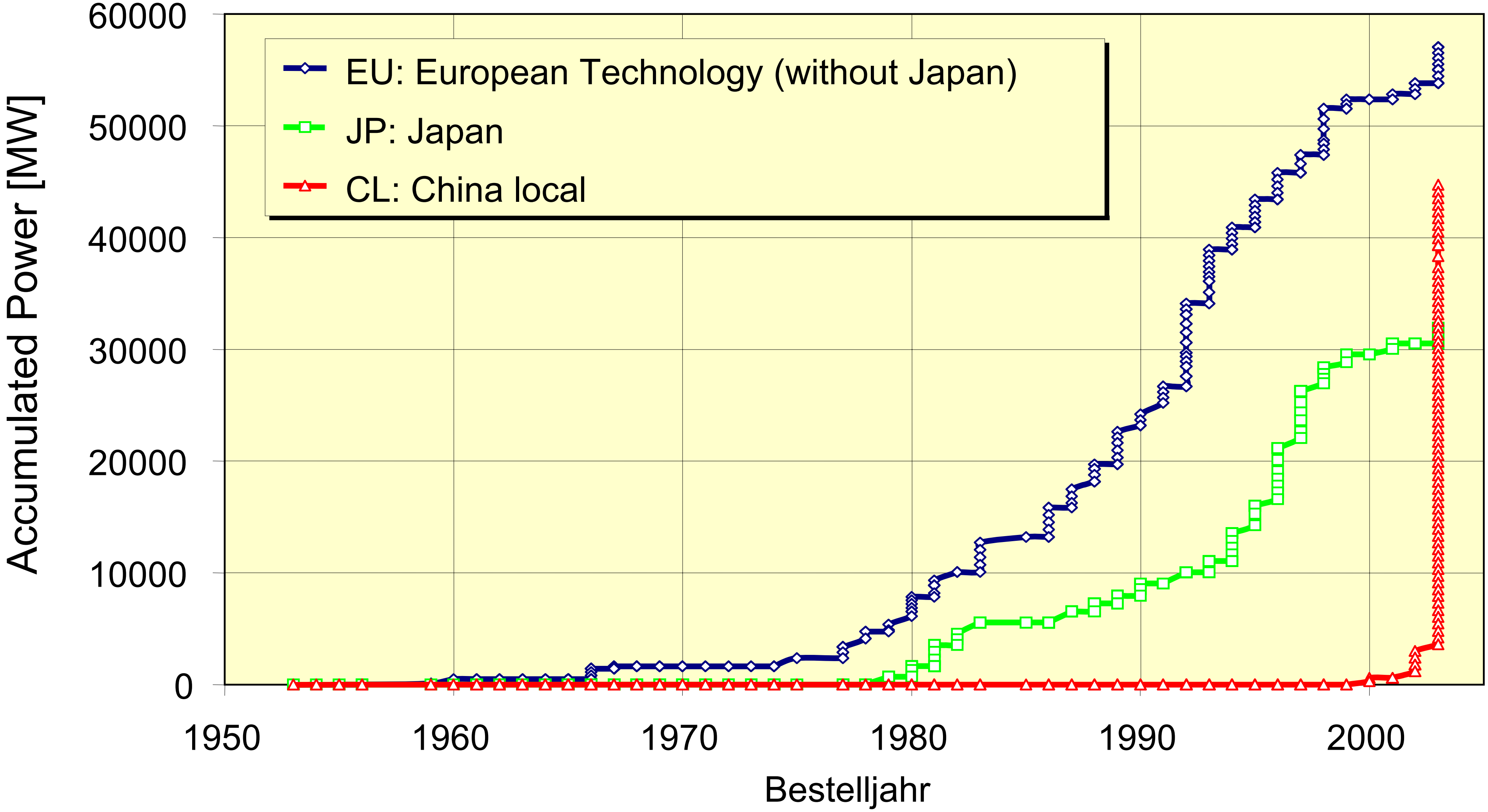
The Problem of limited Gas Resources

- Total World Potential and available Reserves



Quelle : BGR

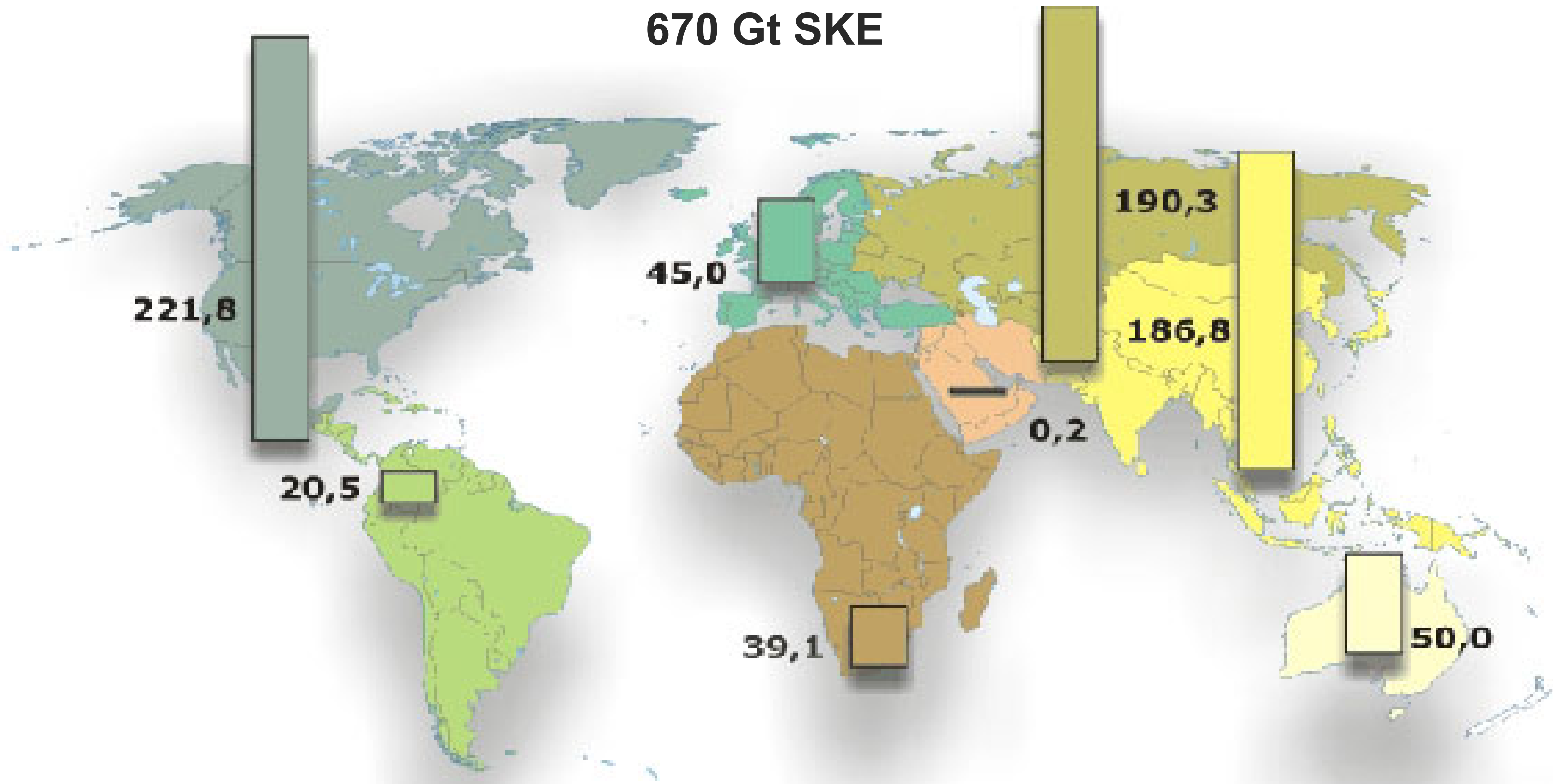
Installation of modern coal power stations in the EU, JA and China



Quelle: Dr. Gasteiger; Alstom VGB-Kongress Okt. 2004

The Coal option

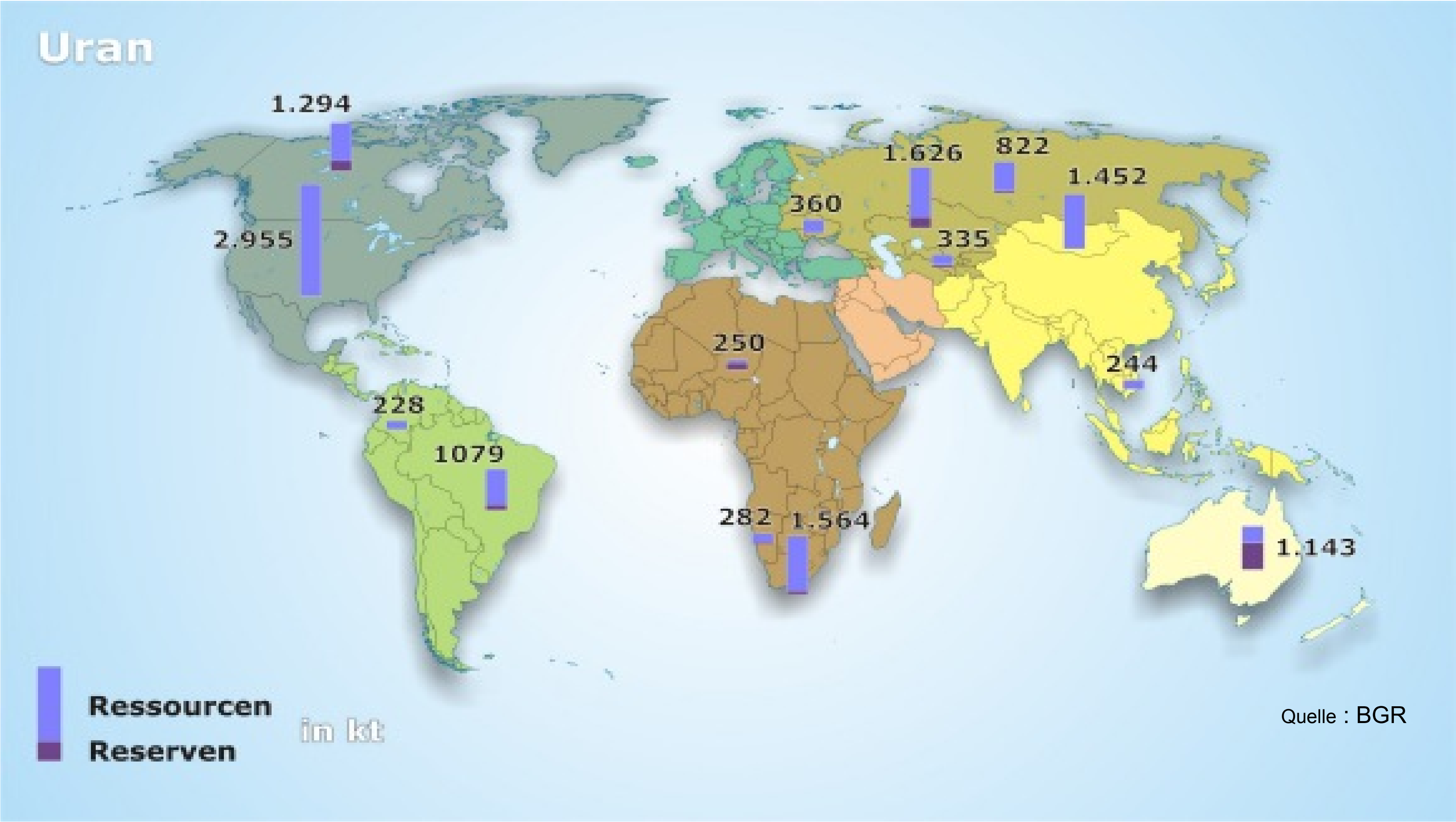
Distribution of coal



Lasts ~ 200 years depending on possible increase of use

Quelle : BGR

The Nuclear Option
Distribution of Uranium Resources

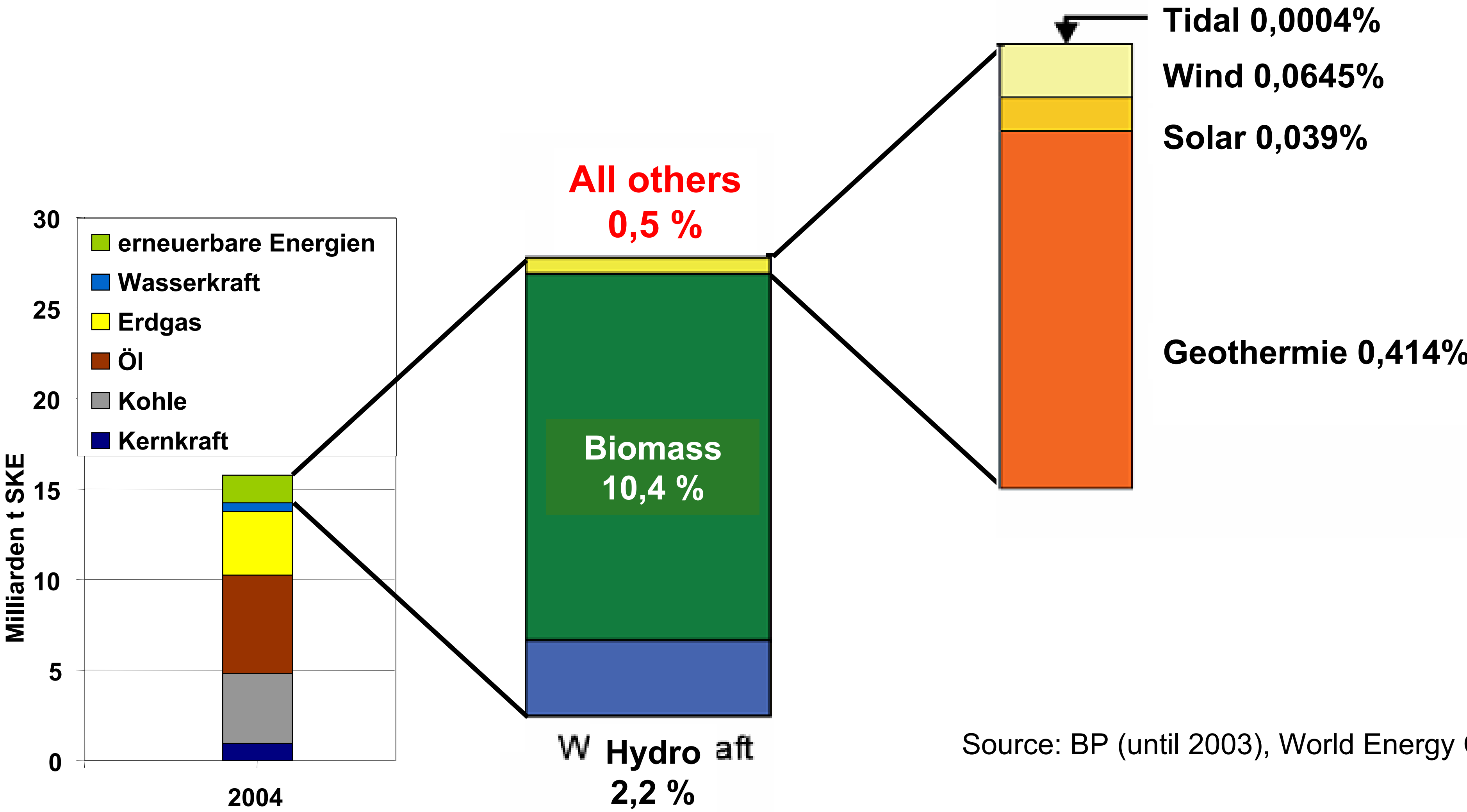


Lasts ~ 80 years depending on increase of use (without breeding)

The Reneable Option

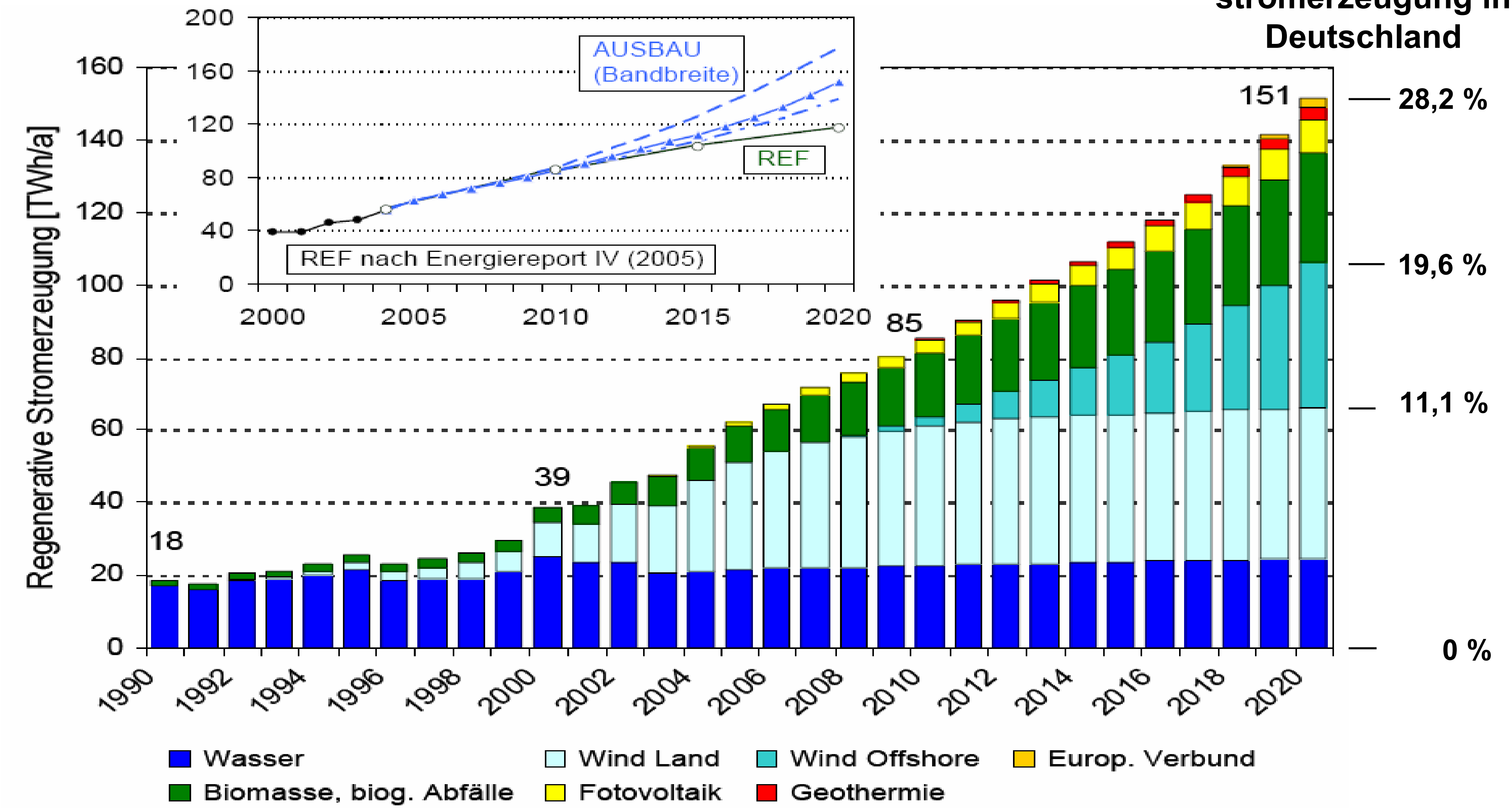
Global energy use

indicating primary energy sources with the focus

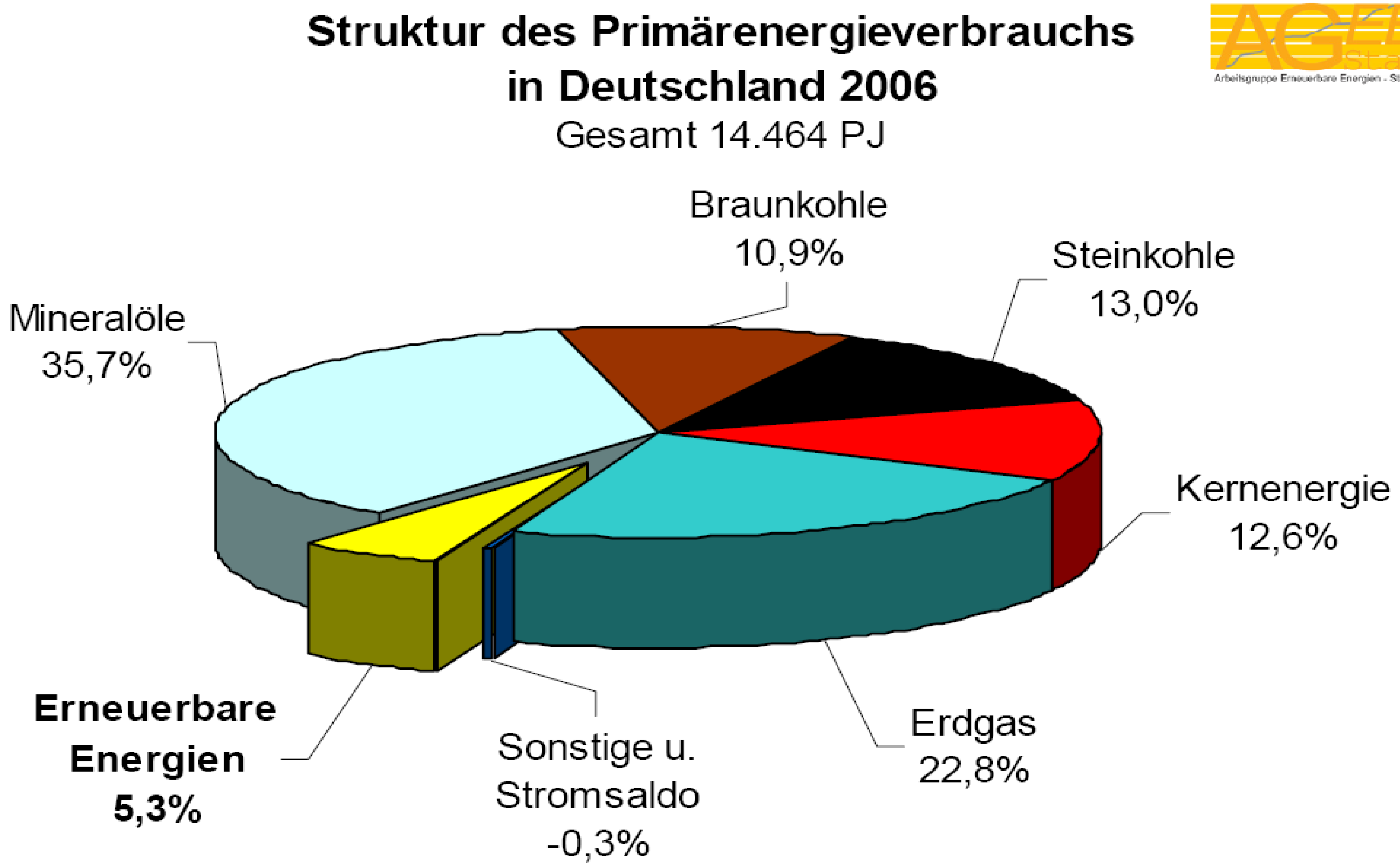


Source: BP (until 2003), World Energy Council

Electric power production from Renewables in Germany



Energy usage in Germany
indicating the primary energy sources

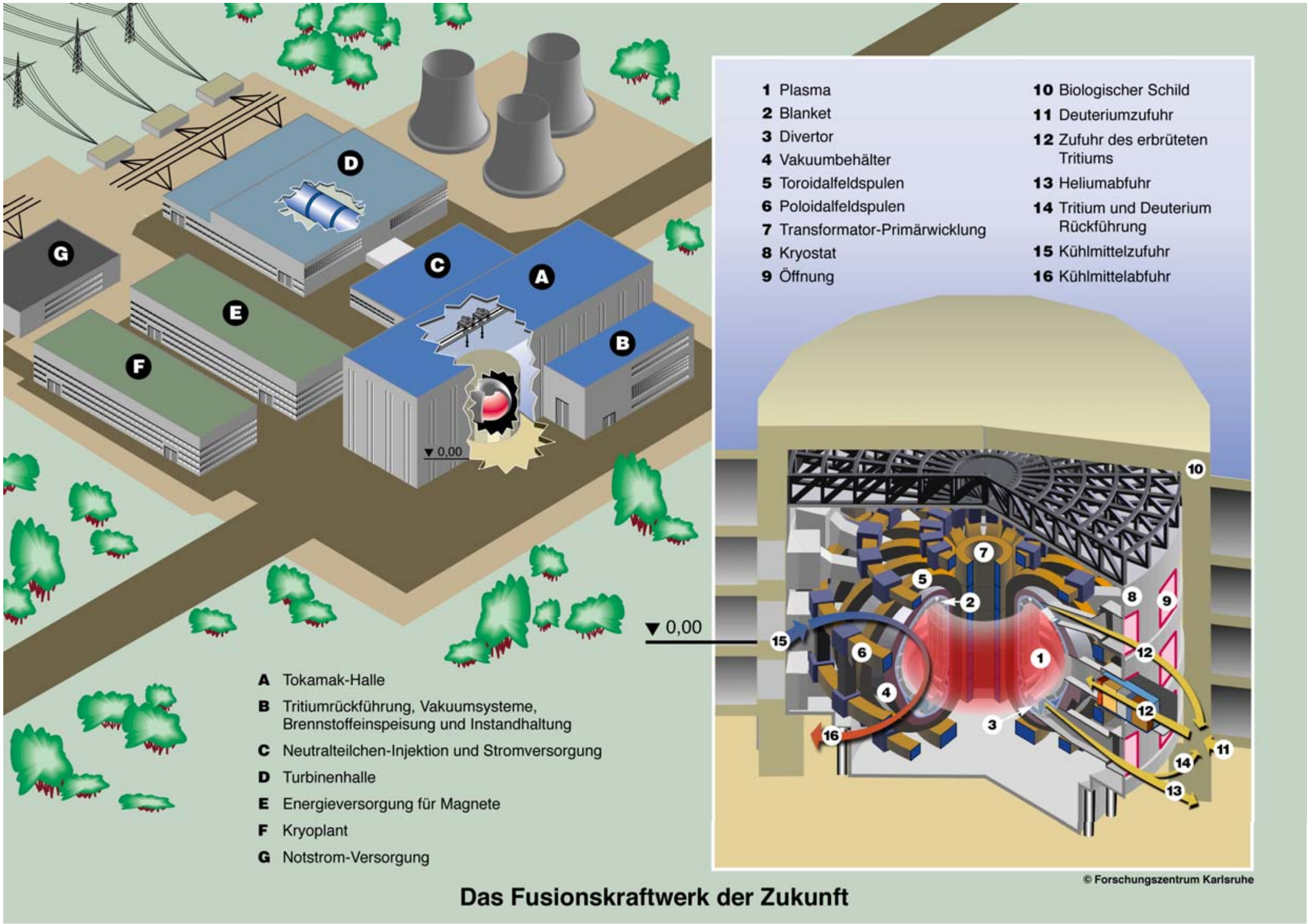


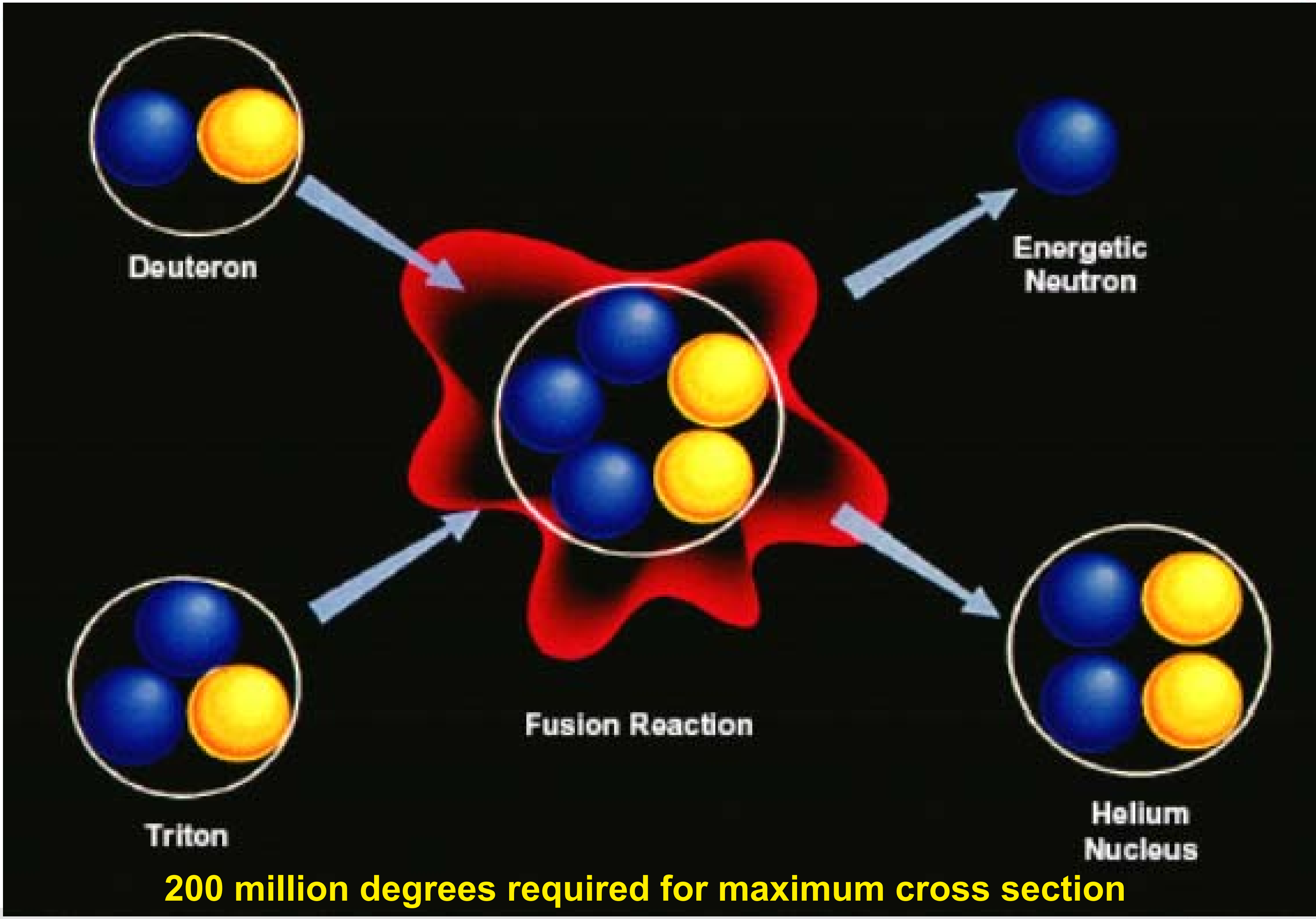
Quellen: Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW) , nach Arbeitsgruppe Erneuerbare Energien-Statistik (AGEE-Stat); Arbeitsgemeinschaft Energiebilanzen; nach Wirkungsgradmethode; vorläufige Angaben, Stand Februar 2007

What are possible solutions to the above problems ?

- **If renewables alone can't solve the problem then there are just three more options with different time scales:**
  - Coal – lasts in the order of 200 hundred years – climate change impact !
  - Nuclear fission – lasts not much longer than oil and gas without breeding
    - new generation of fission power plants required – research need !
  - Nuclear Fusion – lasts millions of years – needs development – time !!
- **In order to tackle our climate change and energy problem mankind will have to develop all options in parallel and utilise the different possible timescales**
  - Most important is to develop energy sources which can be deployed in China and India as well – their economic growth is accelerating the problems
- **Will fusion energy come in time to help solving the above problems ?**
- **The development scenarios for fusion (ITER, Fast Track, Ultra Fast Track)**

Schematic View of a future Fusion Power Reactor




Deuteron
Energetic Neutron
Fusion Reaction
Triton
Helium Nucleus
200 million degrees required for maximum cross section

Needed resources for a D-T-Fusion Power Plant, ~1000 MW electrical :

Deuterium D_2: ~ 100 kg/a → in $5*10^{16}$ kg Oceans

Sufficient for 30 billion years !!

Tritium T_3: ~ 150 kg/a

breeding with Lithium reaction →
Only <u>300 kg Li6</u> needed per year

$^6Li + n \rightarrow {^3T} + {^4He} + 4.8\ MeV$

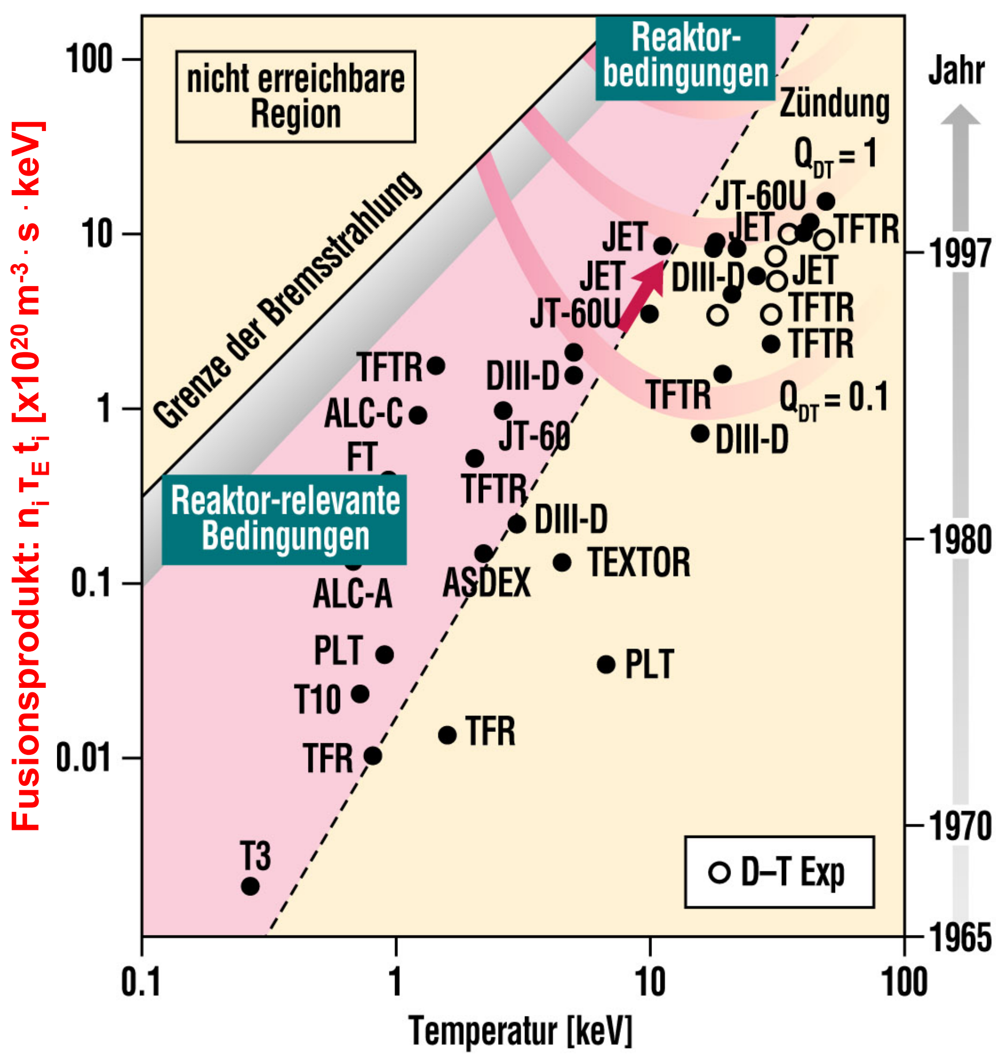
⊕⊕⊕ ○ ⊕ ⊕⊕
○○○ ○○ ○○

About 10^{11} kg Lithium in landmass
Sufficient for 30'000 years

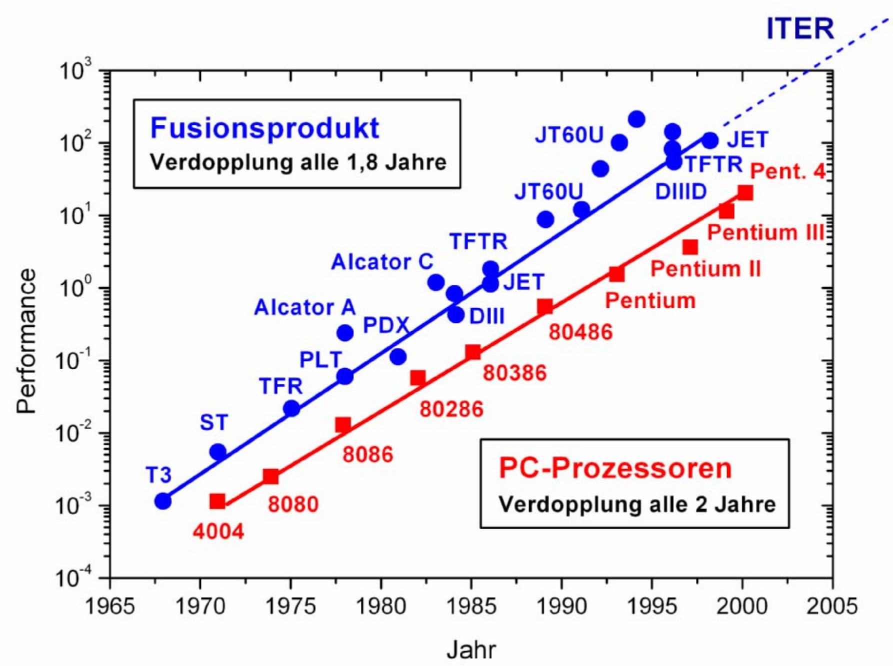
About 10^{14} kg Lithium in oceans
Sufficient for 30 million years !!

Considering all energy is produced by fusion

The Fusion Performance is measured by the Triple Product



Triple Product = the product of density [$10^{20} m^{-3}$], Temperature [KeV] and Energy Confinement Time [s] = $6x10^{21}$ -> ignition



Quelle: Forschungszentrum Jülich

The ITER Machine

Doughnut-Shaped Plasma

- V: 840m^3

R/a: 6.2m /2m

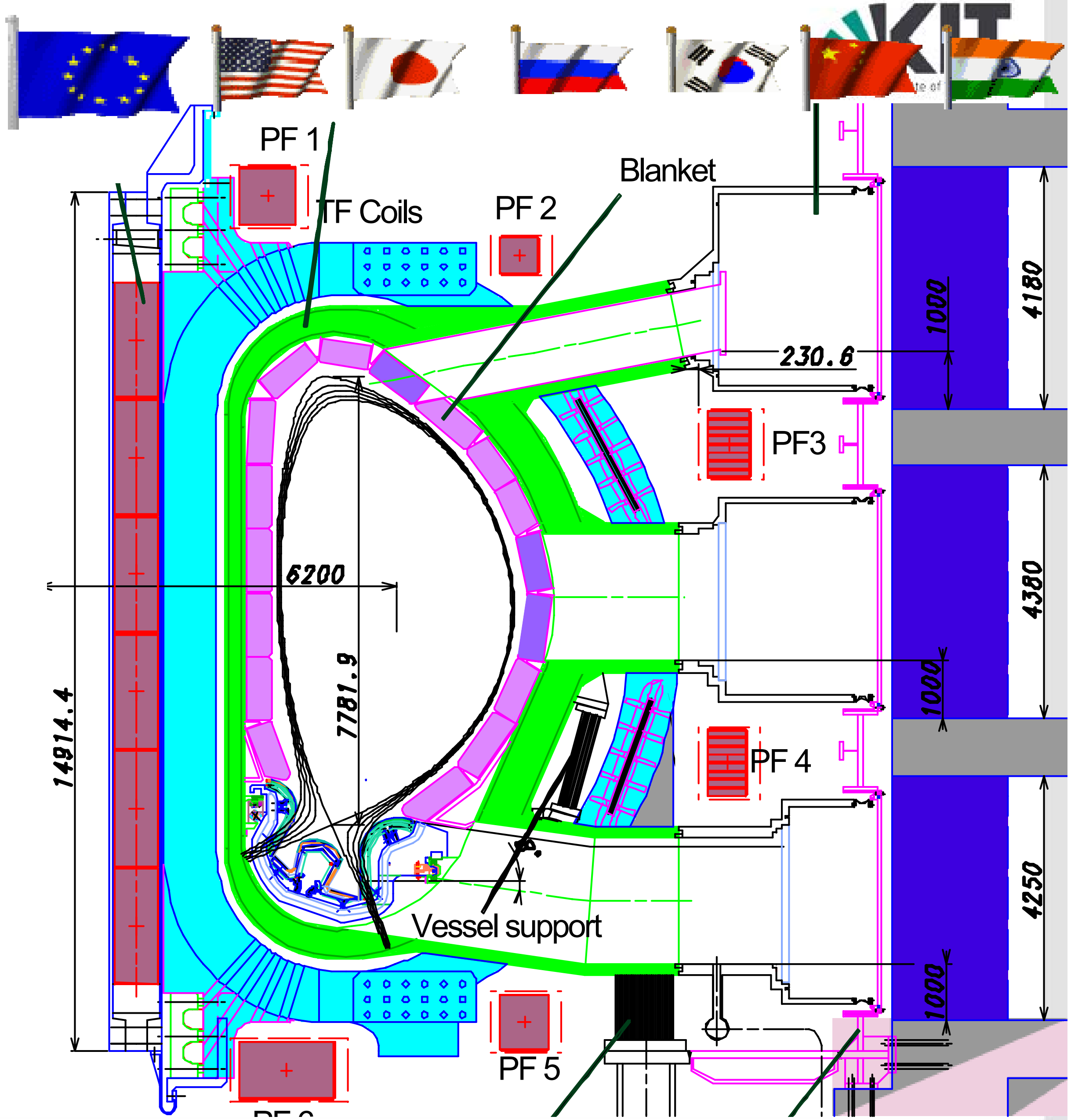
Vertical elongation: 1.85
Triangularity: 0.45

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

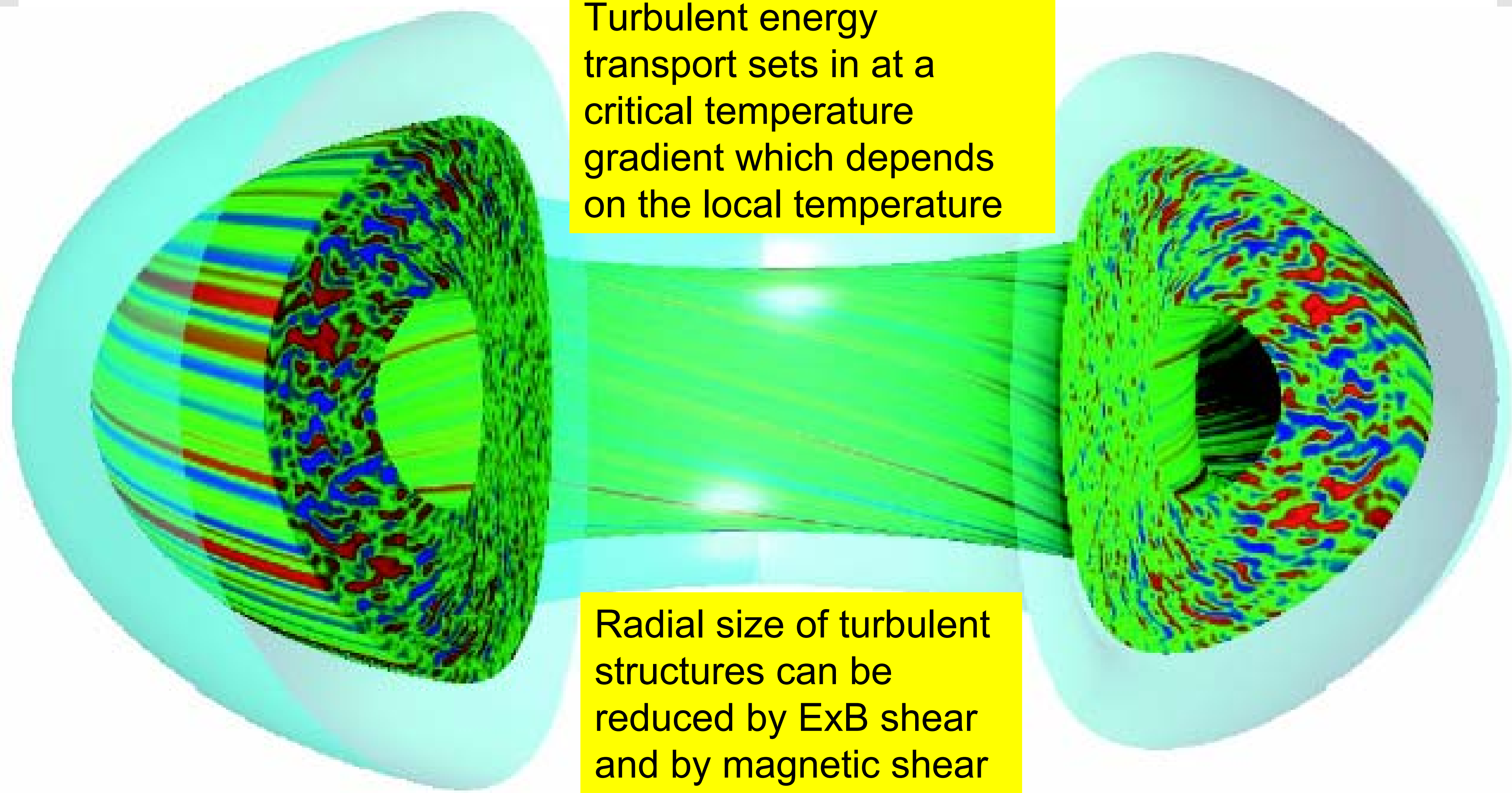
- Fusion Power: 500MW

- Plasma Current : 15MA

- Toroidal field: 5.4T



Energy and Particle Confinement is Turbulence driven

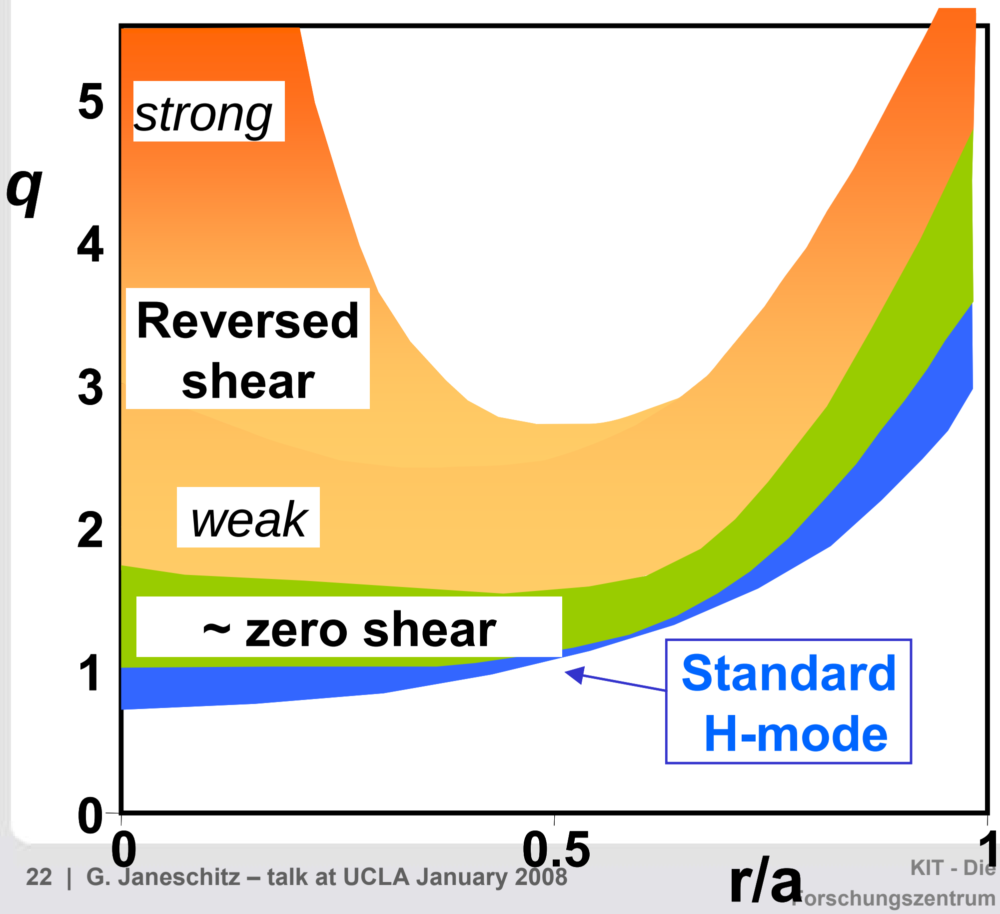


Turbulent energy transport sets in at a critical temperature gradient which depends on the local temperature

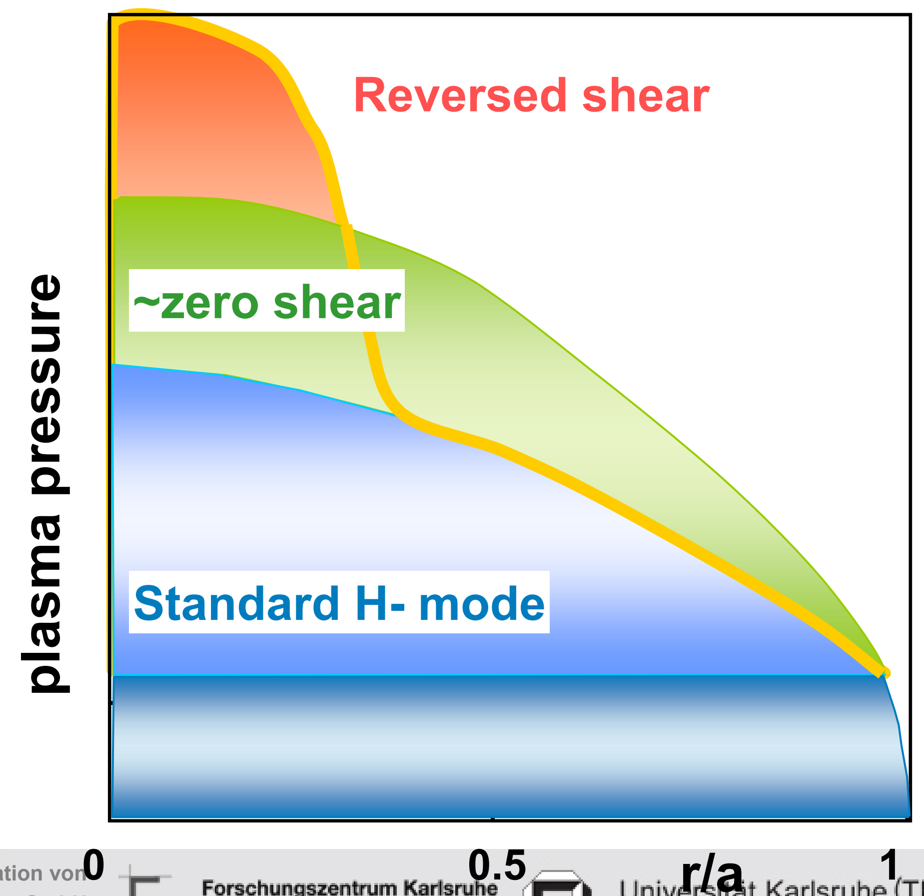
Radial size of turbulent structures can be reduced by ExB shear and by magnetic shear

We can explain the blue profile types by physic models !!

q profiles for standard and advanced scenarios



Pressure profiles for standard and advanced scenarios



A Pedestal Model which is able to reproduce experiments (by G. Janeschitz)

***ExB* velocity shear ⇒ pedestal in MMM model (appreciably lower than experiment)**

- additional magnetic shear stabilization is therefore postulated.

MMM transport gives good profile shape ⇒ threshold for additional shear stabilization.

$$\chi = \chi_{MMM} / \left\{ \left(1 + \left(\omega_{E\times B} / (G\,\gamma_0) \right)^2 \right) \cdot \max\left(1, (s-t)^2 \right) \right\}$$

$$\omega_{E\times B} = \frac{RB_\theta}{B} \frac{\partial}{\partial r}\left(\frac{E}{RB_\theta} \right) \quad \text{where} \quad E = \nabla p_i / (n_i\, e)$$

second factor in denominator - additional shear stabilization

$t \downarrow \Rightarrow$ stabilization ↑ , radial extent ↑

first factor in denominator - *E×B* velocity stabilization.

G is adjustment factor in the *E×B* velocity stabilization

stabilization for $\omega_{E\times B} \sim G\ \gamma_{ITG}$

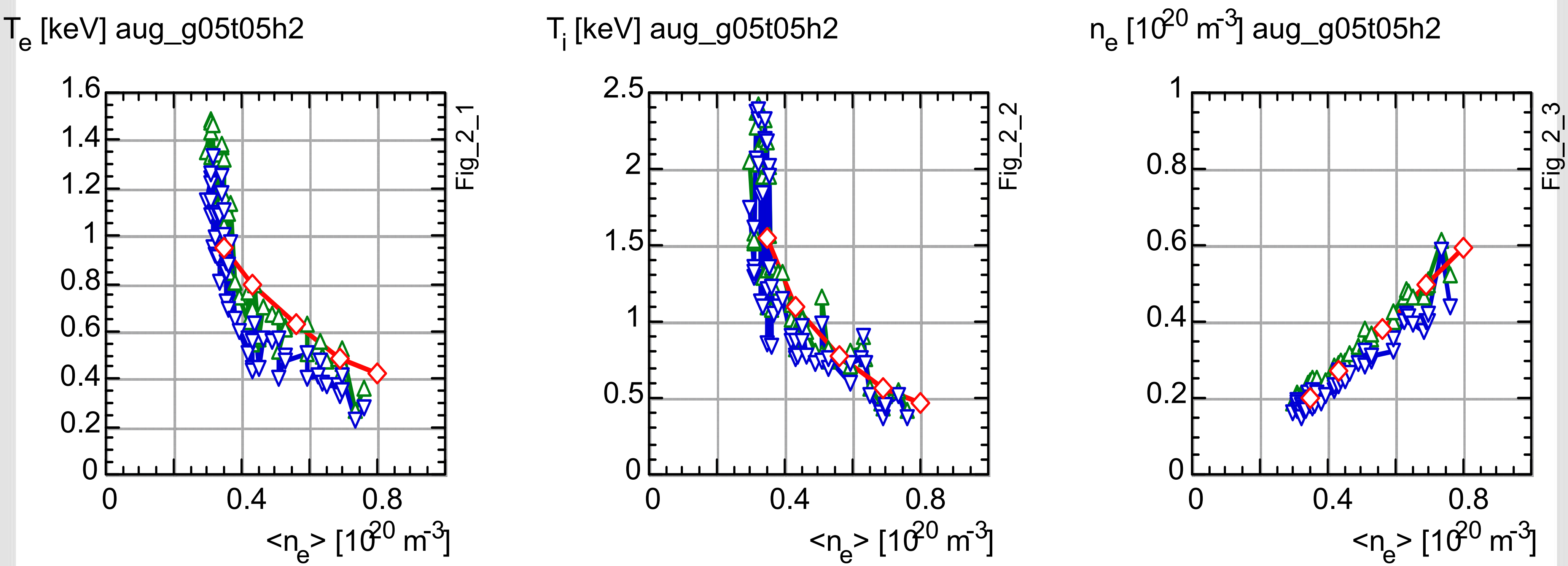
0.5 < G < 2 (*K.H. Burrell, Phys. Plasmas* ***4*** *(1997) 1499*)

$G \downarrow \Rightarrow$ stabilization ↑

adjust *t* & *G* to fit JET discharge (*t=0.5, G=0.5*)

Modeling starts to be able to describe transport

=> predictive capability



with ETG transport added to electrons and corrected fuelling

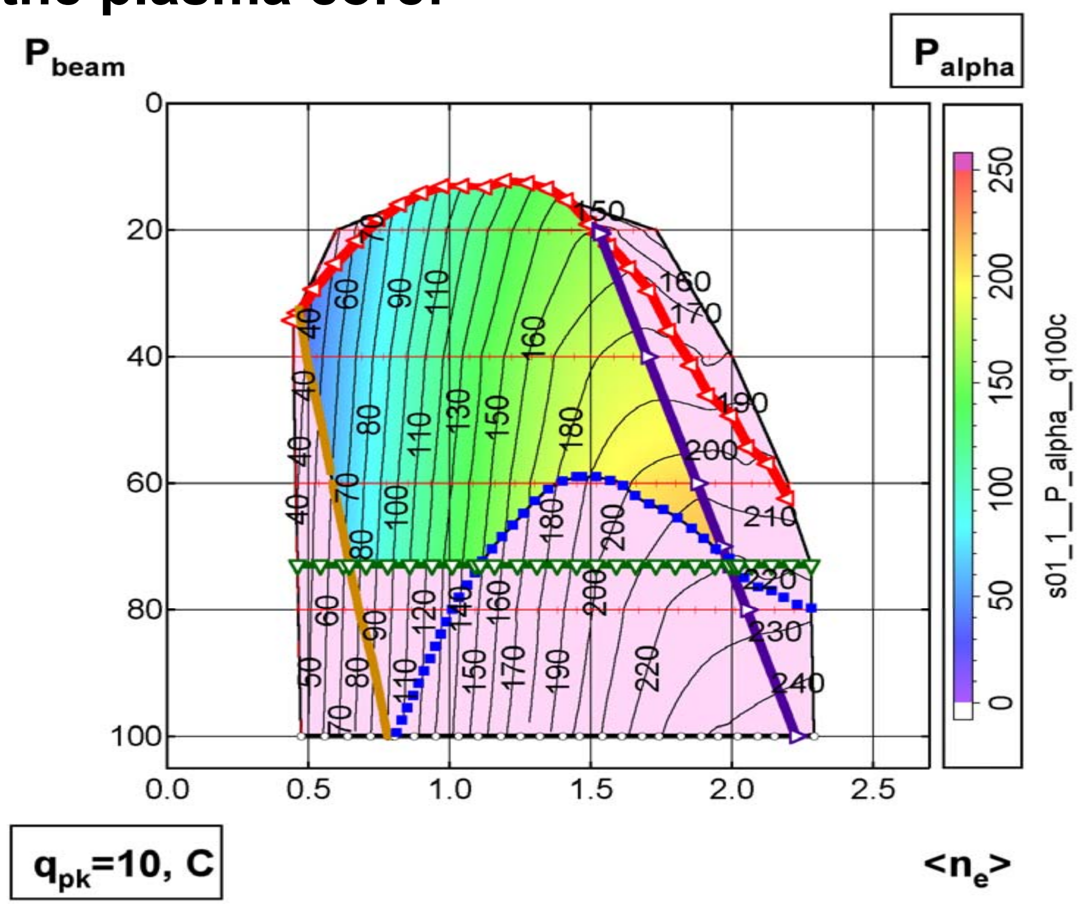
Development of an Integrated Plasma Model

- **One-dimensional modelling of the plasma core:**

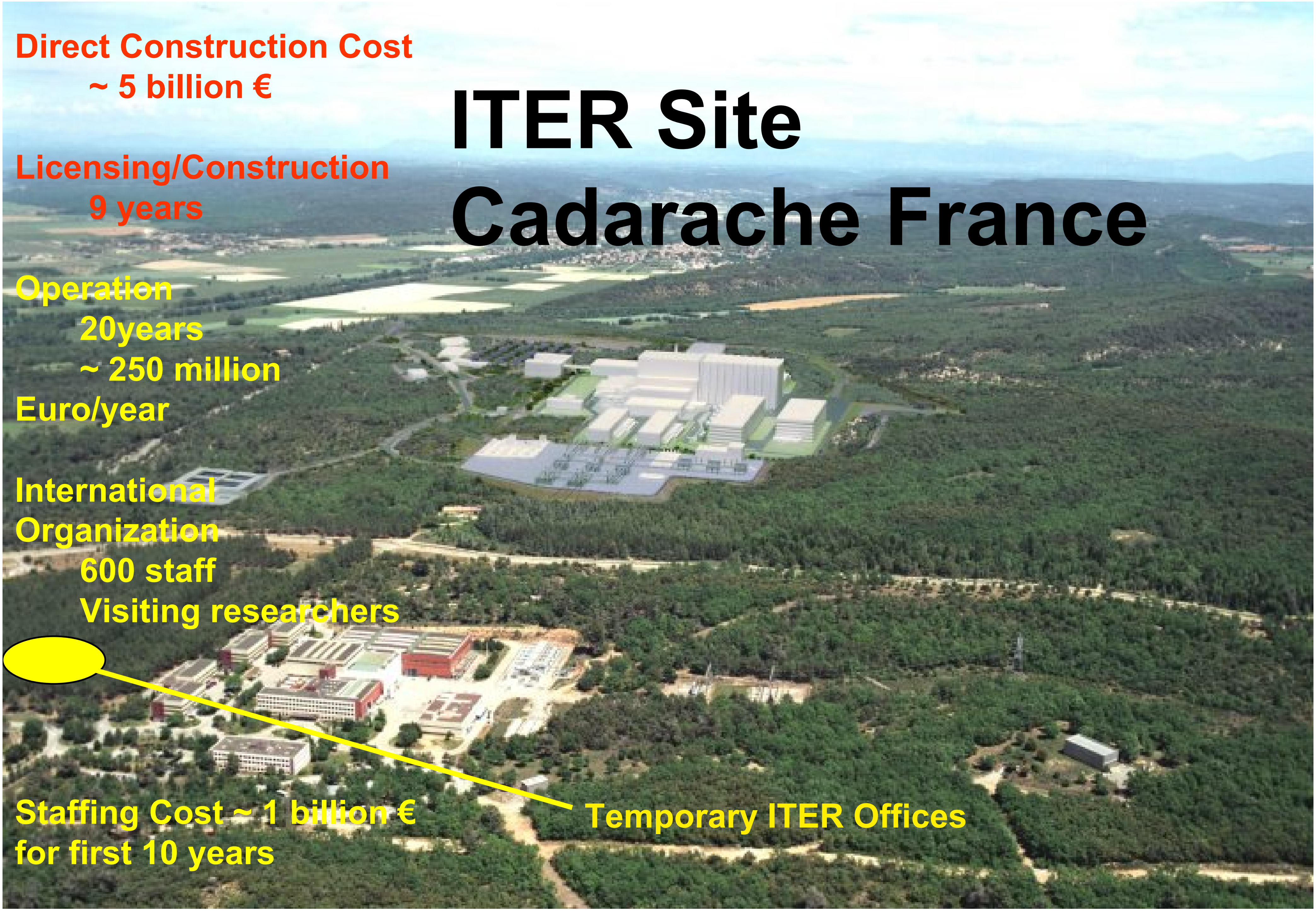
The core model used is the MMM model together with the above pedestal model and a parameterisation table of 2D SOL modelling results

It predicts that ITER will have a wide range of Q> 10 operation (up to 1 GW of fusion power

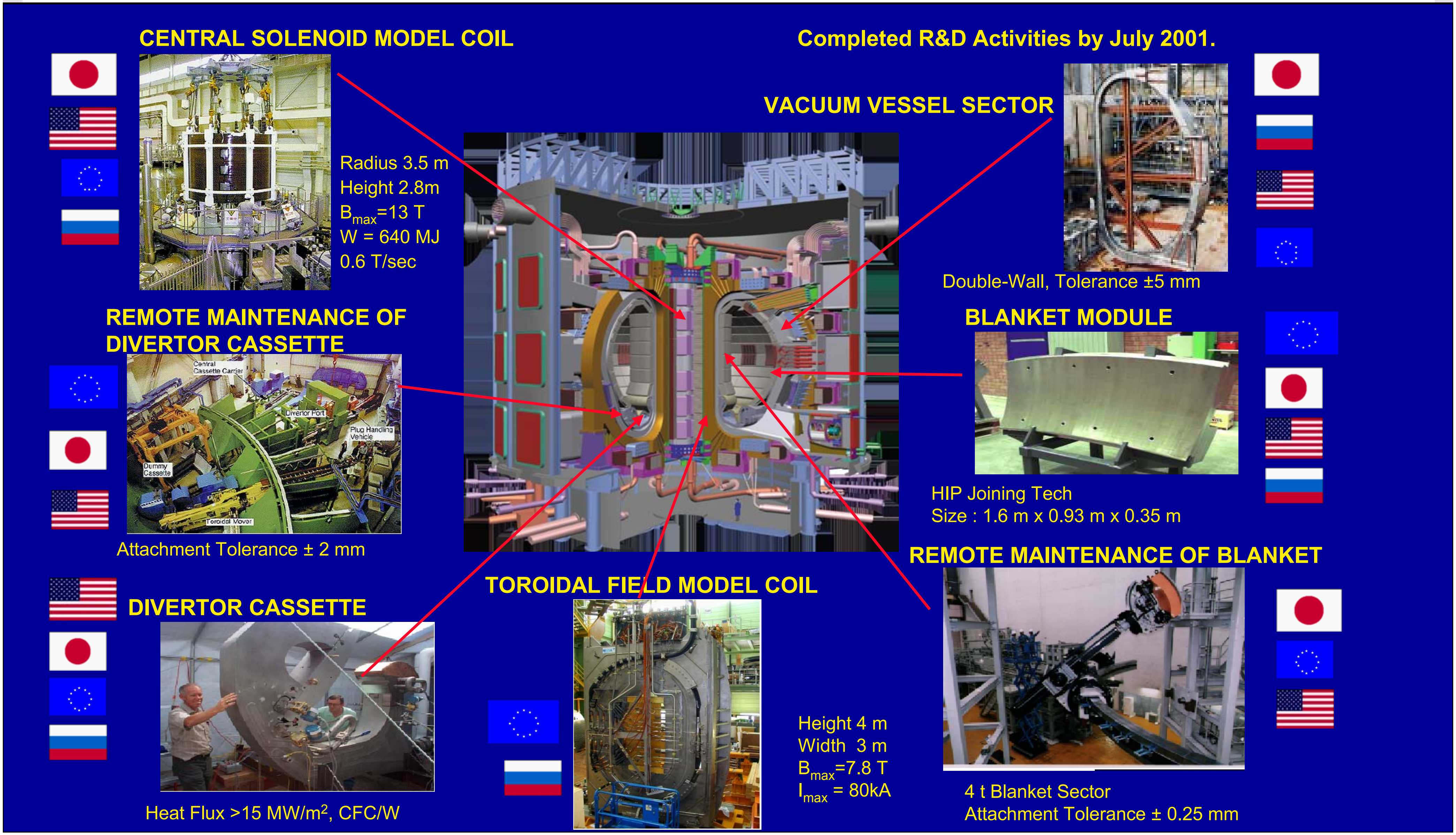
It also shows how the different physics limit border the operation space



Operational and objective limits: Power, Q=5, LH transition, low temperature limit on alpha power, auxiliary power, edge density limit


Direct Construction Cost
~ 5 billion €
ITER Site
Cadarache France
Licensing/Construction
9 years
Operation
20years
~ 250 million
Euro/year
International
Organization
600 staff
Visiting researchers
Staffing Cost ~ 1 billion €
for first 10 years
Temporary ITER Offices

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



The ITER Design Review

A Design review took place during 2007 coordinated by G. Janeschitz where 150 leading scientists from all over the world participated

~ 80 design changes were proposed and will be implemented in order to include new physics results and to solve some design problems which were known but could not be acted on due to lack of manpower.

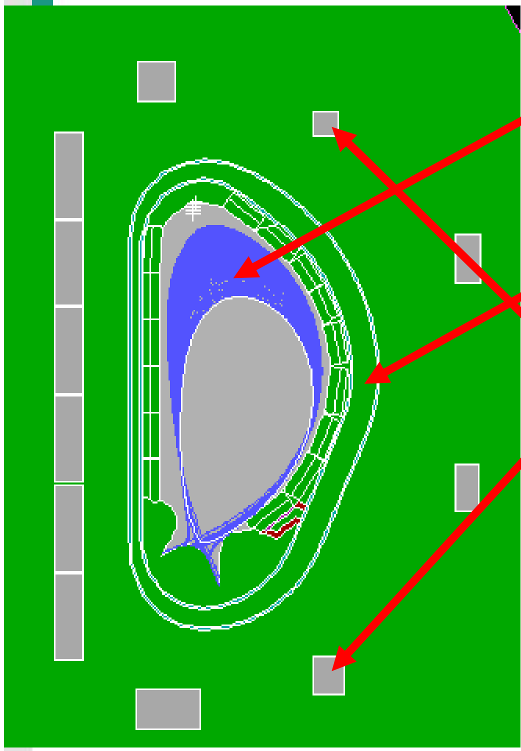
A firm technical basis to start the construction of ITER exists now and the procurement of the long lead items has started with sending the Procurement Arangement for the TF coils superconducting cables to the DAs of the parties.

13 issues pointed out by STAC remain to be tackled until May again in a world wide effort coordinated by G. Janeschitz

The Work on the 13 ITER STAC Issues
Coordinated by G. Janeschitz

topic	Topic Title	Support Contact Person
01.a	Vertical Stability	A. Portone
01.b	Shape Control / Poloidal Field Coils	
01.c	Flux Swing in Ohmic Operation and CS	
04	ELM Control	R. Hawryluk
05	Remote Handling	S. Chiocchio
06	Blanket Manifold Remote Handling	S. Wu
07	First Wall Strategy	
08	Capacity of 17 MA Discharge	P. Thomas
09	Cold Coil Test	S. Chiocchio
10	Vacuum Vessel / Blanket Loading Condition	
11	Test Blanket Modules Strategy	G. Janeschitz
12	Hot Cell Design	
13	Heating Current Drive Strategy, Diagnostics and Research Plan	P. Thomas

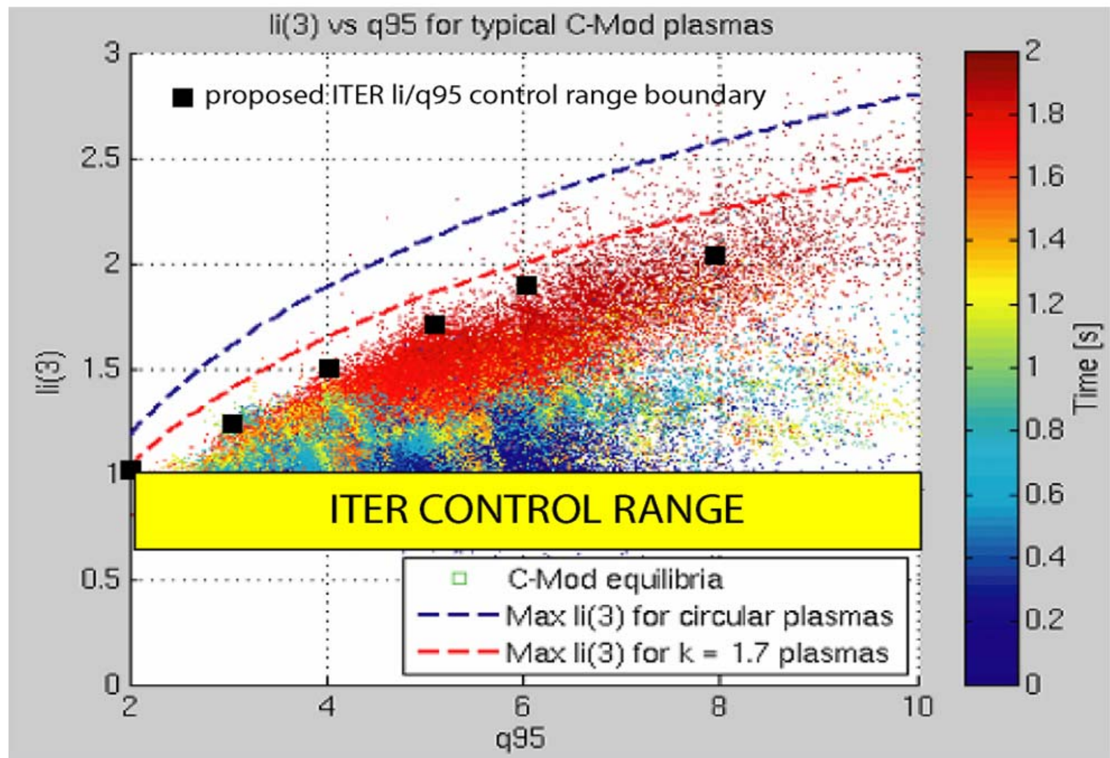
Vertical Stability



High elongation ~ 1.85 (1.7 in "Big ITER")

Thick *double-walled* vacuum vessel

Saturation of P2 and P5 in certain conditions



- **The range of *li*(3) between 0.7 and 1.0 has been specified for the design of the ITER PF system**

- **There is a problem with vertical stability in most discharge phases but they are gravest in Ip ramp-up and ramp-down (high l_i)**

Solution: Improve Passive Stabilization

Karlsruhe Institute of Technology

Connection of toroidal rings of blanket modules provides improved passive stability characteristics:

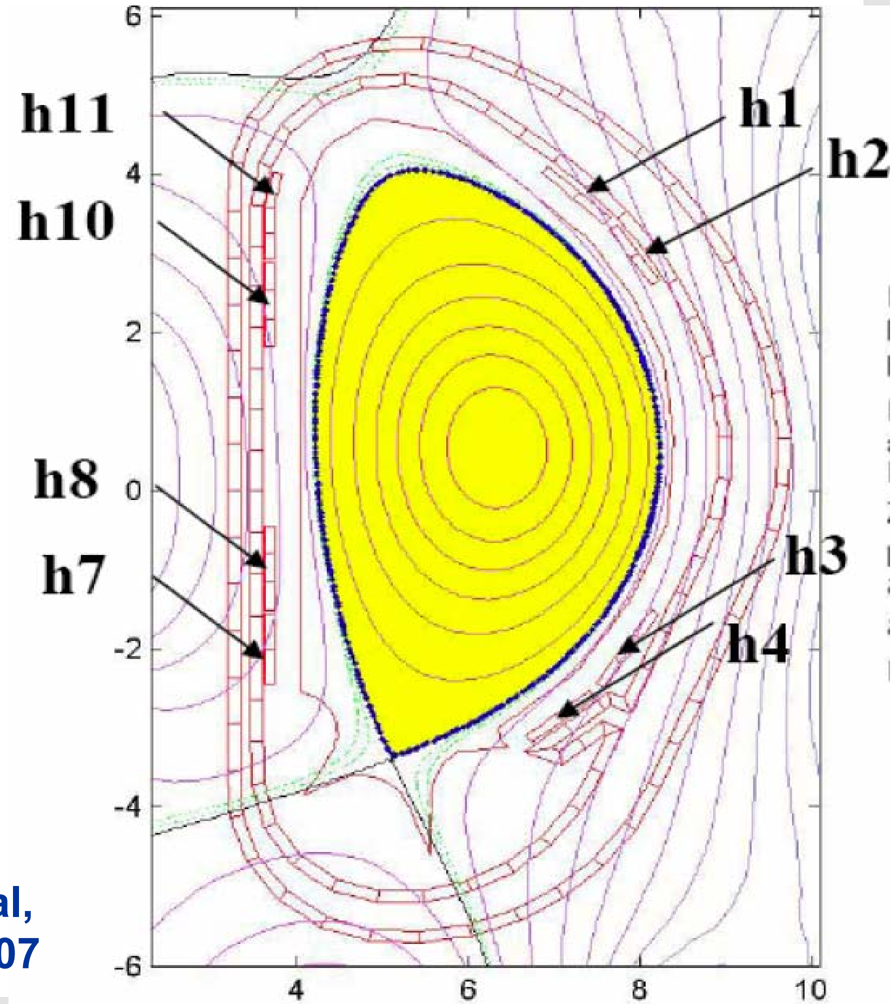
	Stability margin (CREATE)	Stability margin (EFDA)	Growth rate (ms)	M_φ	BAP (mm)
No blanket rings	0.27	0.37	68	3°	20.8
Blanket rings 1 & 5	0.31	0.43	94	9°	31.1
Blanket rings 2 & 4	0.33	0.44	98	11°	33.0
Blanket rings 7 & 11	0.28	0.38	75	7°	25.2
Blanket rings 8 & 10	0.29	0.39	79	9°	26.9
All blanket rings	0.39	0.52	150	22°	52.5

blanket modules

Analysis of disruption forces

Analysis of equilibrium/ control implications

Option of increasing voltage in PF coils from 6 to 9kV rejected by IO

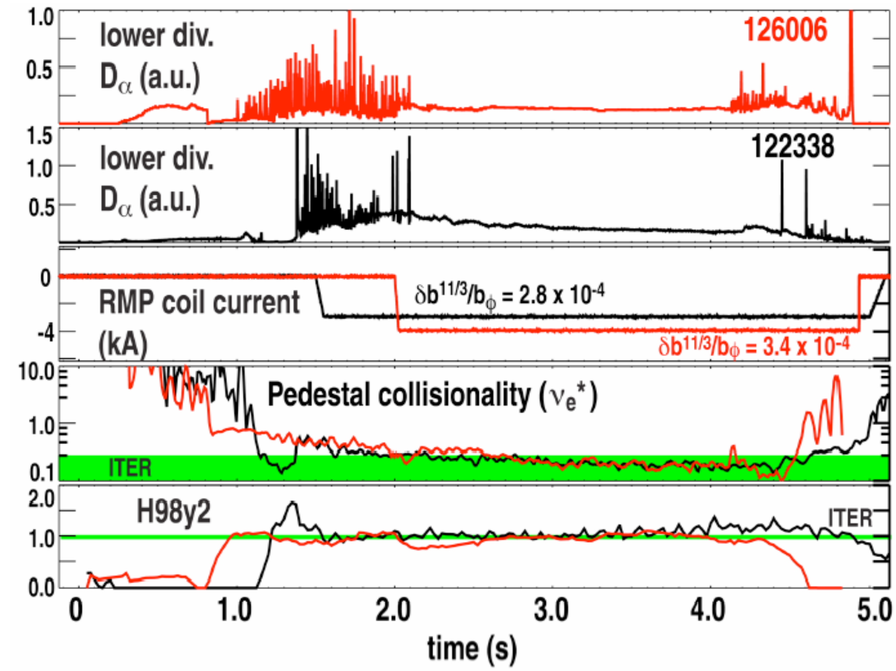


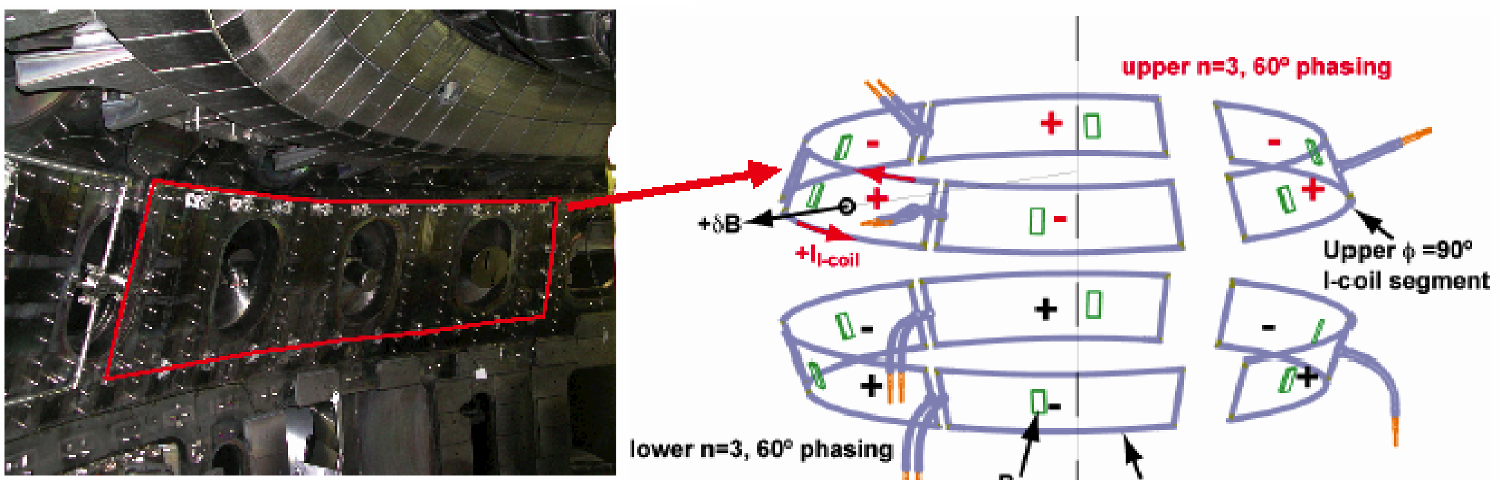
A Portone et al, September 2007

ELM suppression by ergodization

Ergodization works for D3D (and JET).

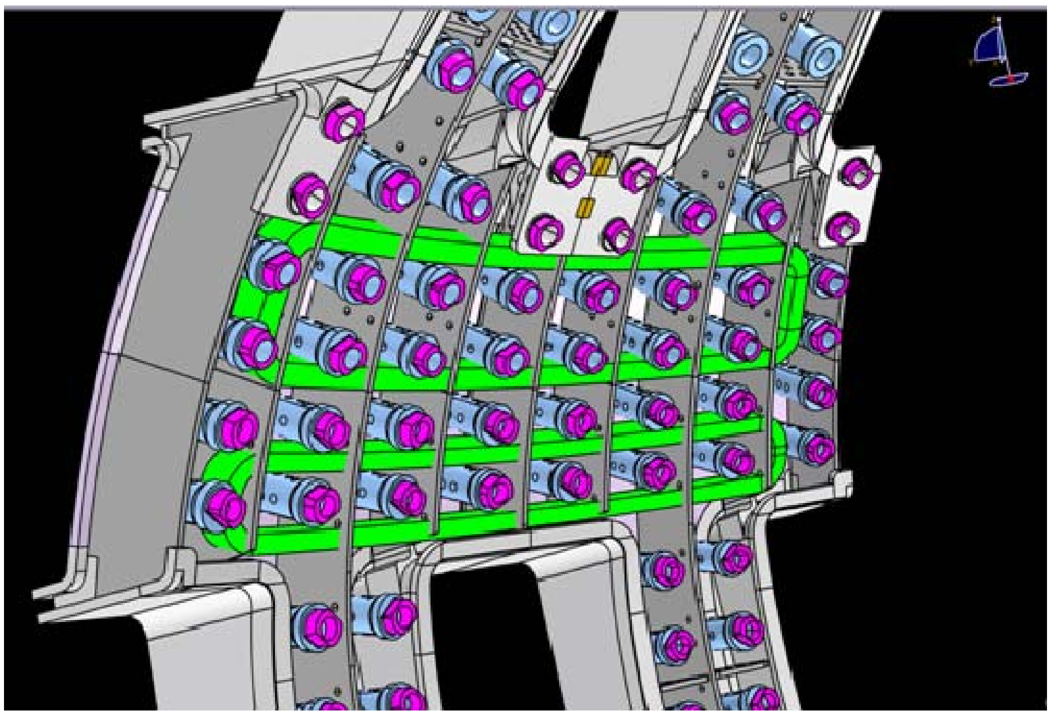
WG-1 has proposed to use a set of 36 Resonant Magnetic Perturbation coils similar to DIII-D

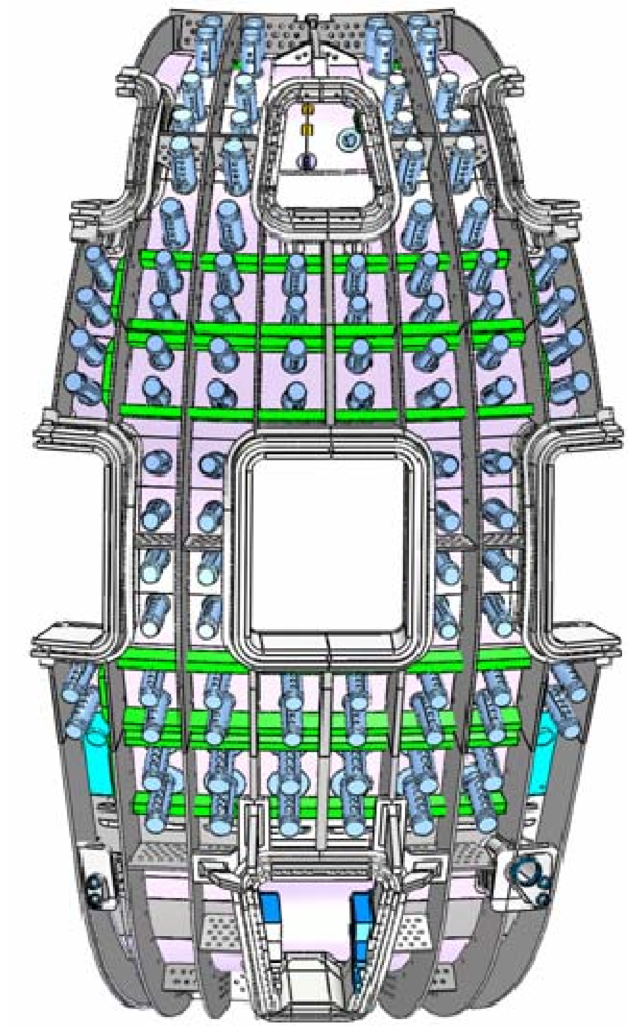




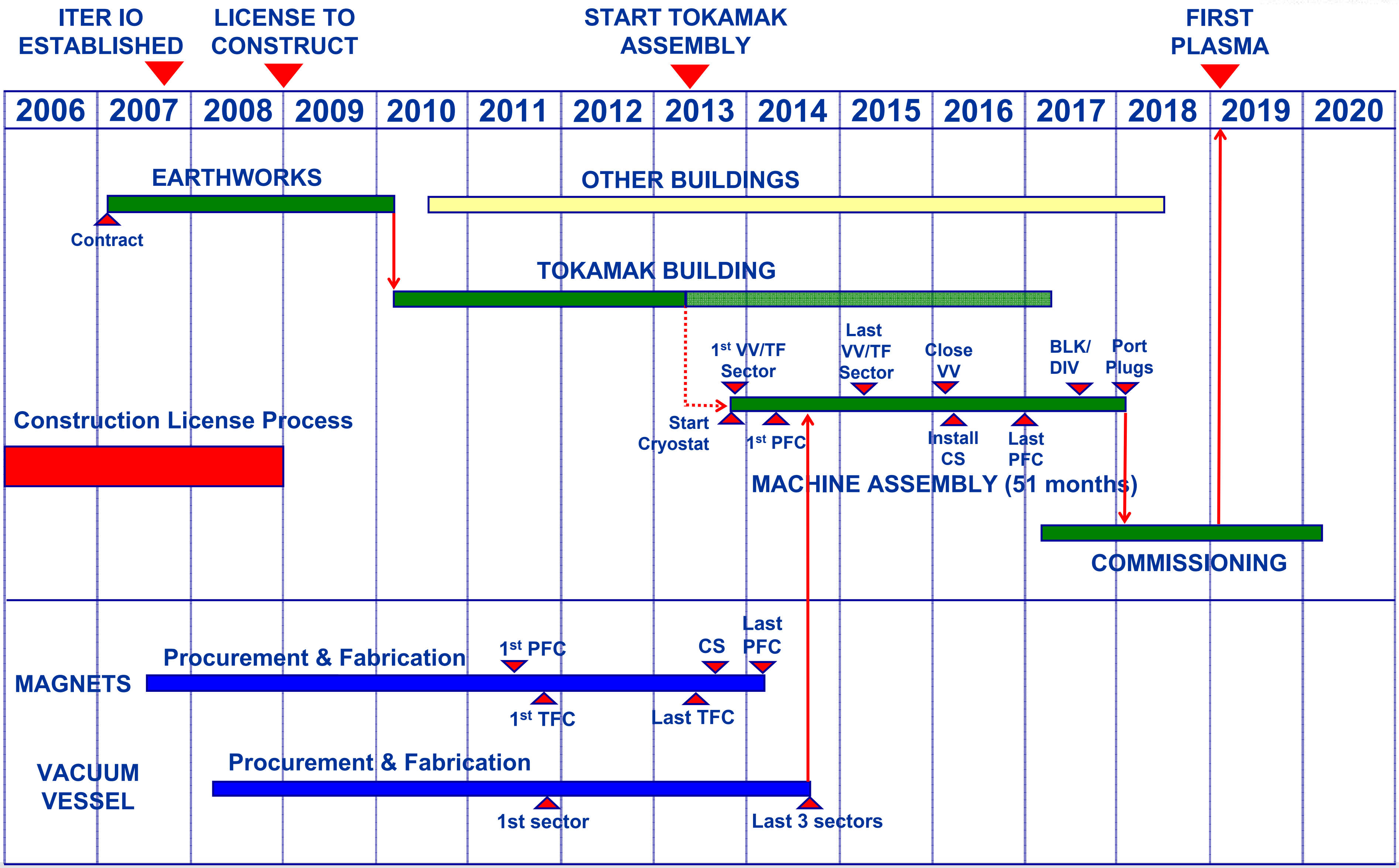
The Work on Elm Control Coil Integration

Integration of ELM control coils ~ 120 kAturns between the VV shels

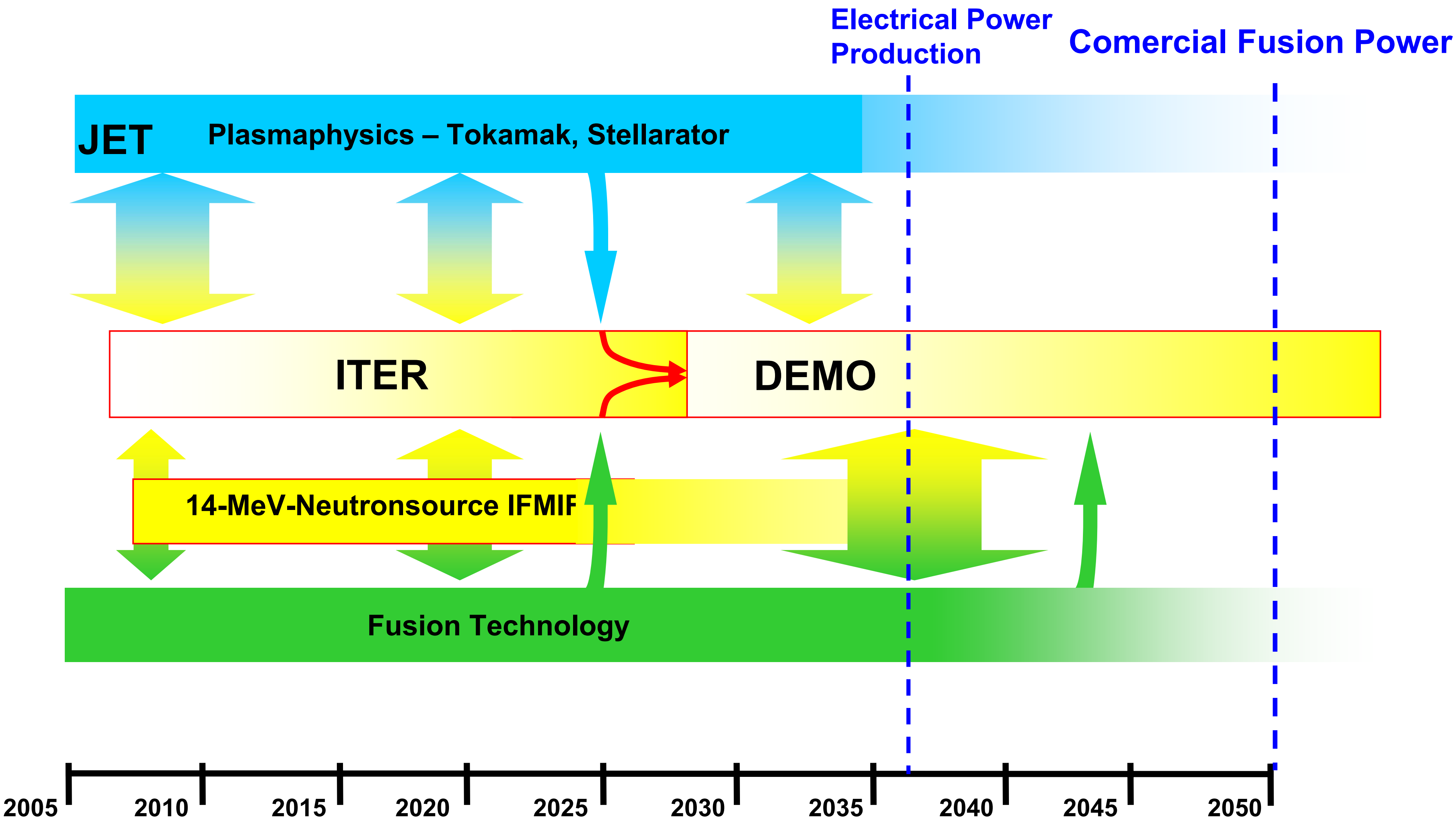




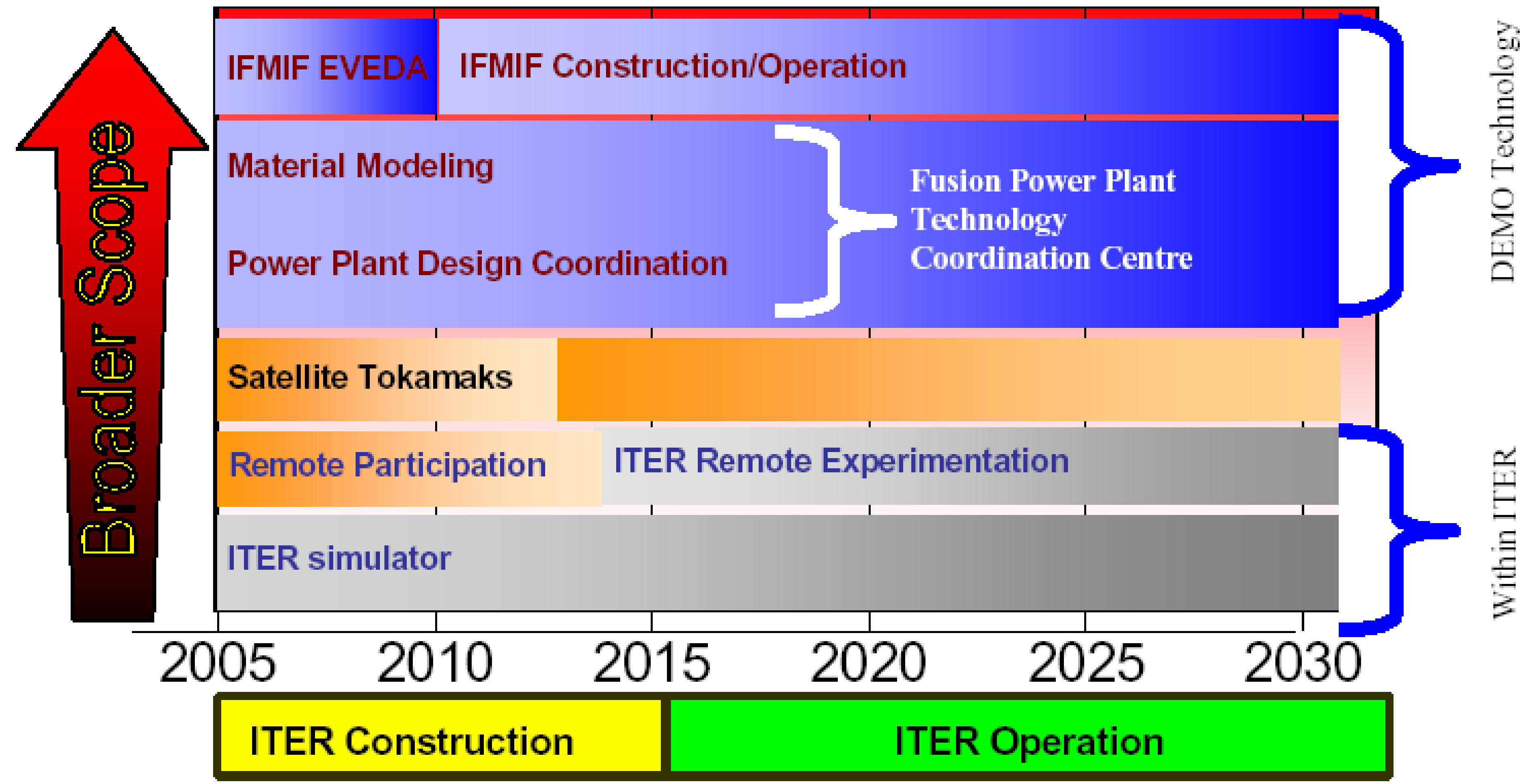
Summary Working Schedule – bottom-up accel.



Road Map to the Fusion Reactor (Fast Track)



Broader Approach i.e. a World Fusion Programme, i.e. FAST TRACK

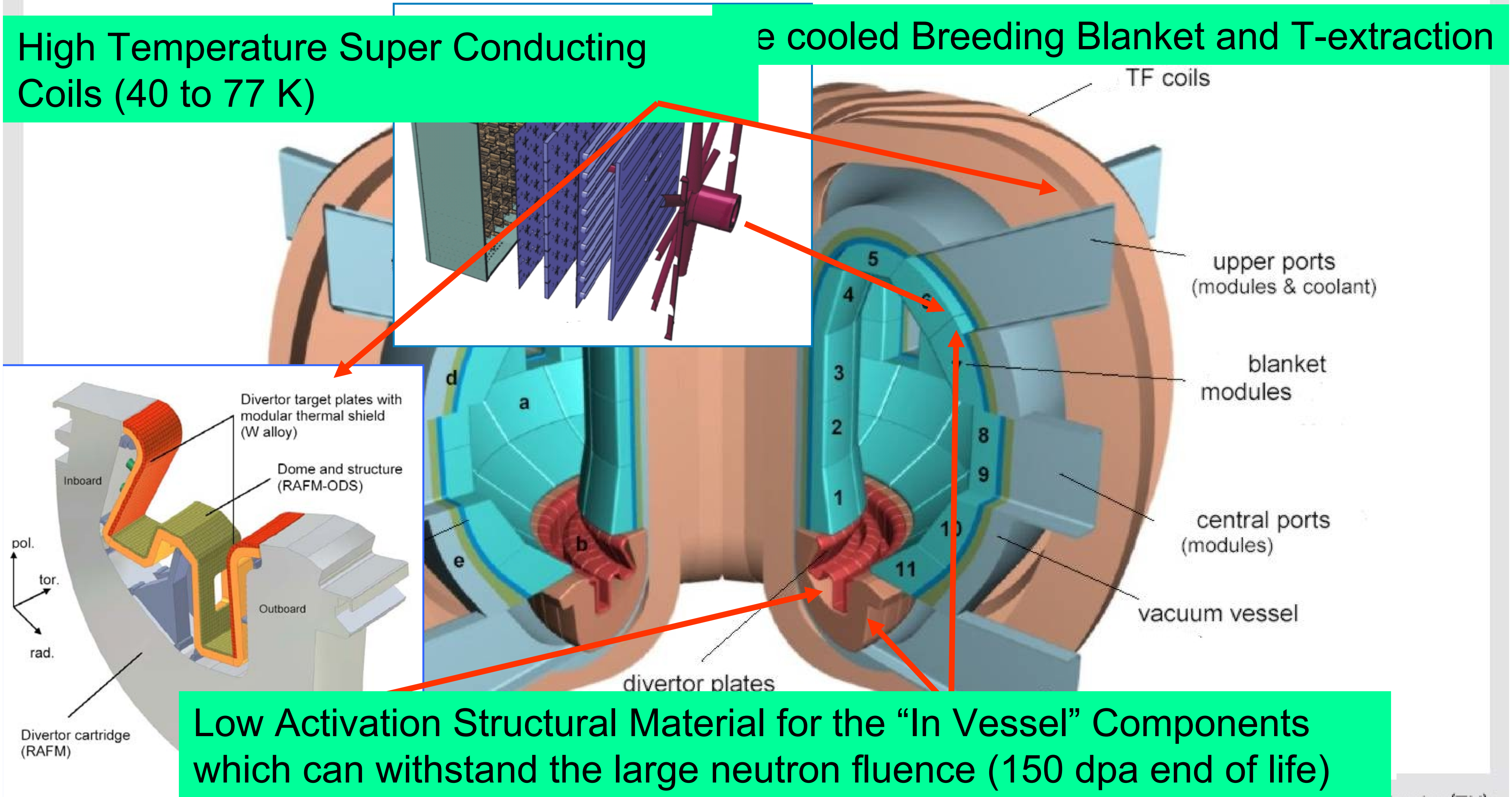


A Schematic view of the elements of the broader scope

Main Technology Developments needed for DEMO; FZK contributes

High Temperature Super Conducting Coils (40 to 77 K)

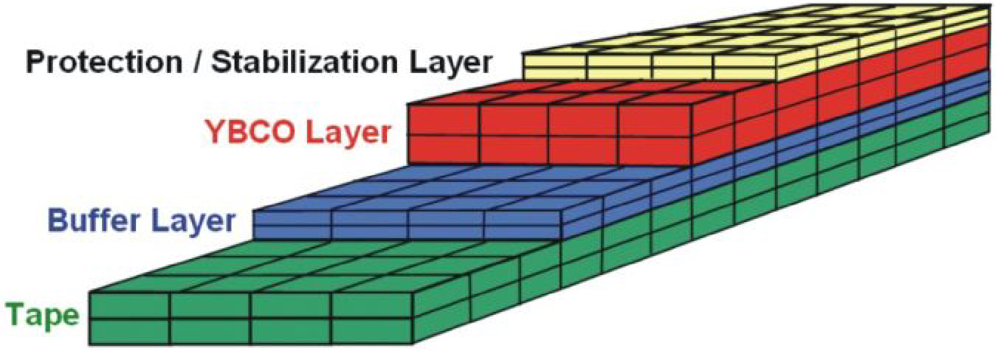
e cooled Breeding Blanket and T-extraction



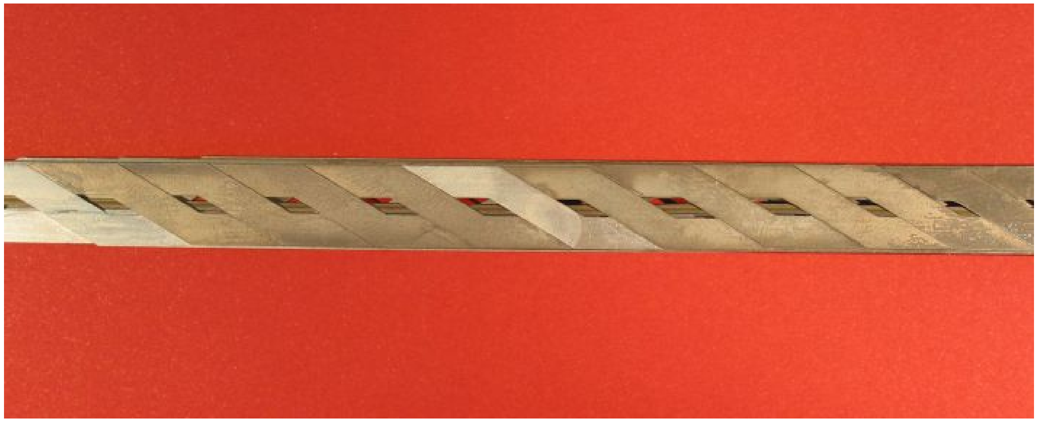
Low Activation Structural Material for the “In Vessel” Components which can withstand the large neutron fluence (150 dpa end of life)

Biggest Problem: How to achieve good ac-loss properties?

Twisting concepts are difficult to implement with YBCO coated conductors
but new concept of a Roebel type conductor has been tested by FZK:



Critical current @77 K approx. 1 kA,



Planned: **Development of ac-loss optimized concepts**
Demonstration of a RACC Cable (≈ 1m) in the kA class

Target: To construct an HTS Fusion Demo-Solenoid ≈ 2013 !

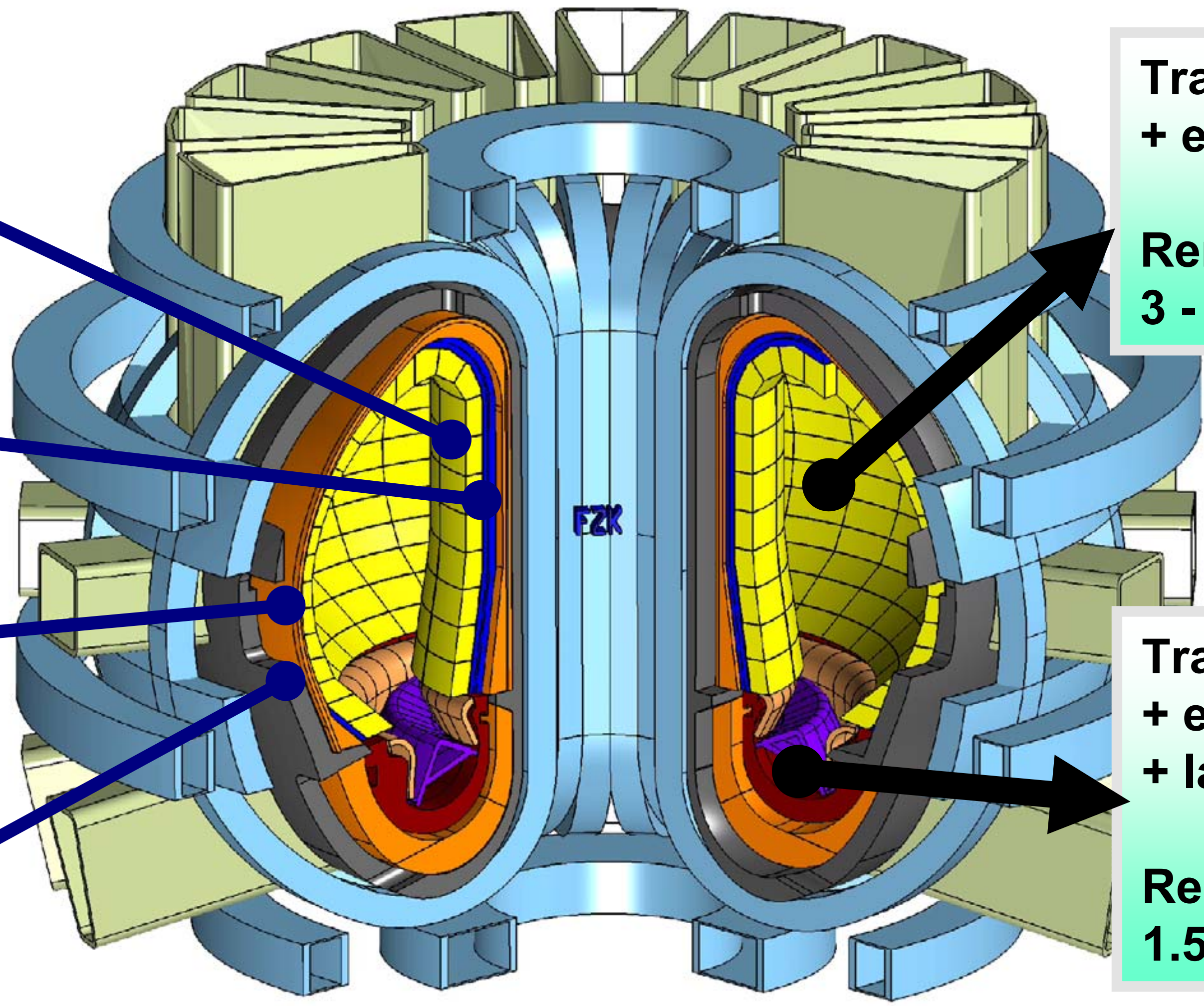
DEMO Fusion Core (FZK)

Pebble Bed Blanket
400-550°C

Vertical Manifold
~320°C

Strong Ring Shield
~320°C

Vacuum Vessel
~100°C



Blanket

Transient thermal
+ electromagnetic loads

Remote replacement
3 - 5 years (80...150 dpa)

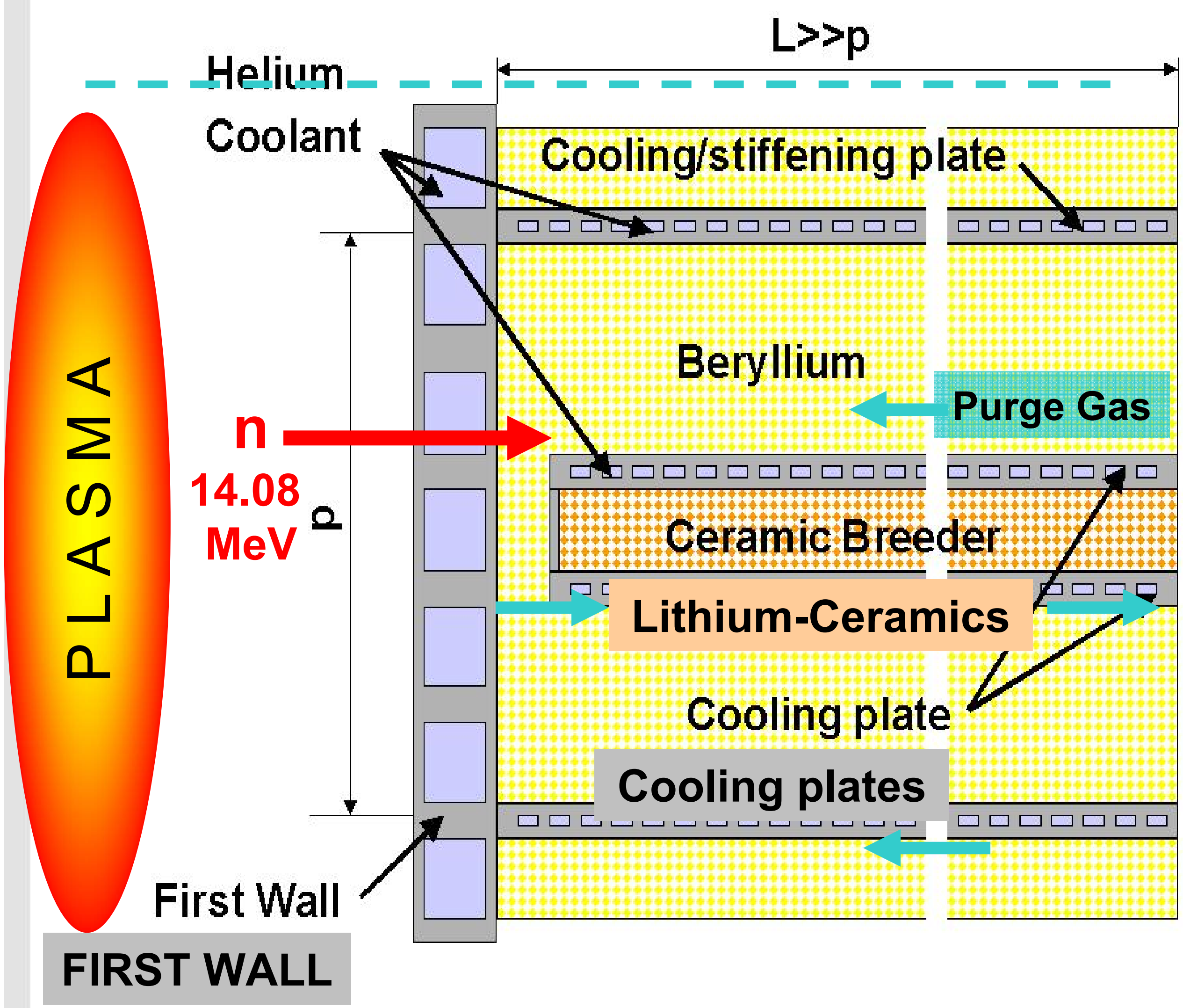
Divertor

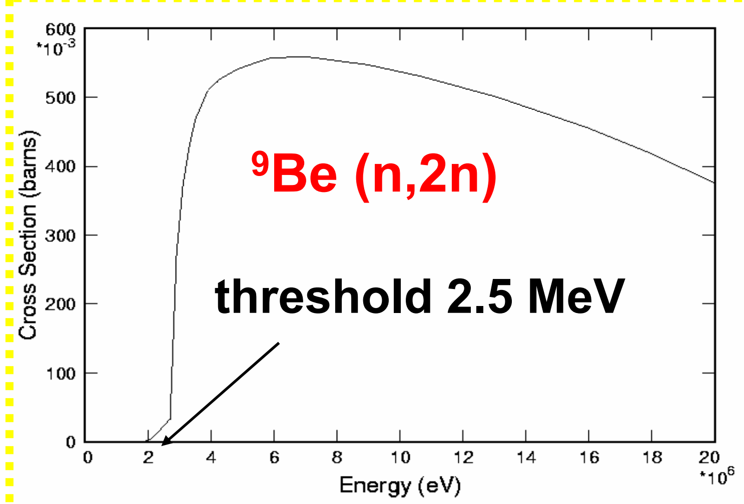
Transient thermal
+ electromagnetic loads
+ large surface heat flux

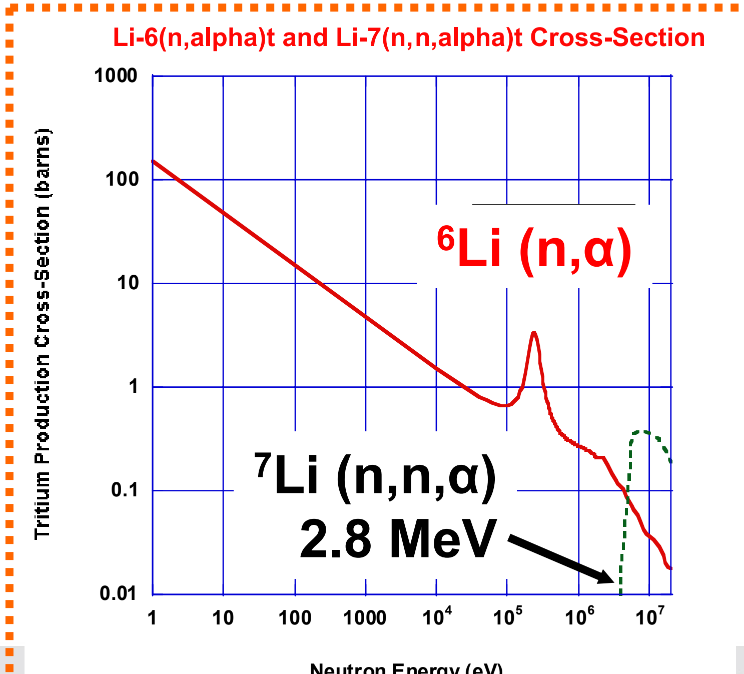
Remote replacement
1.5 - 2.5 years

DEMO = Demonstration Fusion Reactor Plant

FZK Solid breeder concept



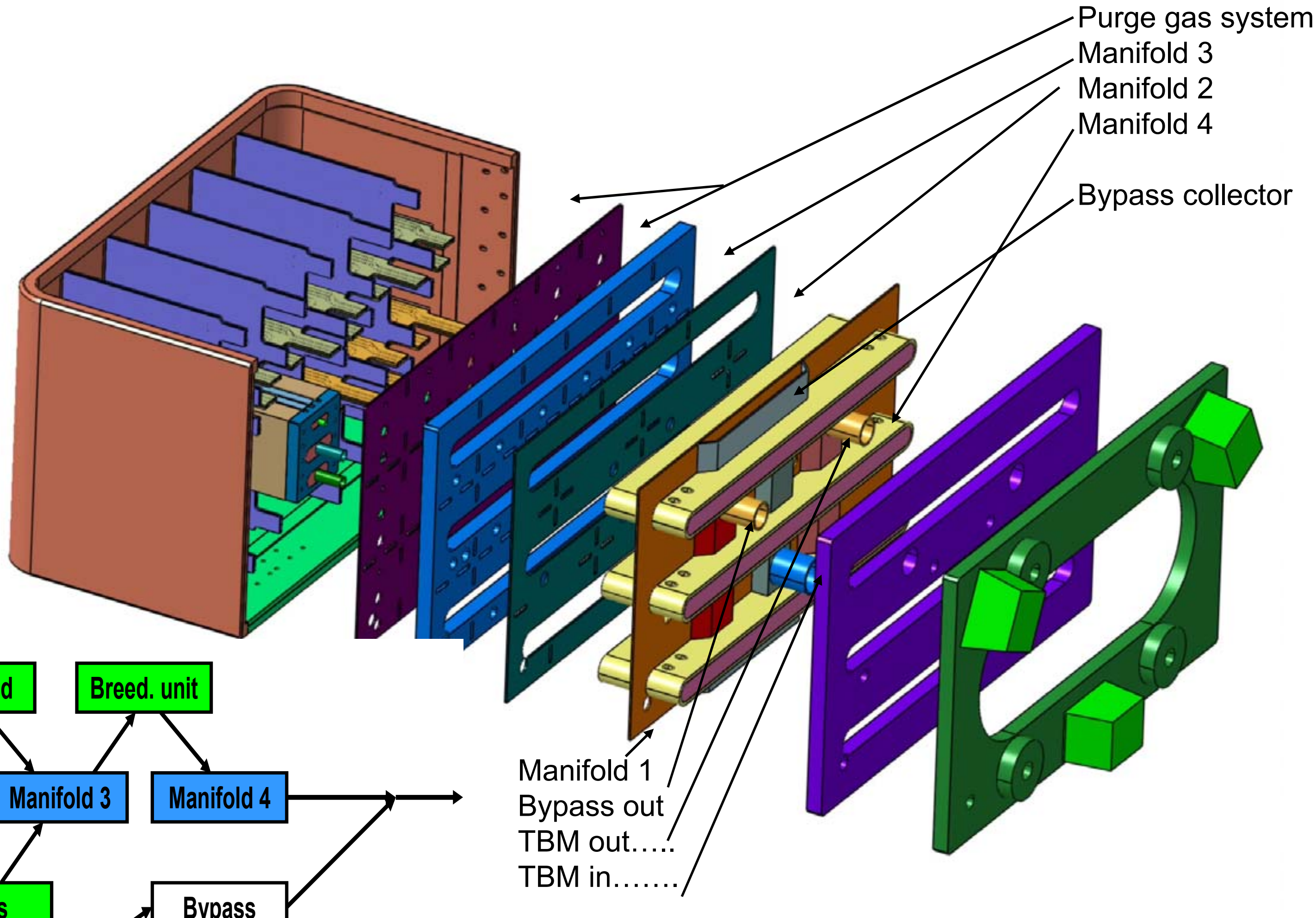


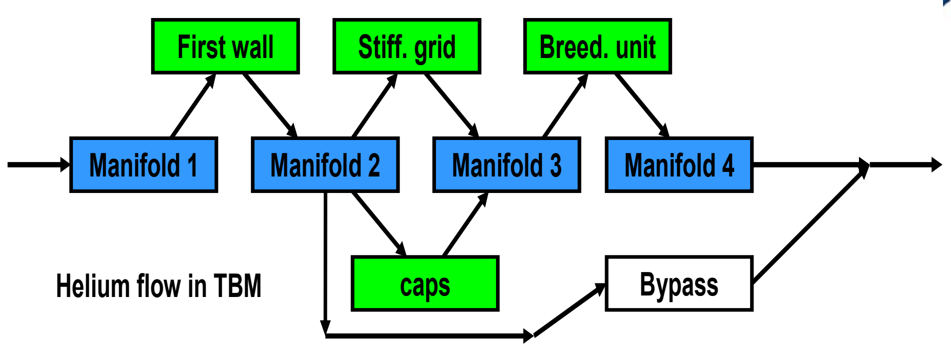


Development of the HCPB TBM for ITER

HELIUM at 8 MPa

Temperature:
300 to 500 °C





DEMO Conceptual Studies – HCPB Integration

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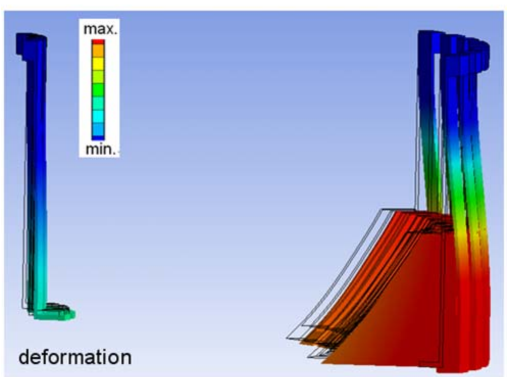
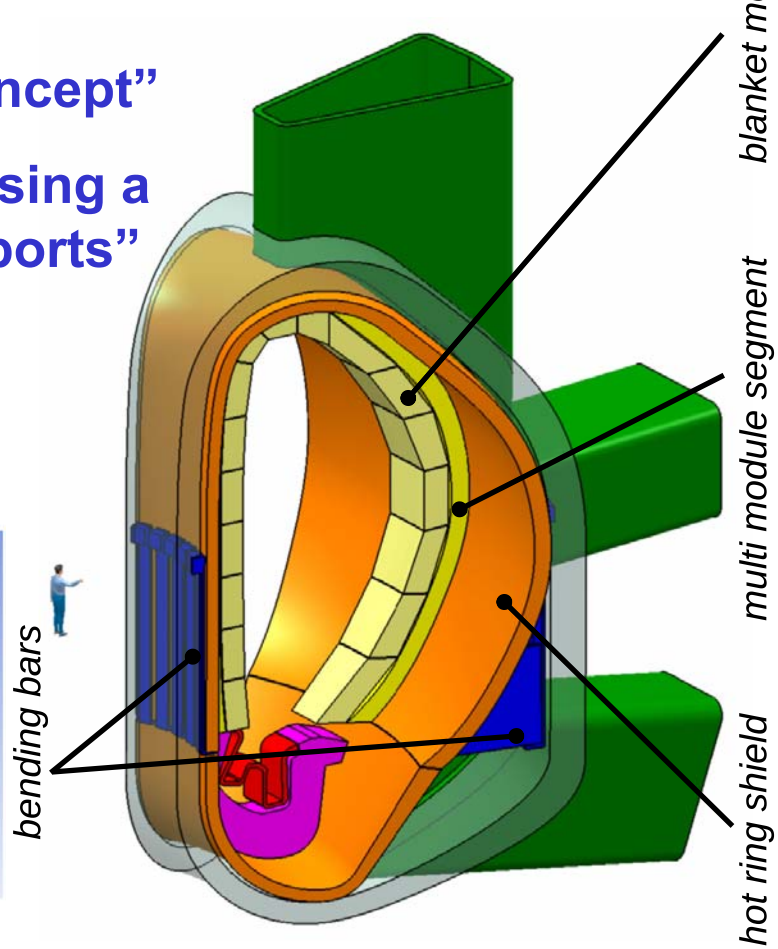
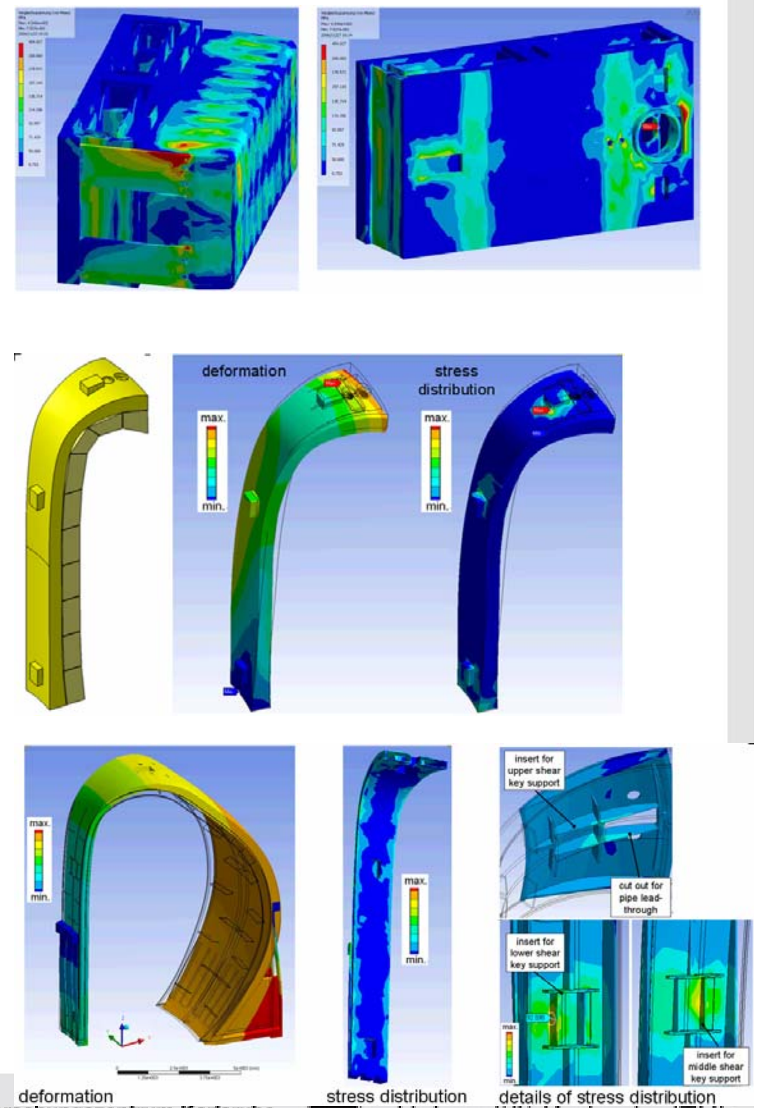
HCPB integration

“hot ring shield concept”

“maintenance by using a limited number of ports”



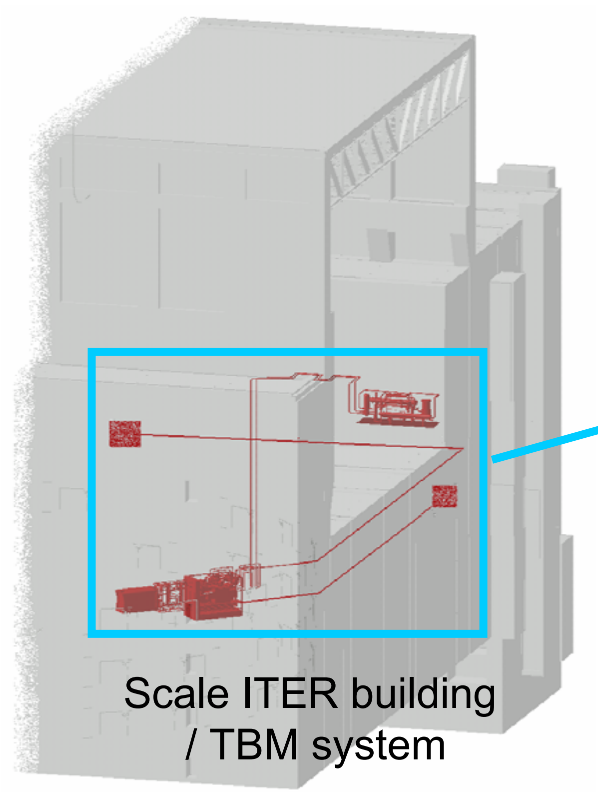


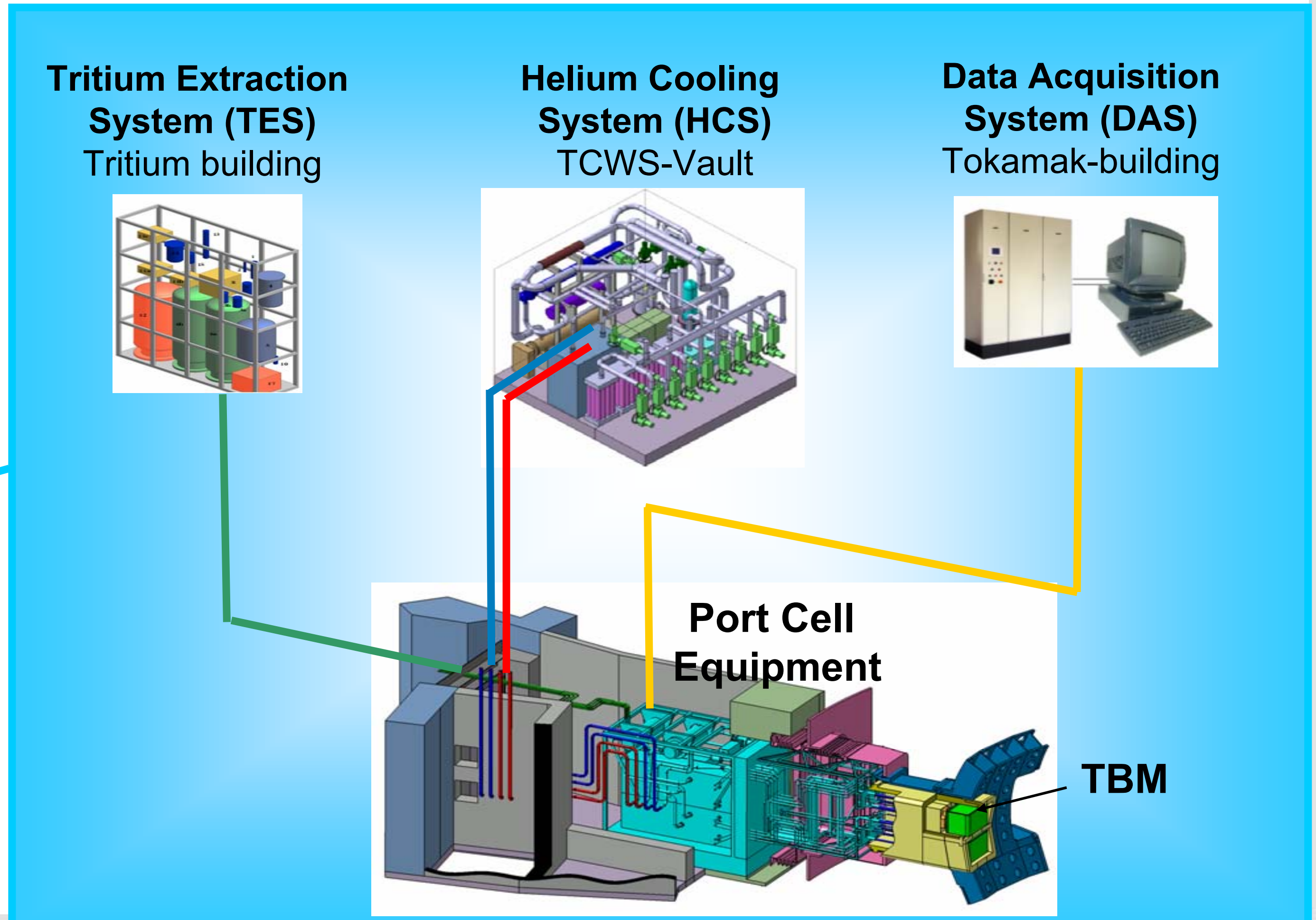


elements of attachment concept

TBM System Development
a large prototypical He loop is built in FZK (HELOKA)

ITER-Reactor building



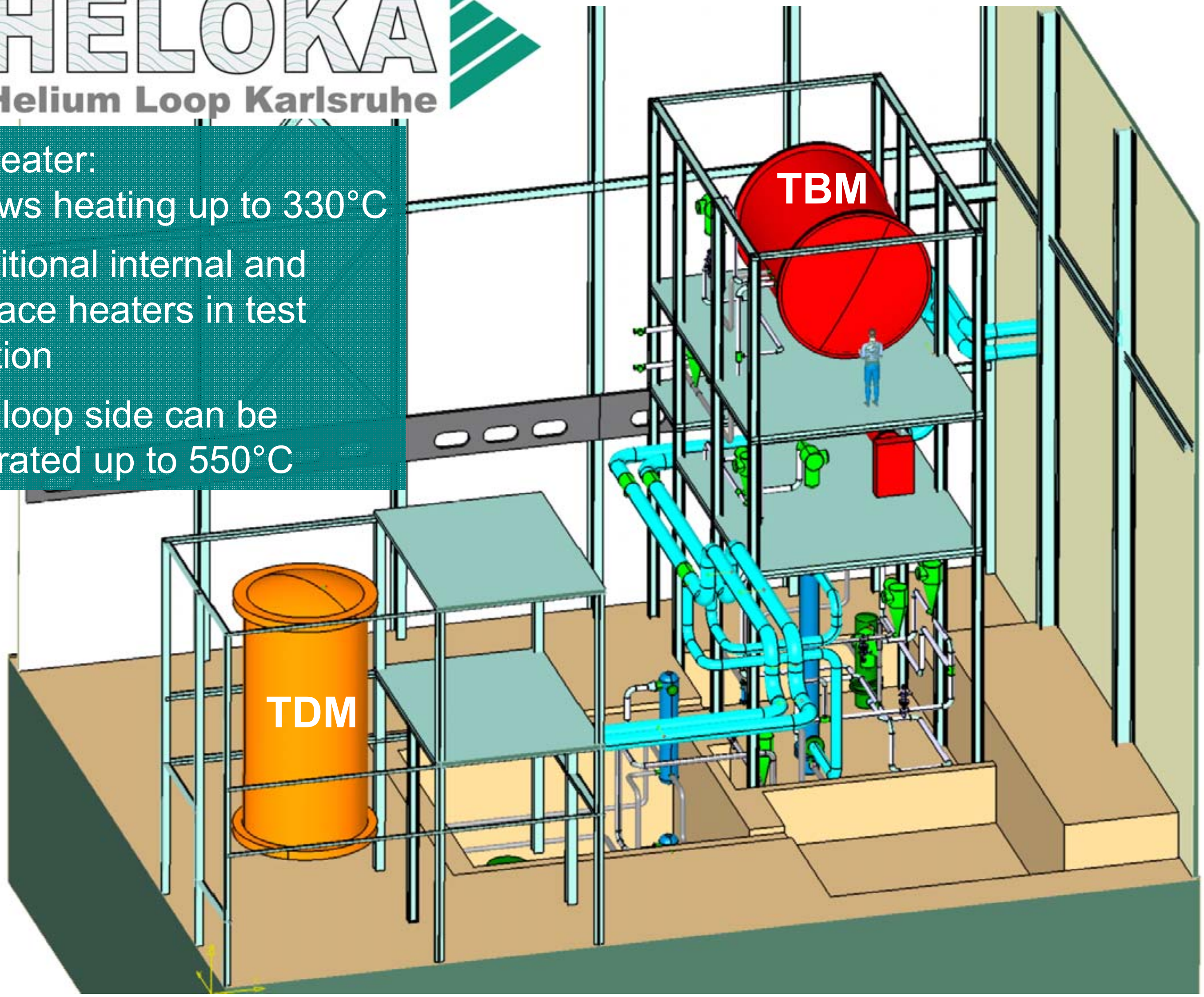


HELOKA
Helium Loop Karlsruhe

** Heater:
Allows heating up to 330°C

Additional internal and surface heaters in test section

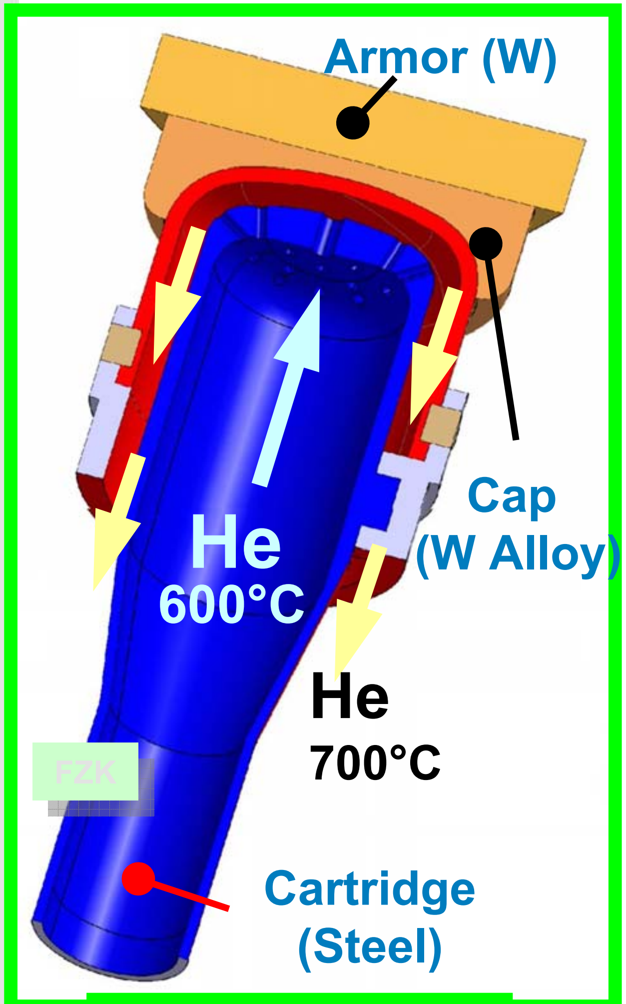
Hot loop side can be operated up to 550°C

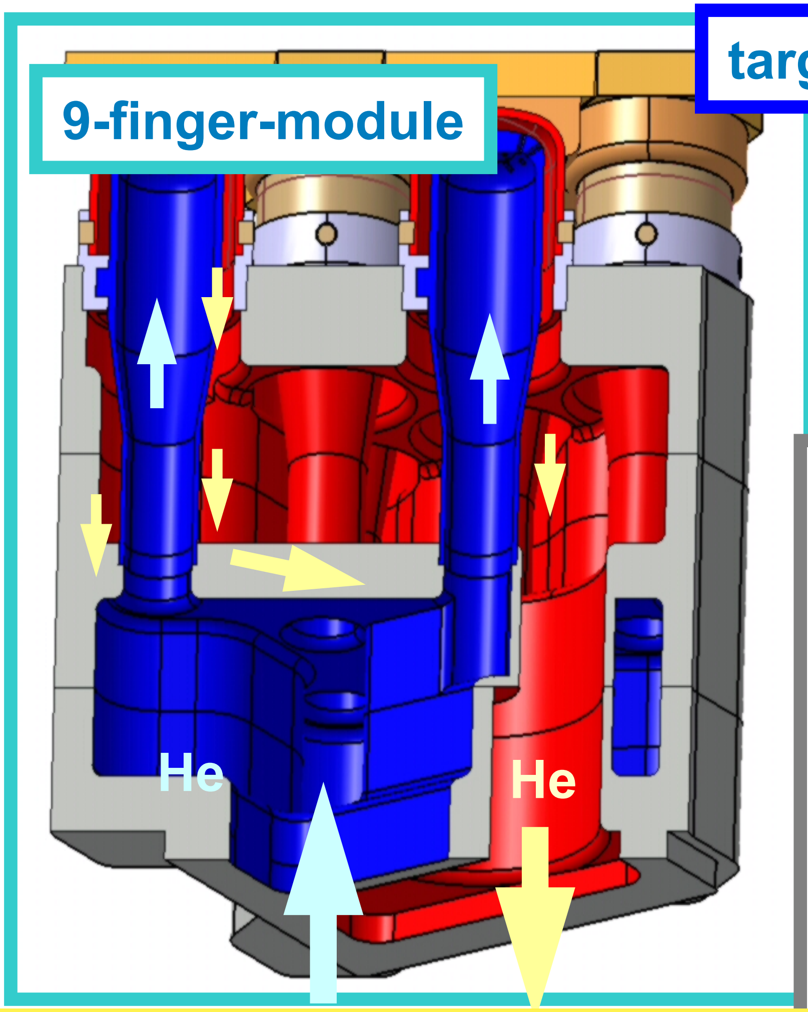


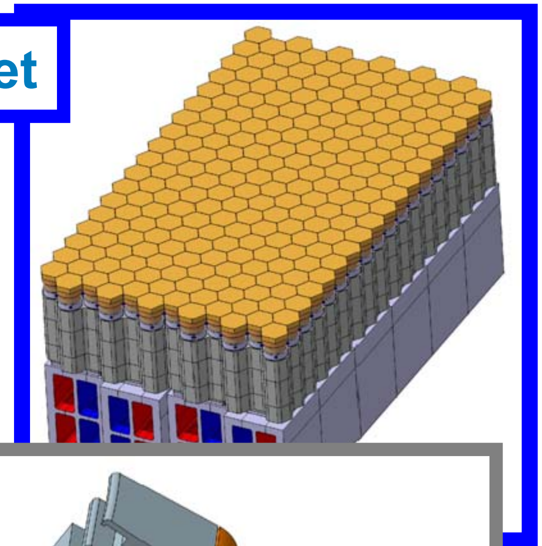
HELOKA-HP/TBM

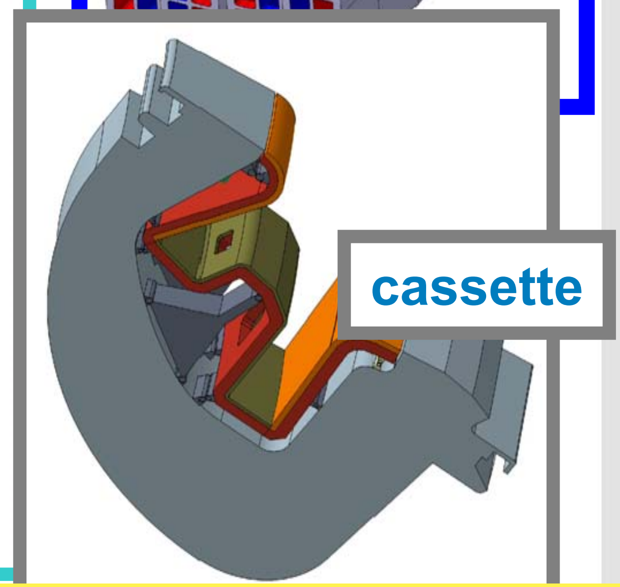
- Qualification for ITER
- Development of Helium Loop Technologies
- 80 bars, (max 100 bars)
- 500°C**
- 1.4 kg/s
- pulsed load operation *ITER scenarios
- long term operation
- Graphite radiation surface heaters

Multiple Jet Cooled Divertor: Modular Concept









13 MWm^{-2} have been achieved in HHF Tests

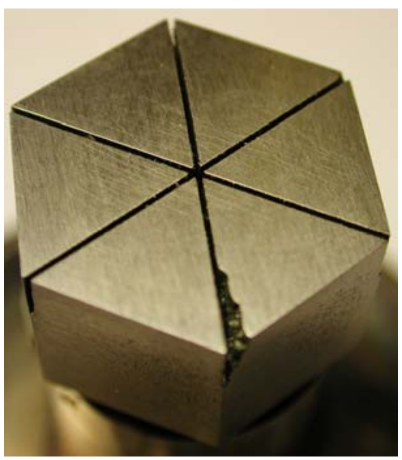
Successful HHF tests of improved mockups showing excellent results

<u>2. series: #17 (FZK, thermo-mechanically optimised)</u>

Test conditions:
- *10 MW/m^2*
- *30s / 30s sharp power ramp*
- *$T_{He,in}$ 550°C, 10 MPa, mfr 7 g/s*

✓ Withstood 89 temperature cycles, w/o significant damage (exp. terminated after slight temperature rise on tile top surface)
✓ He Loop and thimble still intact.

<u>3. series: #22 (Efremov, EDM manufactured)</u>



←before tests

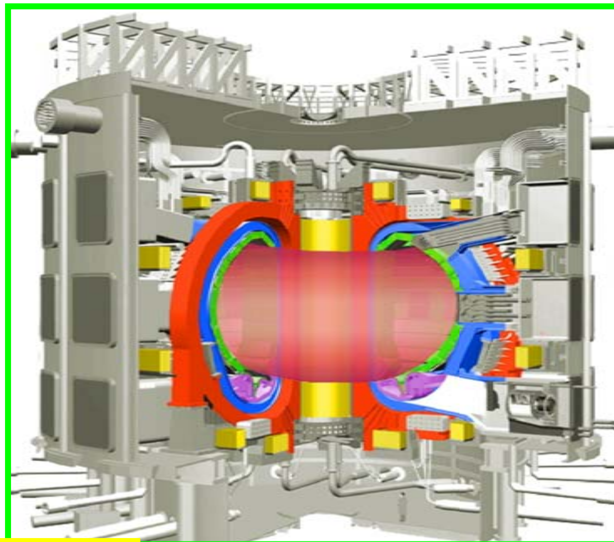
after 100 cycles →

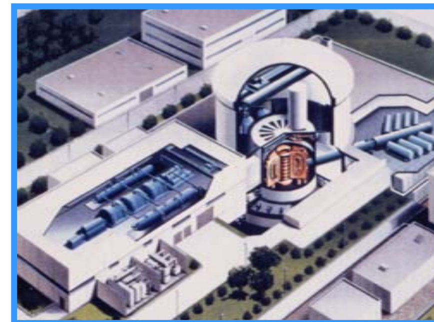
✓Excellent performance.
✓No any damages.
✓No leaks.
✓Stable surface temperature from cycle to cycle.

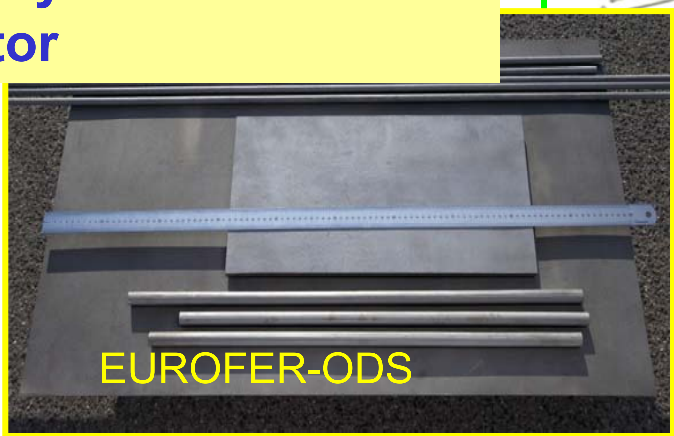
Structural Materials development for DEMO (FZK – World Leader)

EUROFER – Steel for the blanket and divertor

W- alloys for the divertor







Materials

ITER

3 dpa/lifetime

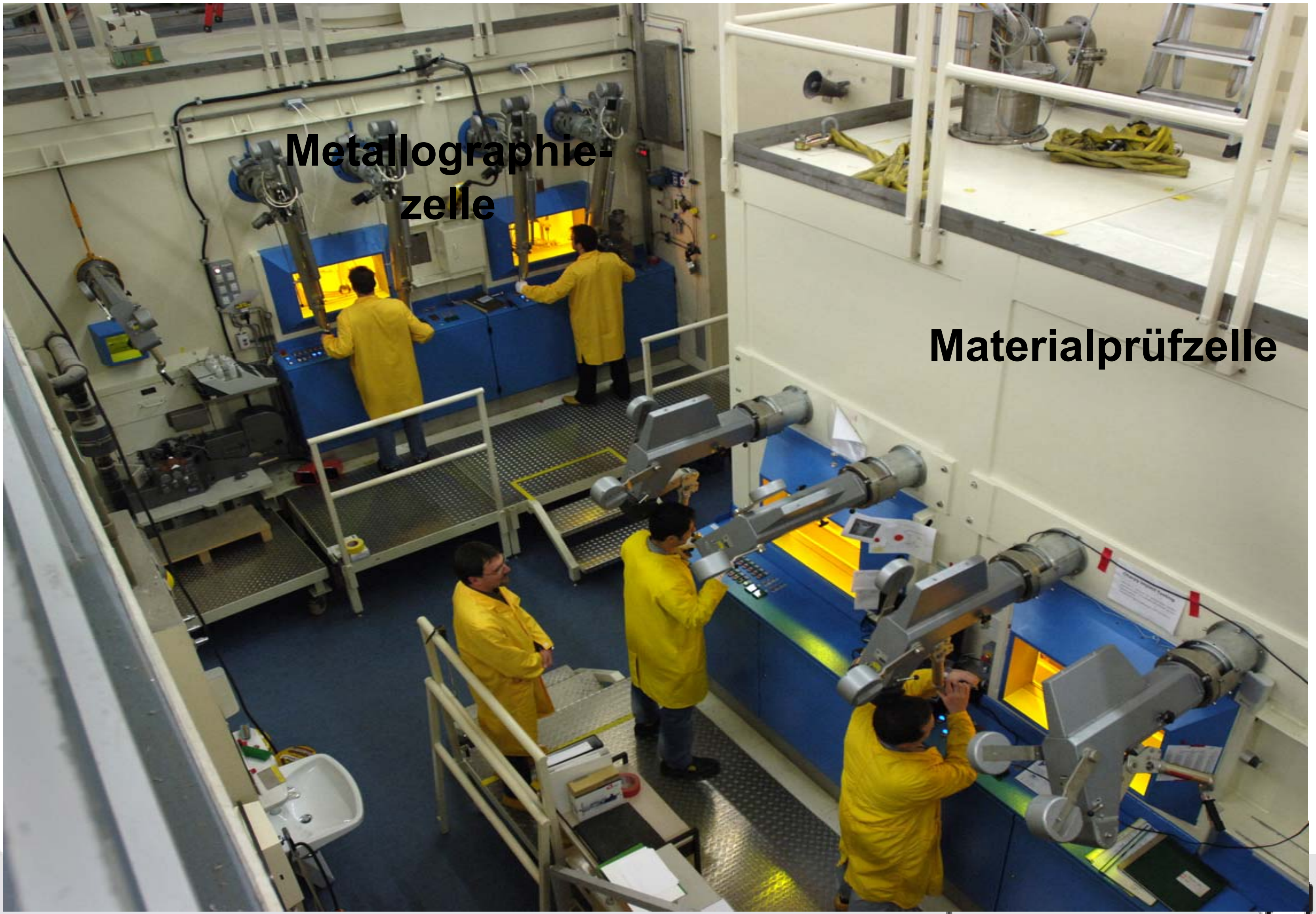
DEMO

30 dpa/year

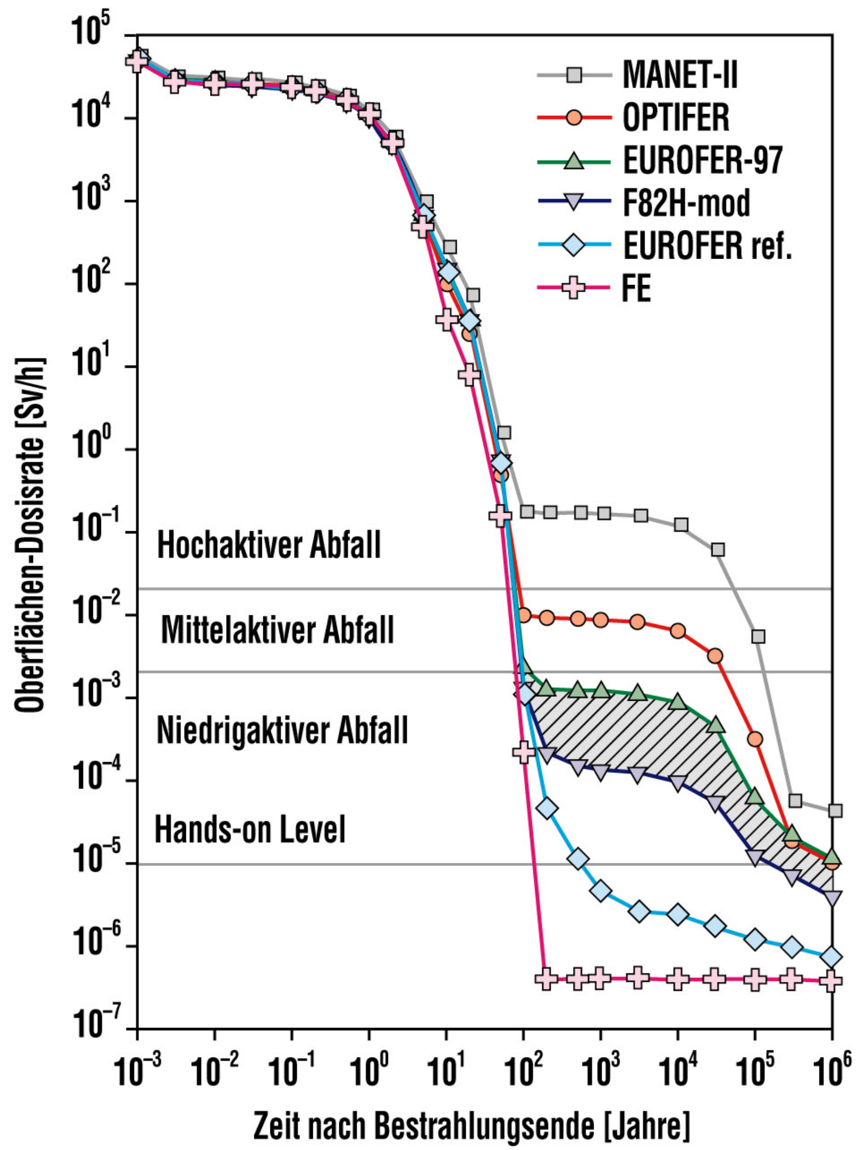
High neutron energy not available in fission reactors

FZK develops and qualifies European reference materials

Fusions-Material-Laboratory



Decay of Dosrate for Eurofer Steel:

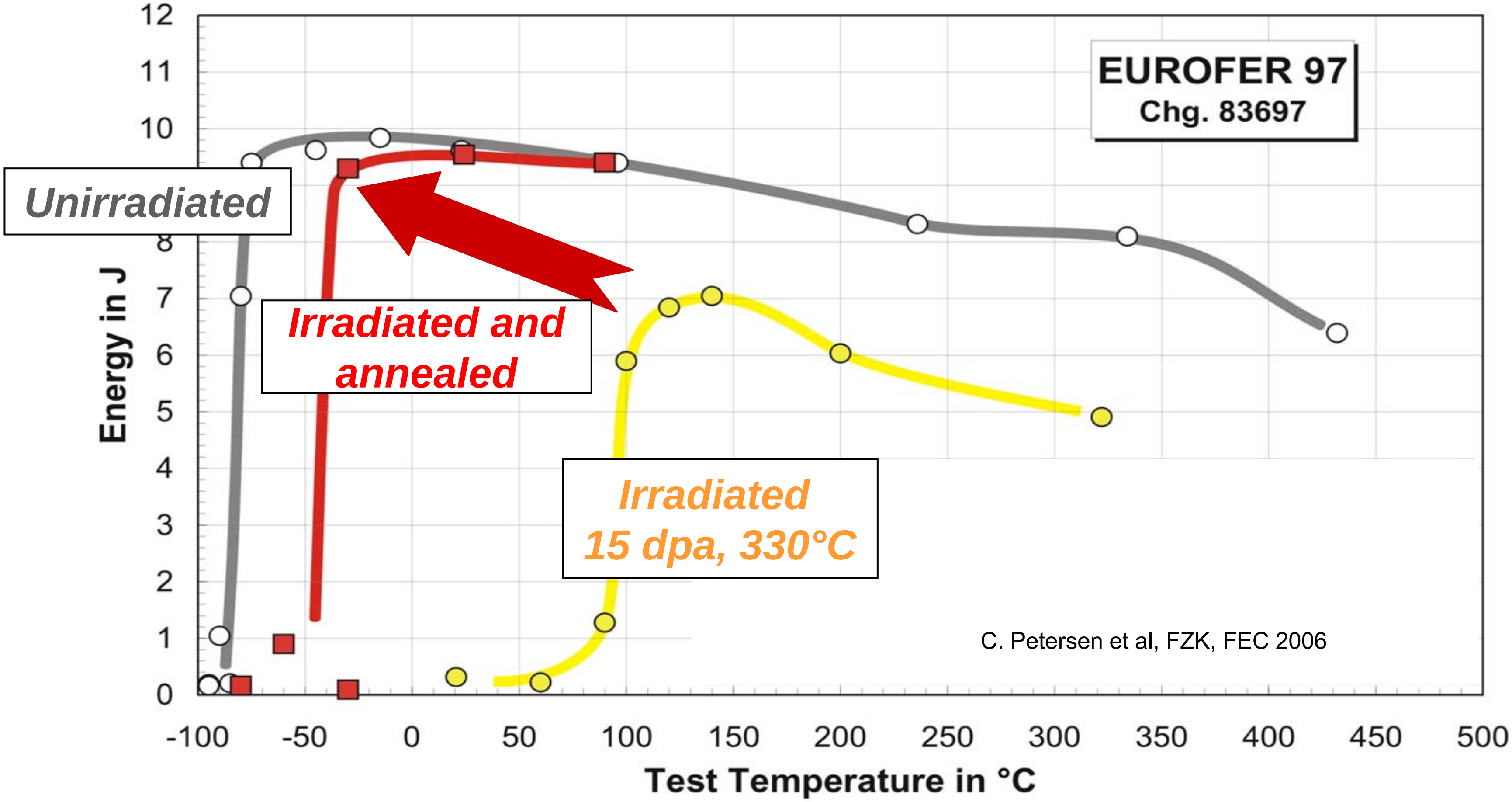


Activation of the material by neutrons

Transmutation in radioactive isotopes by neutron capture (all neutron energies – higher neutron energies responsible for gas production)

Time dependence of the γ dosis rate after irradiation with fusion neutrons of up to 12.5 MWa/m²

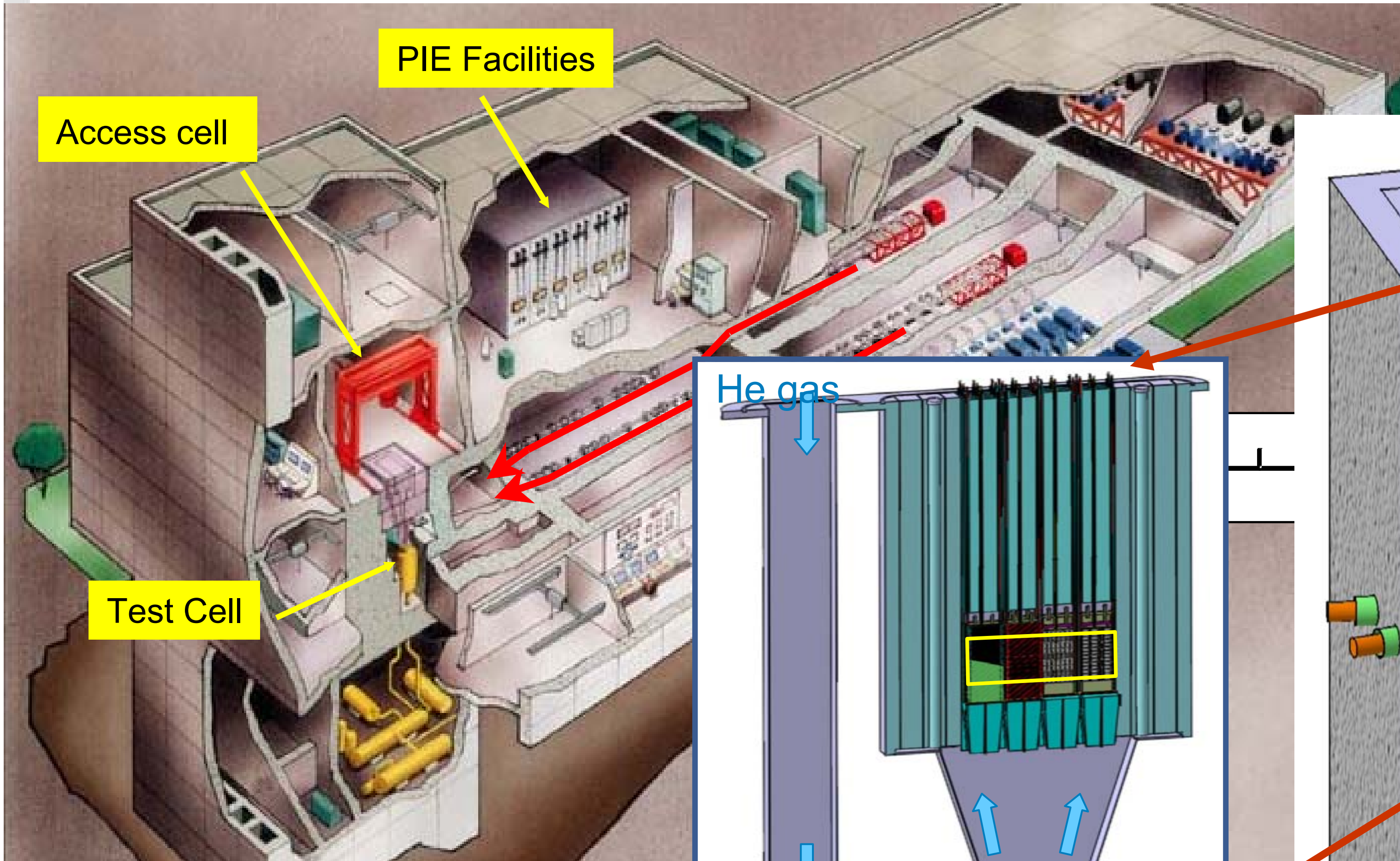
Strategy for recovery of irradiation embrittlement:
Annealing for example at 550 °C/2h

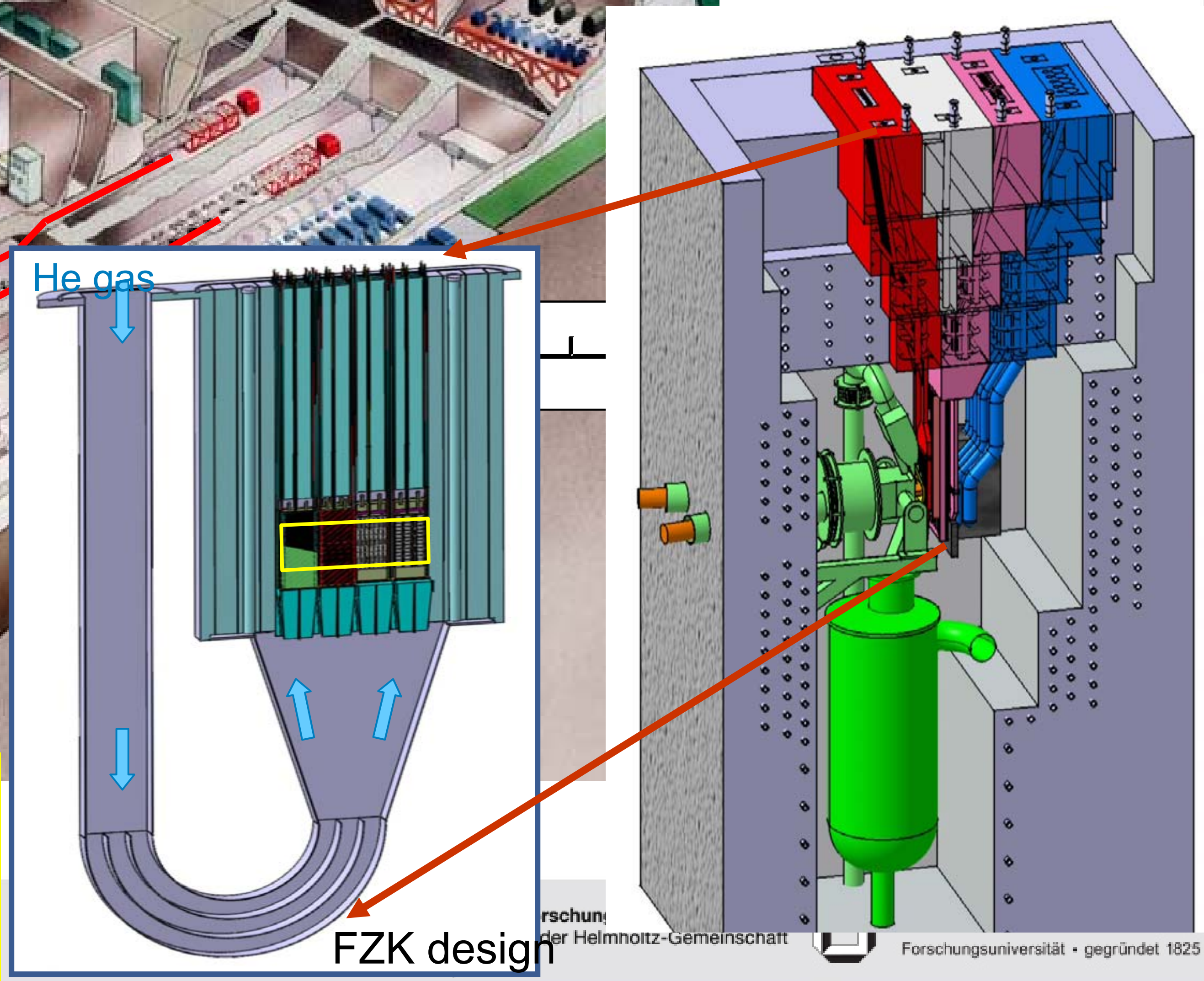


- How often can this recovery be repeated?
- **What happens if larger concentrations of He are present?**
- In a Fusion Reactor the He production is 100 times larger per dpa

International Fusion Materials Irradiation Facility

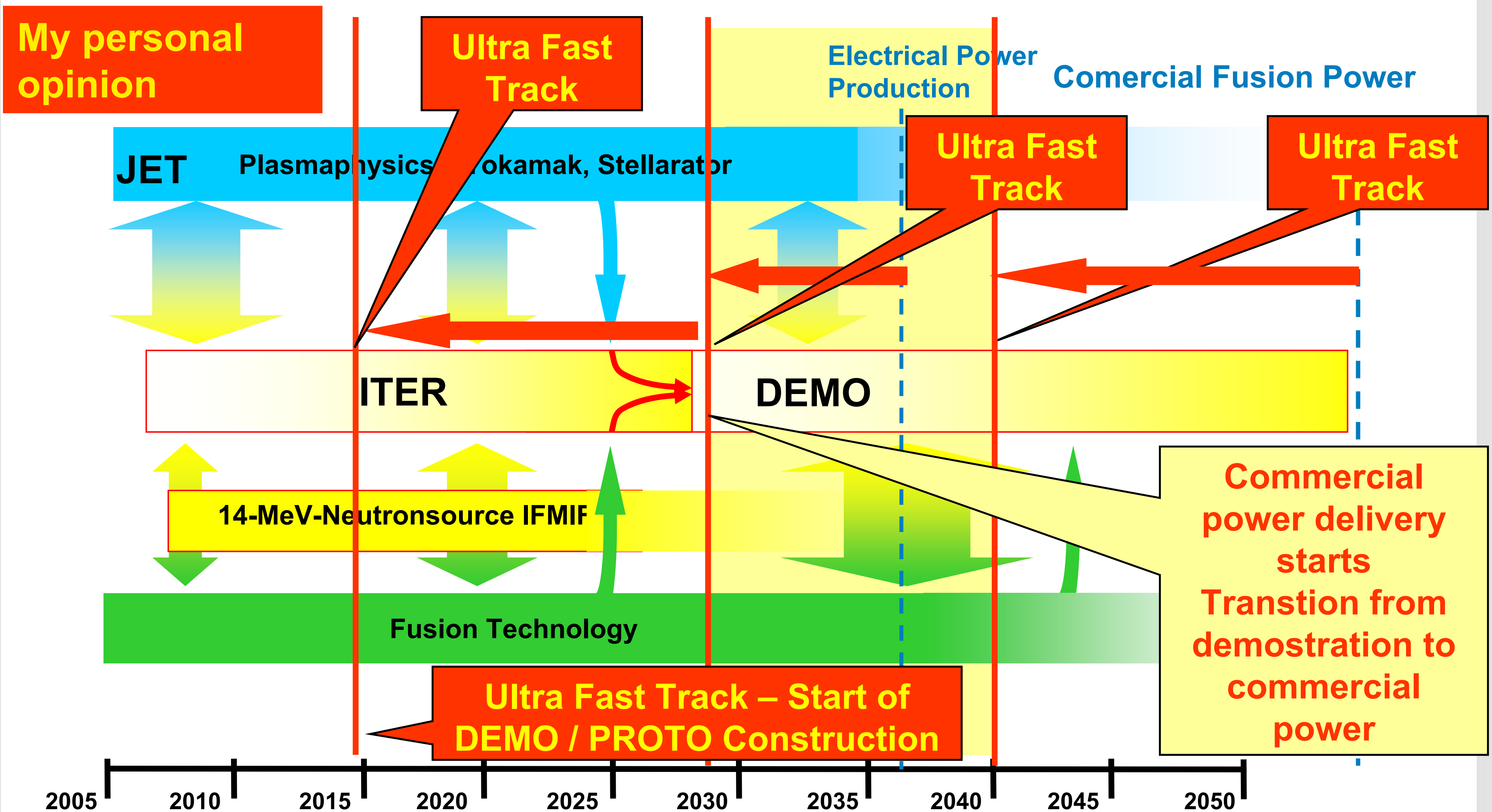
IFMIF





Irradiation of DEMO-relevant structural materials by 14 MeV neutrons – neutron flux twice of DEMO

Road Map to the Fusion Reactor (can we accelerate this?)



Can we accelerate fusion development further ?

- The answer is yes by approximately 20 years => "Ultra Fast Track"

- if the construction of a combined DEMO – PROTO starts in 2015 and the built-up of a team, the design and the R&D in 2010 !!
  - Development and construction cost ~ 15 billion € spread over 15 years
  - A moderate increased economical risk (availability, cost of electricity) versus the Fast Track has to be accepted

- Even in this "Ultra Fast Track" scenario ITER and the Broader Approach are essential elements which also would have to be accelerated
  - Increase of ITER costs ~ 20%, i.e. ~ 1 billion € spread over 10 years
  - IFMIF needs to be constructed earlier (start 2011), cost ~ 1 billion €

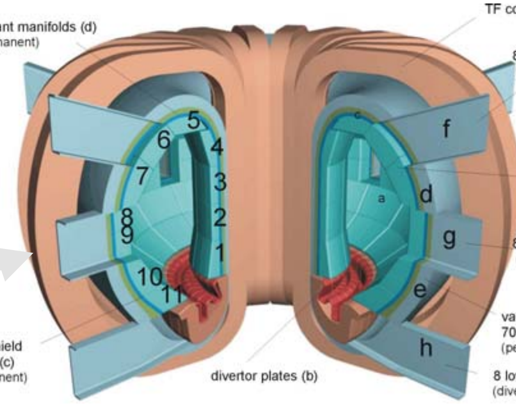
How would an Ultra Fast Track reactor look like ?

- The starting point would be the design of the large ITER machine from the 90^{th}
  - It will be modified to allow stronger plasma shaping and to incorporate a He cooled solid breeder blanket (R ~ 8.5 m) and a He cooled divertor => (~ 1.5 GW electric net output)
  - The "in vessel" components and their material (EUROFER) would be the only new development beyond the existing ITER technology !!
- What is the contribution of ITER, IFMIF and JT60SA ?
  - ITER and JT60SA need to develop the operation scenario for PROTO
  - IFMIF needs to qualify the structural material (EUROFER) for the "in vessel" components – staged operation license may be also required
  - All of the above can be performed in parallel to the construction of PROTO

Energy Conversion Technology

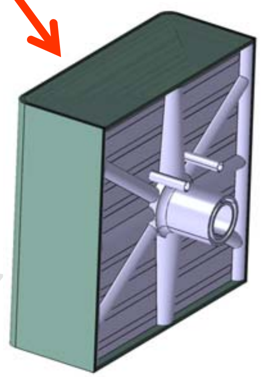
H_2 Production ?

IFMIF



EU DEMO > 2025

Materials

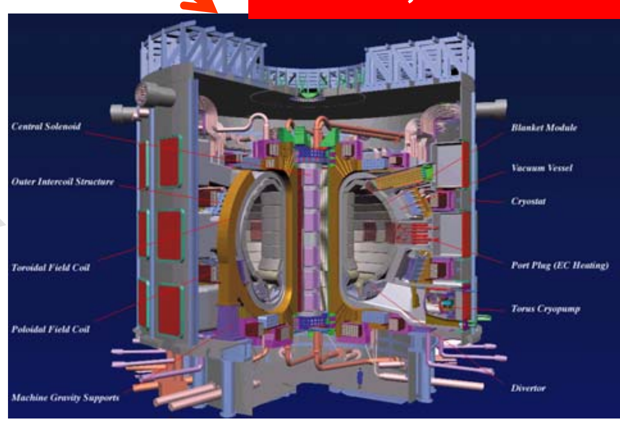


Technology

now

TBM, TDM

Physics &
Technology



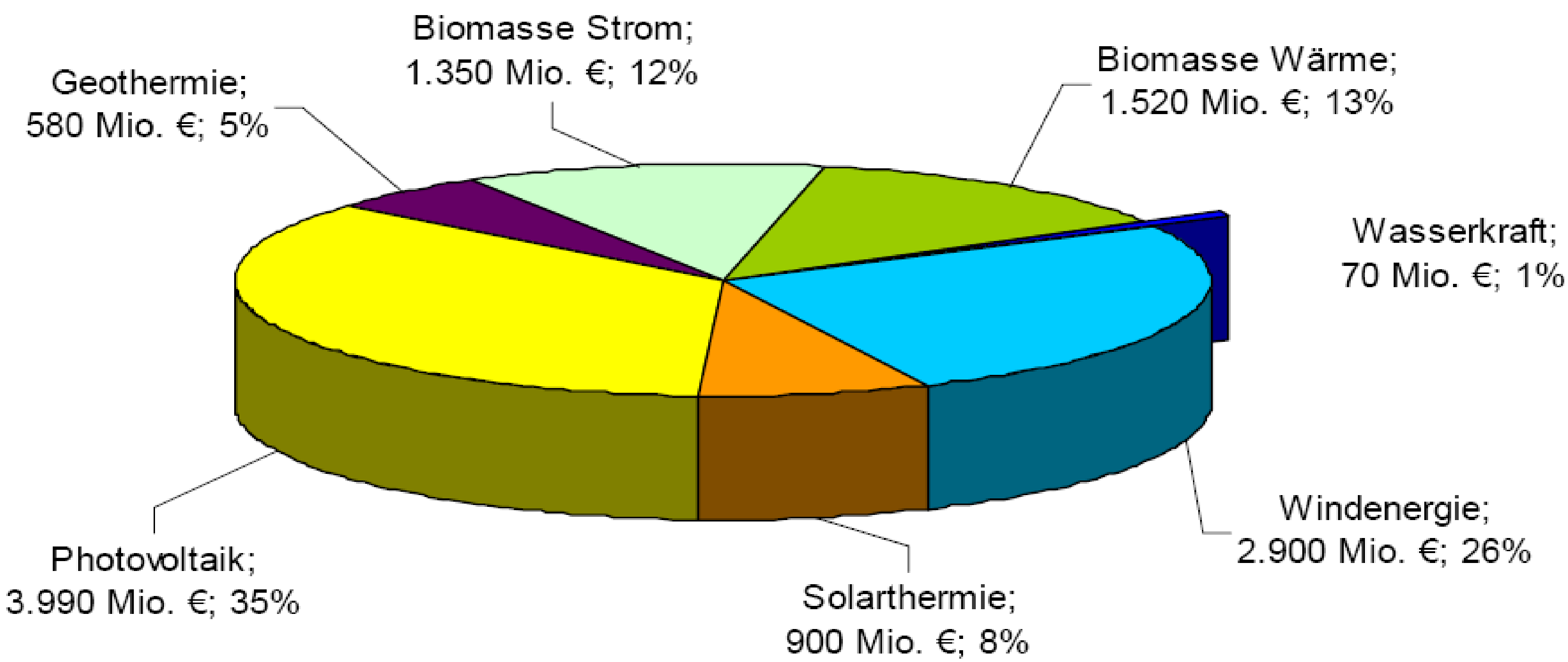
ITER 2019

During this Talk

- 16 500 000 000 kWh primary energy was used worldwide
- 4 950 000 t CO_2 was released into the atmosphere
- more than 10 500 new cars and trucks were produced
- The world population increased by 18 000

- It is time to act and develop new CO_2 free energy sources

Investitionen in Neuanlagen zur Nutzung erneuerbarer Energien in Deutschland 2006
rd. 11,3 Mrd. €

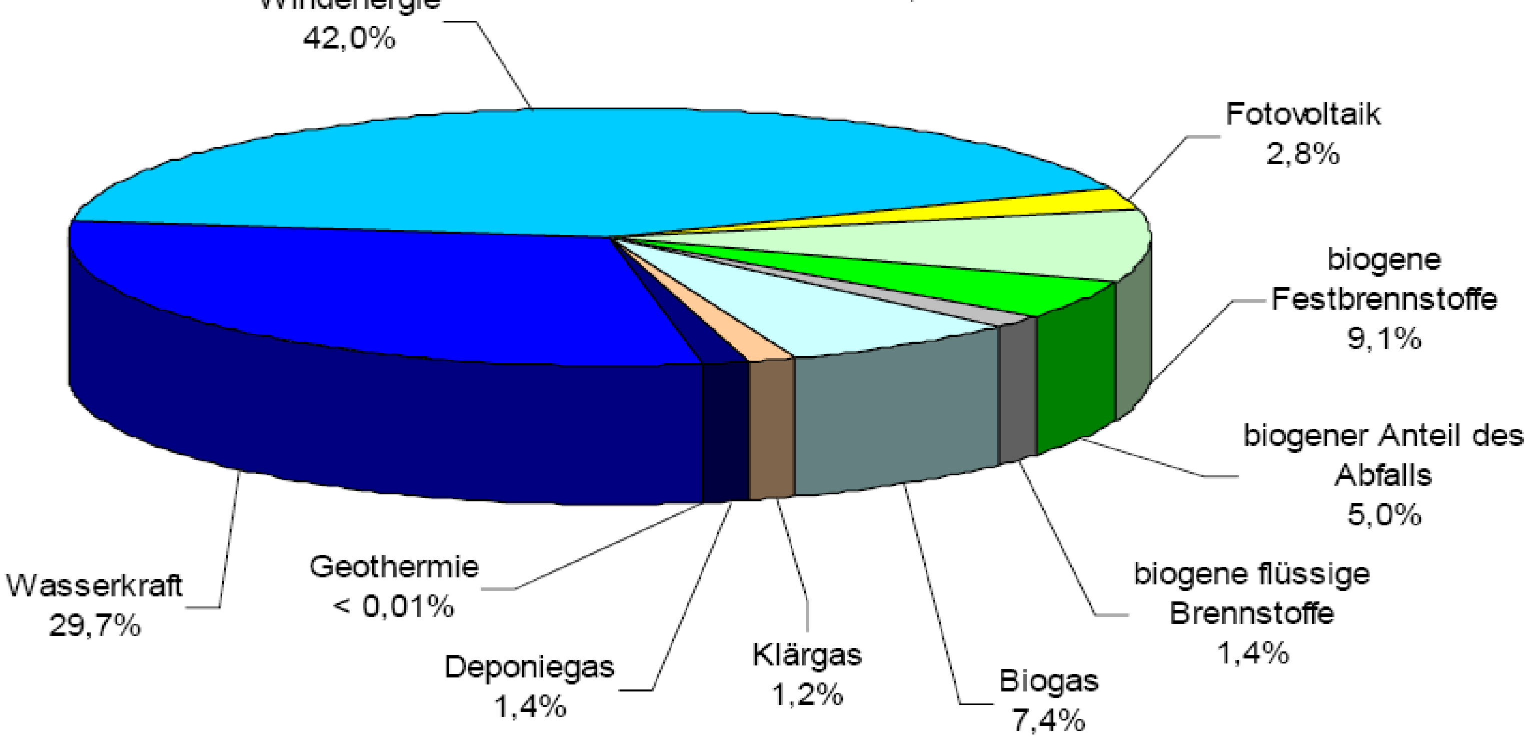


Quelle: Zentrum für Sonnenenergie-und Wasserstoff-Forschung Baden-Württemberg (ZSW), 2007, vorläufige Angaben

Struktur der Stromerzeugung aus erneuerbaren Energien in Deutschland 2006

Gesamt: 72,7 TWh

AGEE Stat
Arbeitsgruppe Erneuerbare Energien · Statistik



gesamte Biomasse: rd. 23 %
(ohne Deponie- und Klärgas)

Quelle: BMU nach Arbeitsgruppe Erneuerbare Energien - Statistik (AGEE-Stat), vorläufige Angaben, Stand Februar 2007

Solarthermisches Kraftwerk in Almeria, Spanien

Zwei Solarkraftwerke mit jeweils 0,5 MW elektrischer Leistung

Quelle: DLR

Syngas aus Biomasse

KIT Karlsruhe Institute of Technology

Biomasse: Holz, Stroh, Heu …

Schnelle Pyrolyse

~ 500°C, τ < 10 s (sechsmal)

Bahntransport
Energiedichte mit Faktor 10

Flugstromvergasung

~ 1200°C
≥ 60 bar
τ 2-3 s)

Gasreinigung
mit Wärmerückgewinnung

~ 60 bar ⇒ CO_2

Synthesegas

Kraftstoffsynthese

~ 60 bar ⇒ Synfuel ⇒ H_2 ⇒ Chemikalien

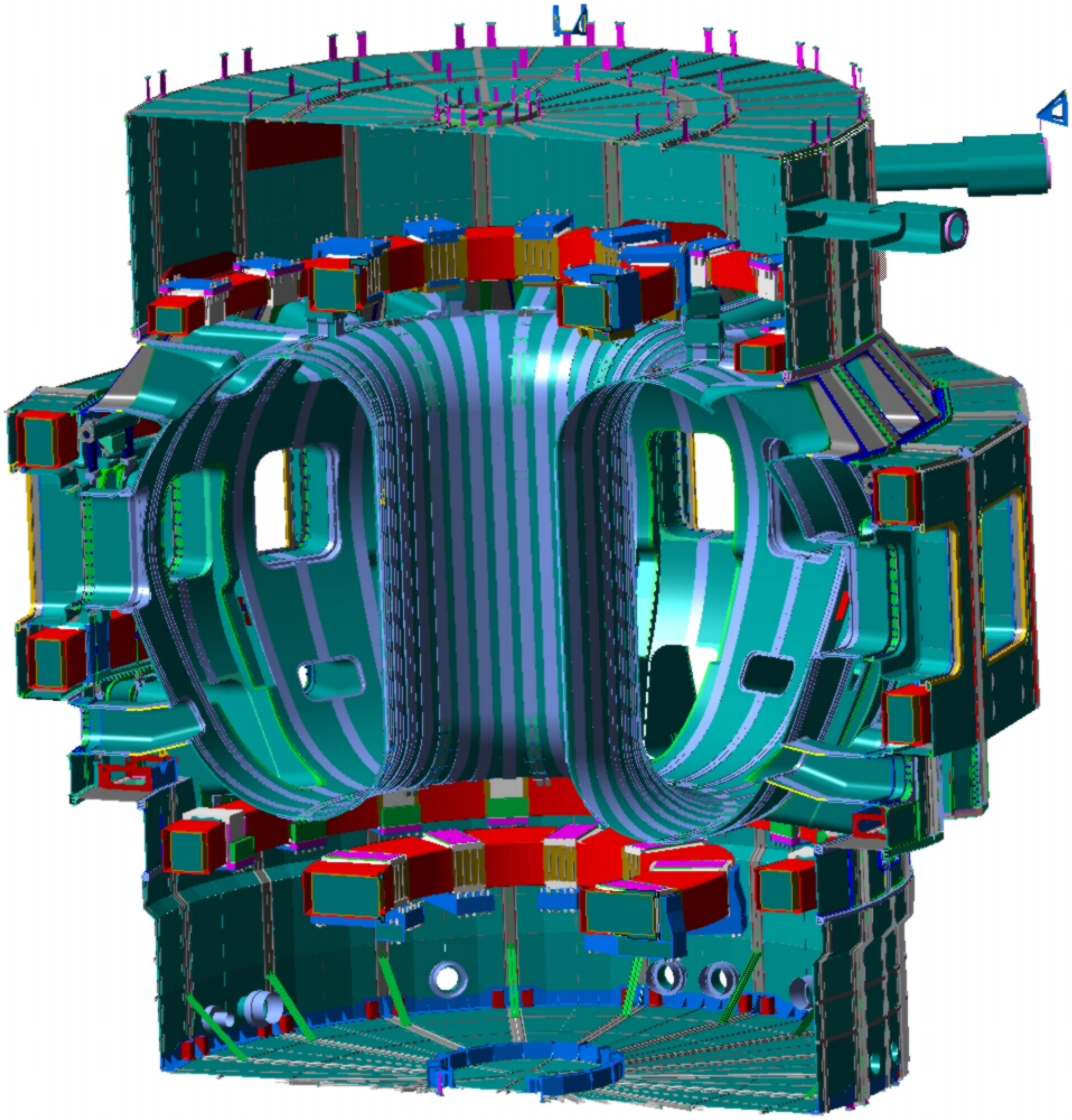
Stromerzeugung

GuD ⇒ Strom + Nutzwärme

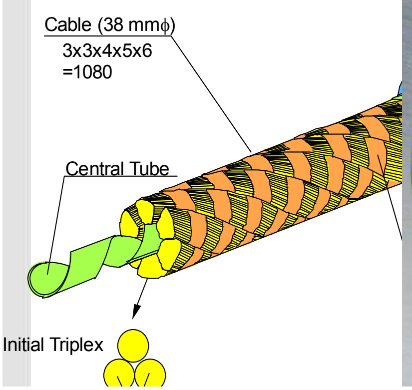
bioliq®
Biomass to Liquid Karlsruhe

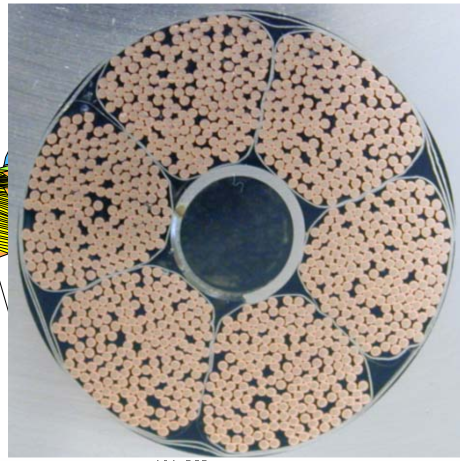
Thermal Shield

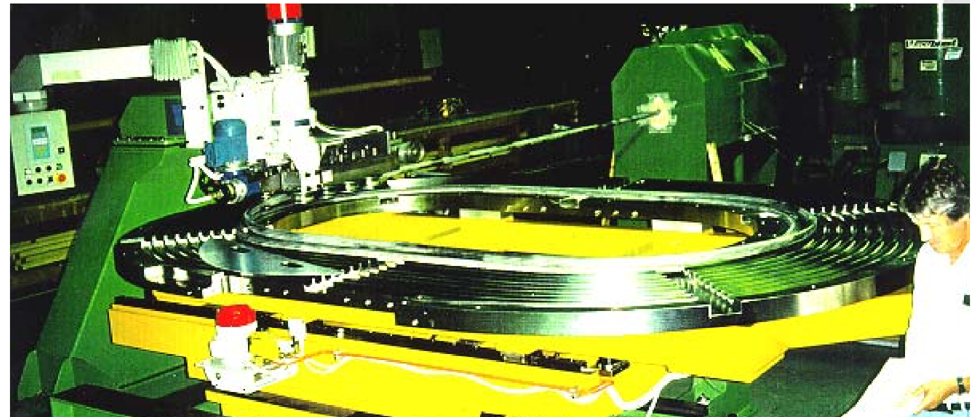
- **Cryostat thermal shield close to the magnet structures and supported in the central region by the TF coils**
- **Most labyrinths eliminated**
- **Reduced thermal radiation to 4K structures**
- **Separation of cold volume from the part crossed by water pipes**
- **Reduced total surface (and cost) of the TS.**

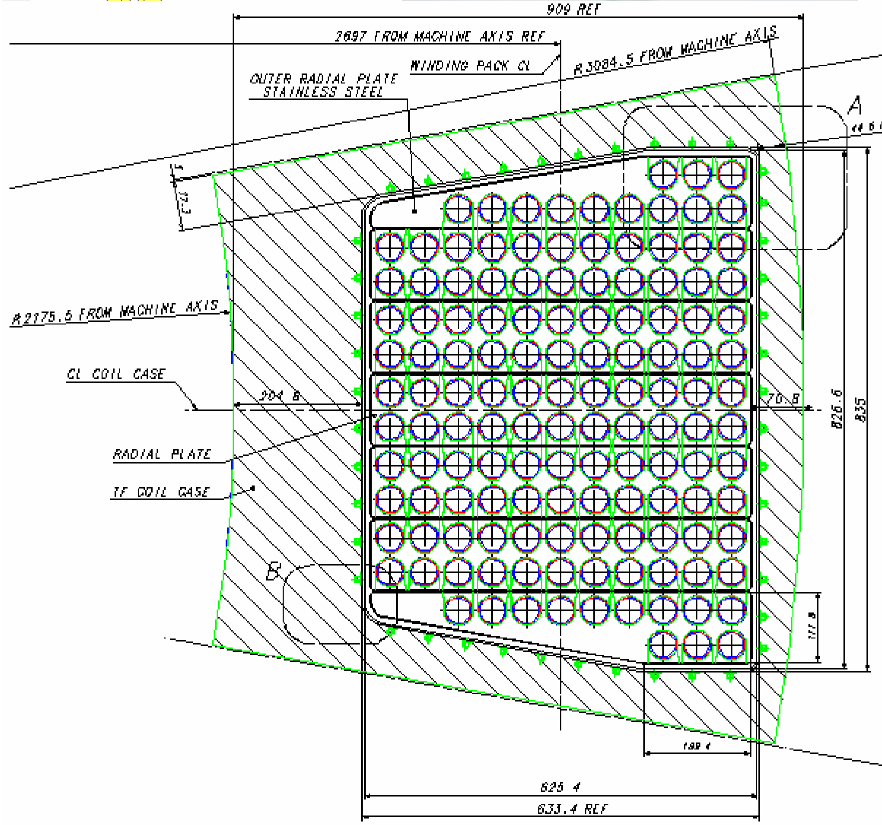


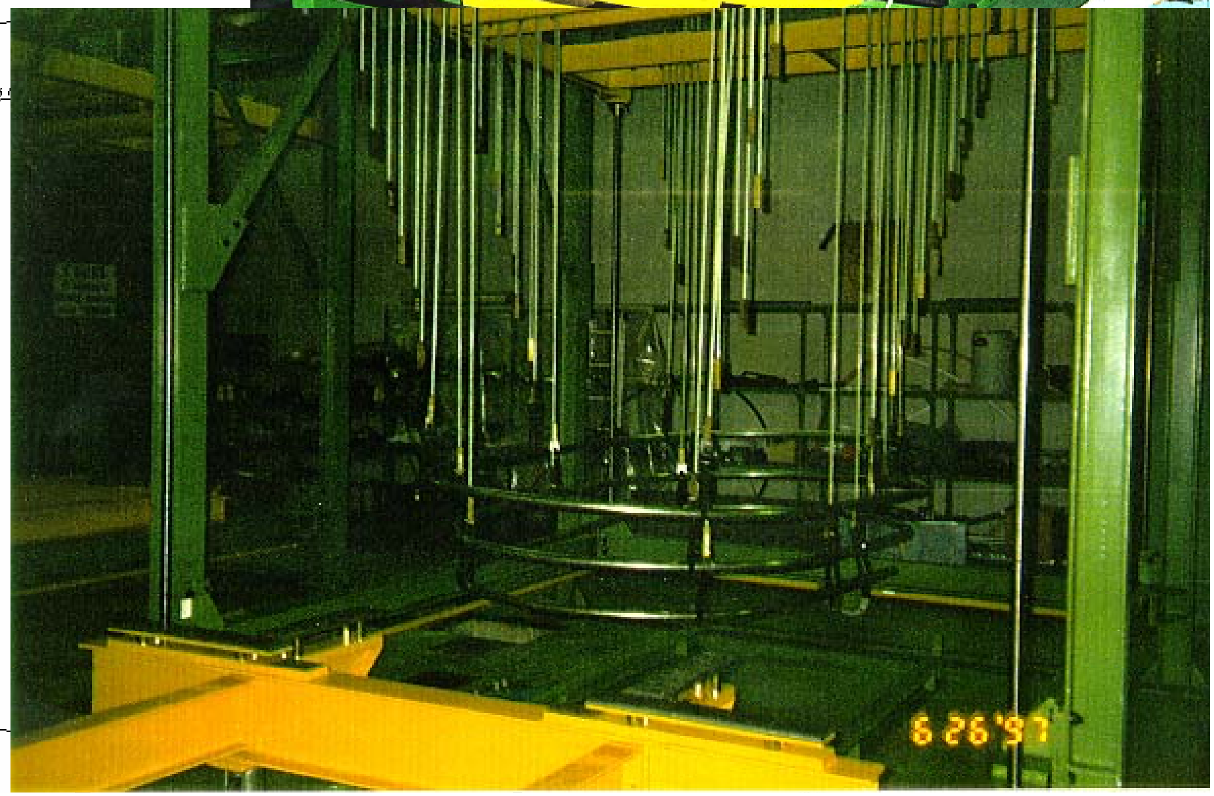
ITER Toroidal Field Magnets



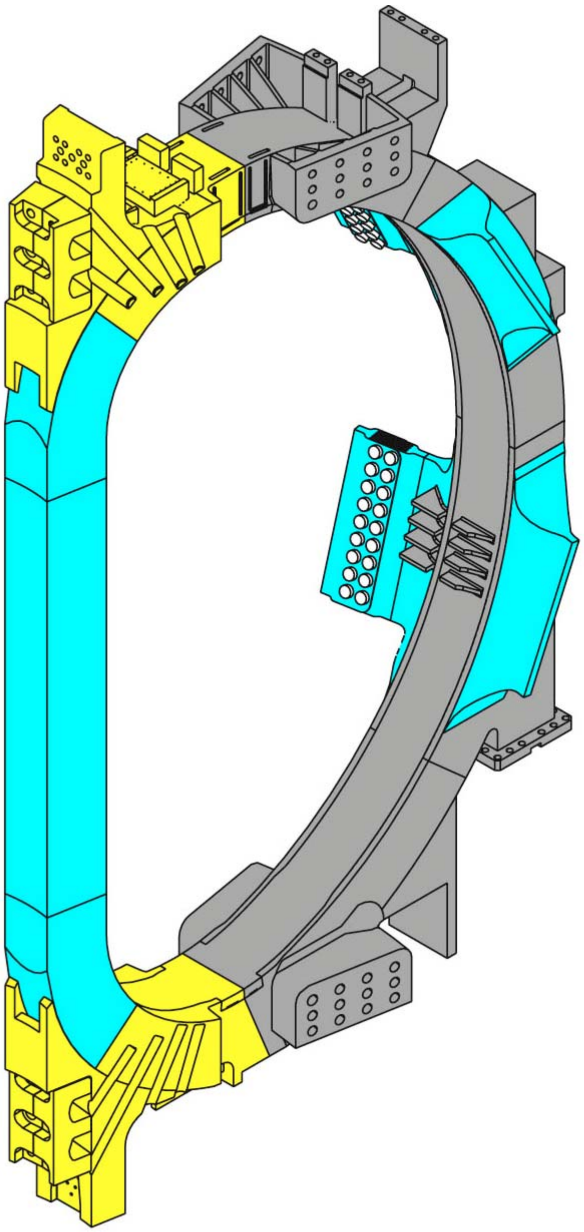


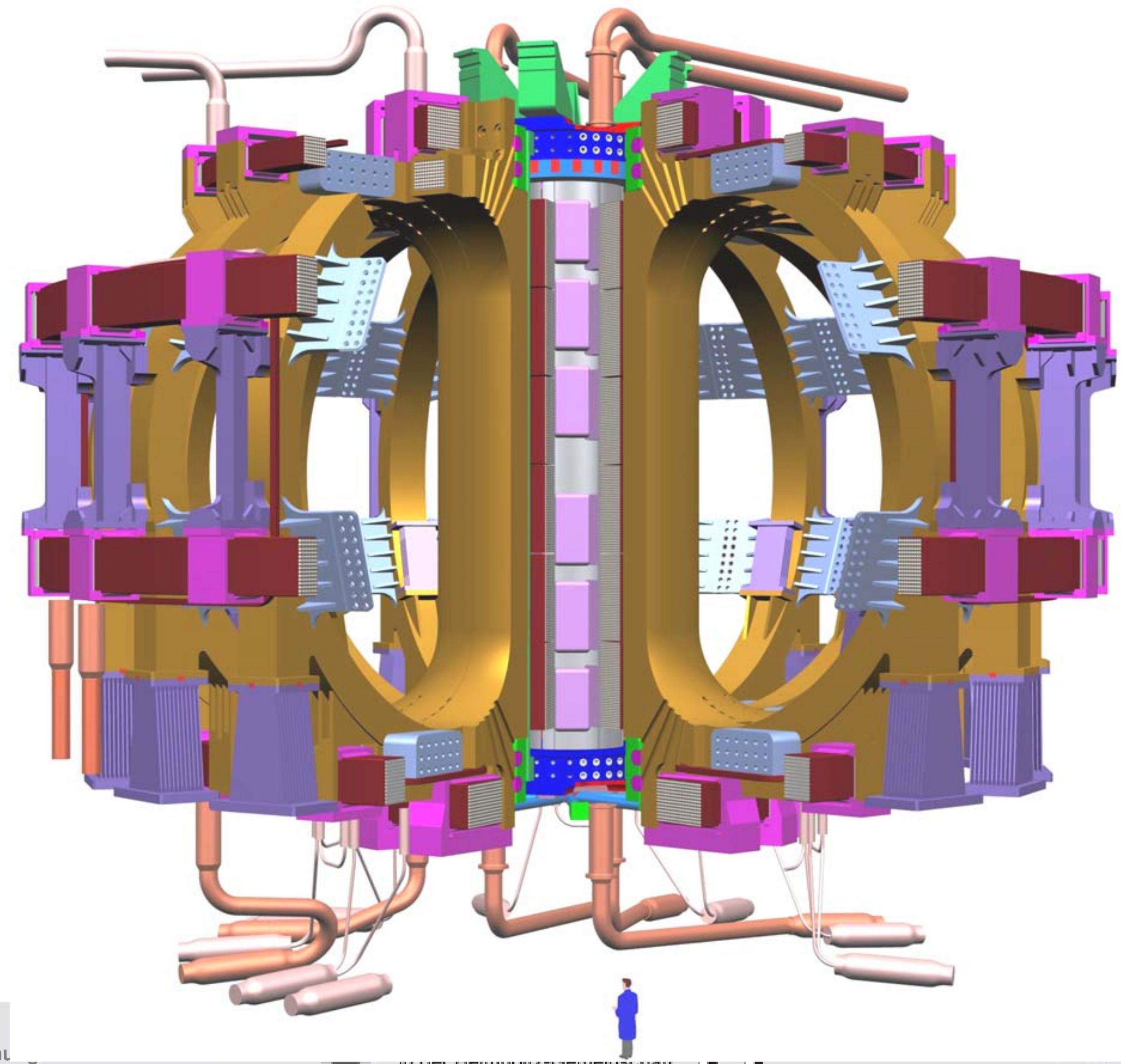




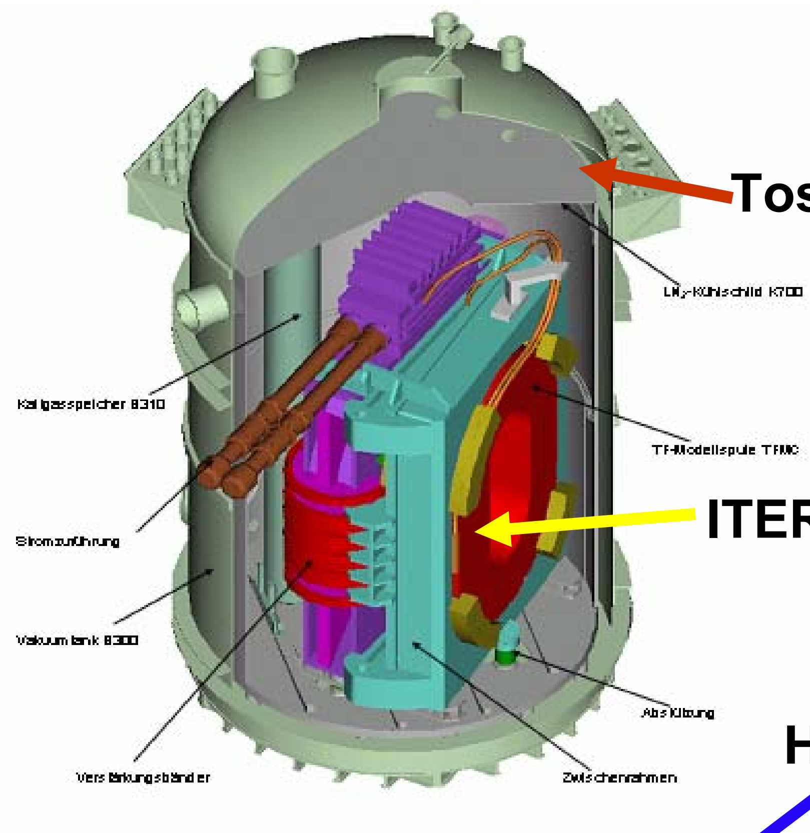


ITER-FEAT coil assembly





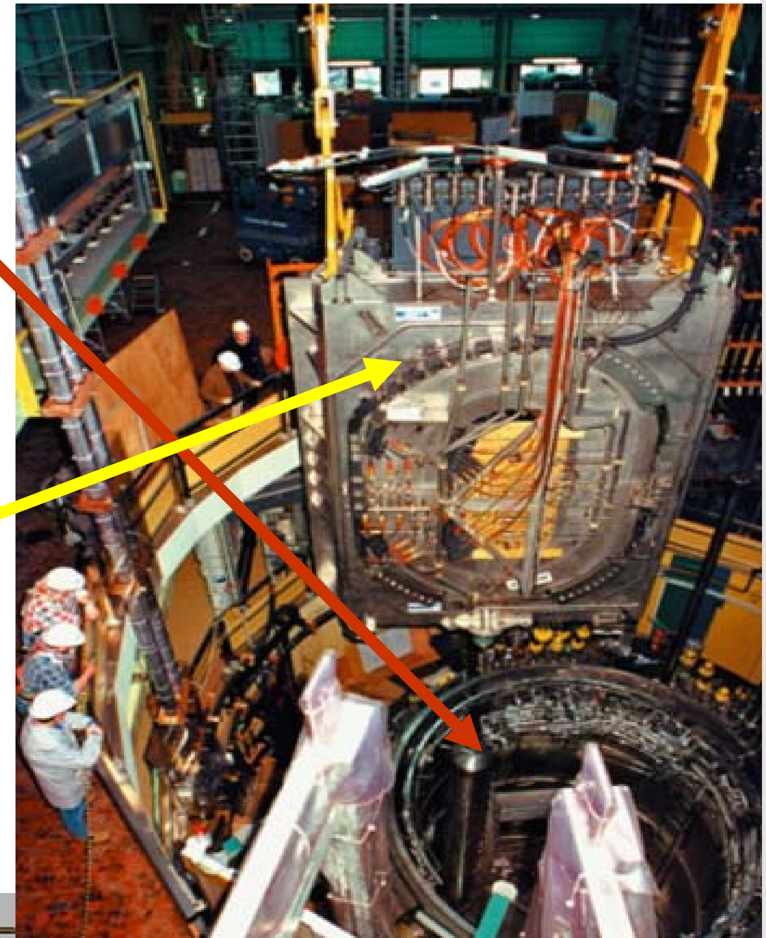
ITER Model Coil, High Temperatur SC Current Leads

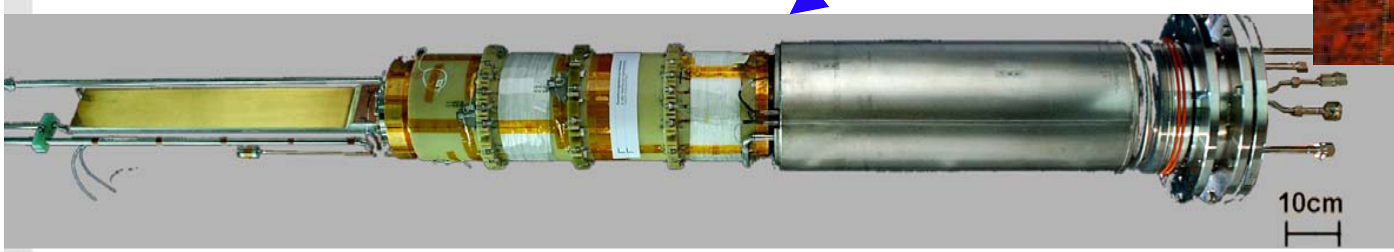


Toska Facility

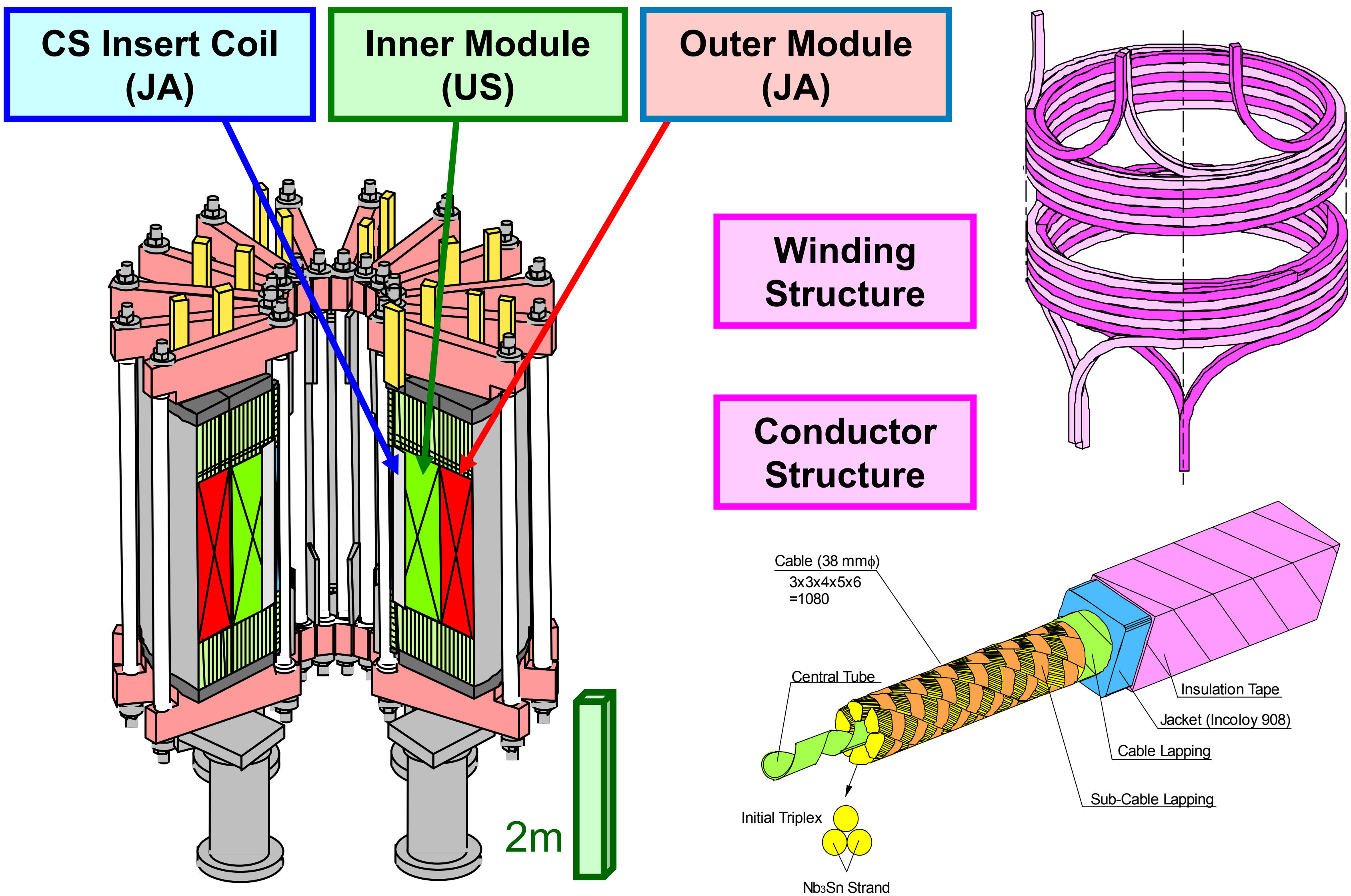
ITER Model Coil

HTS Current Lead





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.

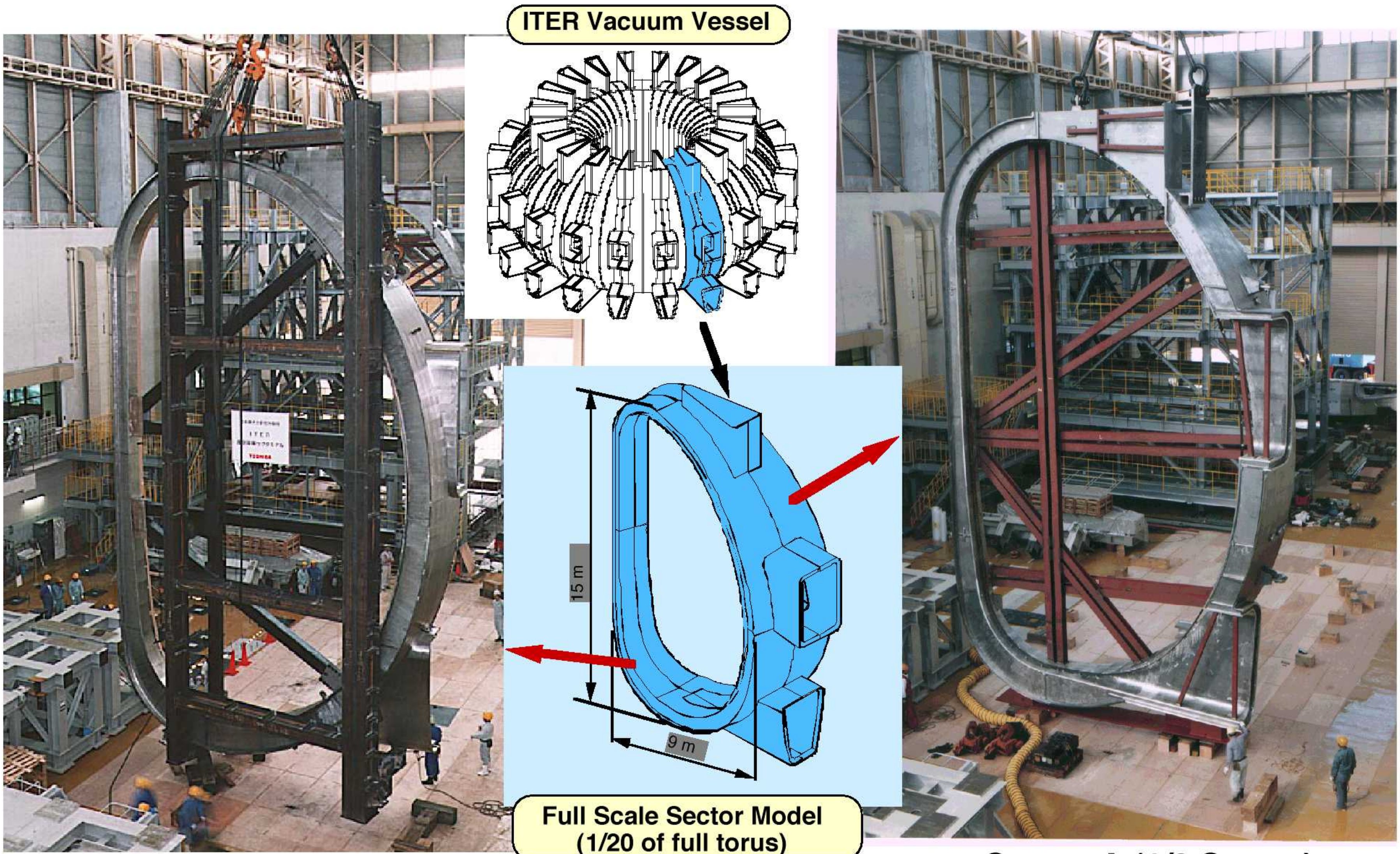
CS Insert Coil (JA)

Inner Module (US)

Outer Module (JA)

CS Model Coil R&D

Closing of the Test Cryostat (JA)



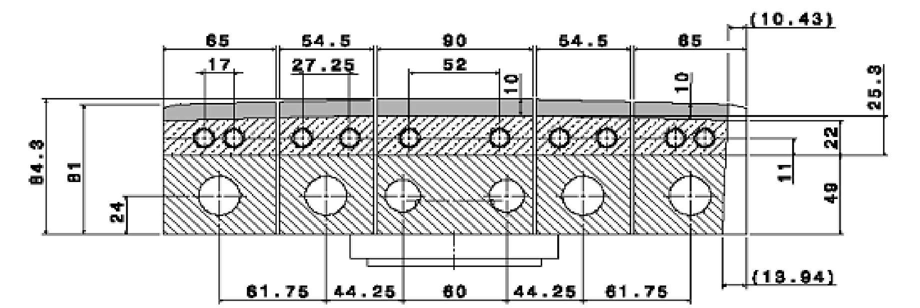
Sector-B (1/2 Sector)

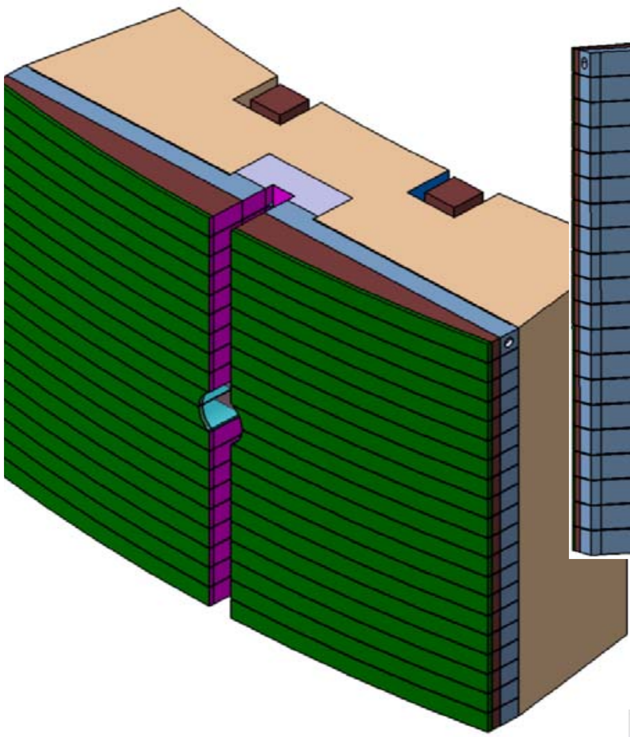
Sector-A (1/2 Sector)

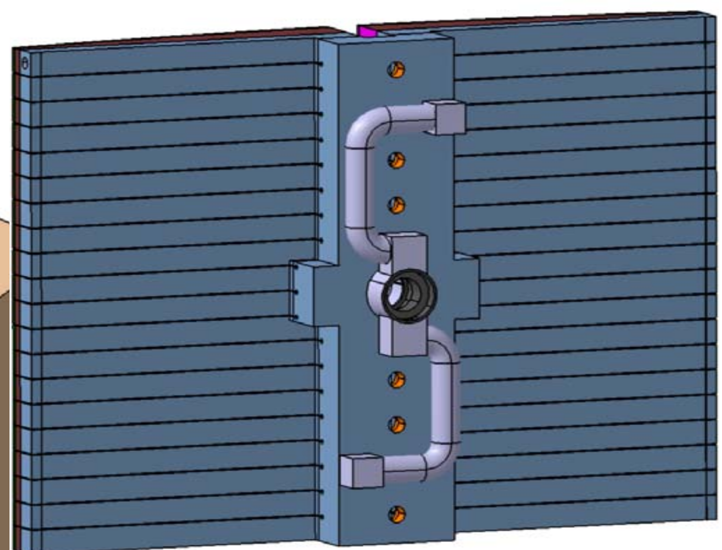
Dimensional accuracy after welding sector halves ± 3 mm

Detailed shaping of the First Wall to shadow all exposed edges

Inner Wall



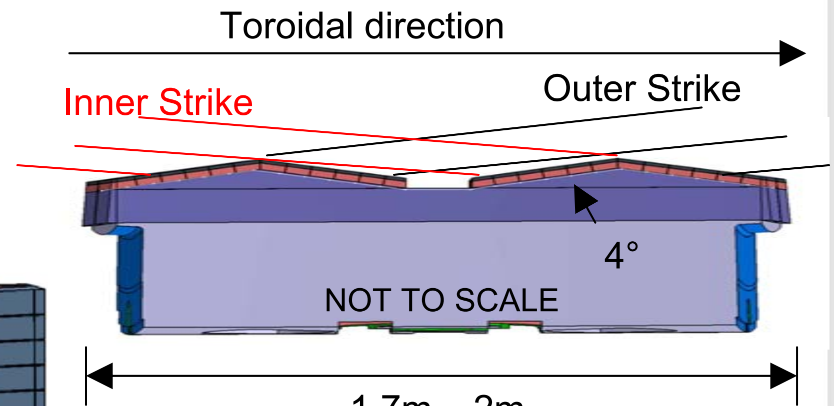




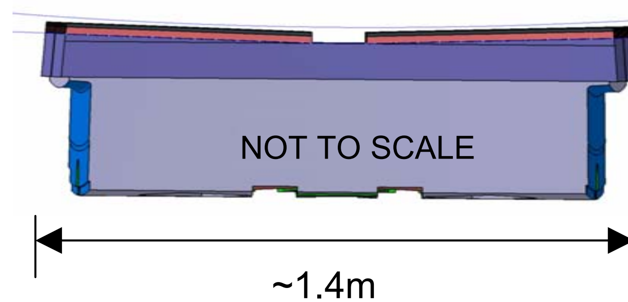
In situ separable FW

Near 2nd X-point

36 of 440 modules



- Bi-directional design
- X-point can move

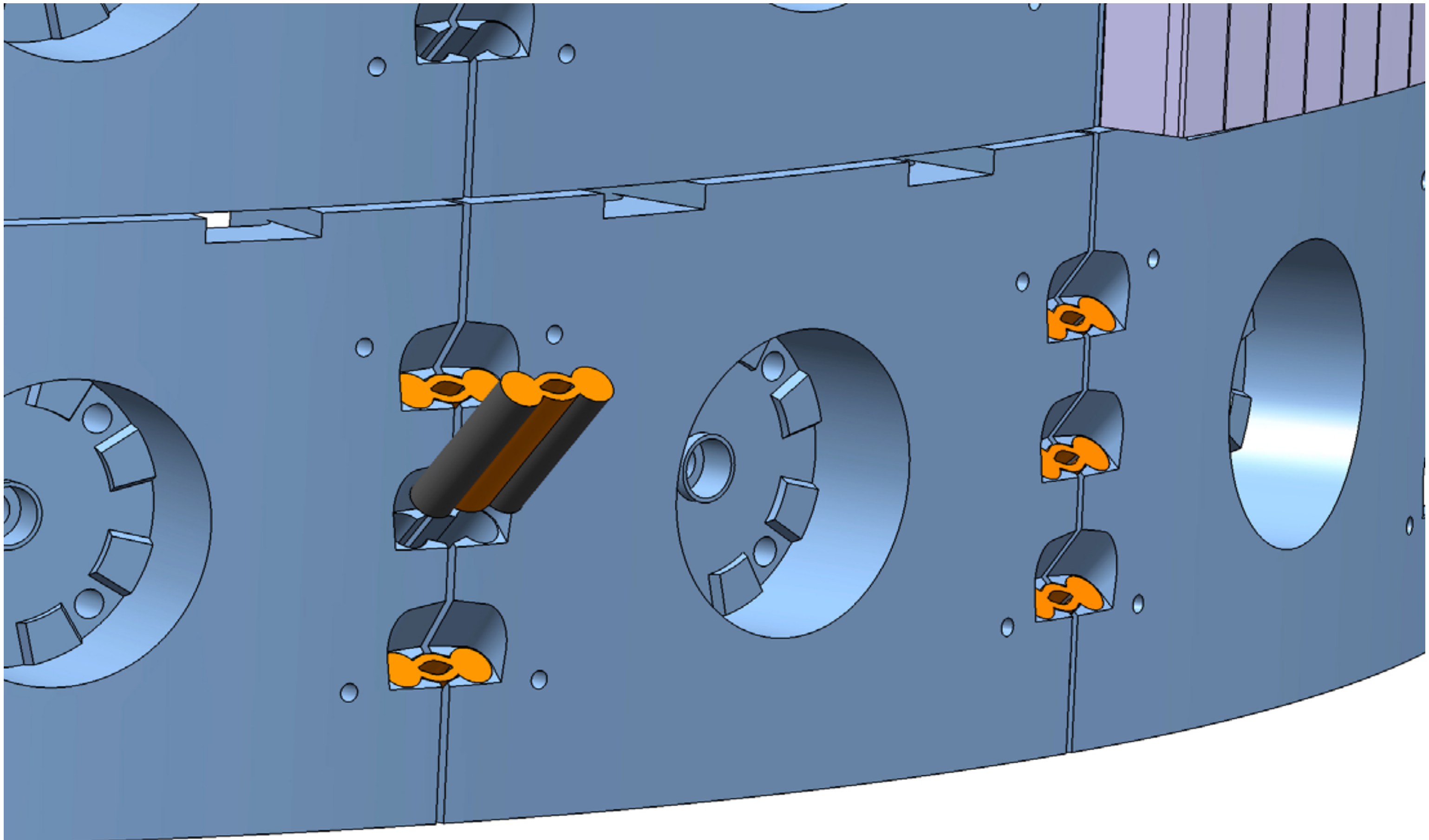


On Outer Wall

260 of 440

Flat surfaces may suffice

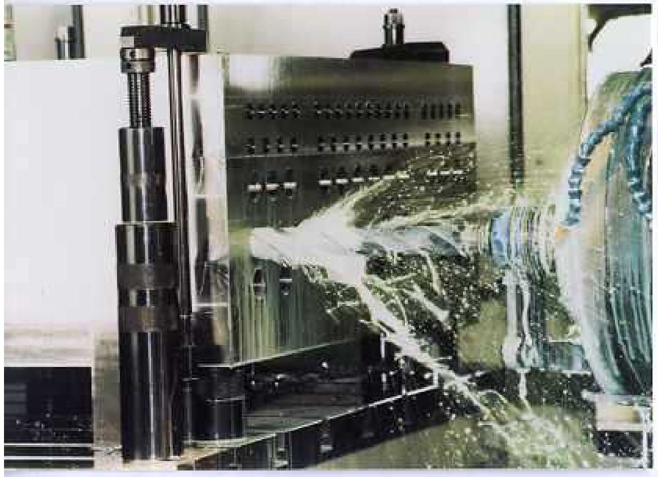
Electrical Straps implementation



CAD view of 3 adjacent strapped shield modules

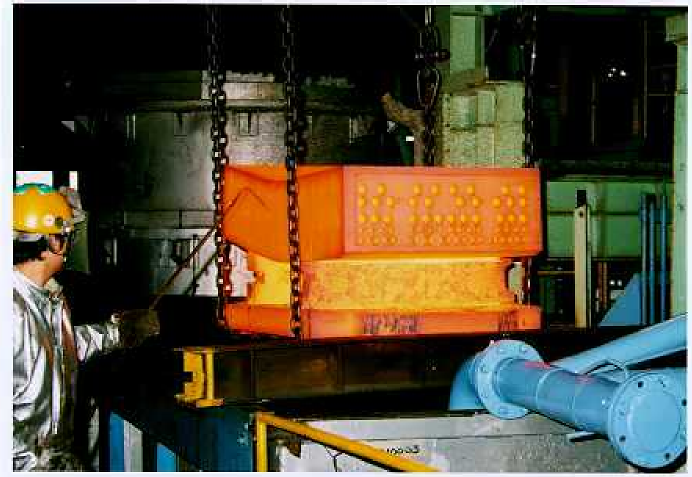
Blanket Module R&D

KIT
Karlsruhe Institute of Technology



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

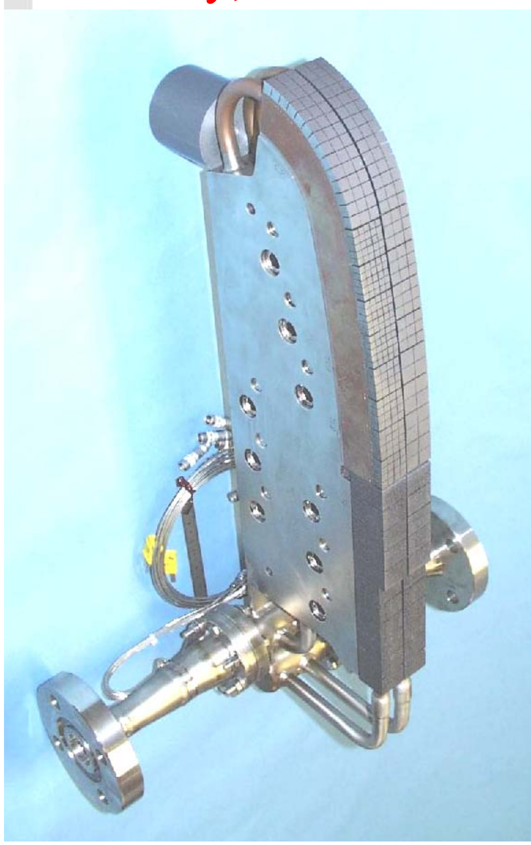
Divertor Prototypical Vertical Target and cassette Mock-ups

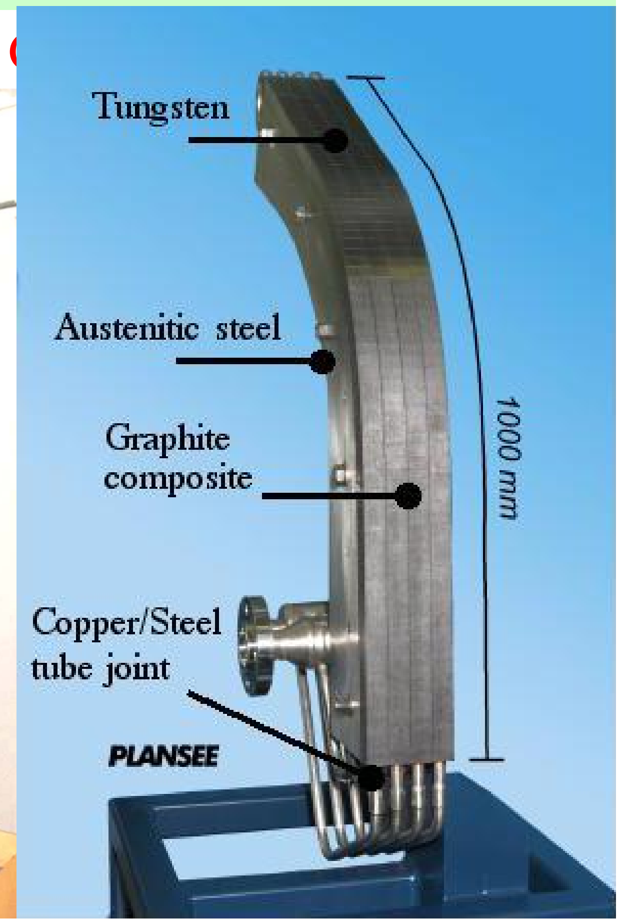
Under high heat flux testing in the Le Creusot e-beam facility, it sustained:

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





ITER Components - FZK Contributions

KIT
Karlsruhe Institute of Technology

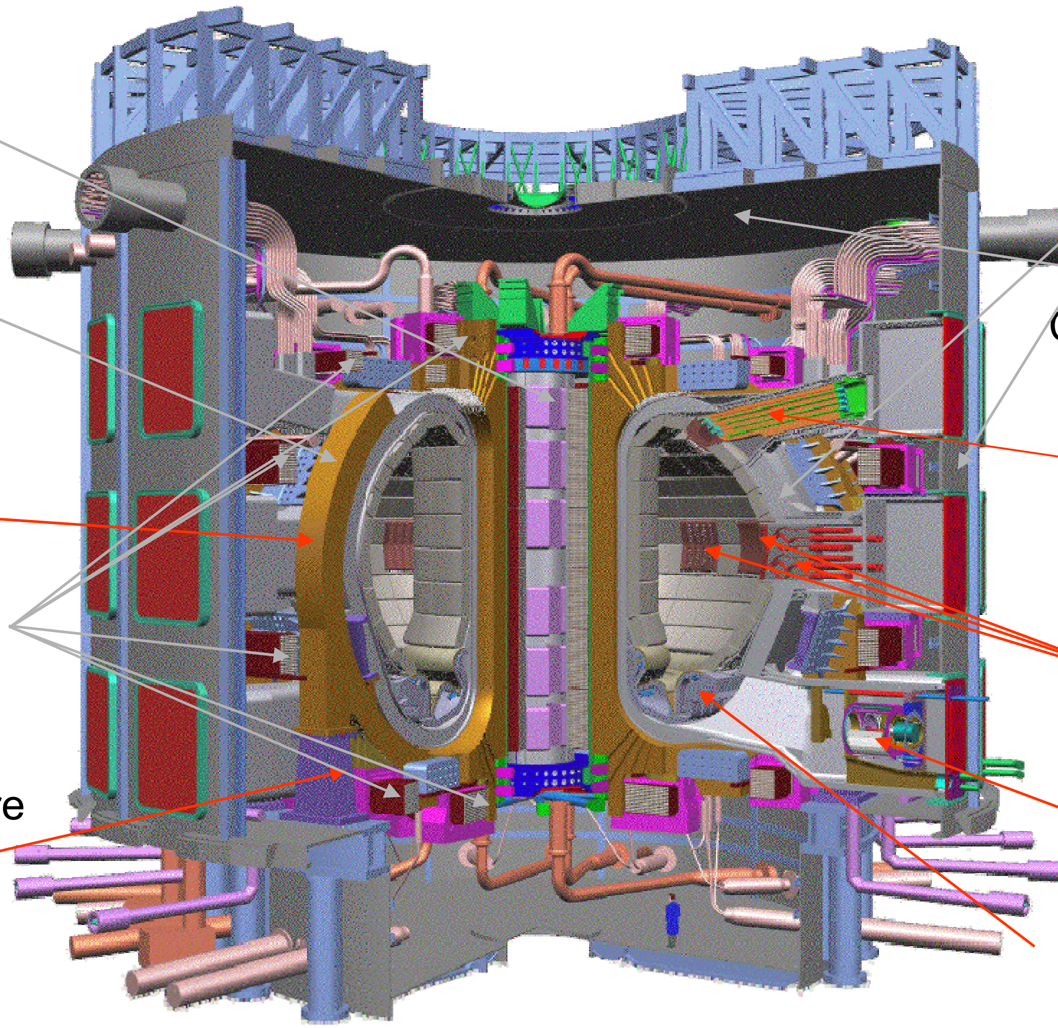
Central Solenoid
Nb_3Sn

Outer Intercoil
Support
Structure

Toroidal Field Coils
Nb_3Sn, 18 Coils
QA and Testing
Current Leads

Poloidal Field Coils
Nb-Ti

Machine Support Structure
Materials Qualification



Vacuum Vessel

Cryostat

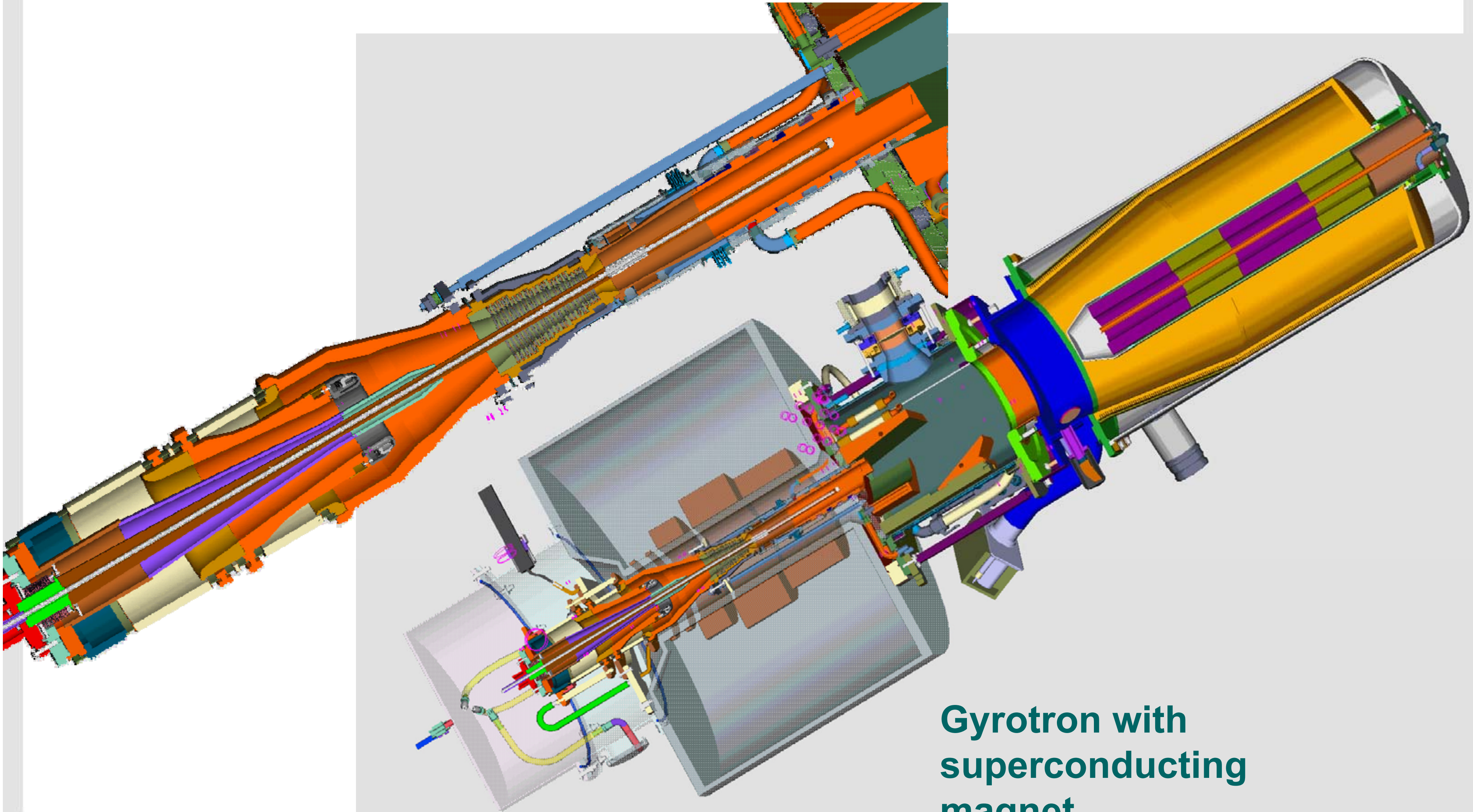
Upper Port Plugs
ECRH

Equatorial
Port Plugs:
Test Blanket
Modules,
Diagnostics

Torus Cryopumps
Tritium-Plant

Divertor
Test module

ECRH: 170 GHz 2 MW Gyrotron Development



Gyrotron with superconducting magnet

Development of a 2MW Coaxial Gyrotron for ITER

Karlsruhe Institute of Technology

- 1st gyrotron prototype:

- SC magnet delivered finally by manufacturer To CRPP (Nov 07)

- prototpype tube installed in the SC magnet, conditioning starting now

- beginning of gyrotron tests: Dec 2007

- experimental pre-prototype tube:

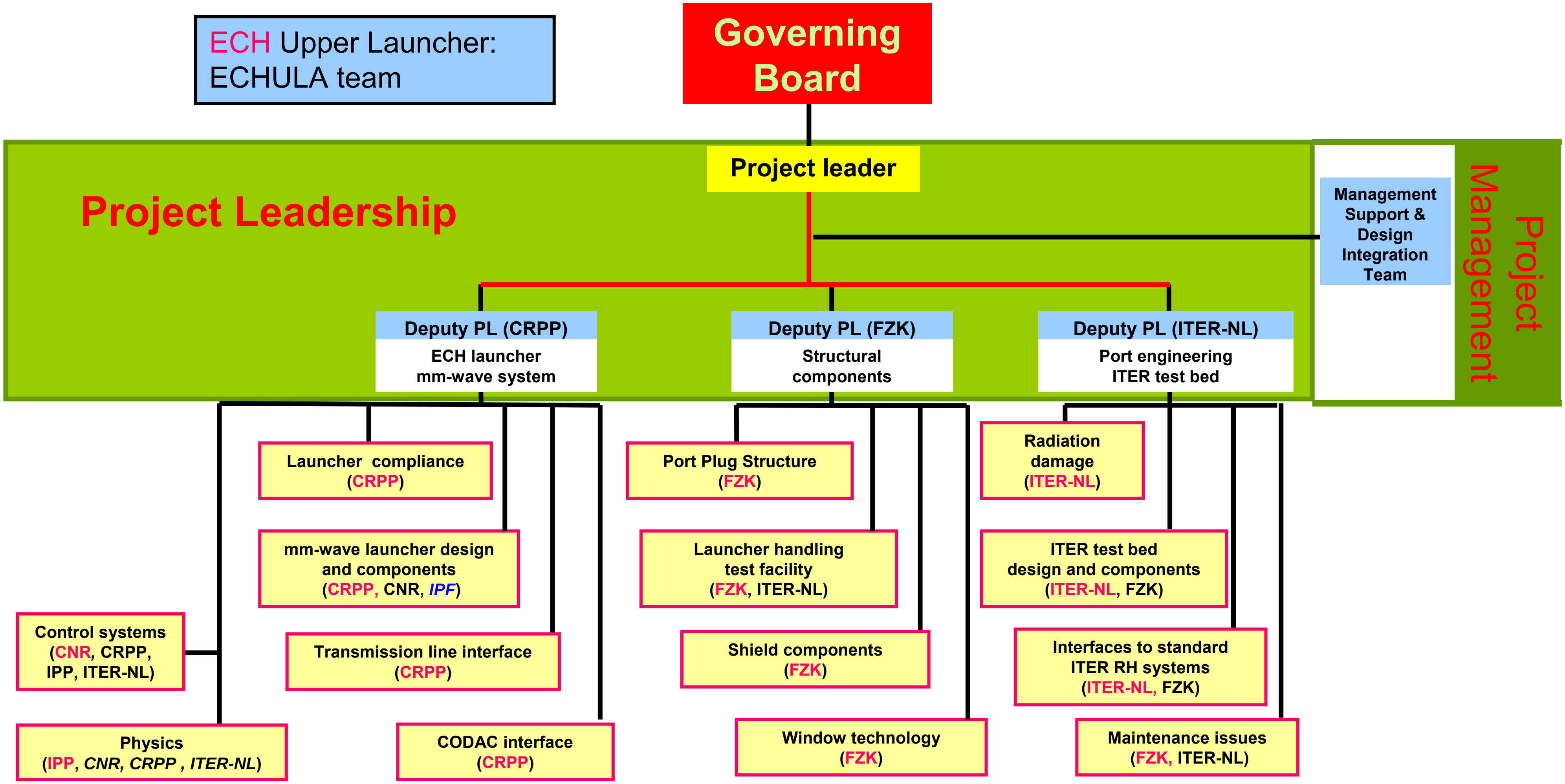
- testing of a RF output system with a new launcher done. A new code for an improved system is under development

- operation of the pre-prototype tube with a modified coaxial insert to reduce parasitic low frequency oscillations worked

- operation with a broad band RF output window (Brewster window)

First prototype gyrotron installed in the SC magnet - ready for operation

Organisation Chart of the ECHULA Consortium

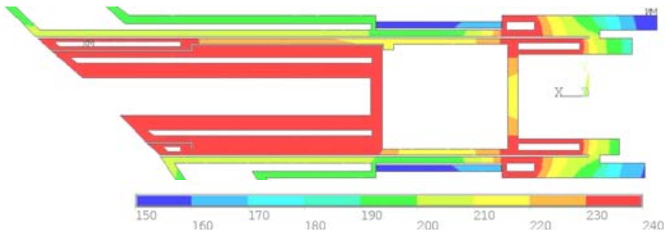


Legend: **Experts team** — Lead association of expert team given in RED

Partners having subcontracts to EURATOM associations given in ITALICS

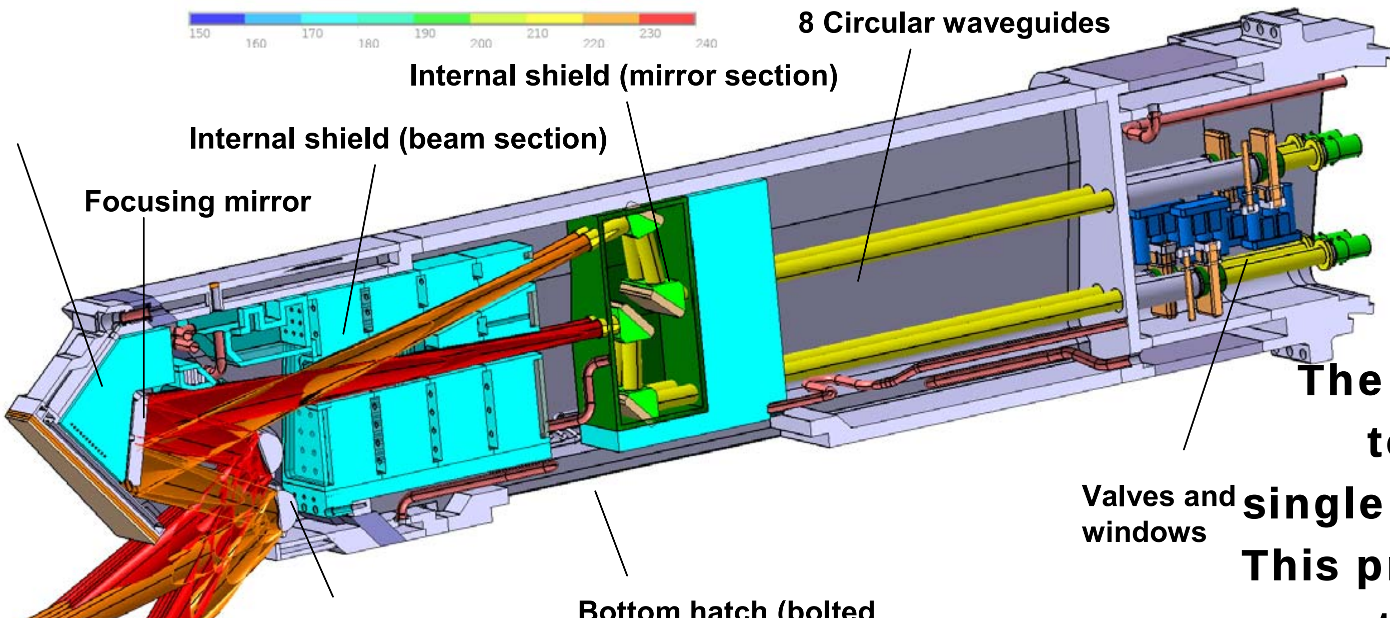
Development of the ITER ECRH Top Port Plugs (I)

- Structural integration of the mm-wave system of the front steering launcher into the ECH upper port structure



Modelling of baking temperatures

A detailed design was developed composed of detachable blanket shield module (BSM) of the main structure setting the frame.

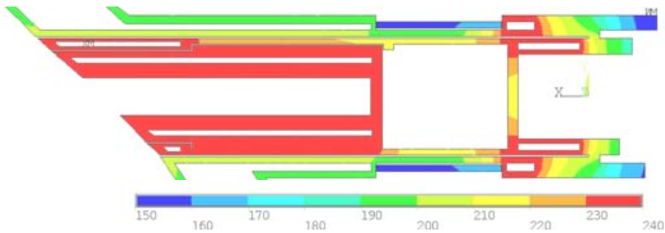


The main frame was modified to a slim wall concept with single and double wall sections. This provides access the central section of the internal shields and the mitre bends.

Development of the ITER ECRH Top Port Plugs (I)

Karlsruhe Institute of Technology

- Structural integration of the mm-wave system of the front steering launcher into the ECH upper port structure



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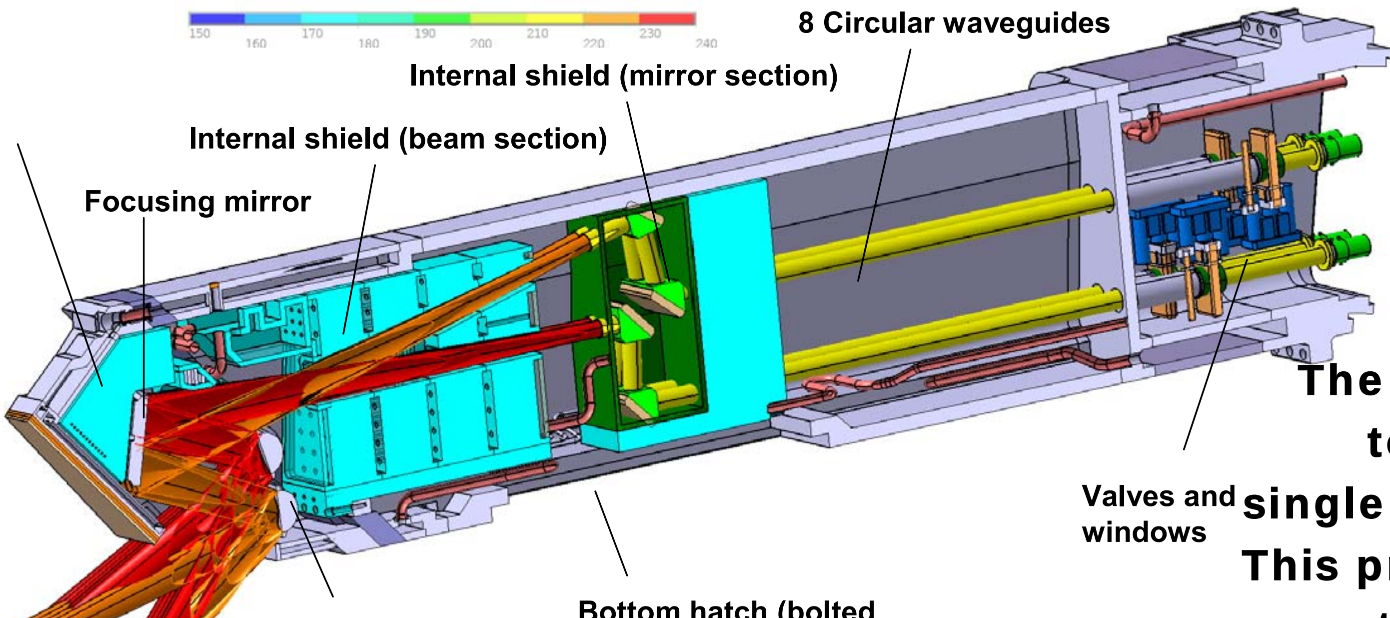


The main frame was modified to a slim wall concept with single and double wall sections. This provides access the central section of the internal shields and the mitre bends.

Development of the ITER ECRH Top Port Plugs (II)

- **Development of the torus window of the front steering launcher for common use at the equatorial and upper port**

A torus window design for the front steering launcher was fixed on the basis of the indirect cooling design with cooling separated from the CVD diamond disks.

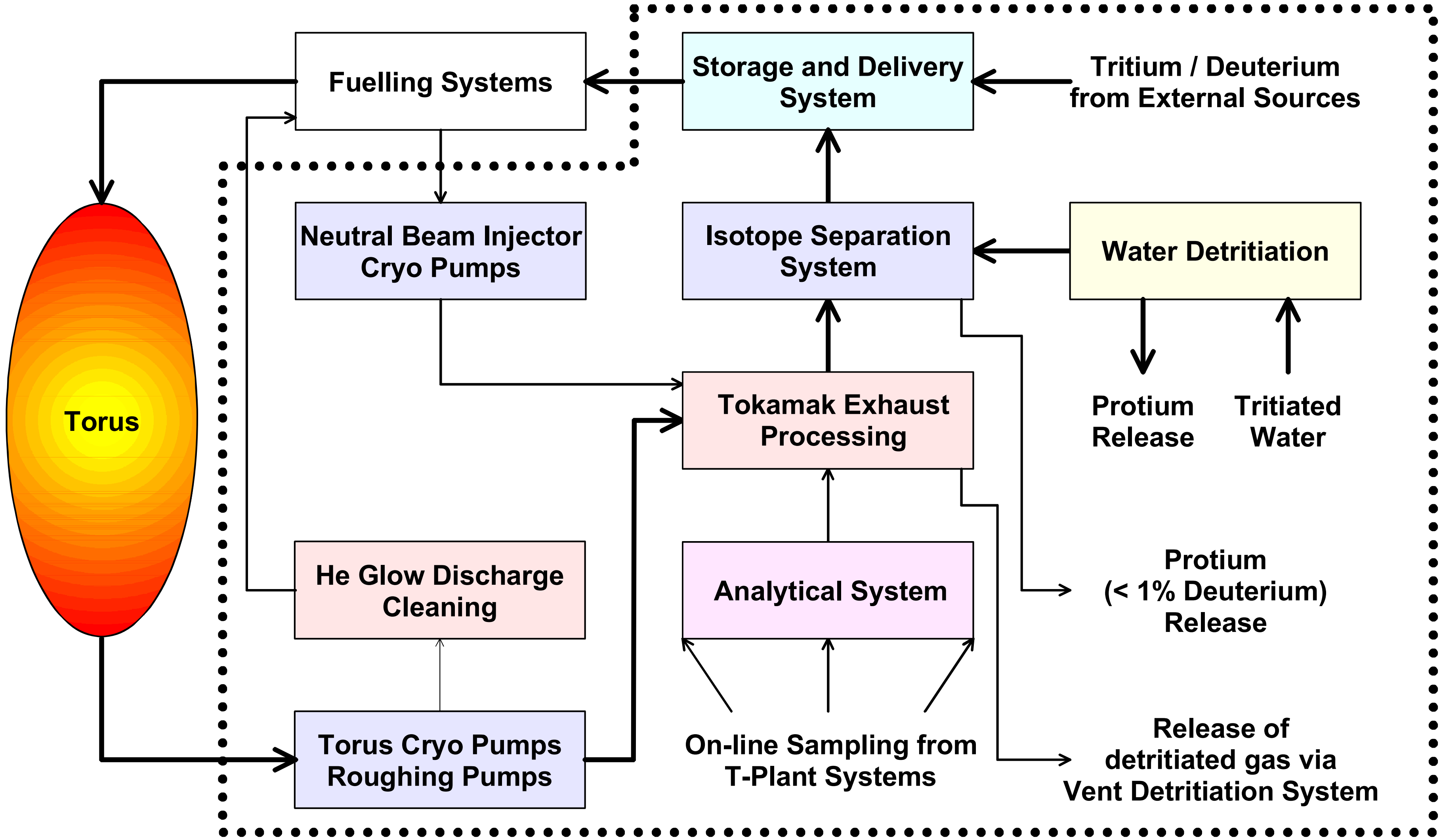
A prototype torus window was manufactured and is being prepared for joint high power experiments with the equatorial launcher design group.

- **Installation of the test platform for the launcher handling test facility and initialising tests on the thermo-hydraulic performance**

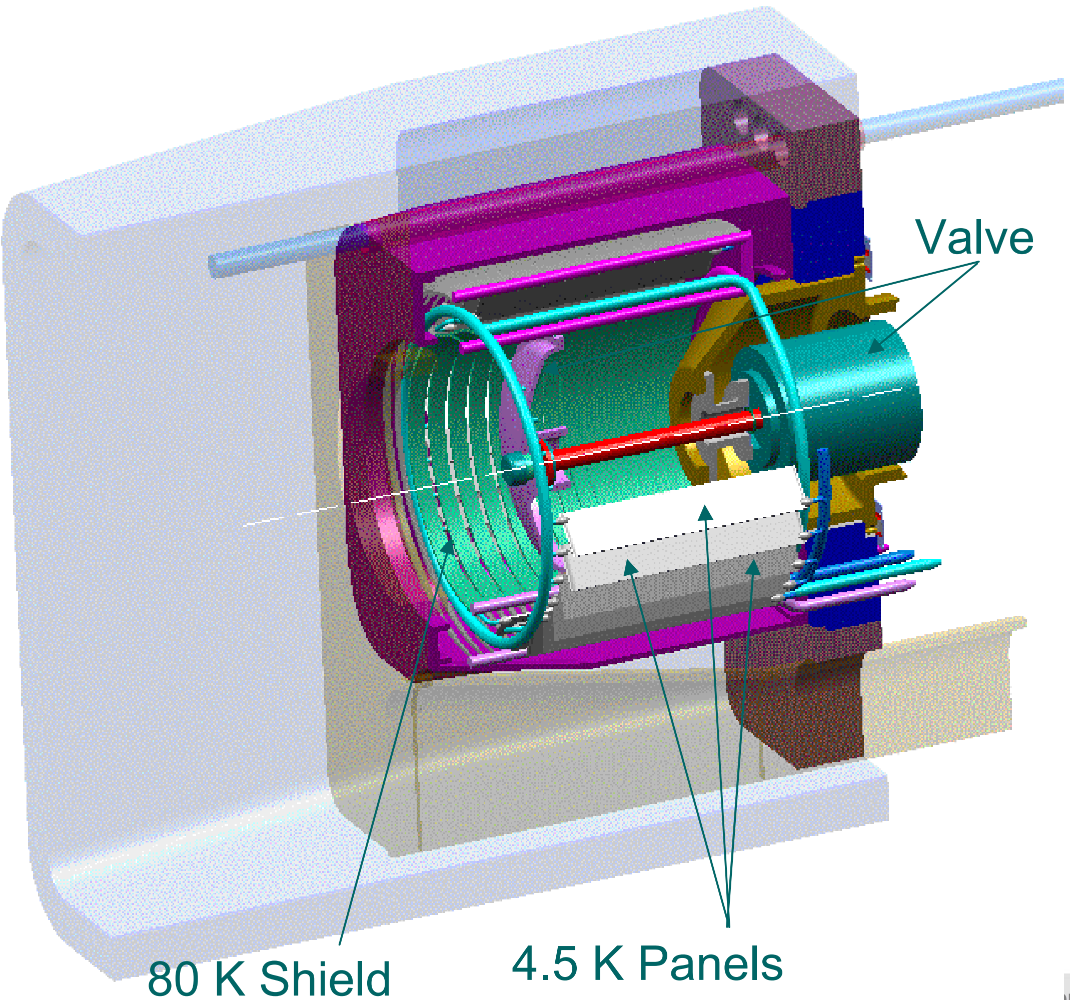
The water loop allowing thermohydraulic tests of the structural system under ITER conditions was installed and put into experimental operation. Alternative manufacturing routes for double wall structure have been studied with promising outcome and first prototypes for thermohydraulic testing are to be received from industrial manufacturing still this year.

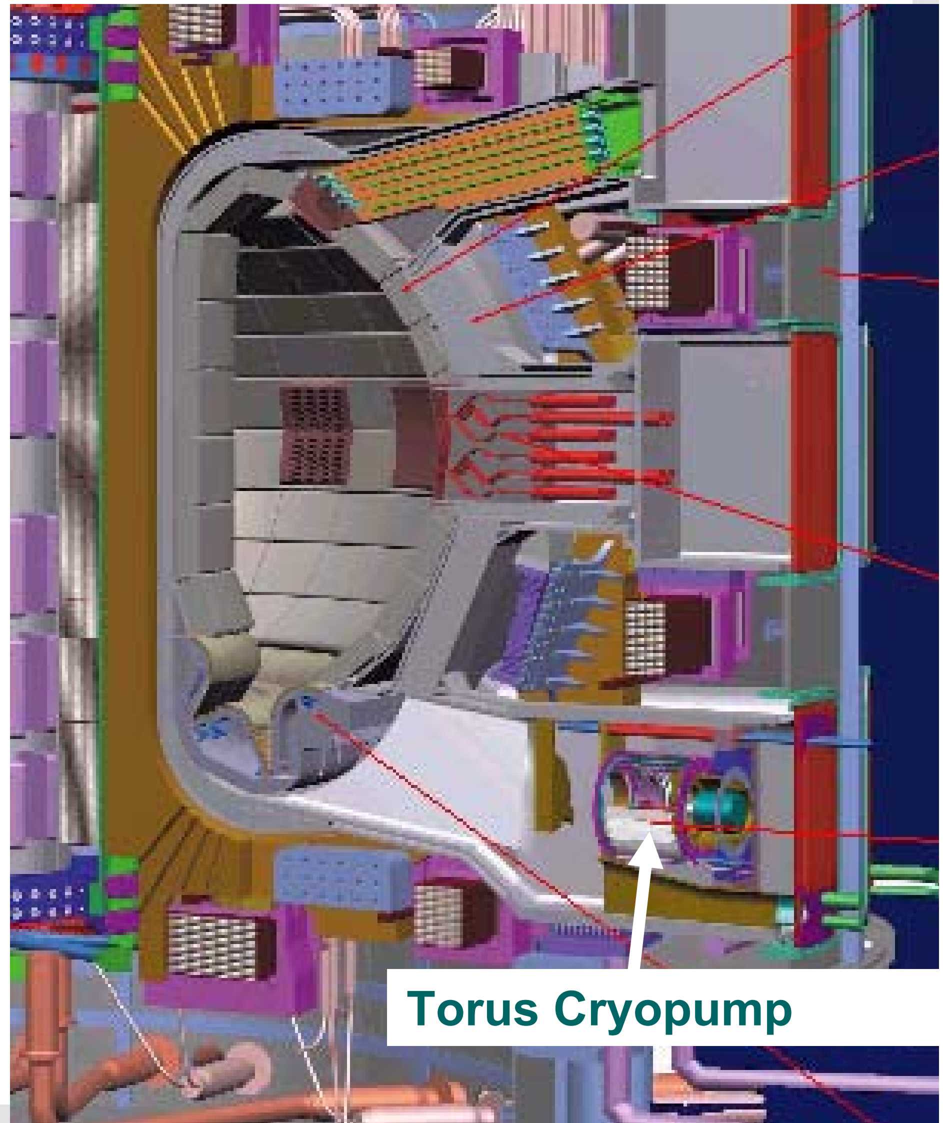
FZK proposes to design and procure the inner Fuel Cycle for ITER

(with exception of the fuelling system)

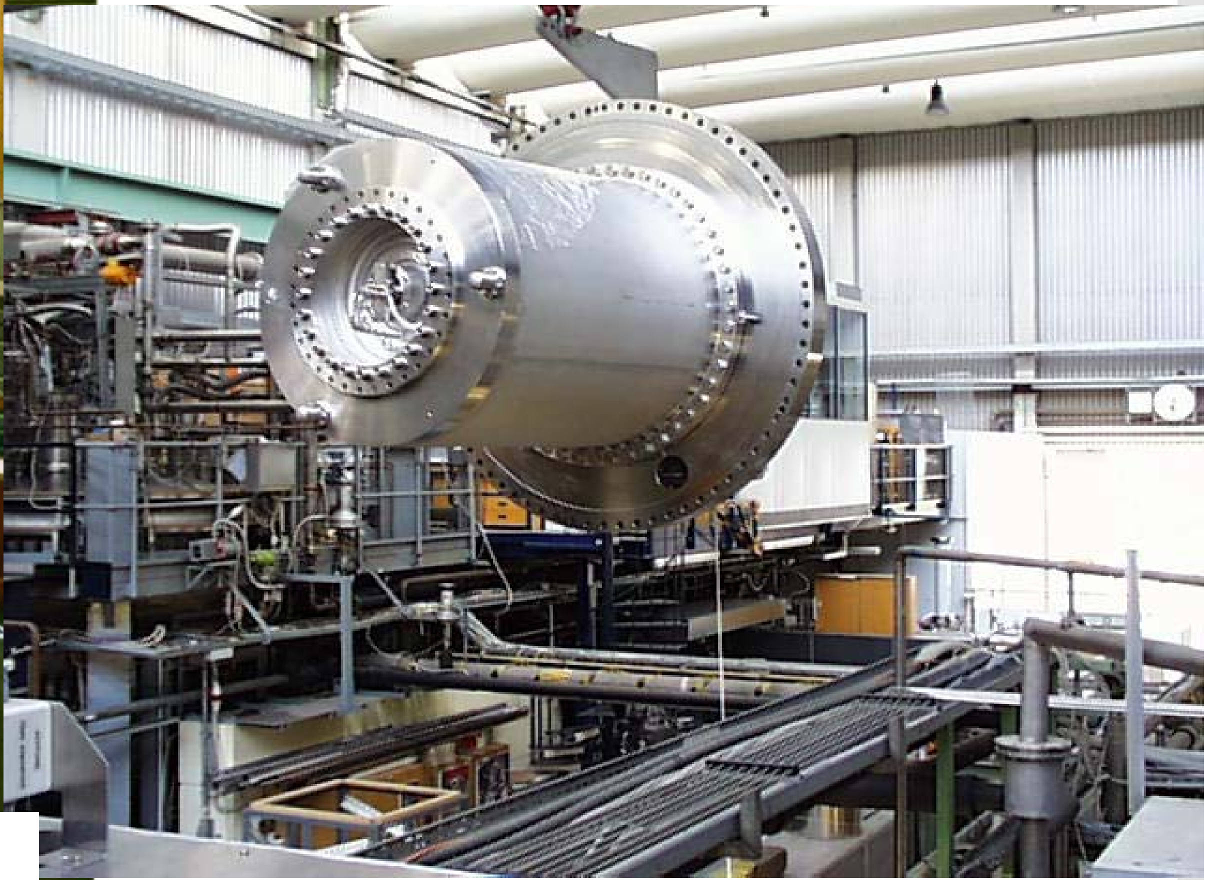


ITER Torus Cryopumps



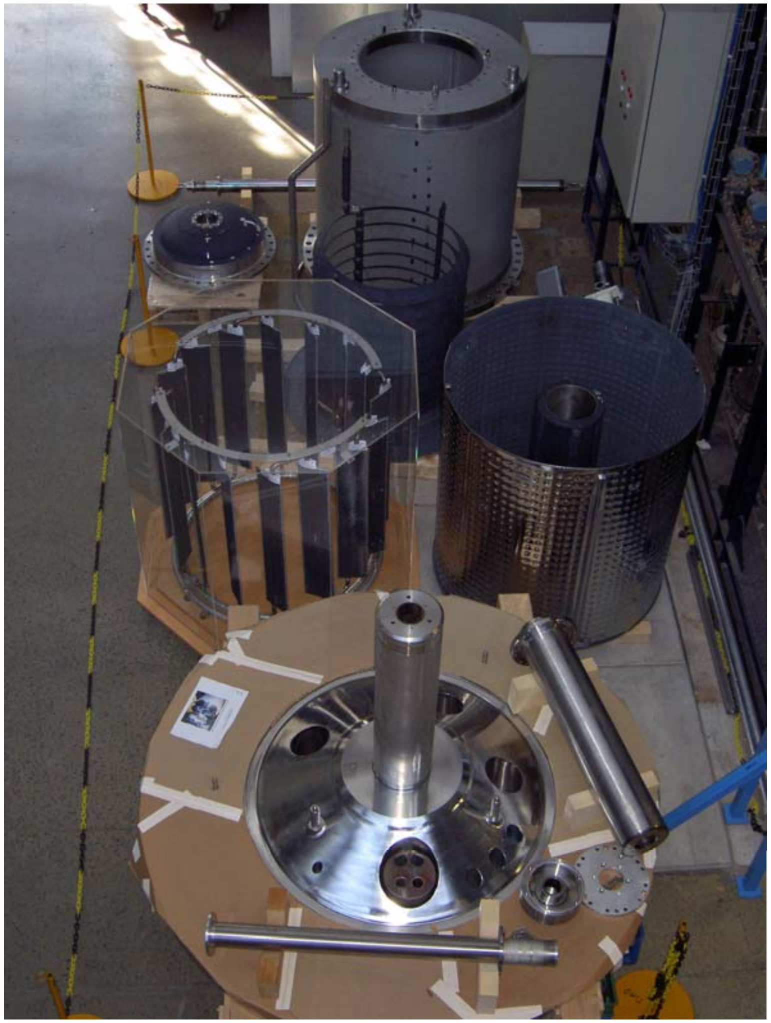


ITER Torus Cryopump Prototype tested in FZK



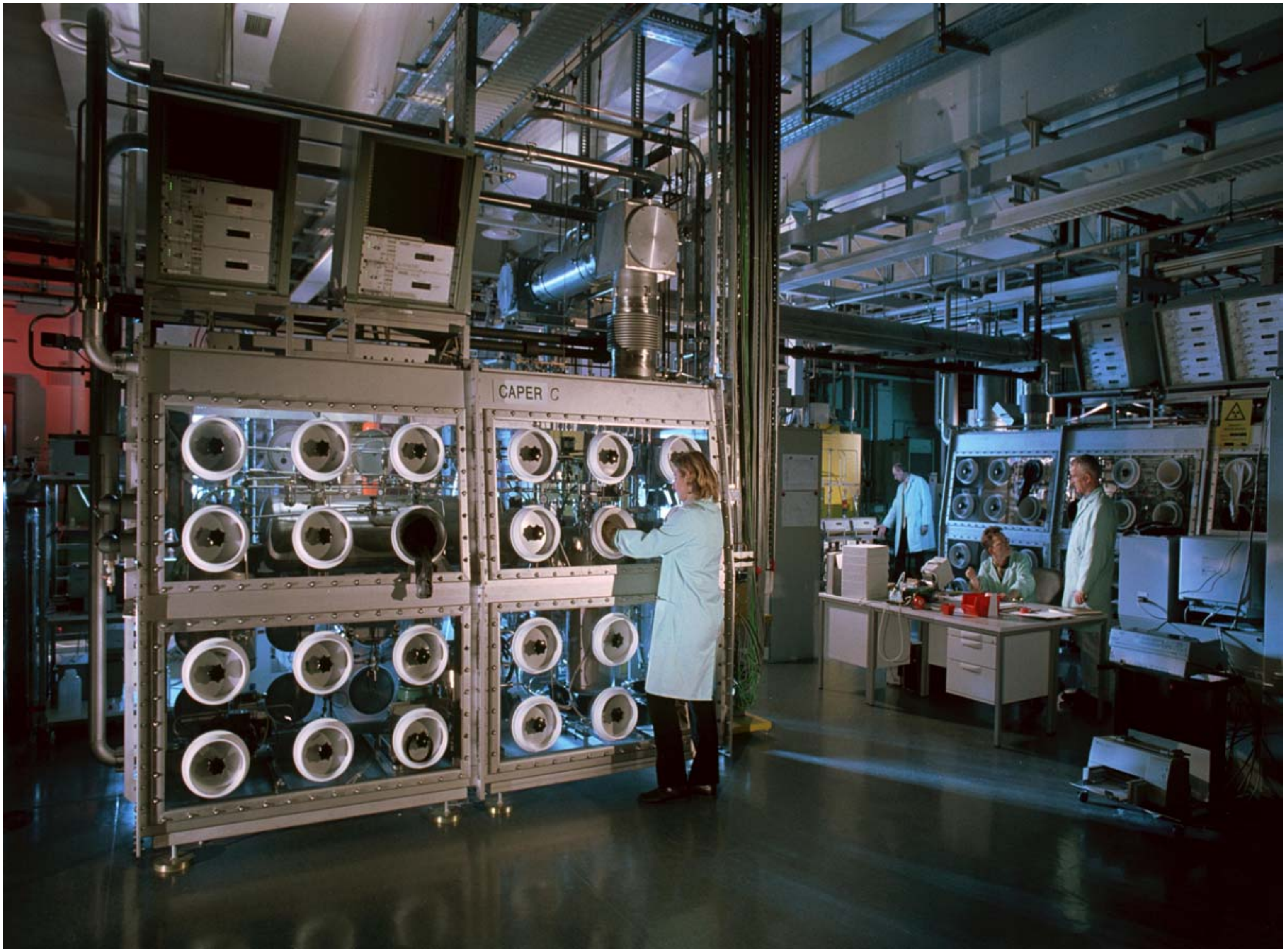
Vacuum Pumping

- **Design activities: cryopumps for the Neutral Beam Test Facility (re-design after change from circular to rectangular beam line vessel) and the ITER cryostat**
- **Contract supervision of the manufacturing of the ITER prototype torus cryopump**
- **R&D activities: post mortem evaluation of the model pump, modelling and validation of ITER vacuum flows by ITERVAC code development and validation experiments in the TRANSFLOW facility; preparation of the TIMO-2 facility for testing the prototype ITER torus cryopump.**



Model cryopump dismantled

Tritium Labor im FZK



Tritium Technology

- New license to operate TLK was assigned by the Local Government. 5 g tritium was bought from Canada and shipped to TLK
- The modelling of the entire fuel cycle was continued. Studies on tritium accountancy and tracking were conducted to develop a strategy for minimizing the uncertainties in tritium accountancy
- Detailed analyses of the ITER ISS-WDS process design reviewed with the possibility of processing highly tritiated water in WDS
- The TRENTA facility which consists of a water detritiation system in combination with a cryogenic distillation system now in operation

cryogenic distillation column with 2.7 m active length and 55 mm diameter.

ITER Safety: Effective Burning Rates of Graphite Dust – H – Air Mixtures

Measurement using small and medium sized open-end combustion tubes

Tested mixtures:	**4-micron graphite dust/ hydrogen/air**
Concentrations:	**$[H_2]$=9÷17 vol. %;** **C_{dust} =100÷600 g/m^3**
Geometry:	**Open-end combustion tube** **15 cm inner diameter, 3 m length** **(PROFLAM I facility)**

Results:

- **Addition of graphite dust generally lowers the efficient flame velocity in H_2/air mixtures.**
- **However, for each hydrogen concentration there is a dust concentration at which the flame velocity is higher than that in the pure H_2/air mixture.**
- **The obtained data will be used to validate 3D CFD code modeling explosion scenarios of severe accidents in ITER.**

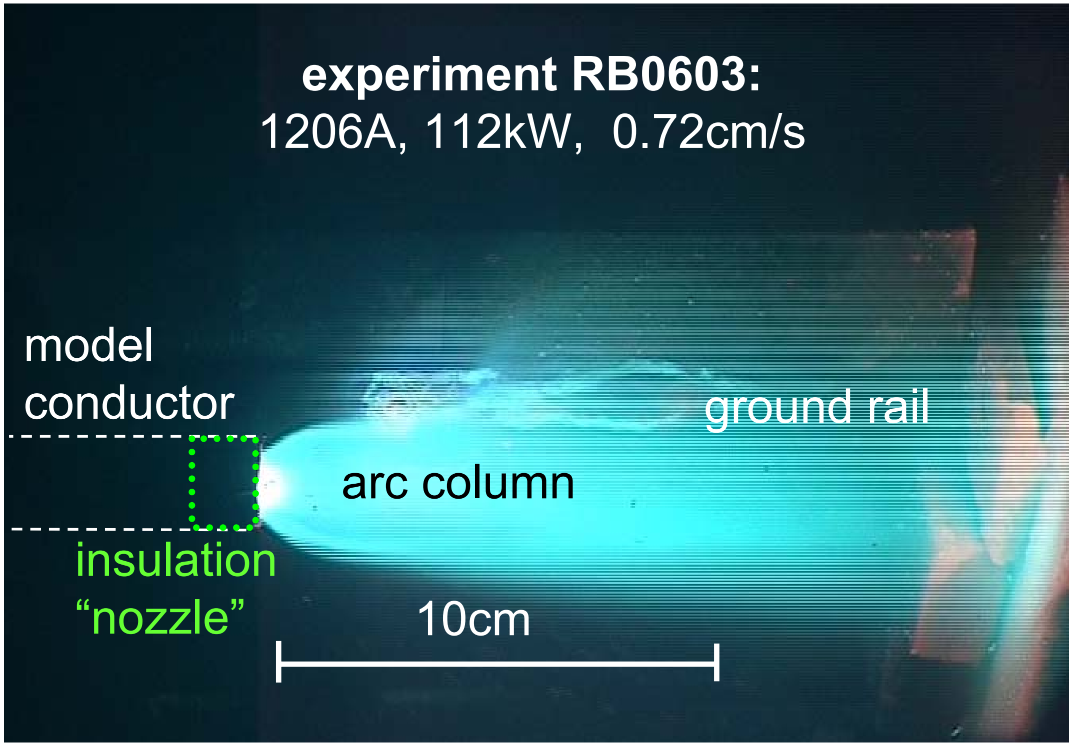
Magnet safety: Model experiments and numerical simulations of high current arcs at the ITER busbars

Karlsruhe Institute of Technology

Example:

"Backward" arc in ***VACARC***:
A ring of the quite robust glass-epoxy insulation acts like a nozzle that shapes the arc column into a rocket-like jet. This effect enhances the arc length, the arc power and its propagation velocity.

This finding must be further investigated and included in the model. The analyses in ITER DDD's usually base on short arc lengths.



Documentation of MAGS with regard to ITER licensing procedure:

- Discussion with EFDA on QA requirements in progress.
- Documentation for INTRA code made available by EFDA as guideline or template.

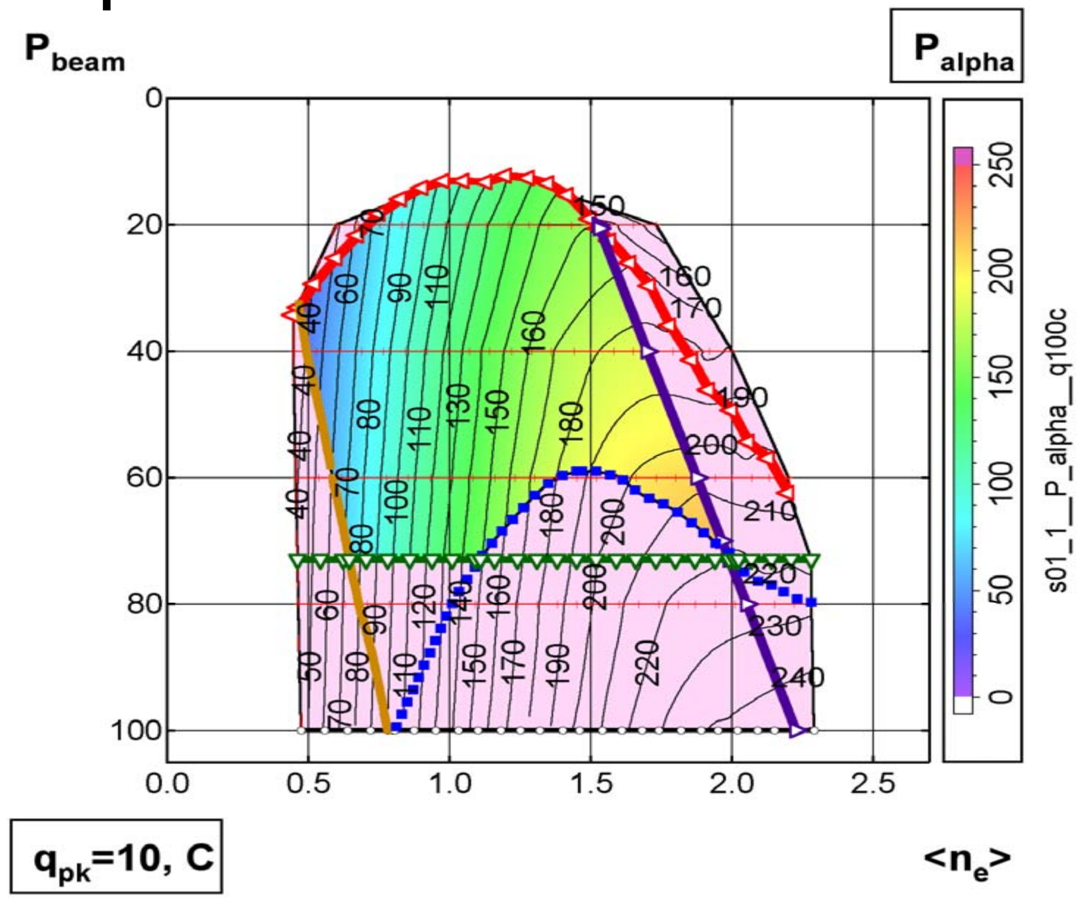
Development of an Integrated Plasma Model

- One-dimensional modelling of the plasma core:

- further validation activities postponed

- initial neon scaling implemented

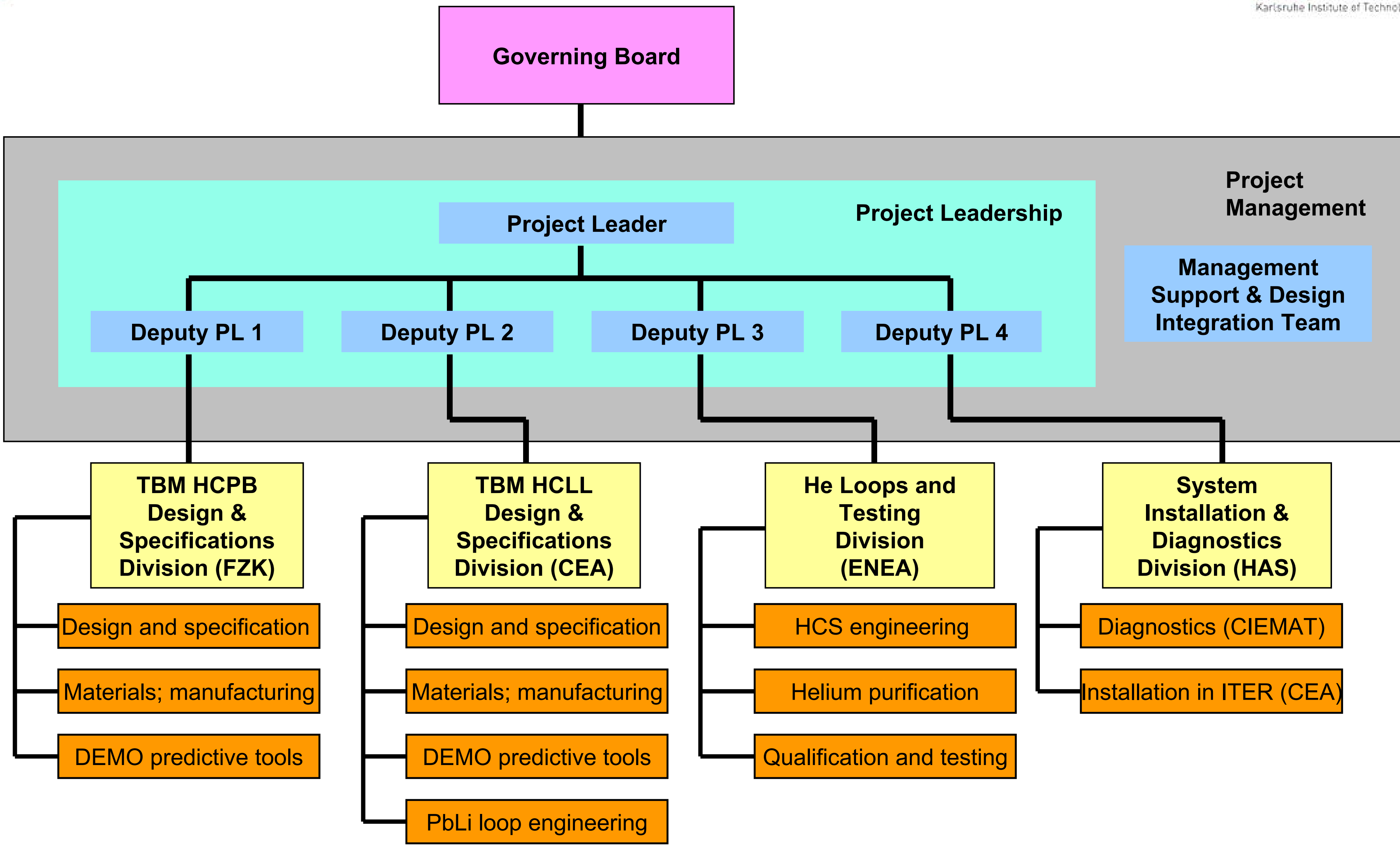
- Major ongoing activity: Development of ITER operating window
  - accomplished: influence of B and k
  - ongoing: influence of peak power at divertor plate, reduced tranport, seeded impurities, helium scaling, and pumping speed



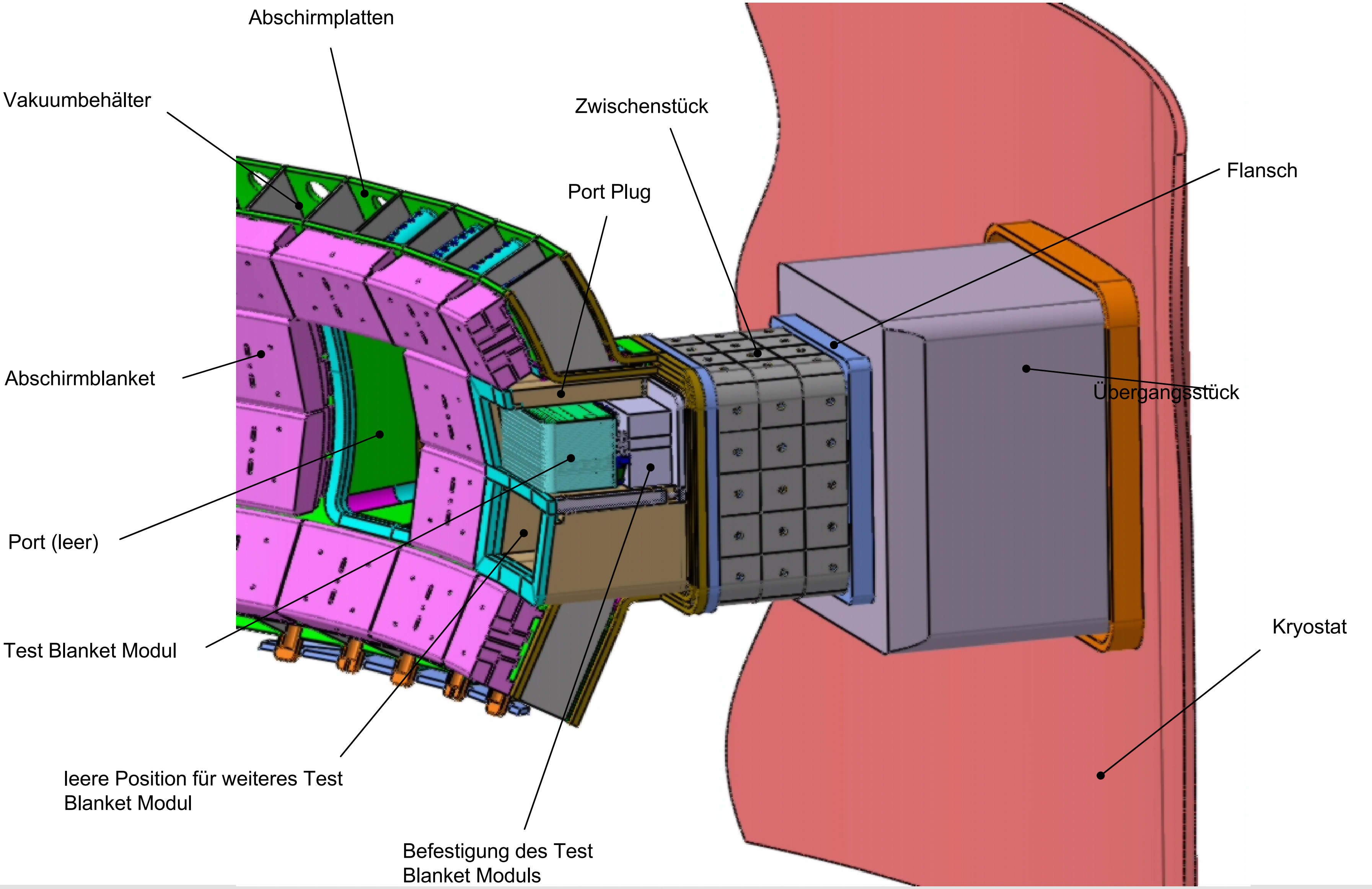
Operational and objective limits: Power, Q=5, LH transition, low temperature limit on alpha power, auxiliary power, edge density limit

Organisation Chart of the TBM Consortium

KIT
Karlsruhe Institute of Technology

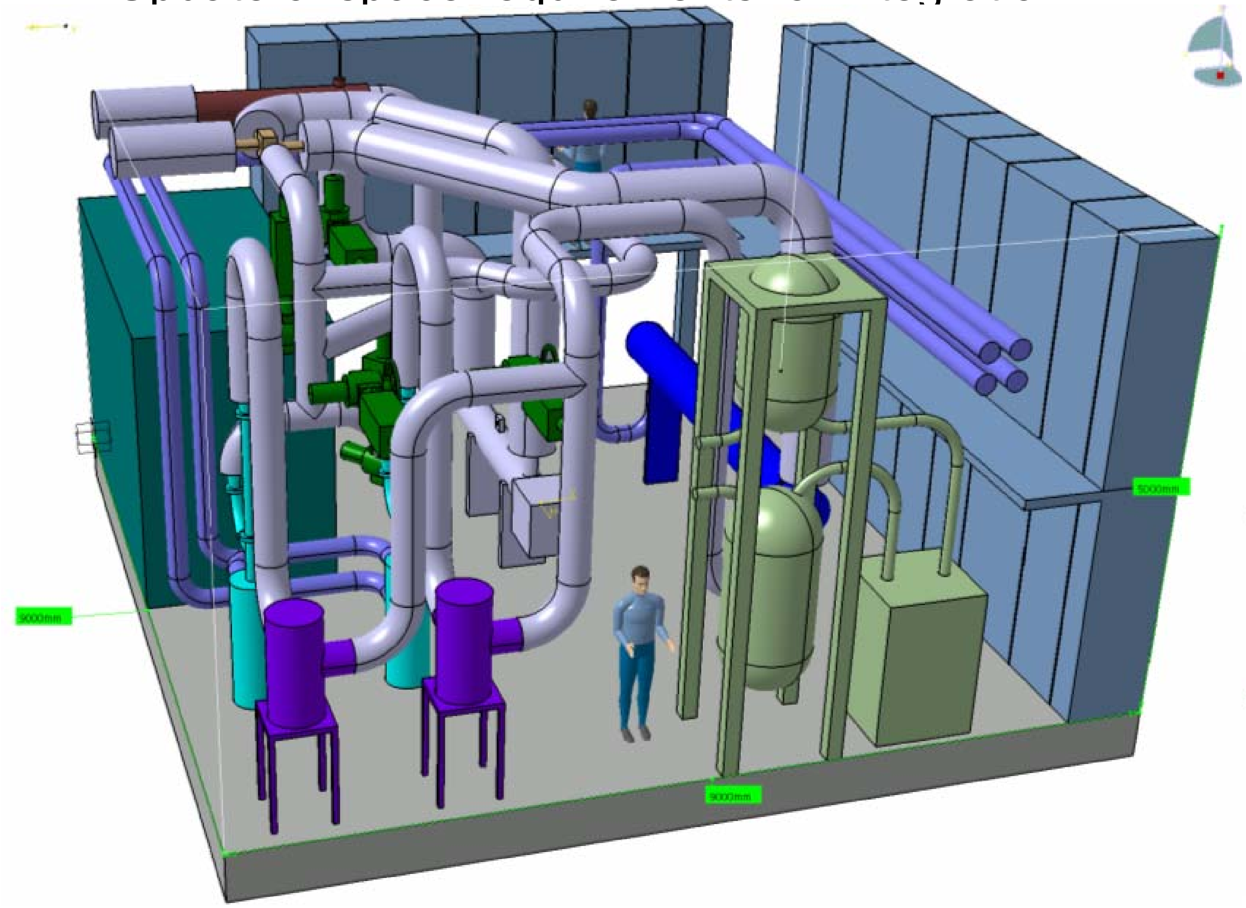


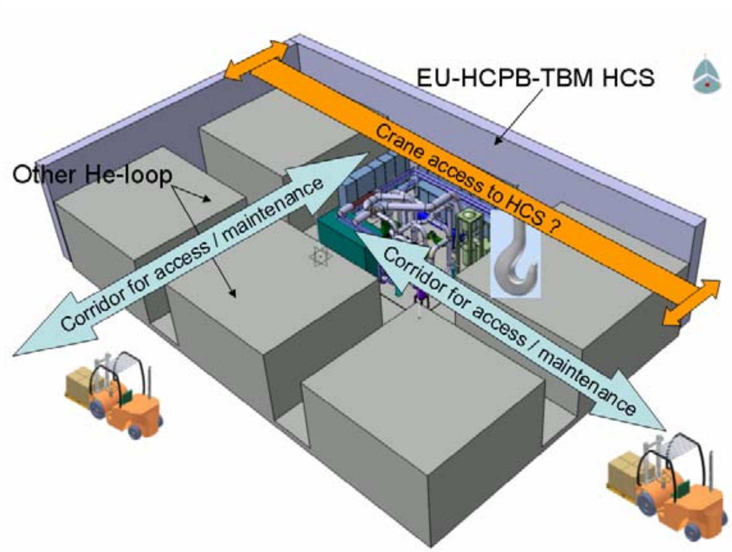
Demo Blanket Test Modules in ITER



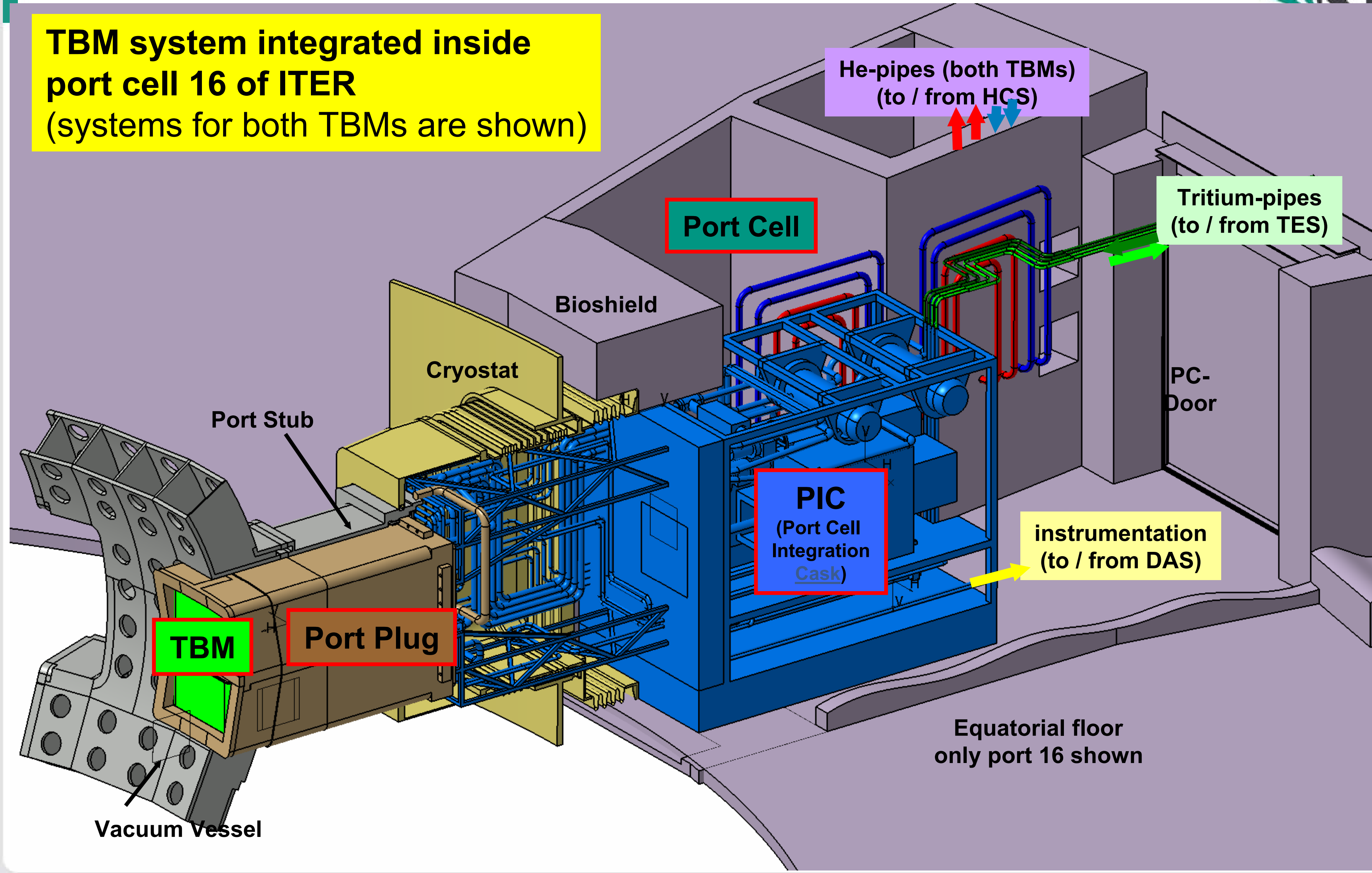
EU HCPB-TBM integration in ITER

- Detailed design of TBM HCS in TCWS-vault of ITER
- Development of maintenance strategies
- Update of space requirements for integration in ITER

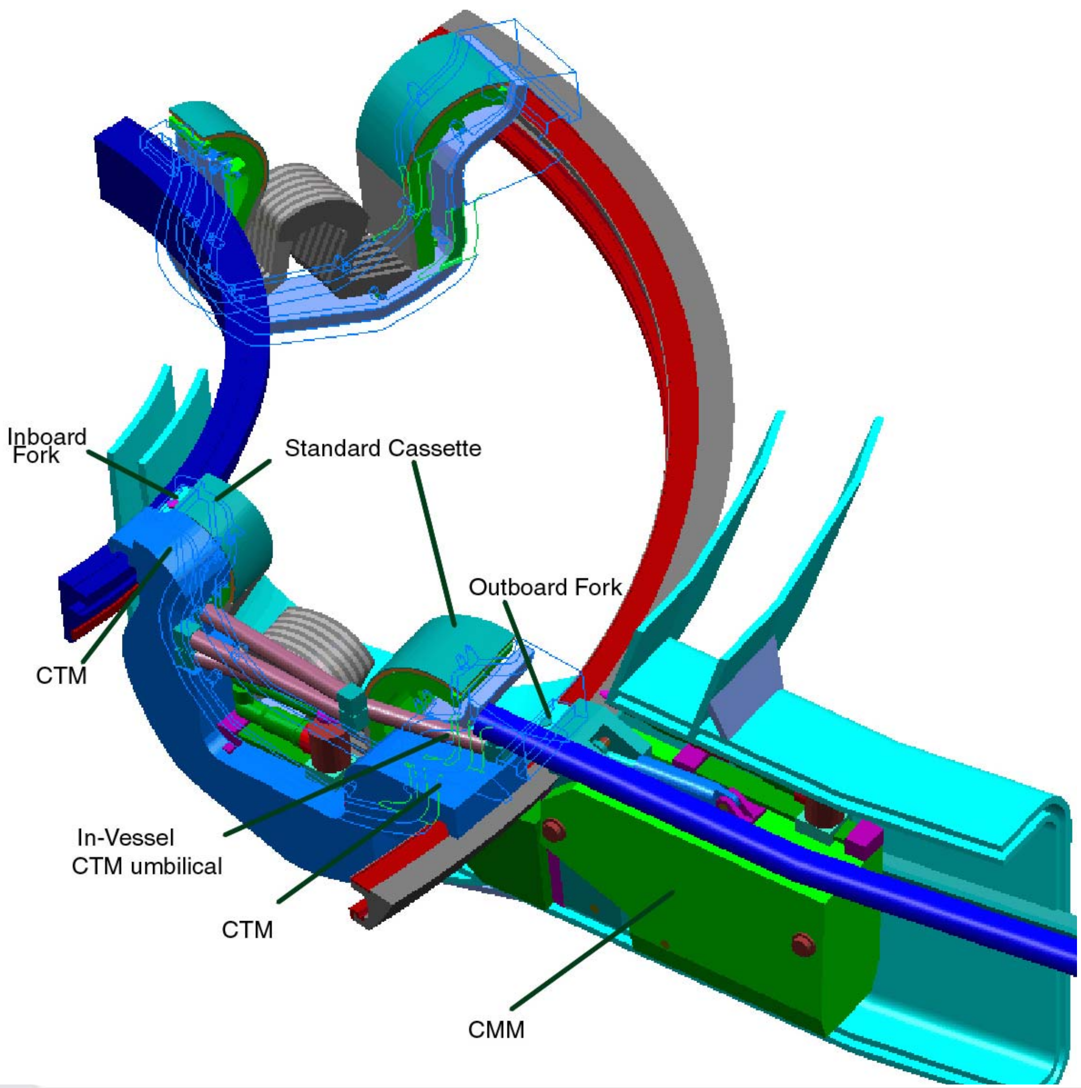


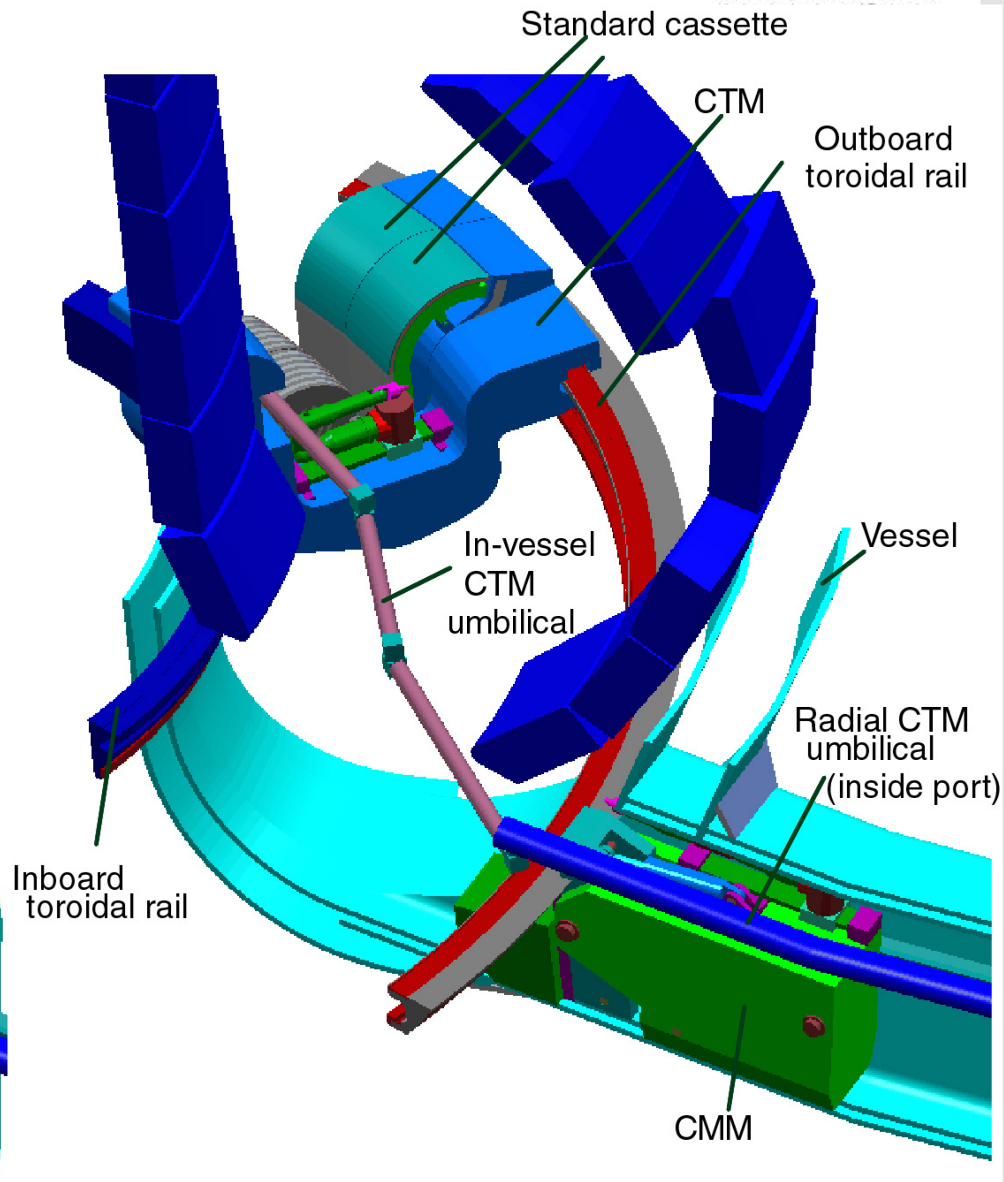


TBM system integrated inside port cell 16 of ITER
(systems for both TBMs are shown)

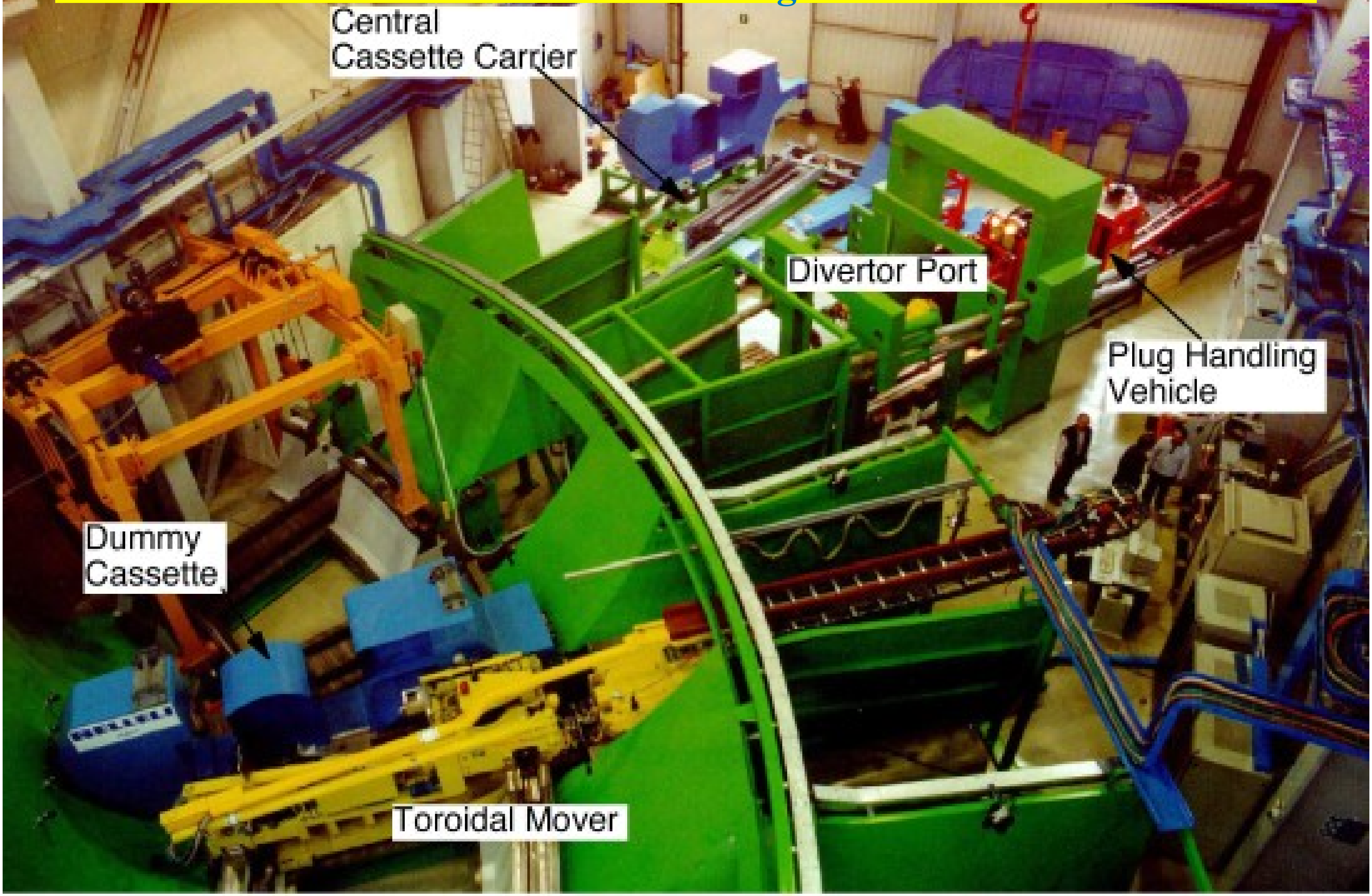


Remote Maintenance of the Divertor - cassette toroidal and radial mover

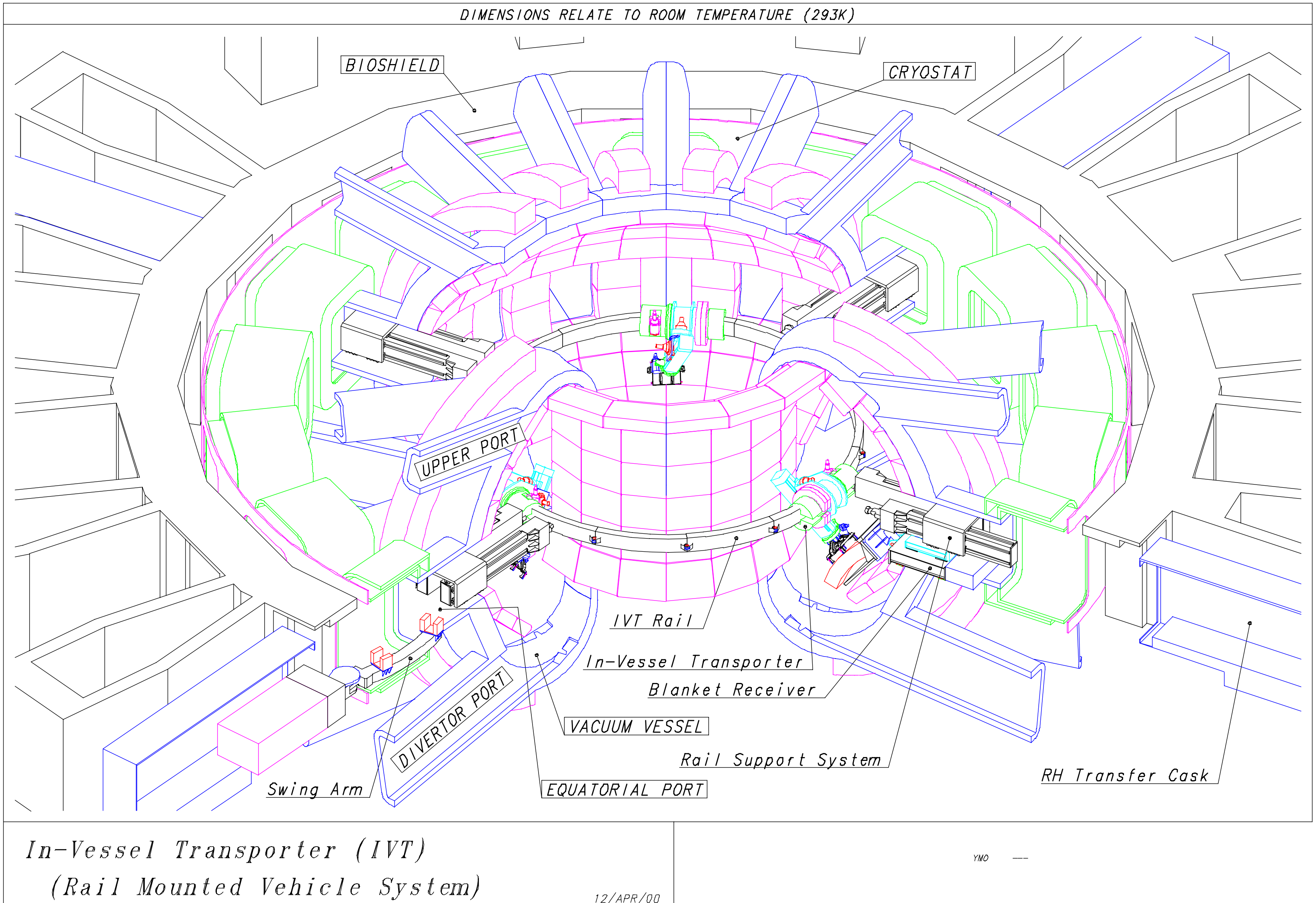




Divertor Remote Handling Test Platform

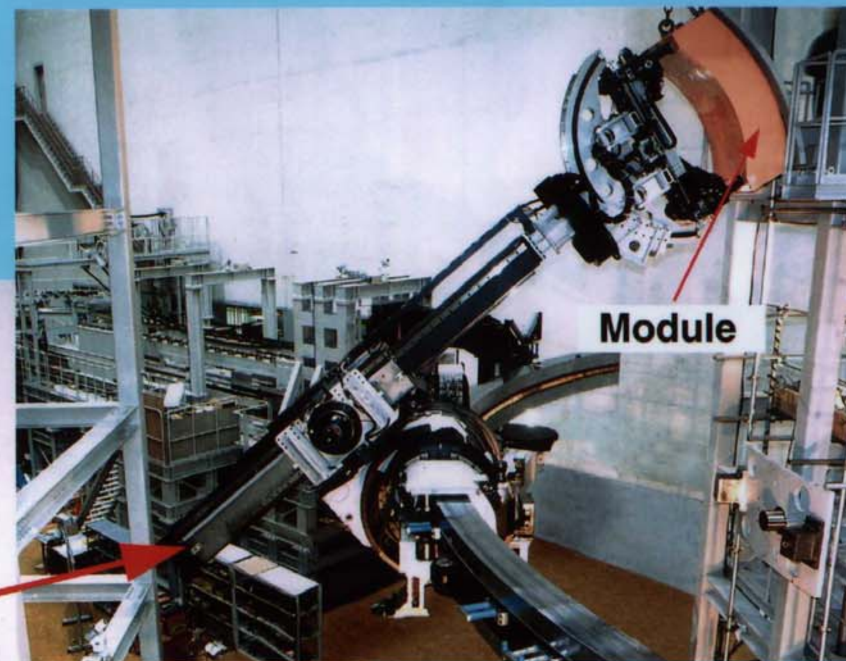


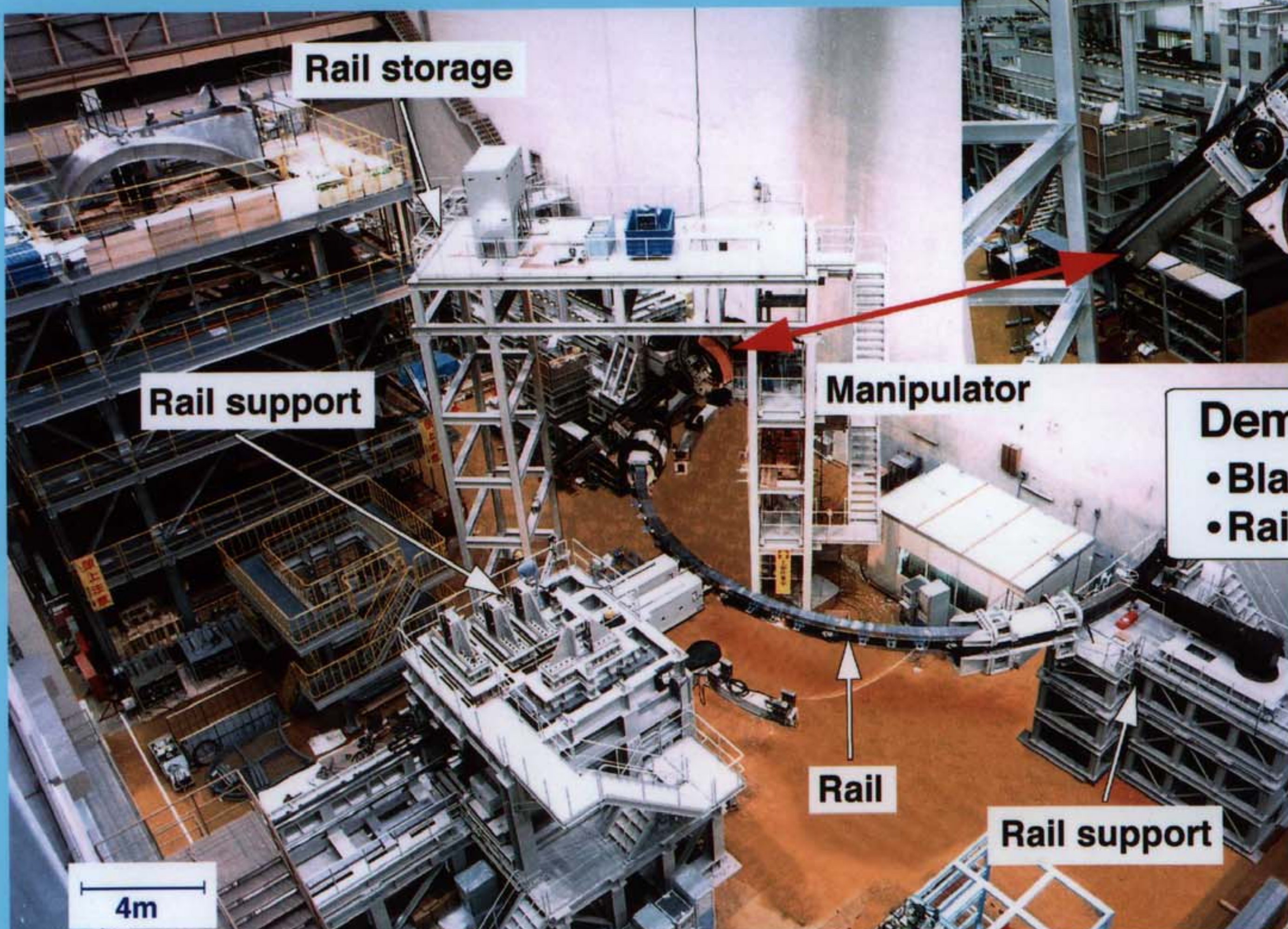
In Vessel Transporter for Blanket Maintenance



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..