KIT
Karlsruhe Institute of Technology

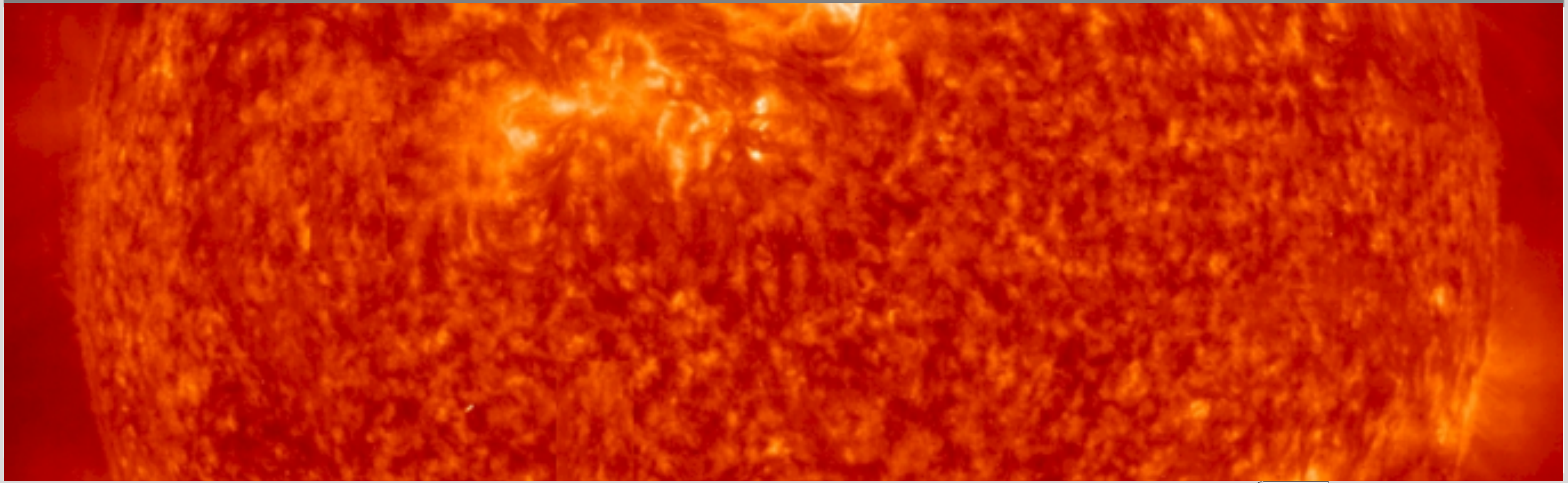
IAM
Institut für Angewandte Materialien

EUROfusion

STEELS FOR NUCLEAR FUSION REACTORS

Michael Rieth

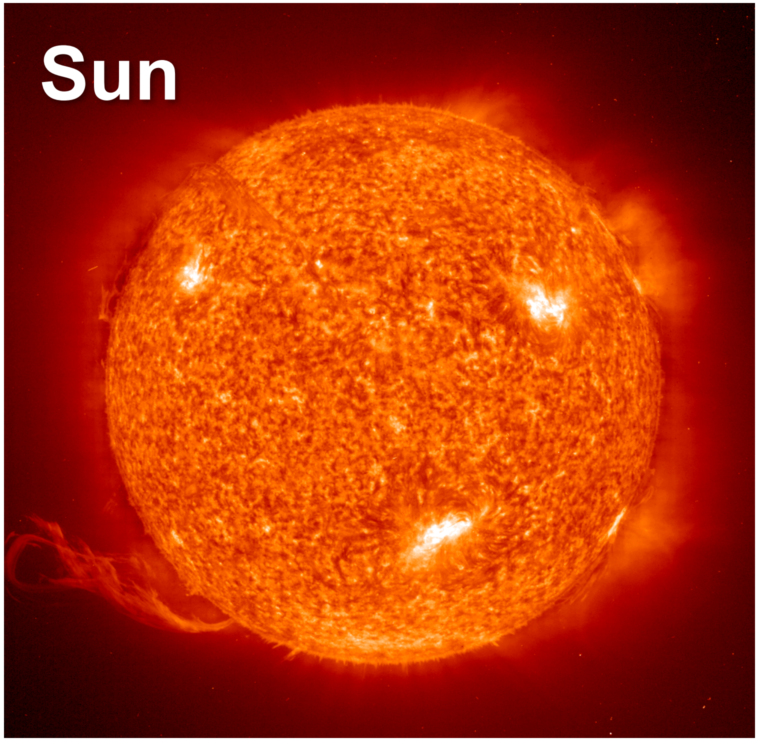
INSTITUTE FOR APPLIED MATERIALS – APPLIED MATERIALS PHYSICS

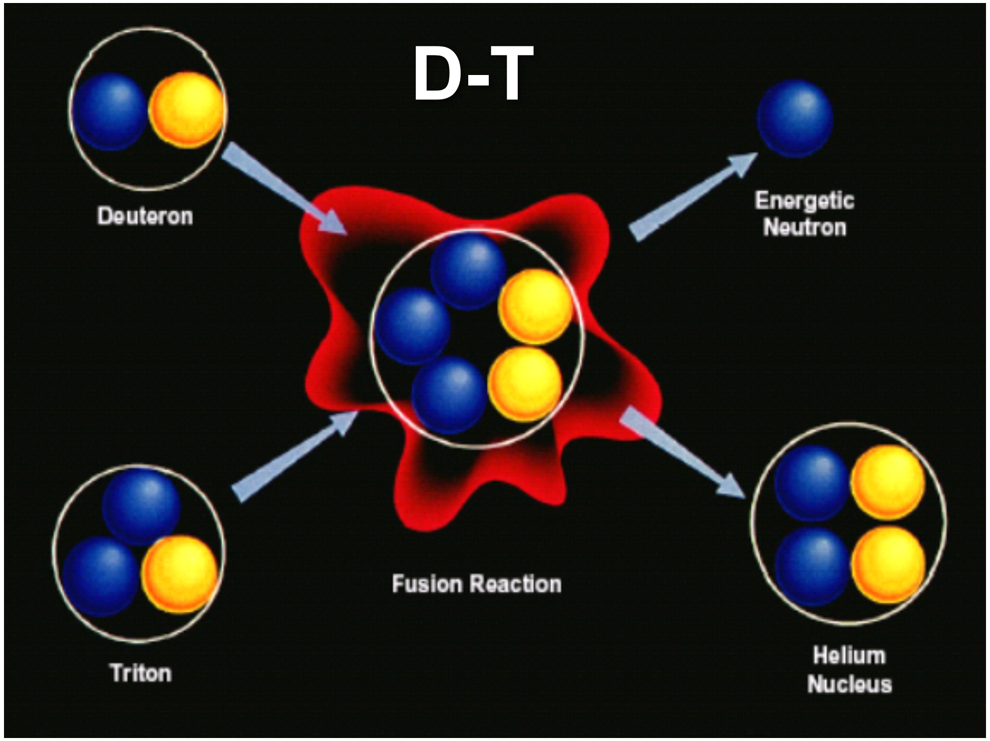


Contents

- Fusion Energy Generation
- Fusion Reactor Components
- Steel Demands for a DEMOnstration Reactor
- Steel Challenges for In-Vessel Components
- EURO*fusion* Steel Development Project

Nuclear Fusion





Gravity confined

T = 15 Mio. °C

$E_t = 3.7 \times 10^{17}$ GW

→ $\rho_E = 30$ W / m³

Magnetic confinement

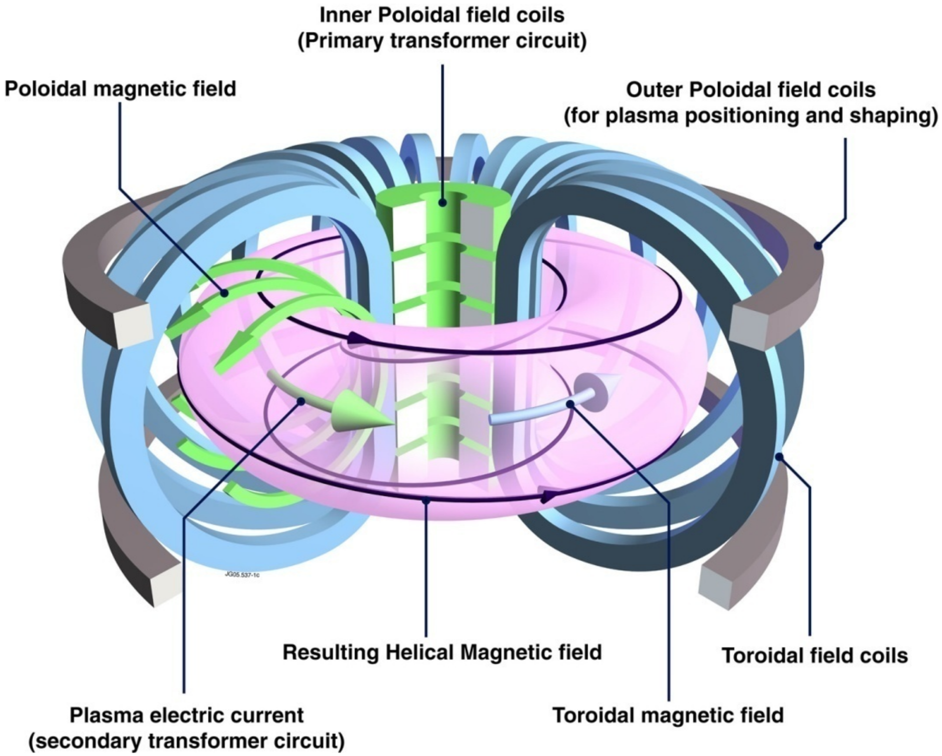
$E_t \sim 3.5$ GW

$\rho_E \sim 4$ MW / m³

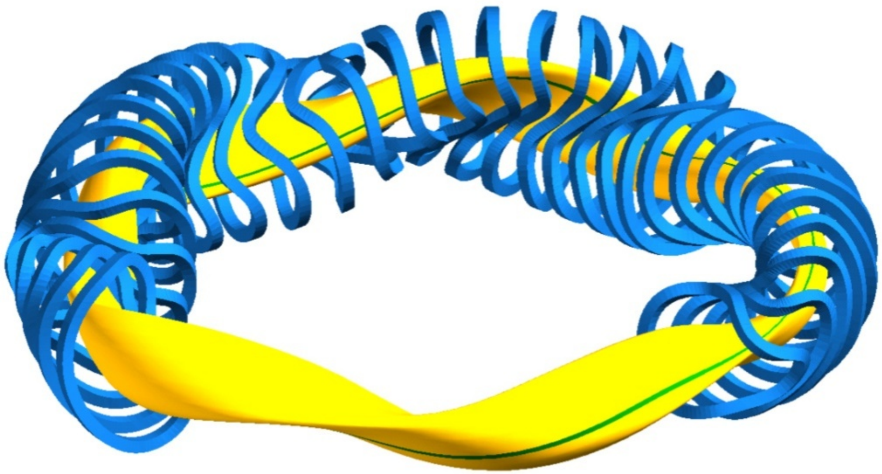
→T = 100 Mio. °C

Magnetic Confinement

Tokamak



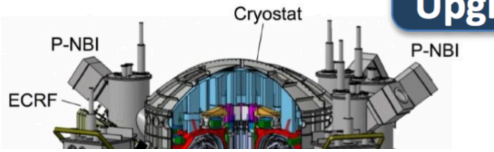
Stellarator



Tokamak Plasma Discharge

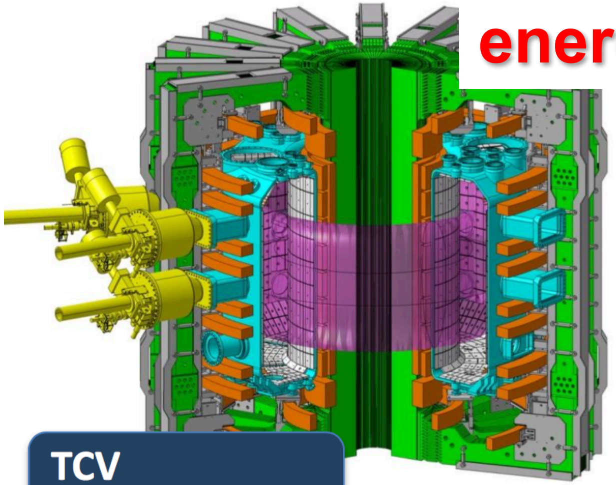
Existing Plasma Facilities

JET

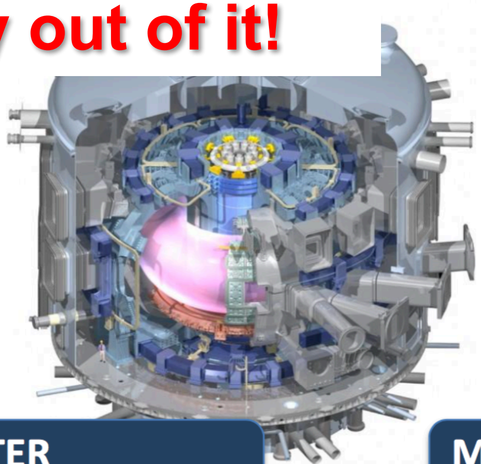


ASDEX Upgrade

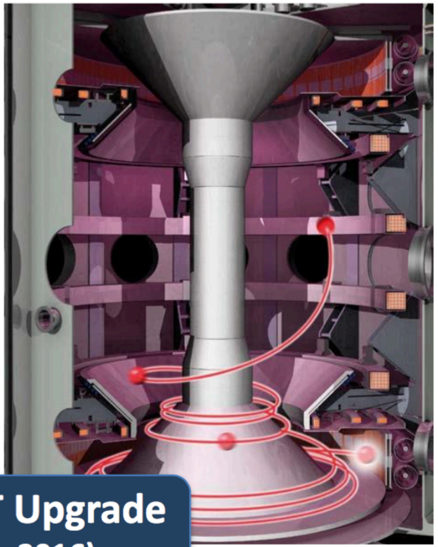
Nuclear fusion is relatively easy to accomplish. The trick is to gain energy out of it!



TCV
(Restart in 2015)

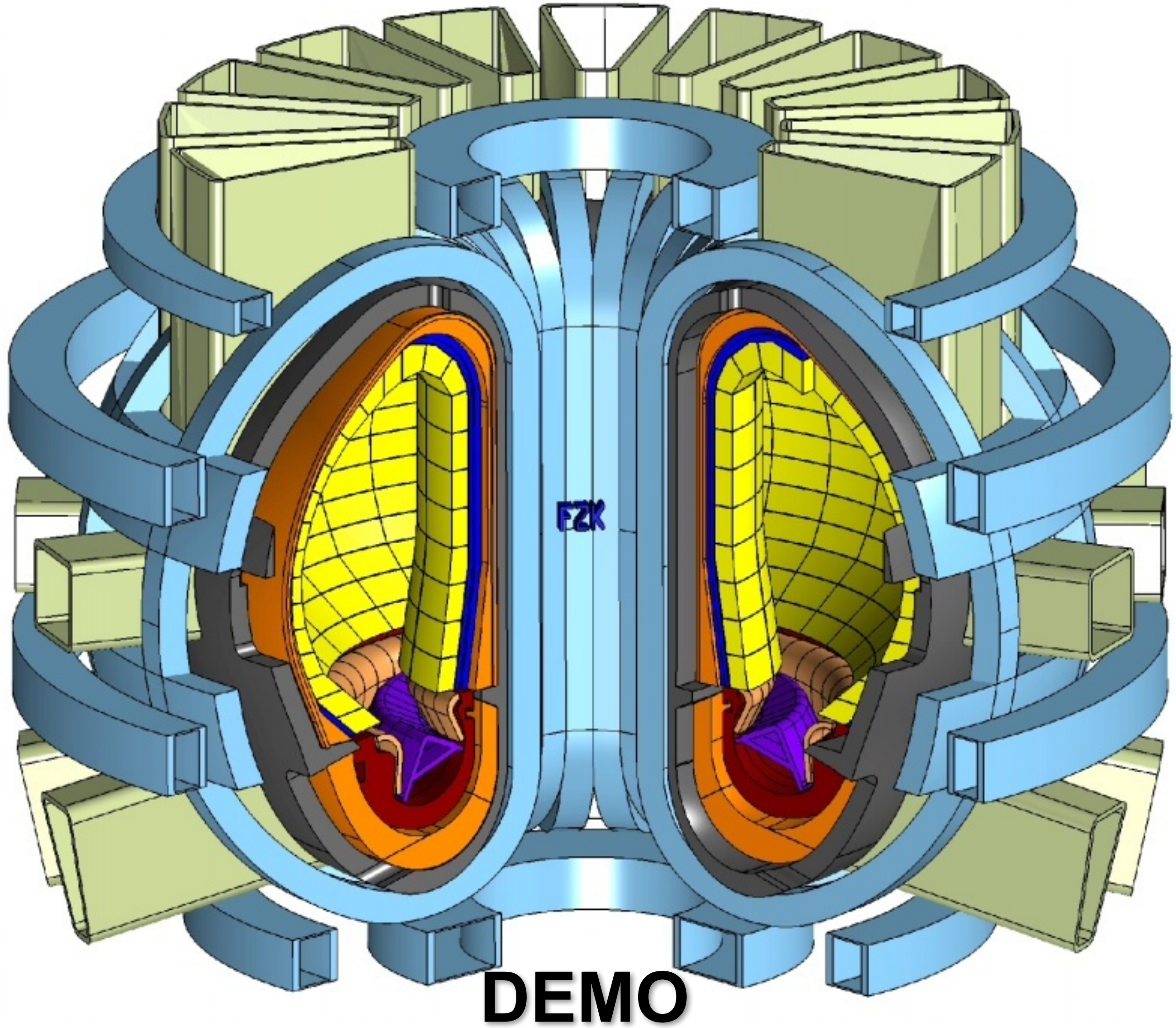


ITER
(Our target device)



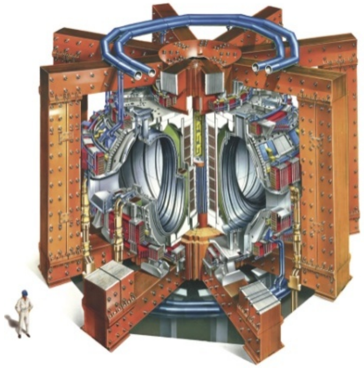
MAST Upgrade
(Start in 2016)

Roadmap to Fusion Power

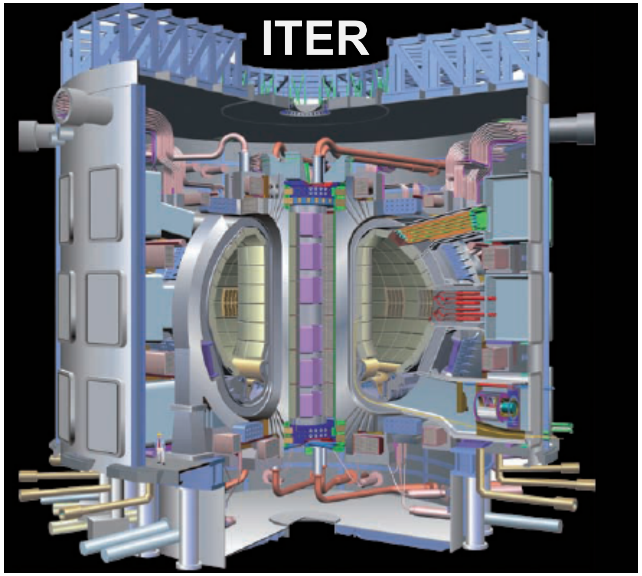


DEMO

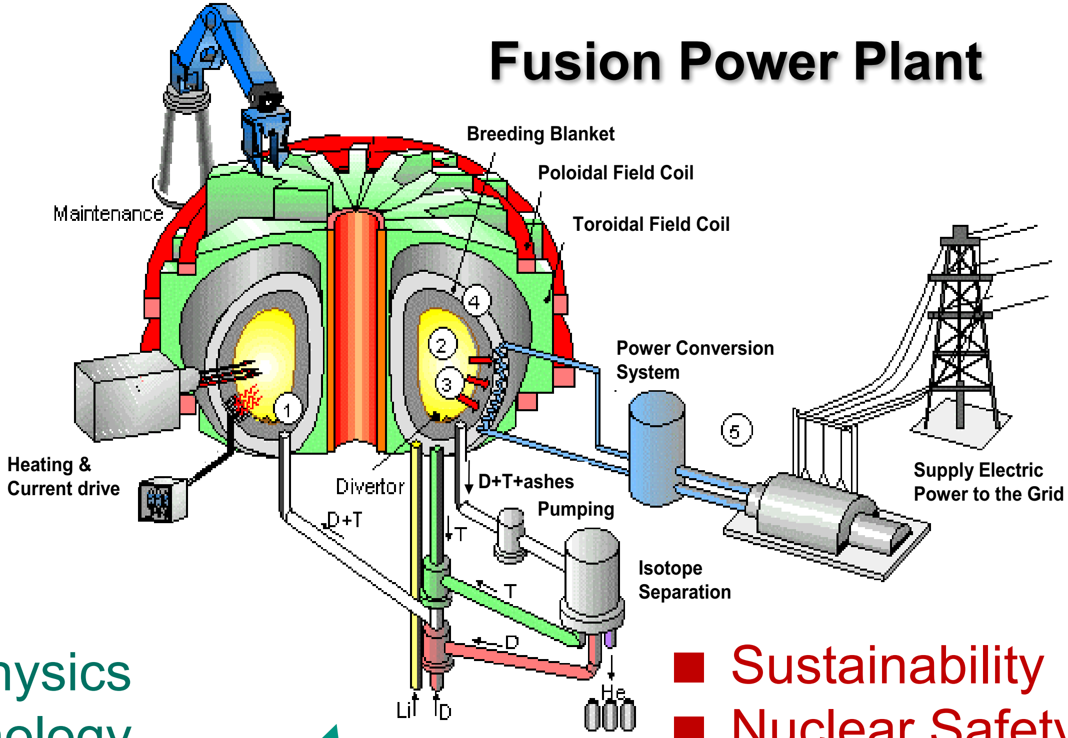
JET



WHERE IS THE CHALLENGE?



- Test device for plasma physics
- Safety → Standard technology


Fusion Power Plant

- Sustainability
- Nuclear Safety
- Economy

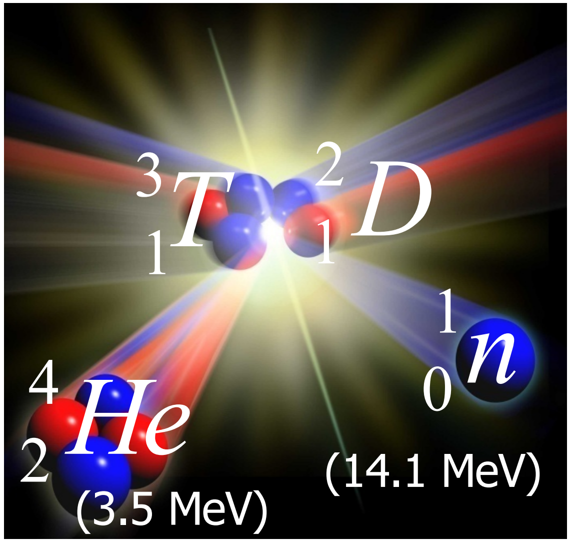
DEMO – the step in between

Fusion Reaction: Deuterium-Tritium Fusion

$^{2}D + {}^{3}T \rightarrow {}^{4}He + n + 17.6$ MeV

⊕ ⊕ ⊕⊕
○ ○○ ○○ ○

⊕ Proton
○ Neutron



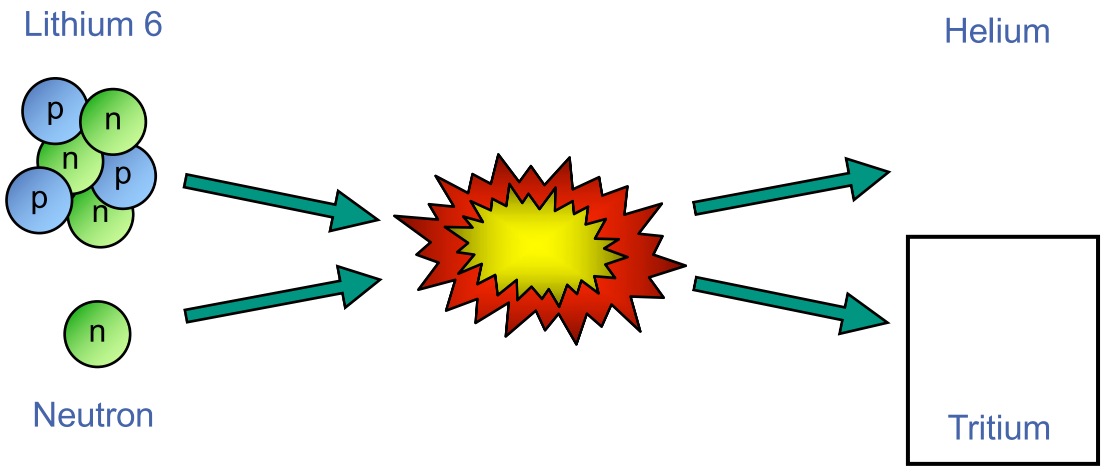
- Kinetic energy (½ $m\ v^2$) of α-particles (^{4}He) and neutrons = 17.6 MeV
- α-particles and neutrons shall have the same impulse ($m * v$) → neutron must be 4 times faster than Helium

➡ kinetic energy distributed by mass ratio m_n/m_α= 4/1=(14.1/3.5),

➡ **80% of energy in kinetic neutrons**

Fuel

Tritium does not occur in Nature and thus has to be produced (from Lithium)



Tritium is radioactive. There is not enough tritium due to ist half-life of 12 years. Therefore tritium has to be produced from lithium by „breeding“.

The resources for Fusion are <u>Deuterium</u> and <u>Lithium</u>

„Fuel for ever !“

The fuel required to cover the energy consumption of a 4 persons household per year fits easily into bag.

Source: Forschungszentrum Jülich

75 mg Deuterium
225 mg Lithium

contained in:

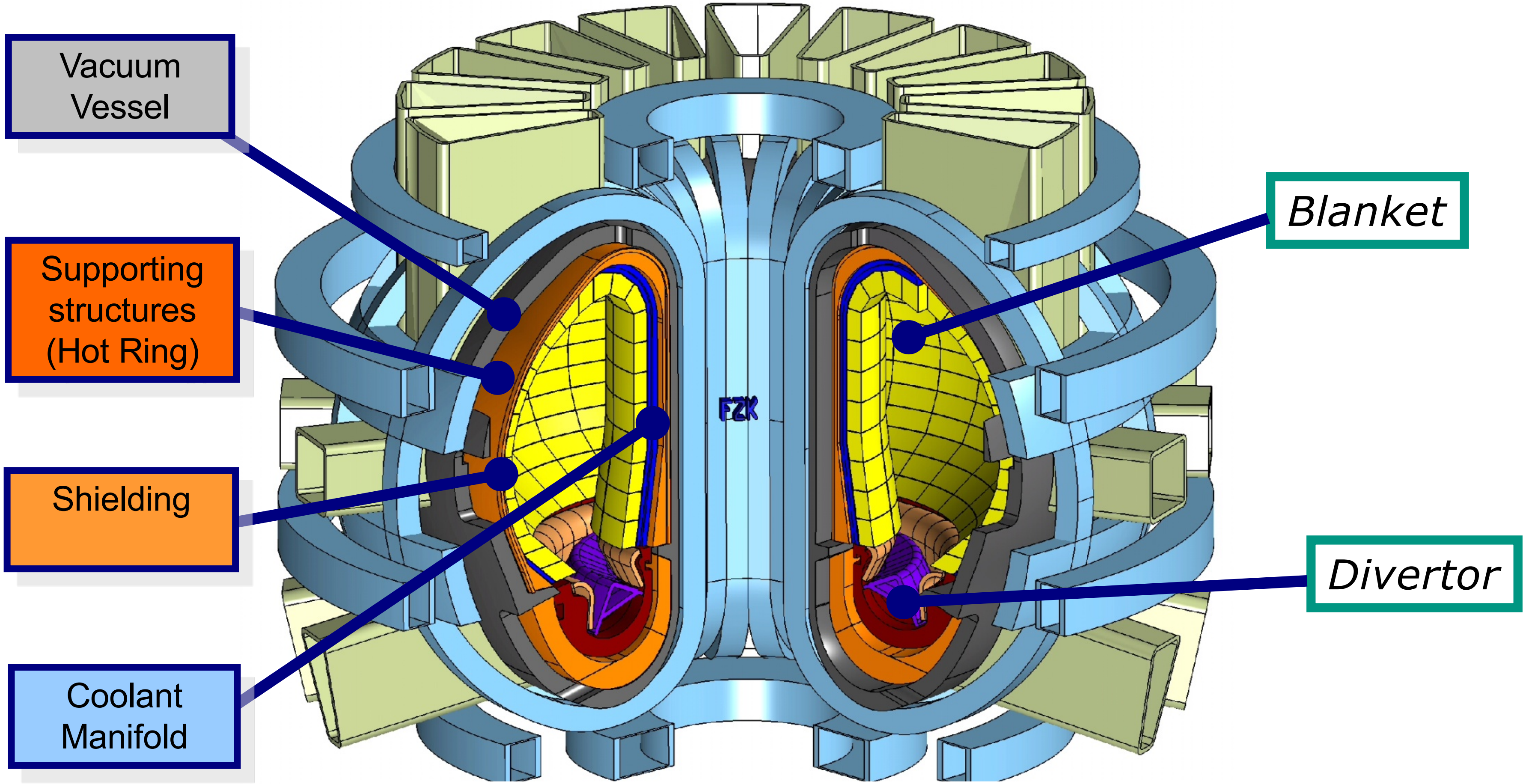
2 Liters water and
250 g rocks

energy content:

48000 Millionen Joule
equivalent to
1000 Liters light fuel oil

Introduction to the reactor - components

Fusion Reactor Core



Vacuum Vessel

Supporting structures (Hot Ring)

Shielding

Coolant Manifold

Blanket

Divertor

Basic Design for a DEMO (Demonstration Fusion Reactor Plant)

Power Flow and Distribution

Power flow in a DEMO

- Fusion Power P_{fus}= 3 GW
- External heating and current drive $P_{H\&CD}$= 50 MW (200 MW)

Power loads for PFC

(PFC=Plasma-facing components)

- P_n = 2.4 GW
- P_{rad}= 500 MW
- P_{part}= 150 MW

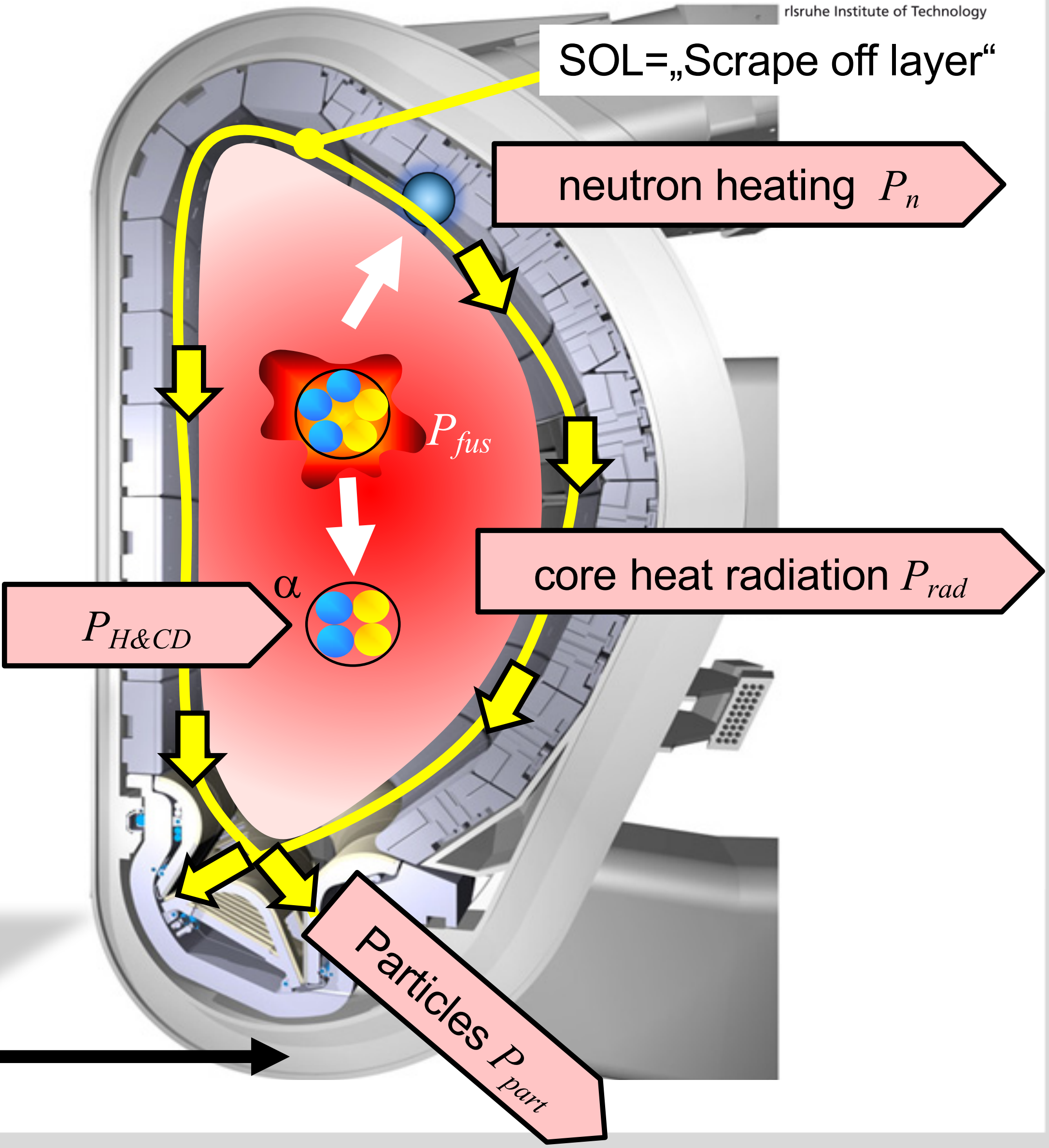
DEMO with *R*=9m

Blanket Area A=1000m²

- q_n =2.4 MW/m² (mean)
  2.9 MW/m² (max.)
- q_{rad}=0.5 MW/m² (mean)

Divertor

- q_{part}=10-20 MW/m²



R=9m

Breeding Blanket Functions and Requirements

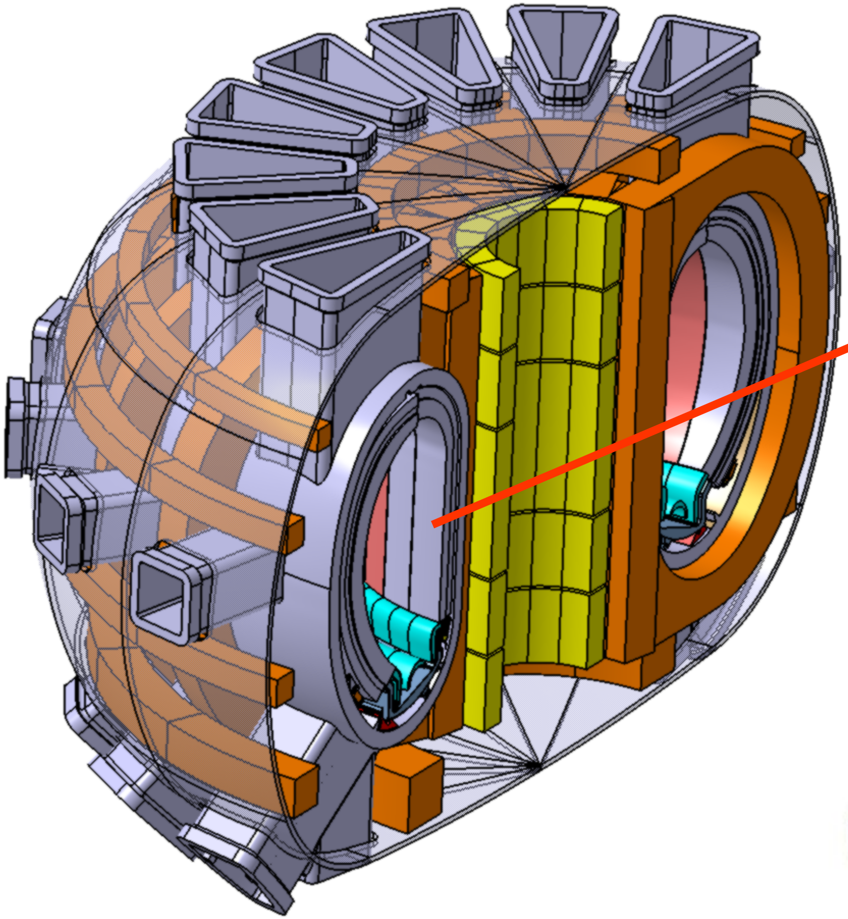
- **Main functions of the blanket:**

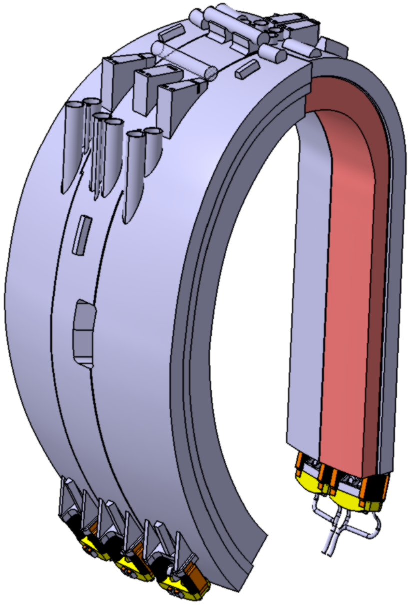
1. **Tritium production** (breeding) and extraction
2. Transforming surface and neutron power into heat and collection of the **heat for electricity production**
3. Contribute to the **shielding** of the Vacuum Vessel and Toroidal Field Coils

- **The design has to be featured in order to achieve:**

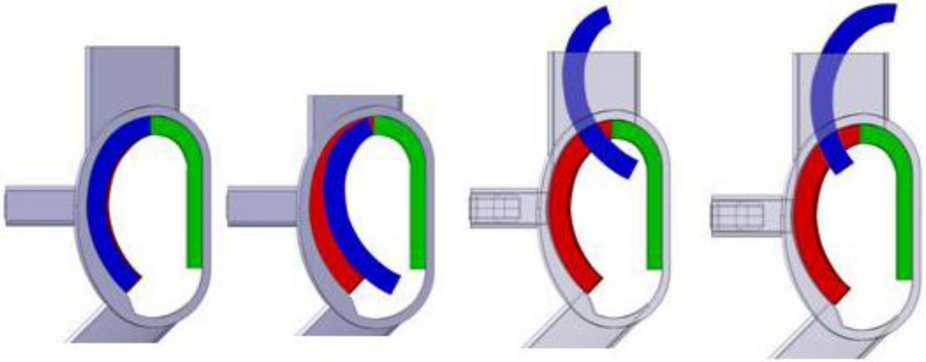
1. Low maintenance time
2. Sufficiently long lifetime
3. High safety level (e.g. accidents, operations, etc.) and low environmental impact (including waste)
4. Reasonable direct cost including operation (e.g. small dimensions, high efficiency, etc.)

HCPB: Breeder and Neutron Multiplier





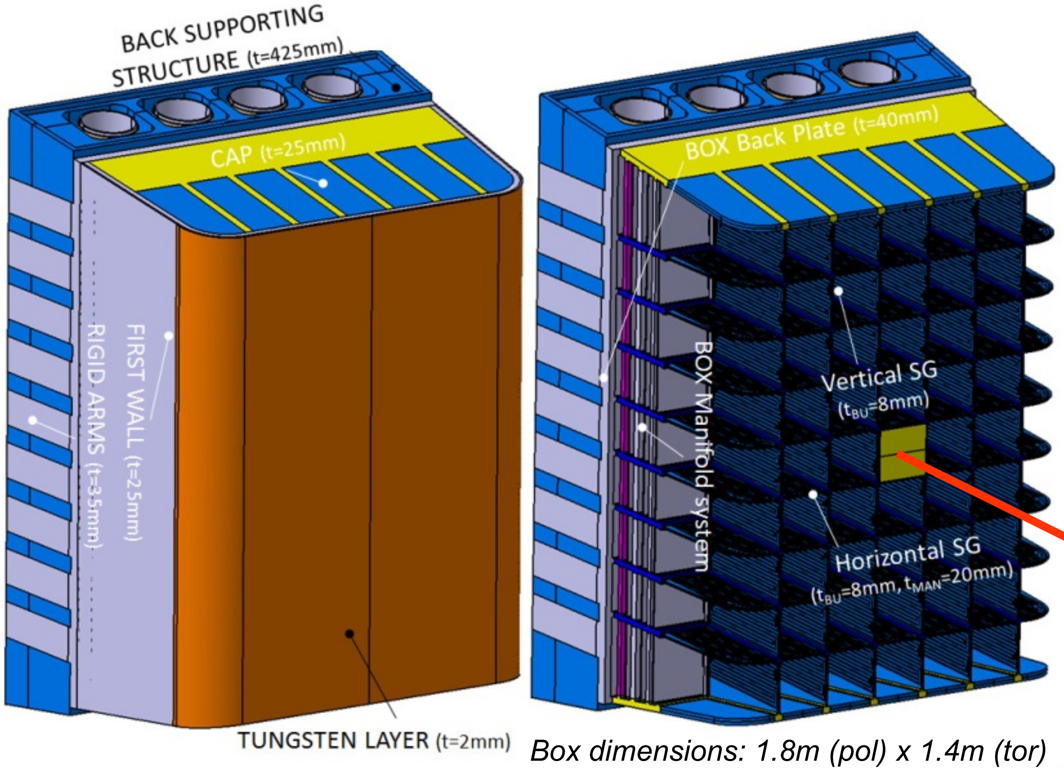
5 blanket segments (3 OB and 2 IB) for each 22.5°- sector (16 TF coils)



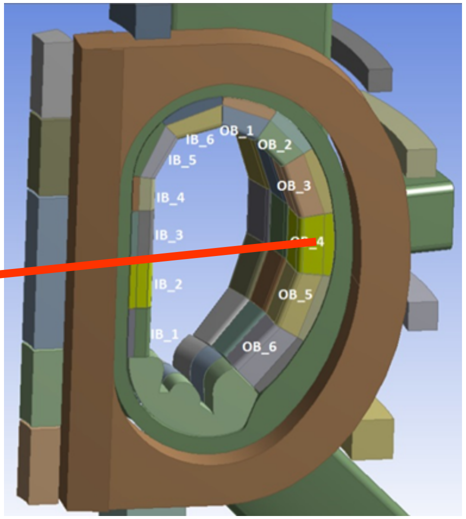
Example of kinematics for OB segment extraction

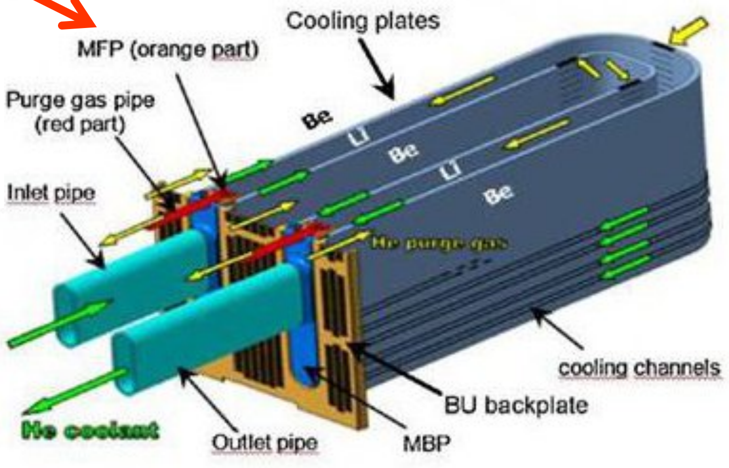
Daniel Iglesias et al., Blanket Segment Remote Maintenance, EFDA-WP13-DAS07-T05 (CCFE)

HCPB Blanket: EU DEMO-2050 (KIT, 2013)



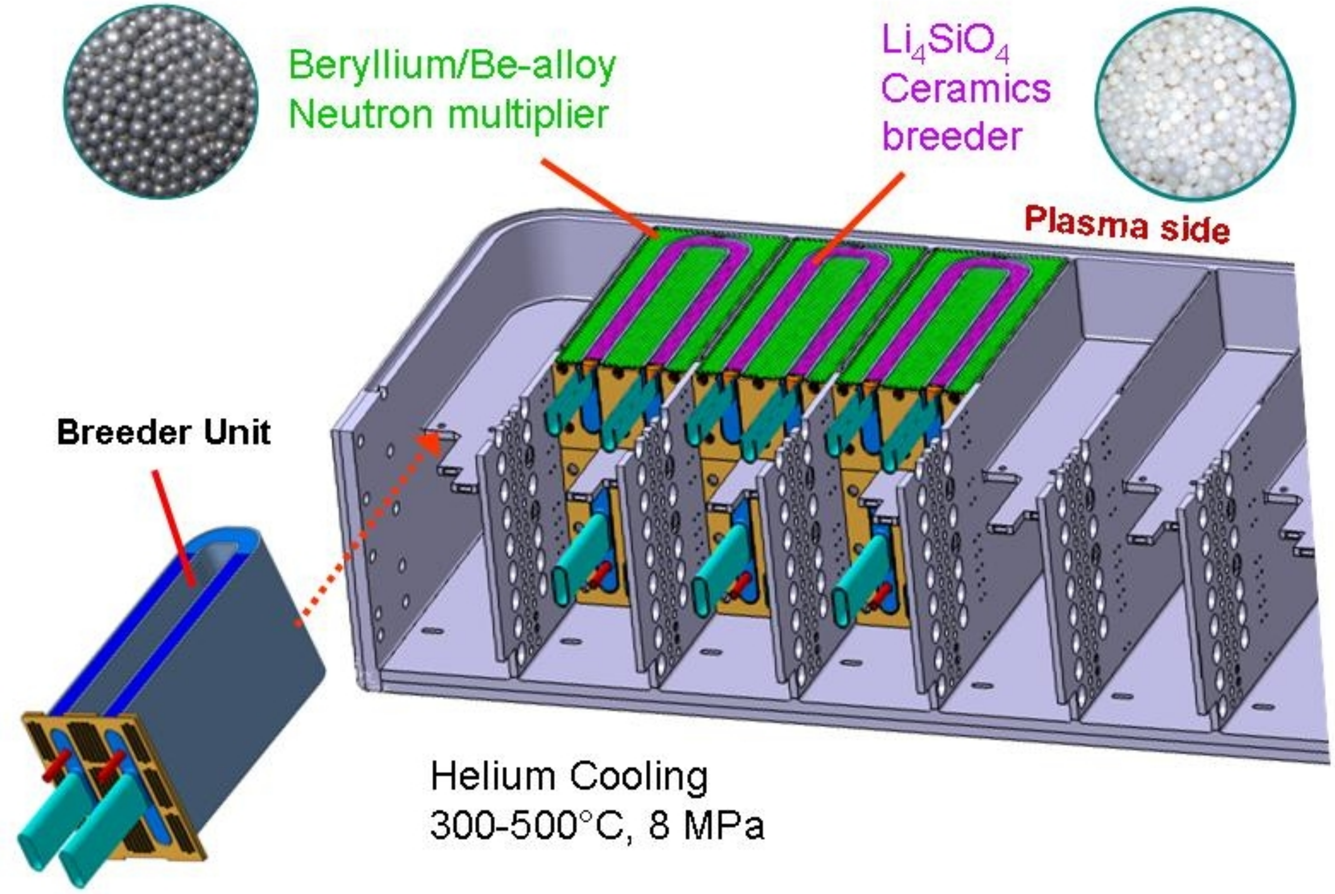
Box dimensions: 1.8m (pol) x 1.4m (tor)





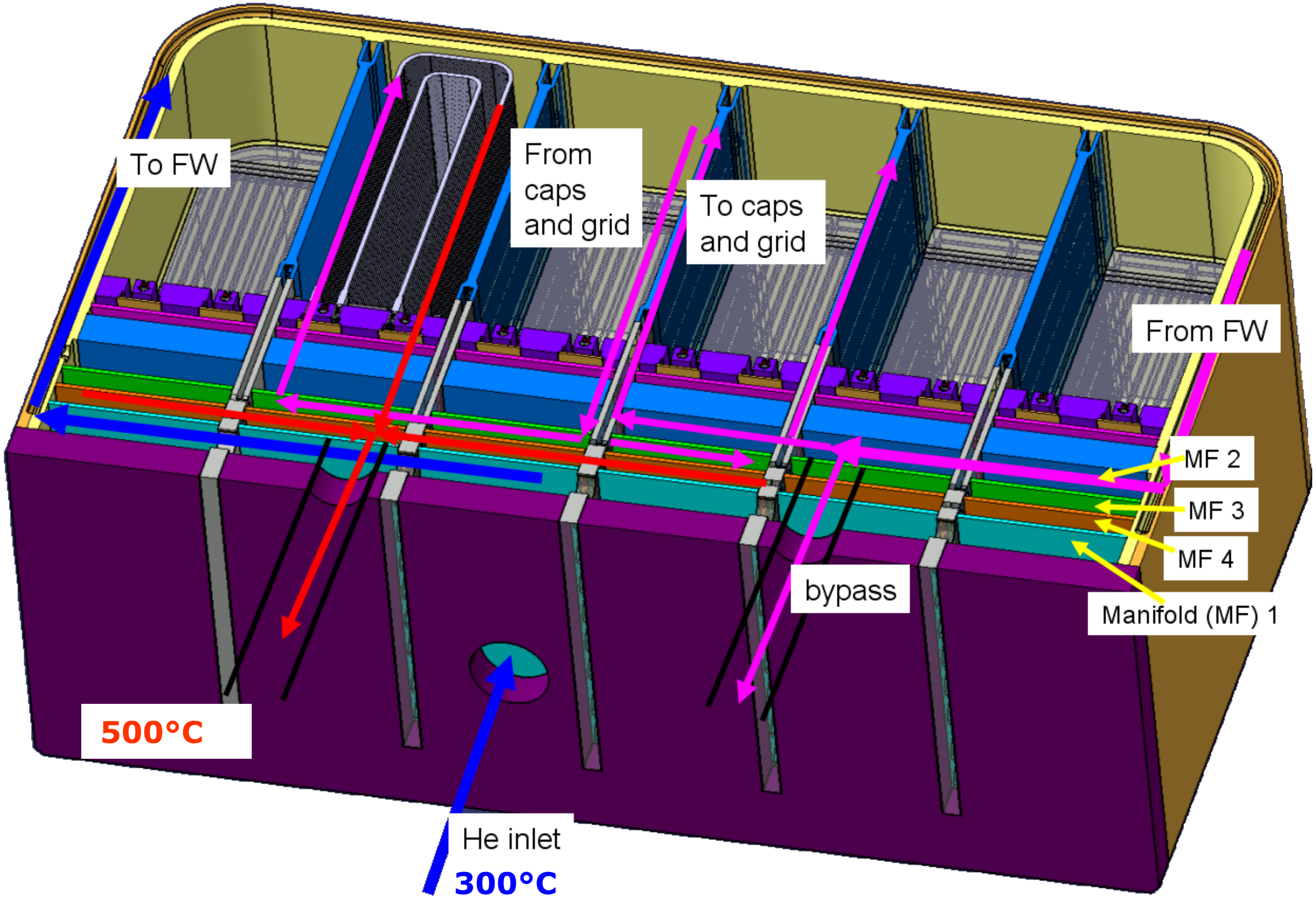
Operational parameters	Values
FW heat flux (peak)	0.5 MW/m^2
Neutron wall load (peak)	1.7 MW/m^2
He Coolant pressure	8 MPa
He Coolant temp. (inlet/outlet)	300 / 500°C
Power Generation System	Water-steam Cycle (Rankine)

HCPB: Breeder and Neutron Multiplier



F. Cismondi, HCPB TBM 2008 (KIT)

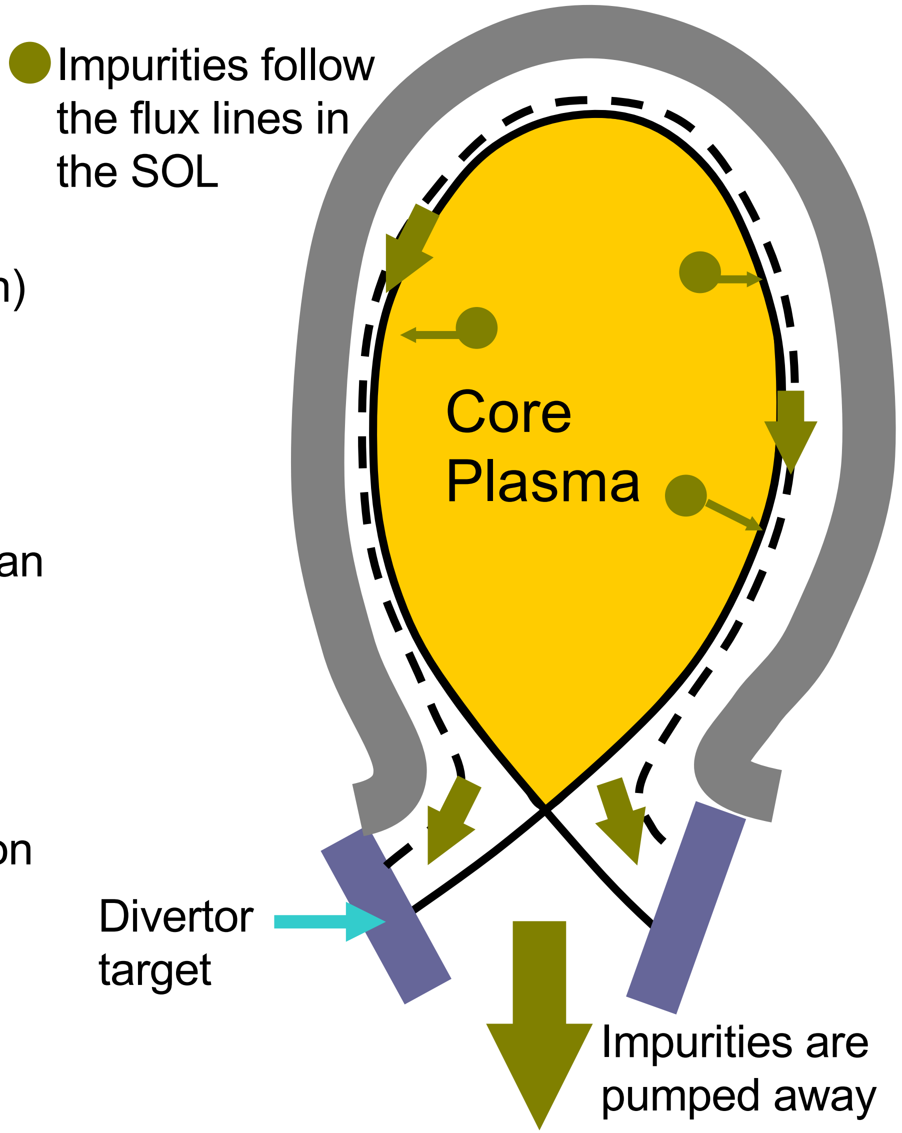
HCPB: Manifold system



F. Cismondi, HCPB TBM 2008

Divertor

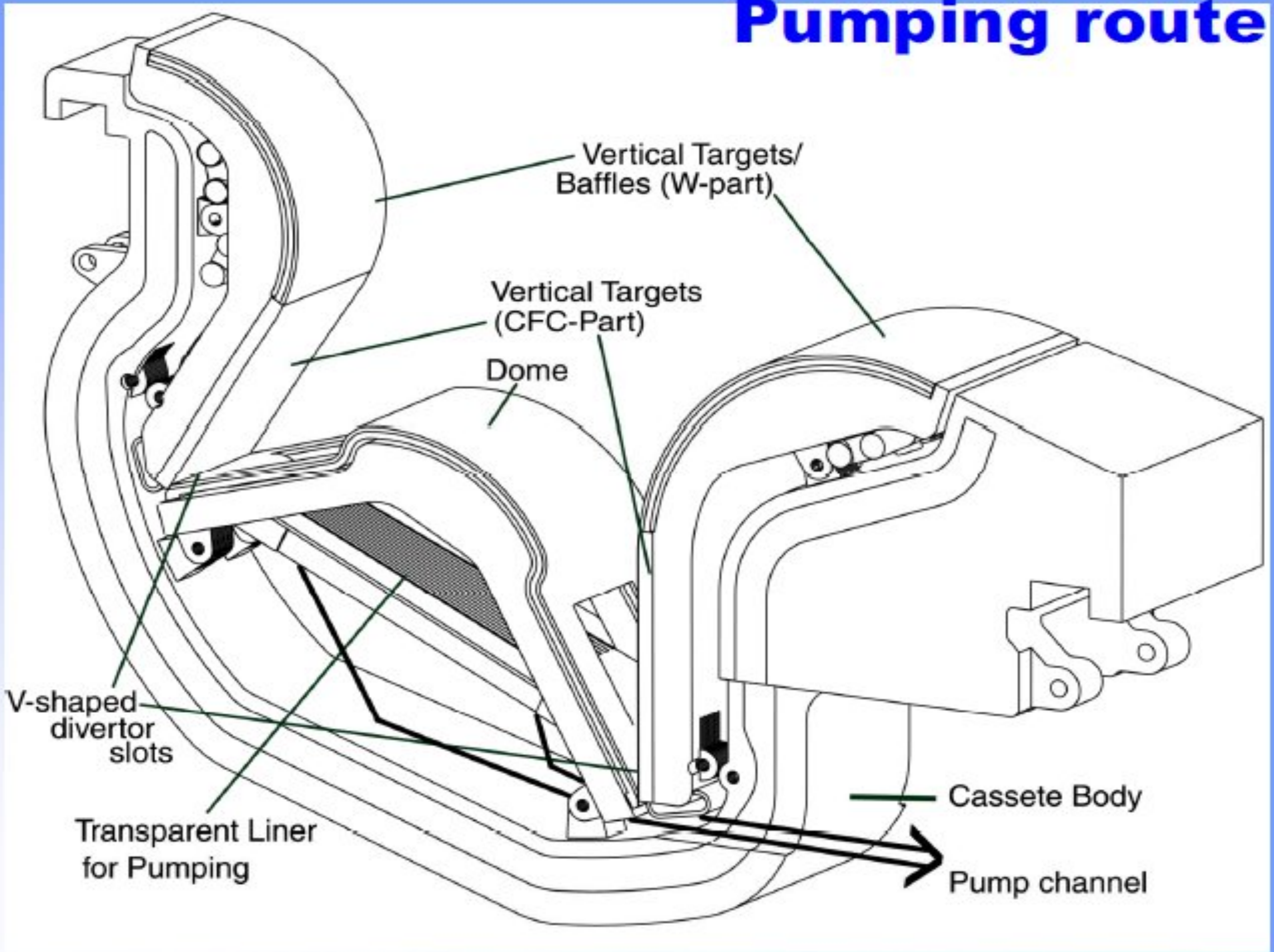
- Helium ("ash" from the D-T fusion reaction) diffuses into the SOL and follows the flux lines towards the divertor
- Impurities can originate from the surface (e.g. water, CO, C, chlorine, sulphur) → can be desorbed thermally or by impact of particles (ions, atoms, electrons …)
- Wall material can be introduced to the plasma by sputtering, arcing or evaporation (e.g. W)



● Impurities follow the flux lines in the SOL

Impurities are pumped away

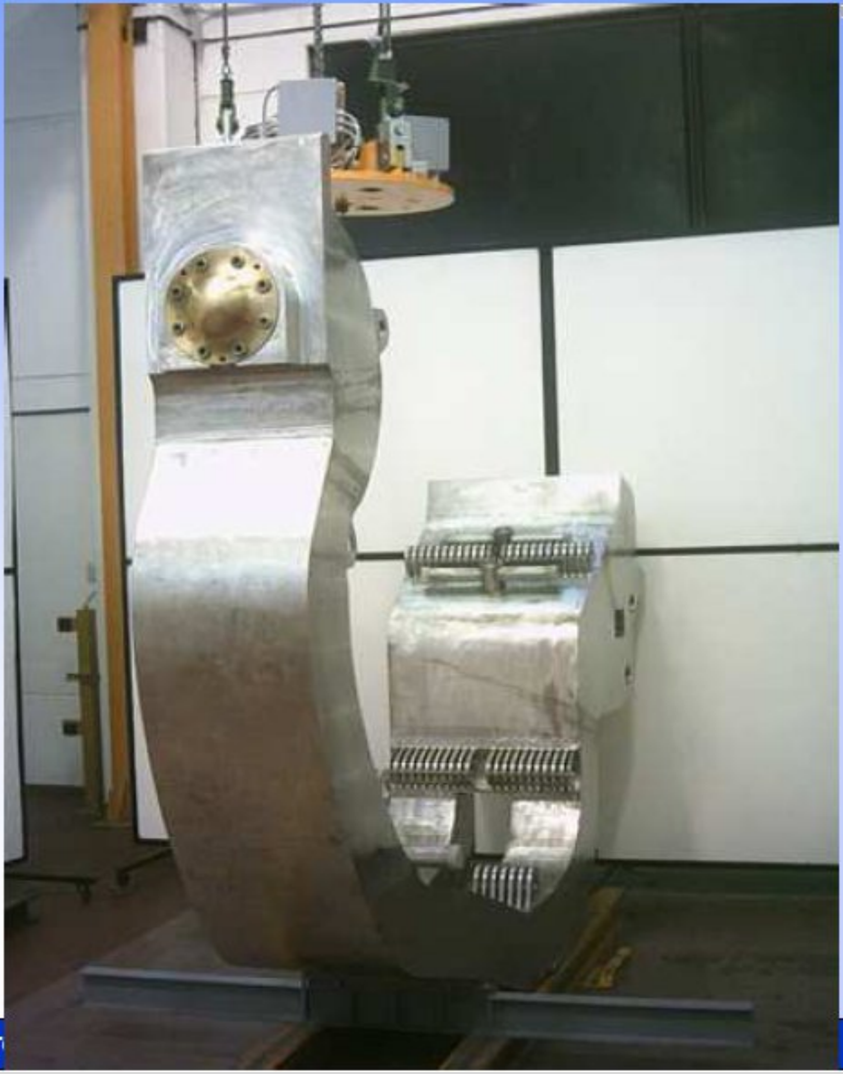
Pumping route



B.Riccardi Cadarache, 11 June 08

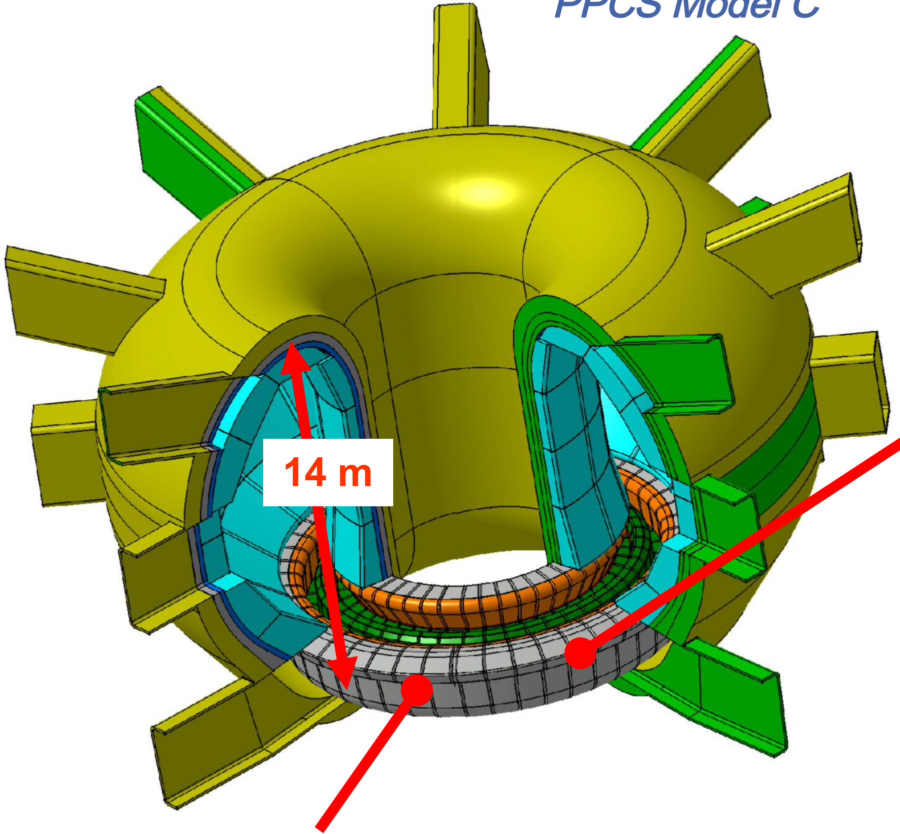
Outer and Inner Vertical Target Dome Liner, Cassette

AnsaldoRicerche

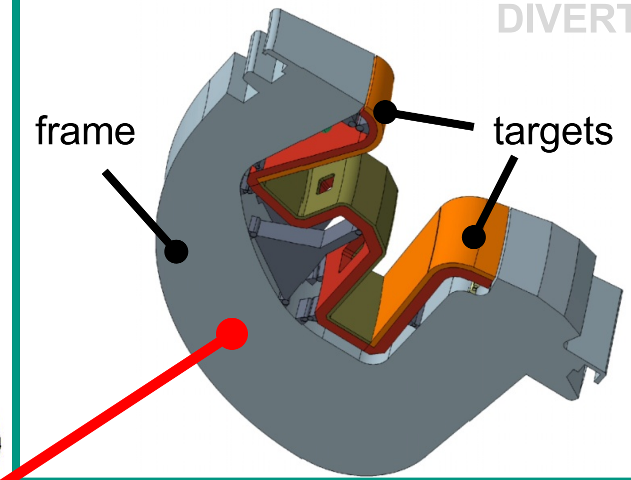


DEMO Divertor

DEMO FUSION REACTOR



DIVERTOR CASSETTE



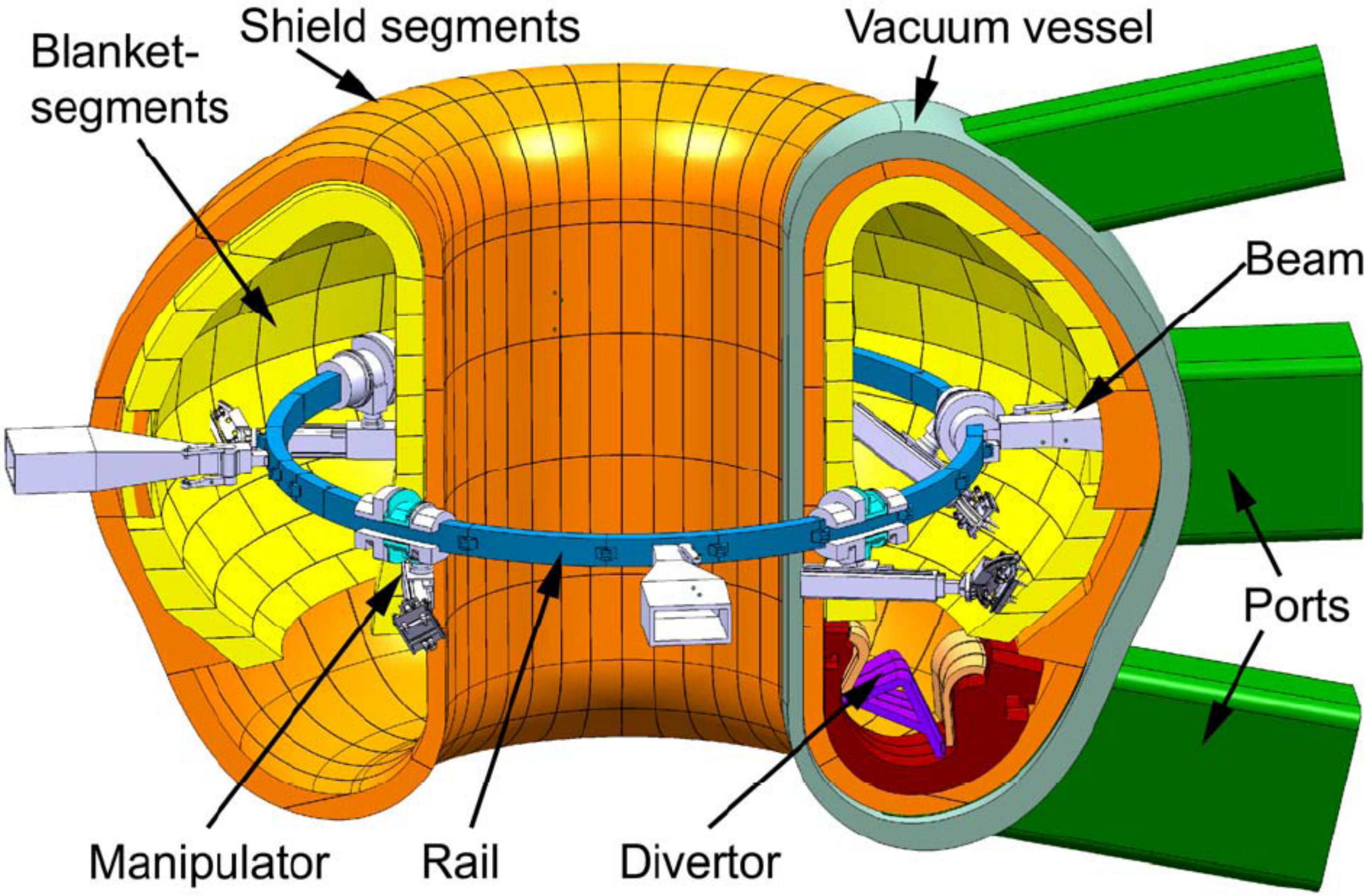
approx.
4 m x 4 m
x 1 m

DIVERTOR MAIN FUNCTIONS

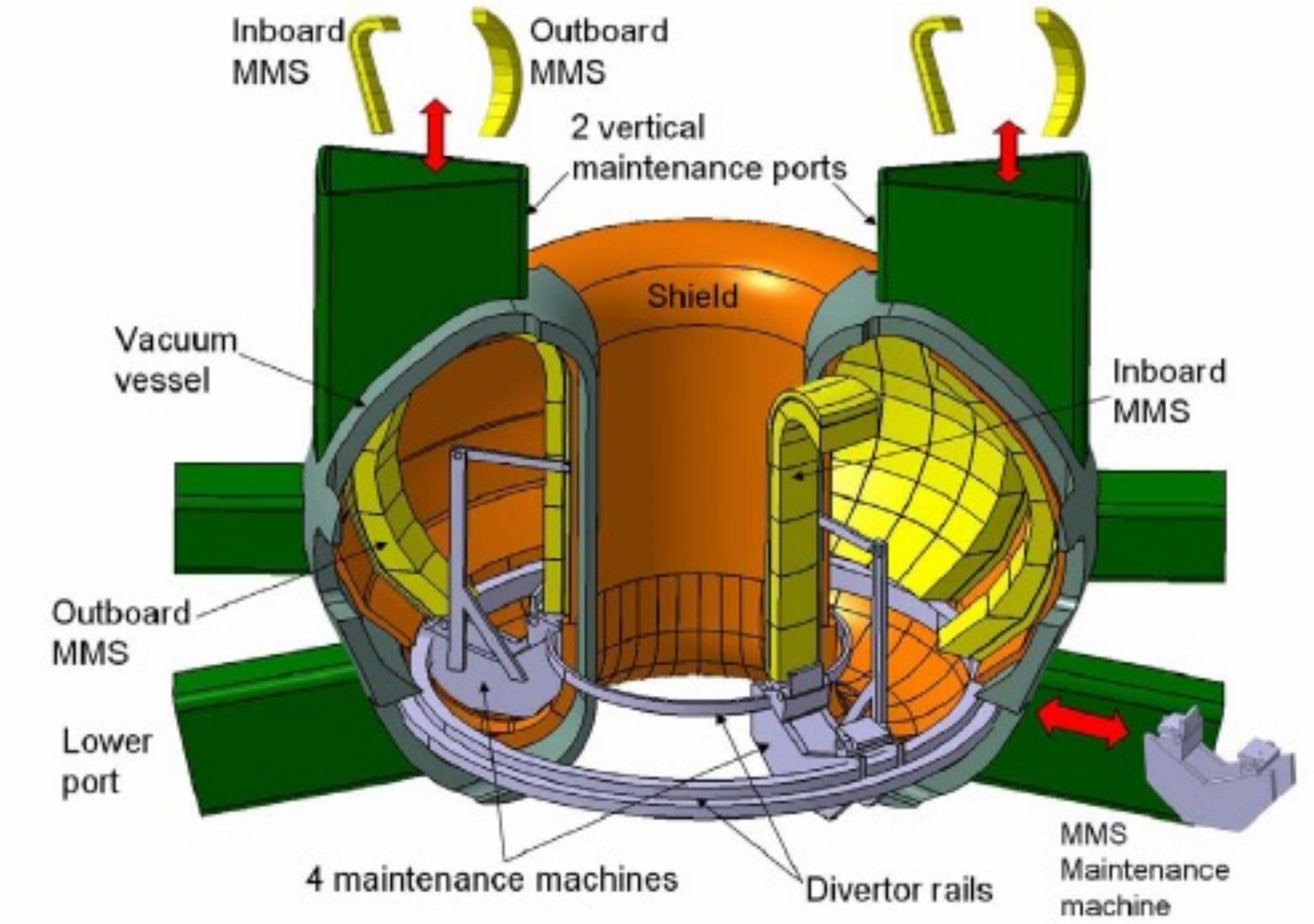
1.) **Used for high <u>Quality</u> Plasma**
Neutralization of Plasma Particles
Removal of Neutral Gas & Particles

2.) **Direct 15% of total Thermal <u>Power</u> into He-Flow**

Maintenance System: ITER Configuration

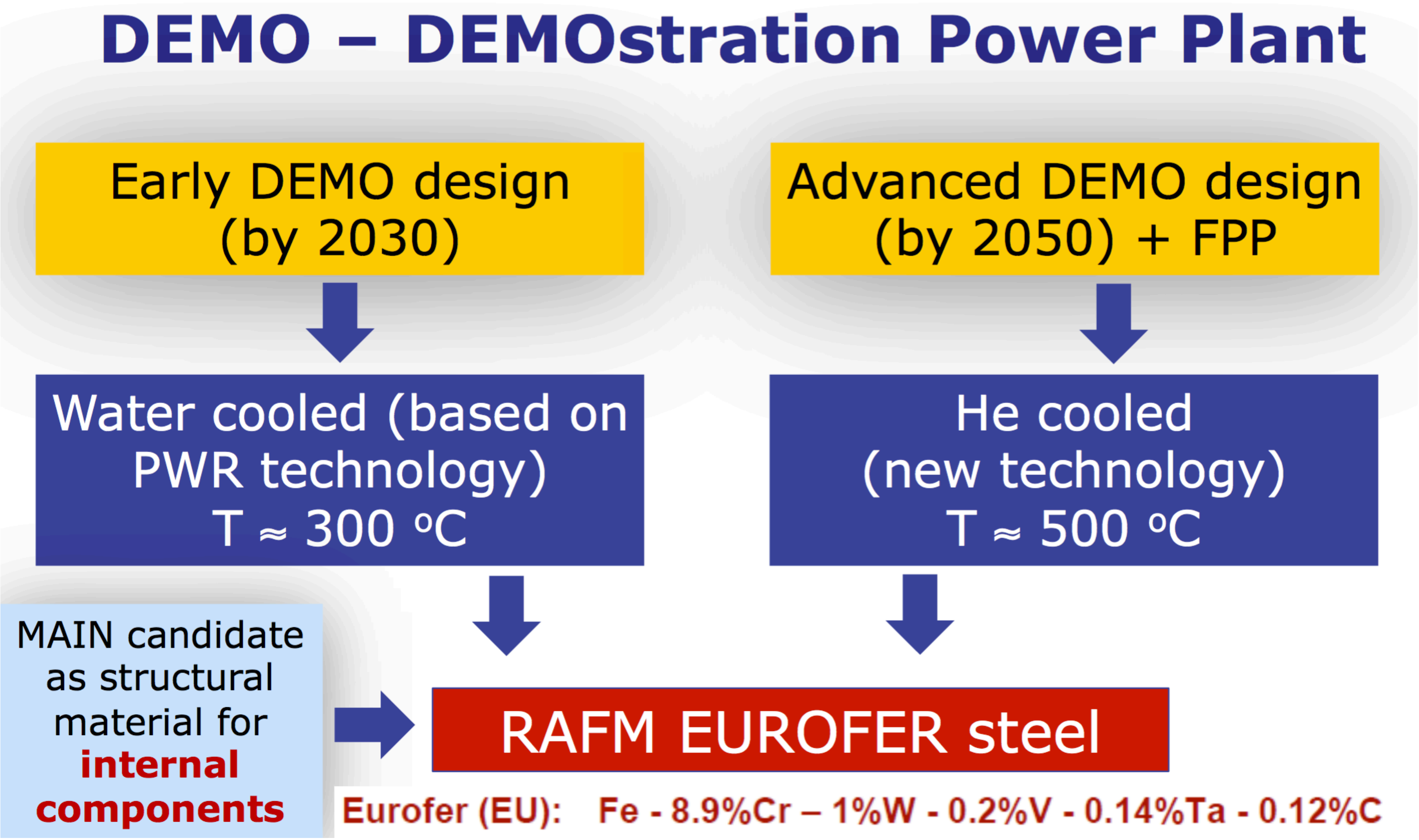


Maintenance System: Vertical port



Steel Demand - DEMO

Future Steel Demand



DEMO – DEMOstration Power Plant

Early DEMO design
(by 2030)

Water cooled (based on PWR technology)
T ≈ 300 °C

Advanced DEMO design
(by 2050) + FPP

He cooled
(new technology)
T ≈ 500 °C

MAIN candidate as structural material for **internal components**

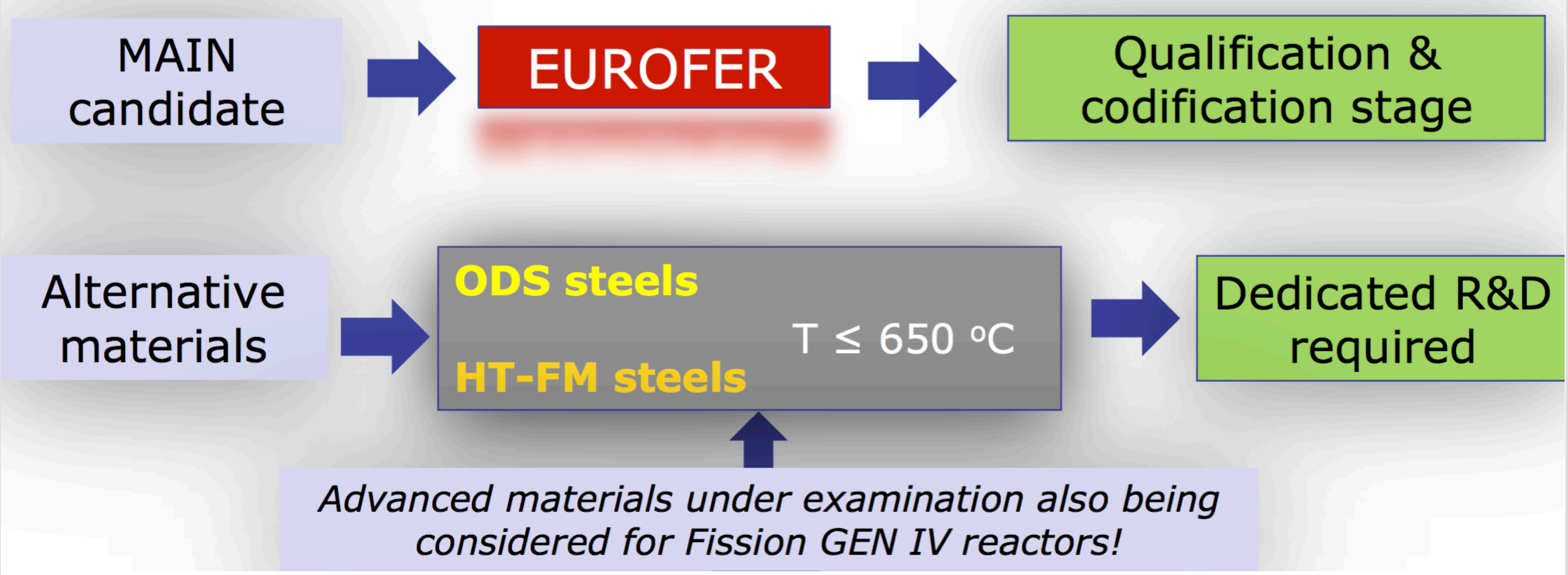
RAFM EUROFER steel

Eurofer (EU): Fe - 8.9%Cr – 1%W - 0.2%V - 0.14%Ta - 0.12%C

Steel Demand - DEMO

Structural Materials: Internal components

Components	Quantity needed / tons
Blanket	~ 2,180
Divertor Cassette Body	~ 1,170

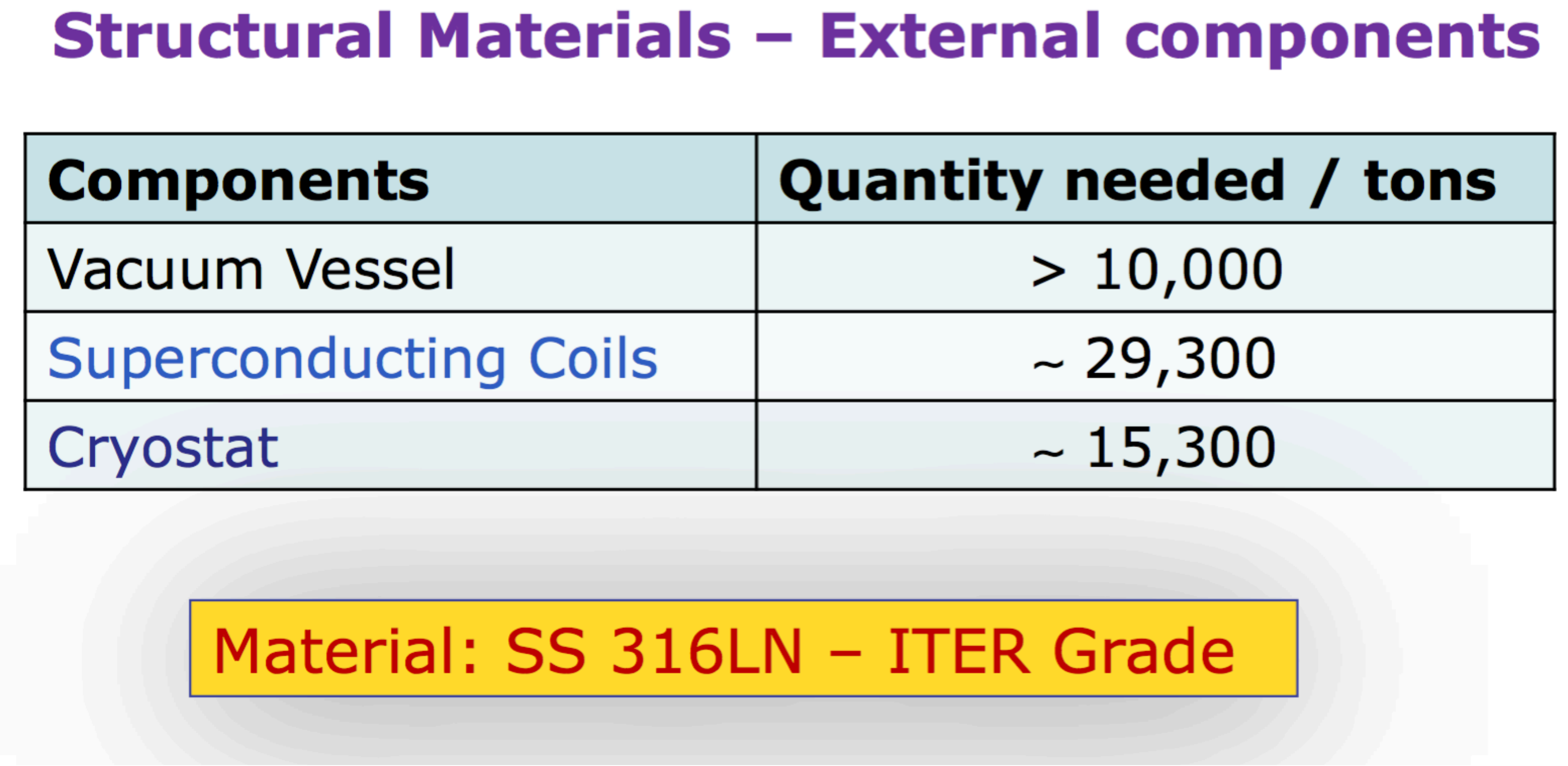


MAIN candidate → **EUROFER** → Qualification & codification stage

Alternative materials → **ODS steels** / **HT-FM steels** (T ≤ 650 °C) → Dedicated R&D required

Advanced materials under examination also being considered for Fission GEN IV reactors!

Steel Demand - DEMO



Structural Materials – External components

Components	Quantity needed / tons
Vacuum Vessel	> 10,000
Superconducting Coils	~ 29,300
Cryostat	~ 15,300

Material: SS 316LN – ITER Grade

Steel Demand - DEMO

DEMO – DEMOstration Power Plant (BoP part)

Components	Total weight / tons per unit
Steam generators	~ 800
Turbines HP/LP	~ 120 - 200
Pressurisers	~ 106
Generators	~ 250

Total weight per reactor: 4,500 tons


Generator


Pressuriser


Steam generator


Turbine

DEMO: Total steel needs

Components	Steel	Quantity needed / tons
Blanket	EUROFER	~ 2,180
Divertor Cassette Body	EUROFER	~ 1,170
Vacuum Vessel	SS (ITER grade)	> 10,000
Superconducting Coils	SS (ITER grade)	~ 29,300
Cryostat	SS (ITER grade)	~ 15,300
BoP	SS	~ 4,500

- **3,300 tons EUROFER**
- **> 62,450 tons SS**

cf ~ **406 M€**

Steel Challenges (in-vessel components)

DEMO Blanket – Assumptions & Requirements

DEMO is a pulsed device with pulses of at least 2 h. The neutron wall load is ~1.3 MW/m^2 (conservative), 15 dpa/fpy in steel is taken as a benchmark. **Starter Blanket**: ~**1.33 fpy** or 4 calendar years.

→ Starter Blanket **steel dose 20 dpa (conservative)**
→ Starter Blanket **steel 6000-9000** large-amplitude **fatigue cycles**

A **second Blanket**, lasting 11-16 calendar years could then be assumed. At 30% availability, this is **3.3-4.8 fpy.**

→ Second Blanket **steel dose 50-70 dpa**
→ Second Blanket **steel 13000-20000** large-amplitude **fatigue cycles**

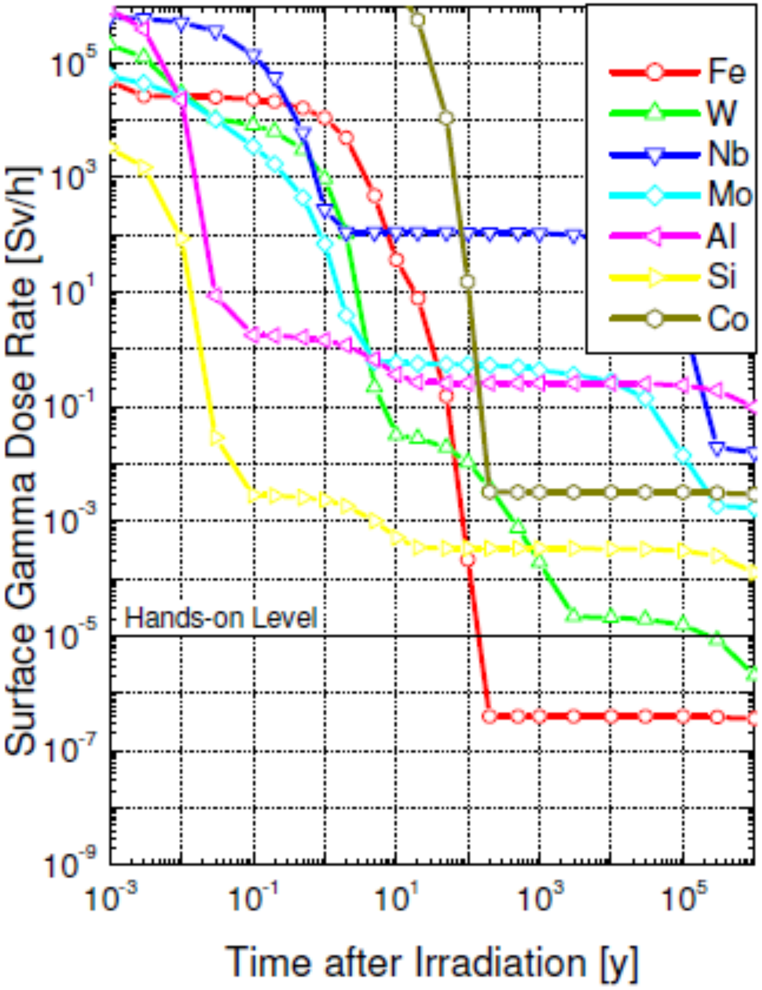
DEMO will keep as back-up option the possibility to use water in the breeding blanket (such as the **Water Cooled Lithium Lead** concept in PPCS) and to rely on a technology similar to Pressurized Water Reactors (PWR) in the BoP. For this, the **coolant inlet temperature must be reduced to $T_{inlet} < 300°C$.**

→ **increased radiation embrittlement concerns for the ferritic steel structure**

EUROFER – Activation response

- Production of radioactive isotopes by high-energy radiation (neutrons)
- Aim: „Hands-on“ limit after 100 years
- Reference element: Iron
- Elimination of certain elements:

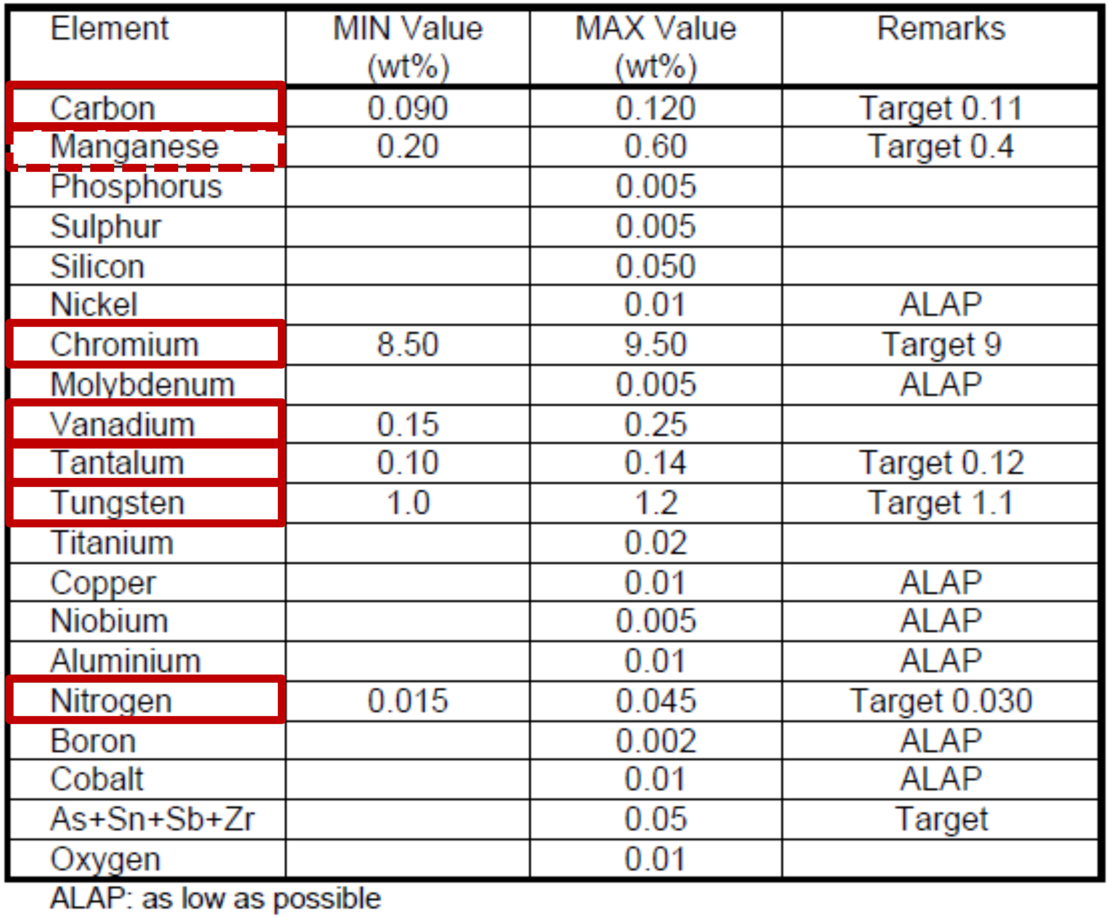
  Ni, Nb, Mo, Al, Co



A. Möslang, IAM-AWP, 2015

EUROFER – Alloying elements

- Replacment of certain elements
  - Mo -> W
  - Nb -> Ta
- Reduce impurities
- **Low Activation Steels: Fe-Cr-W-V-Ta-C-N**



Element	MIN Value (wt%)	MAX Value (wt%)	Remarks
Carbon	0.090	0.120	Target 0.11
Manganese	0.20	0.60	Target 0.4
Phosphorus		0.005	
Sulphur		0.005	
Silicon		0.050	
Nickel		0.01	ALAP
Chromium	8.50	9.50	Target 9
Molybdenum		0.005	ALAP
Vanadium	0.15	0.25	
Tantalum	0.10	0.14	Target 0.12
Tungsten	1.0	1.2	Target 1.1
Titanium		0.02	
Copper		0.01	ALAP
Niobium		0.005	ALAP
Aluminium		0.01	ALAP
Nitrogen	0.015	0.045	Target 0.030
Boron		0.002	ALAP
Cobalt		0.01	ALAP
As+Sn+Sb+Zr		0.05	Target
Oxygen		0.01	

ALAP: as low as possible

DEMO Blanket – Materials & Strategies

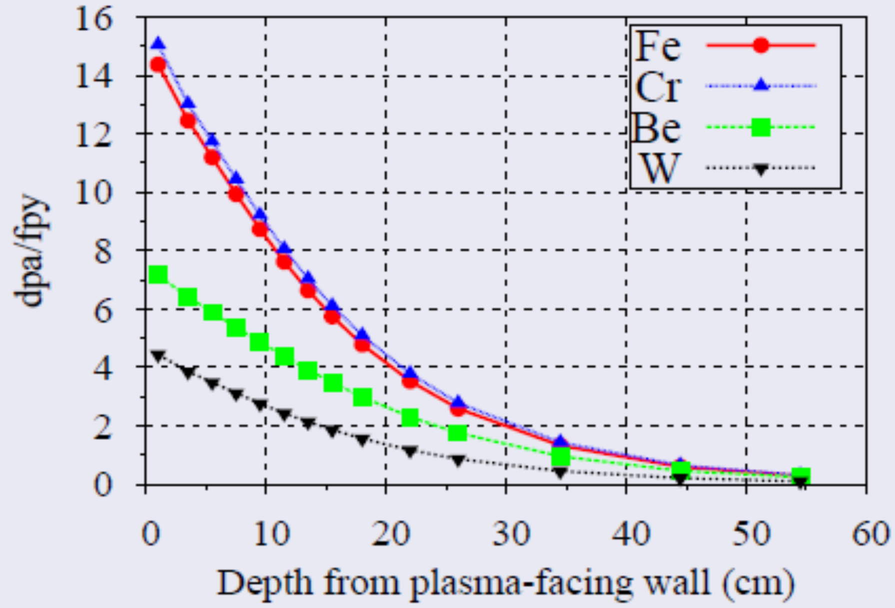
Materials

- Baseline → **EUROFER**
- Development of steels with advanced properties for the plasma-facing part of the blanket (15-30 cm)
  → **Advanced Steels for higher temperatures and doses**

Topics

- **Ferritic ODS steels**
- **RAFM for high temperatures**
- **RAFM for water cooling**

dpa/fpy as a function of depth into the outboard equatorial FW

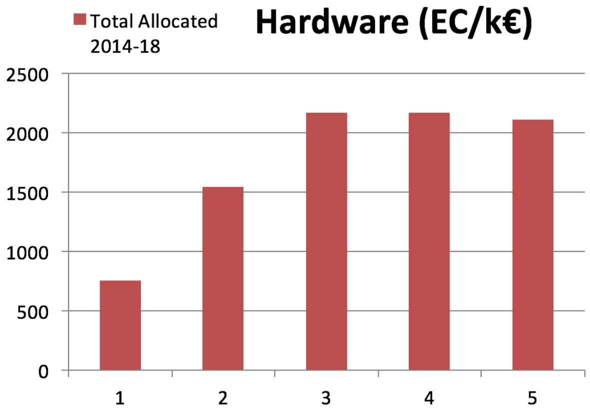


M. Gilbert, CCFE

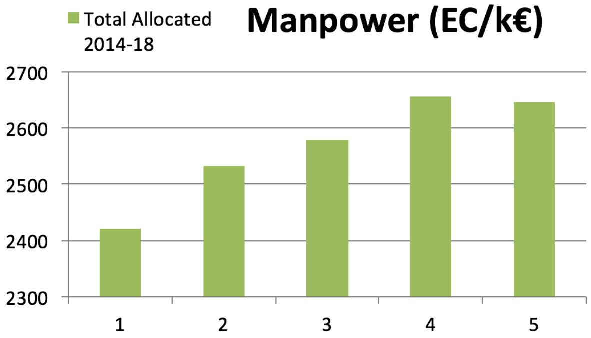
EURO*fusion* Steel Development

Budget (w/o overheads)

wpMAT

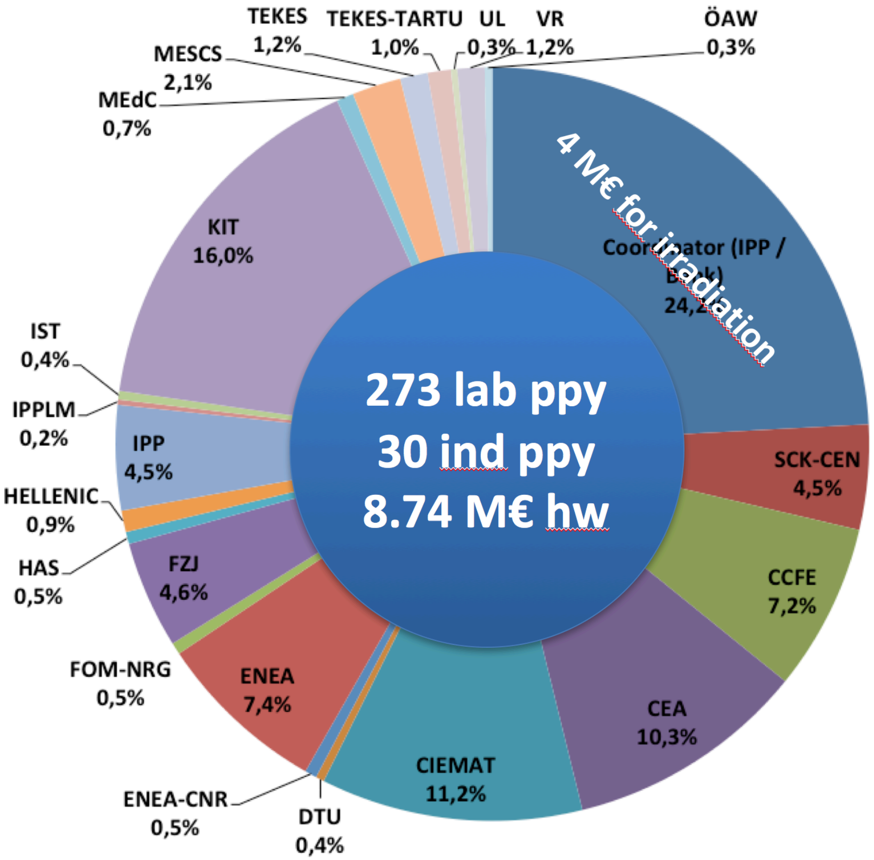


Hardware (EC/k€)



Manpower (EC/k€)

Total Allocated Resources by RU



4 M€ for irradiation

273 lab ppy
30 ind ppy
8.74 M€ hw

Advanced Steels (AS): Objectives

ODS steel: Fabrication & Demonstration

- Production of a 100 kg 14%Cr ODS steel batch by mechanical alloying
  - Plates: thickness 2 mm, size 2 m²
  - Demonstration of applicability to first wall
- Alternatives to mechanical alloying (feasibility studies and industrial large-scale fabrication)

Optimization of RAFM steels for possible water cooling

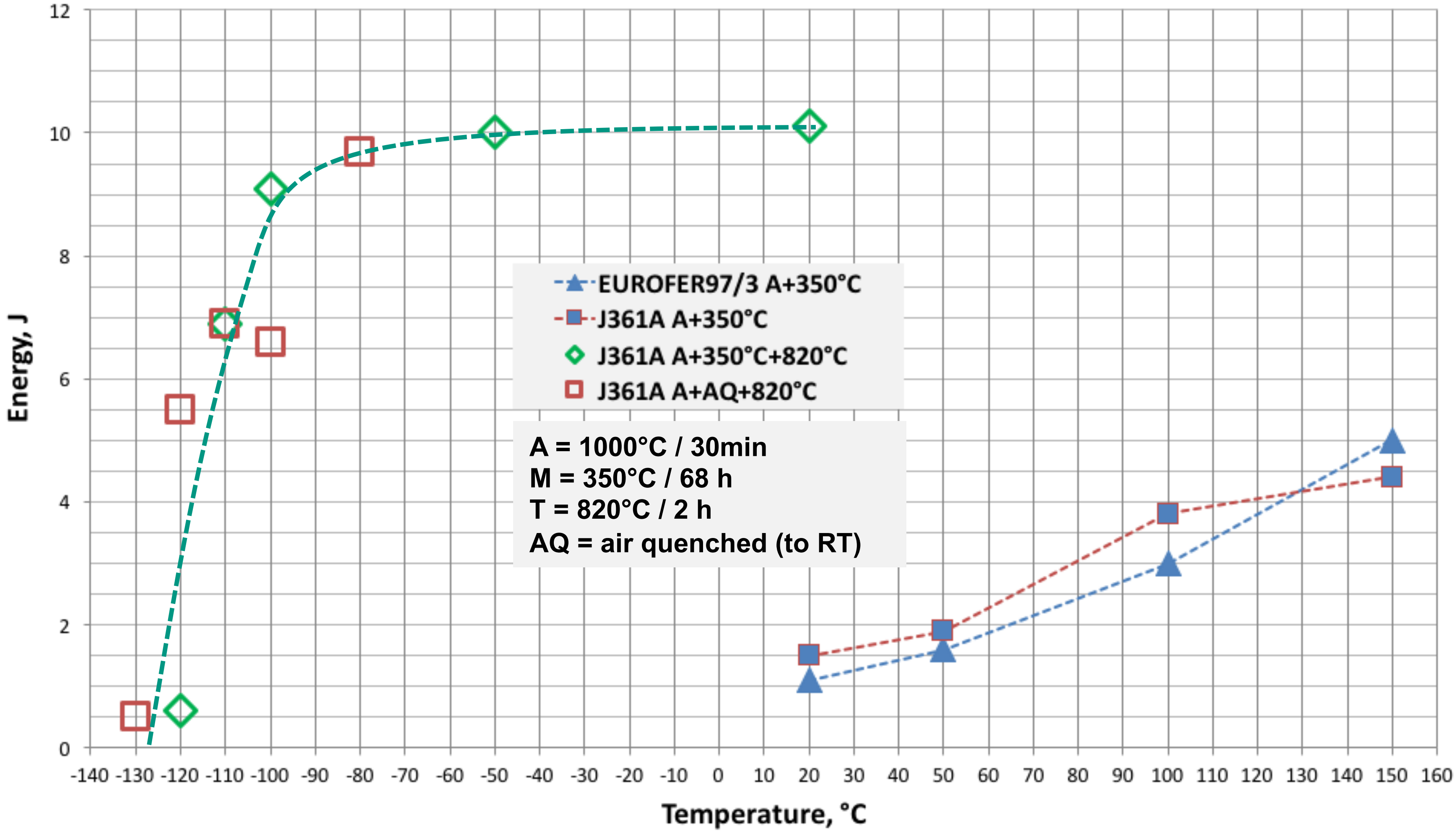
- Specific thermal treatments (for optimum DBTT)
- Change of chemical composition (for optimum DBTT)

Development of RAFM steels for high temperature applications

- Specific thermal treatments on EUROFER
- Special thermo-mechanical treatments (TMT)
- Fine tuning of the chemical composition

RAFM: Reduced Activating Ferritic-Martensitic

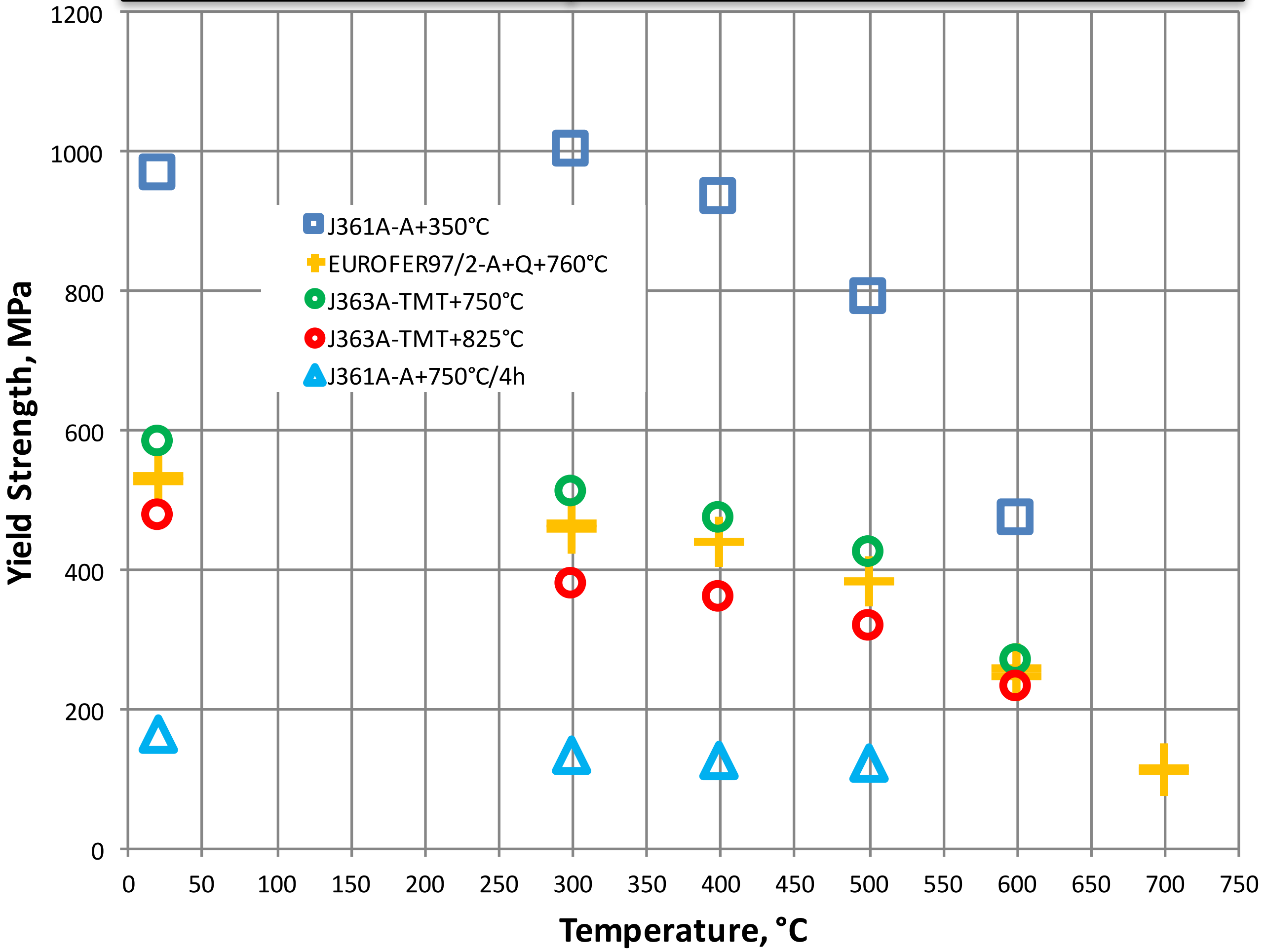
Toughness – Limits of Heat Treatment



A = 1000°C / 30min
M = 350°C / 68 h
T = 820°C / 2 h
AQ = air quenched (to RT)

Strength – Limits of Heat Treatment

A: 980°C – 1000°C	TMT: 1150°C → 900°C → WQ

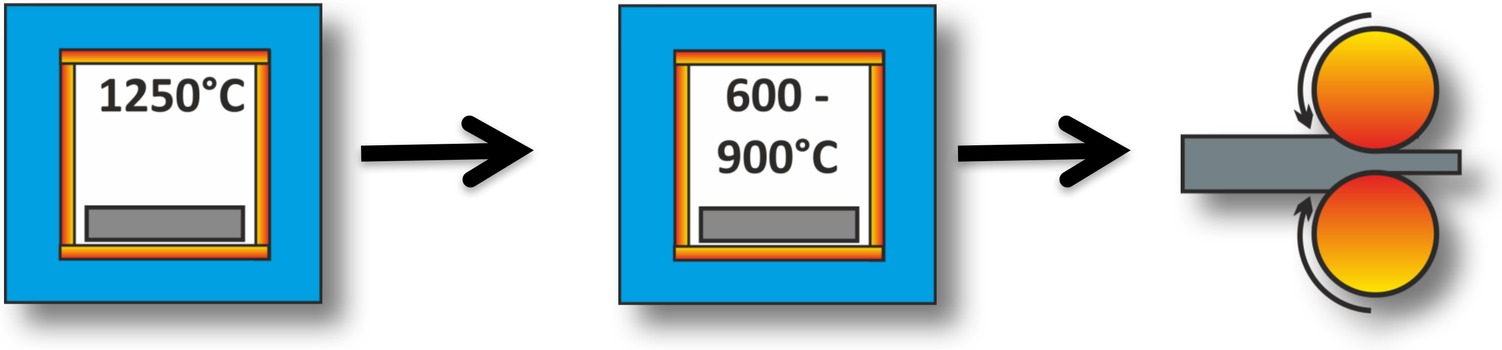


Effect of Extreme Thermo-Mechanical Treatments

Very high austenitization temperature for full dissolution of secondary phases

→ Increase PAG size for improved creep strength (lower diffusion)

→ Possible problem: Retain enough ductility at RT



Dissolution of all secondary phases (carbides, nitrides)

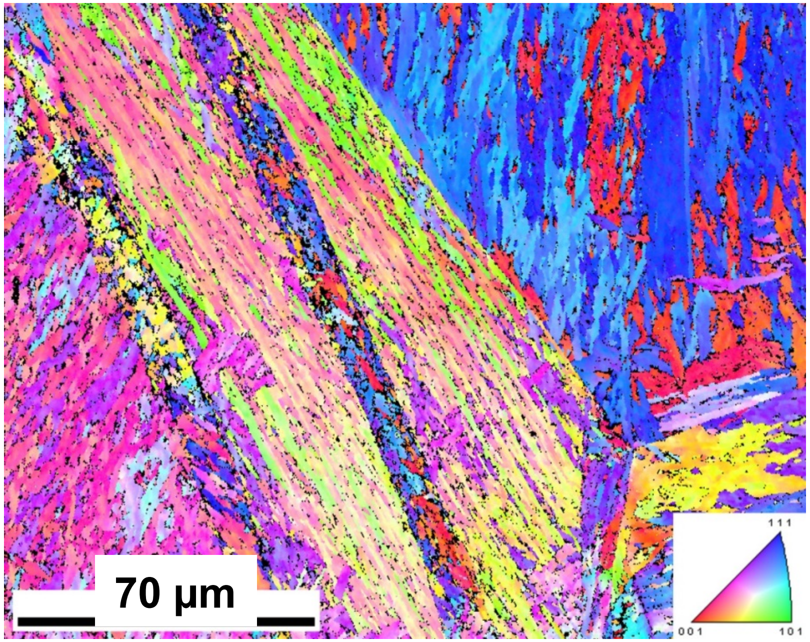
Cooling to rolling temperature in furnace (metastable austenite phase)

Rolling in the austenite phase

Effect of Extreme Thermo-Mechanical Treatments

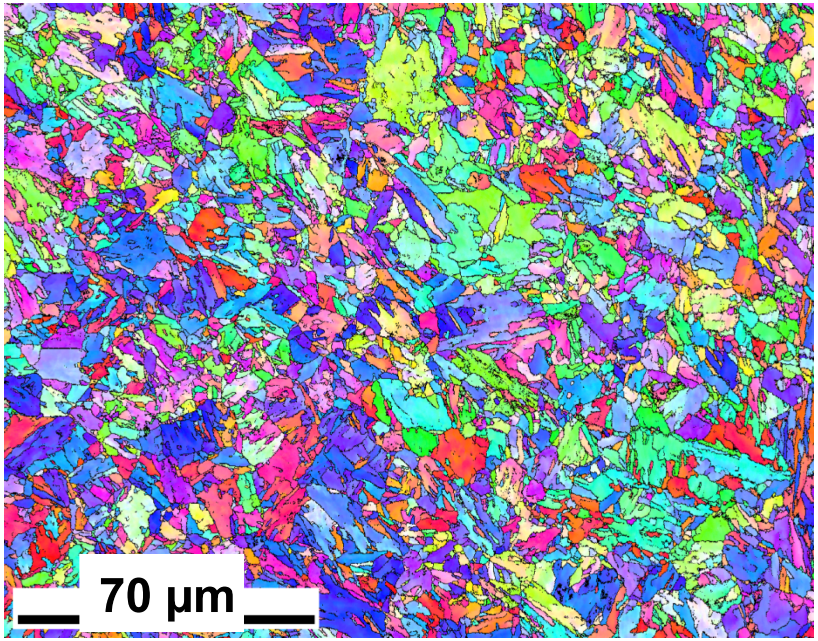
EUROFER

Extreme TMT



1250°C/30 min + TMT at 800°C + 750°C / 2h

Standard Heat Treatment



1050°C / 30min + 750°C / 2h

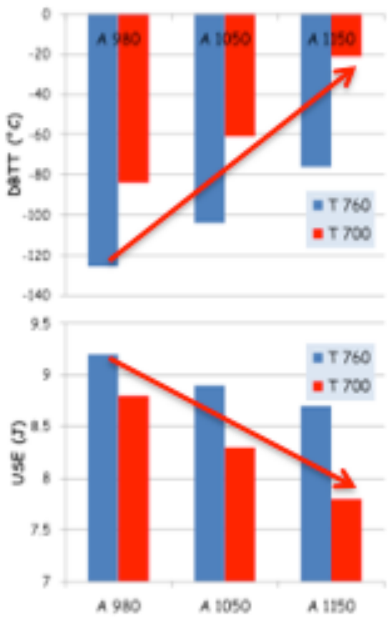
- Very large prior austenite grains (0.5-1 mm)
- But fine martensite laths

Advanced Steels: High Temp. Applications

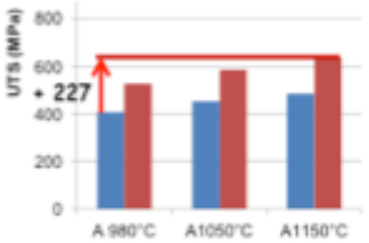
Adjustment of EUROFER properties by varying heat treatment temperatures

- **Austenitisation: 980 °C – 1150 °C**
- **Tempering: 700 °C – 760 °C**

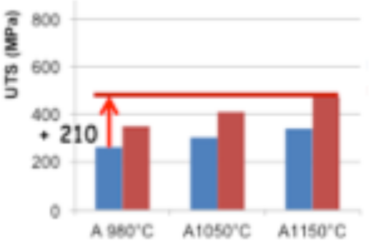
Charpy Properties



Tensile Strength

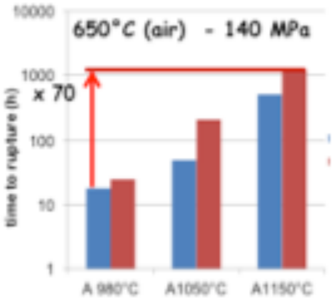


T_{test}: 550°C



T_{test}: 650°C

Creep Strength



J. Henry, CEA

Advanced „EUROFER-type“ Steels

Development of RAFM steels for high temperature applications

- Special thermo-mechanical treatments (TMT, „aus-forming“, …)

TMT at OCAS, Gent, Belgium

Advanced „EUROFER-type“ Steels

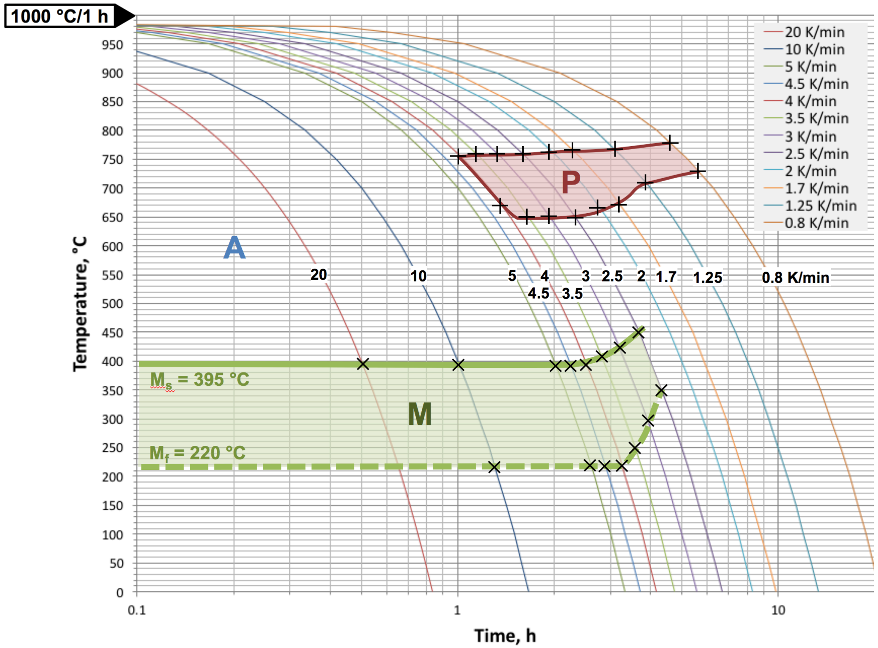
Optimization of RAFM steels for possible water cooling

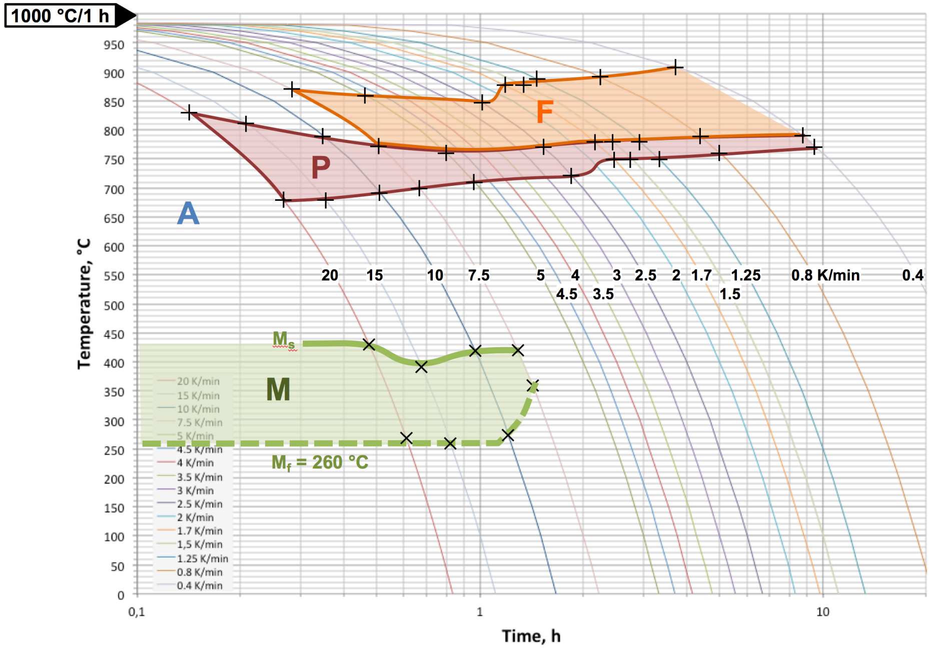
- Change of chemical composition
- Specific thermal treatments (for optimum DBTT)

Several batches have been produced CSM, Italy

Effect of Carbon Content on Phase Transformation

CCT Diagrams

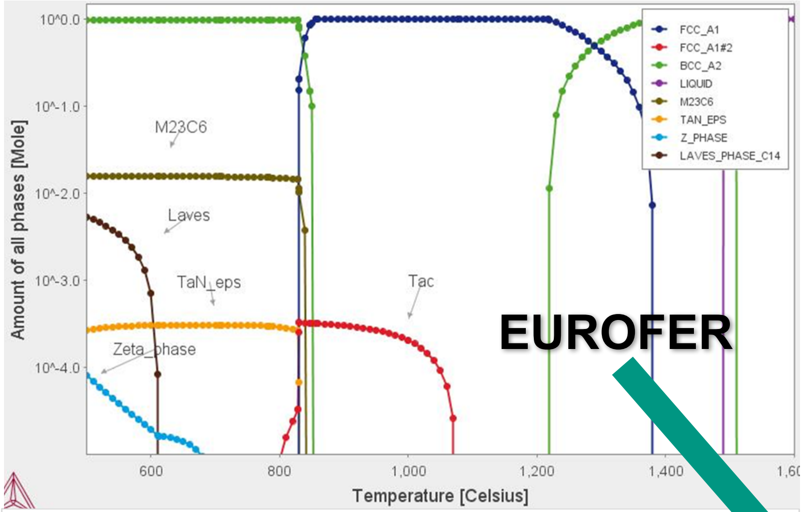




Advanced „EUROFER-type“ Steels

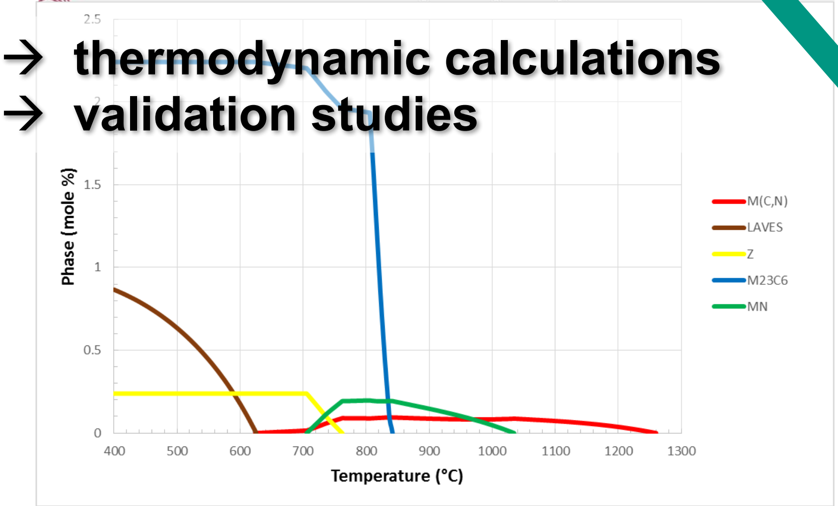
Development of RAFM steels for high temperature applications

- Fine tuning of the chemical composition



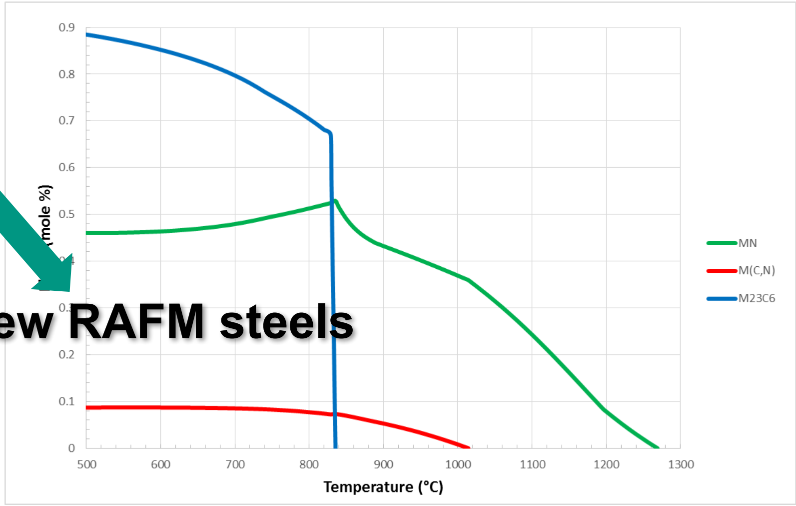
EUROFER

Many batches have been produced at OCAS, Belgium



→ **thermodynamic calculations**

→ **validation studies**

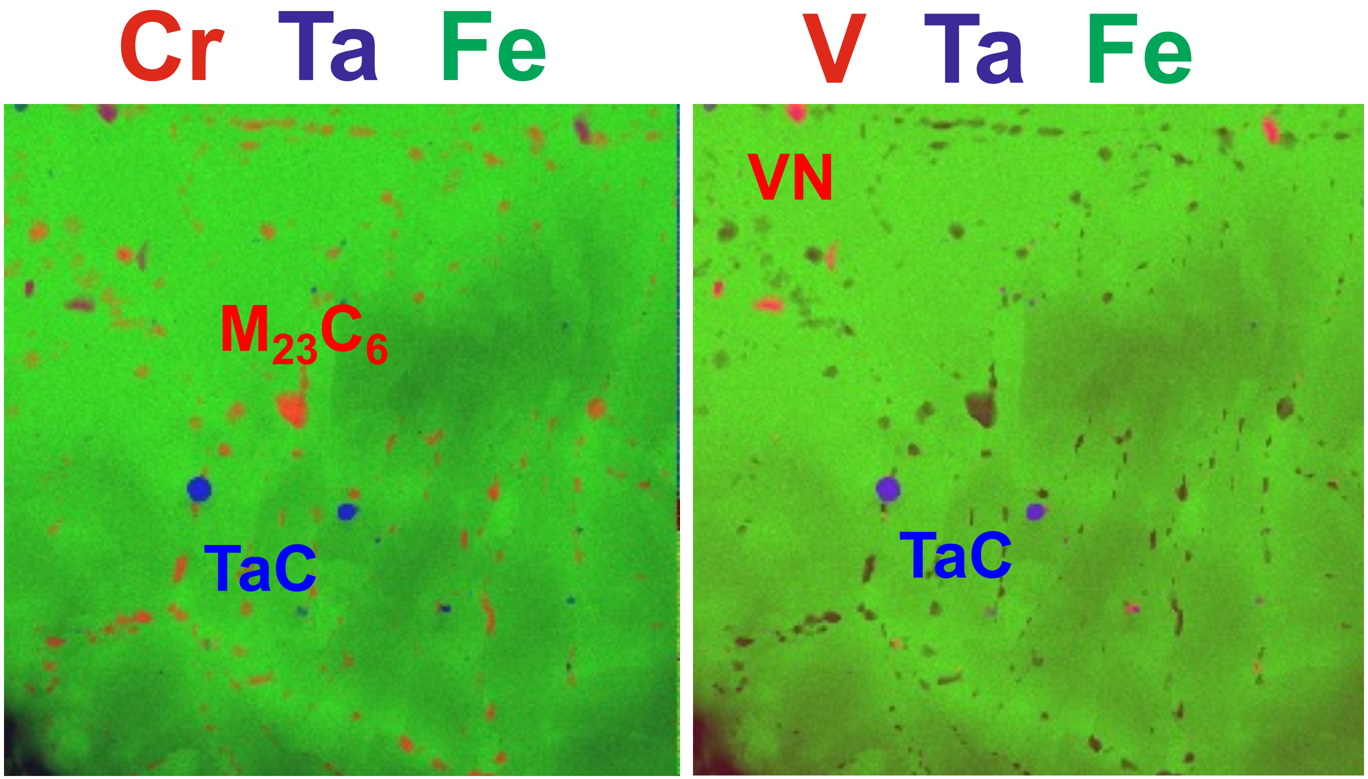


new RAFM steels

Validation Studies for Thermodyn. Mod.

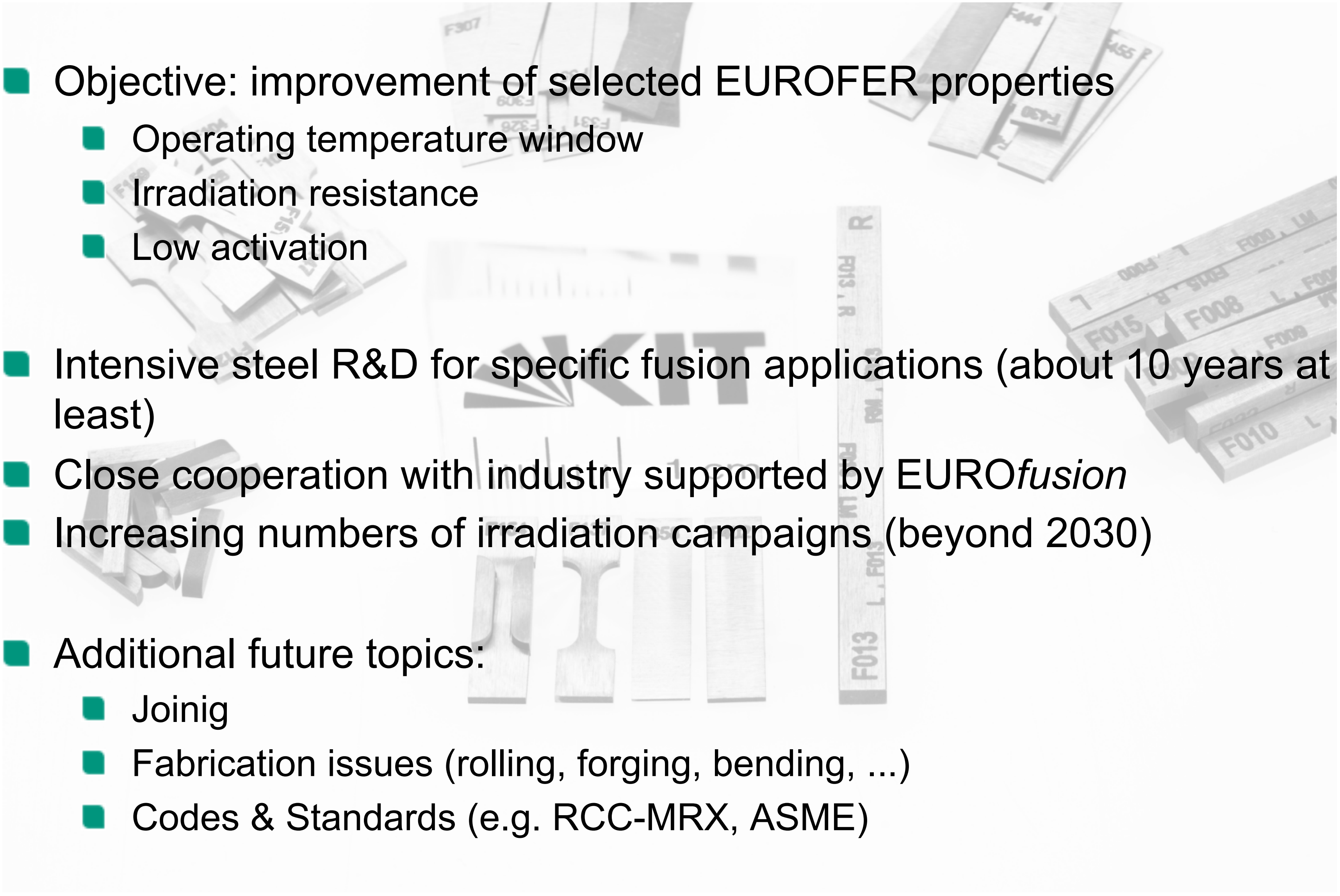
TEM studies on aged Eurofer samples

→ 30000 h, 550-600 °C: **Is there Z phase Cr_2TaVN_2 ?**



- → **Precipitation maps**
- → **Correct parameters for simulation**

Outlook



- Objective: improvement of selected EUROFER properties
  - Operating temperature window
  - Irradiation resistance
  - Low activation

- Intensive steel R&D for specific fusion applications (about 10 years at least)
- Close cooperation with industry supported by EURO*fusion*
- Increasing numbers of irradiation campaigns (beyond 2030)

- Additional future topics:
  - Joinig
  - Fabrication issues (rolling, forging, bending, ...)
  - Codes & Standards (e.g. RCC-MRX, ASME)


HAPPY BIRTHDAY

CONGRATULATIONS, OCAS !!!

Austrian Academy of Sciences
AUSTRIA

Ecole Royale Militaire Laboratory for Plasma Physics
BELGIUM

Ruđer Bošković Institute
CROATIA

Technical University of Denmark
DENMARK

University of Tartu
ESTONIA

Technical Research Centre of Finland
FINLAND

Commissariat à l'énergie atomique et aux énergies alternatives
FRANCE

GERMANY

GERMANY

Max-Planck-Institut für Plasmaphysik
GERMANY

National Center for Scientific Research "Demokritos"
GREECE

Wigner Research Centre for Physics
HUNGARY

Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile
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SPAIN

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SWEDEN

Foundation for Fundamental Research on Matter
THE NETHERLANDS

UNITED KINGDOM

wpMAT

Partners:

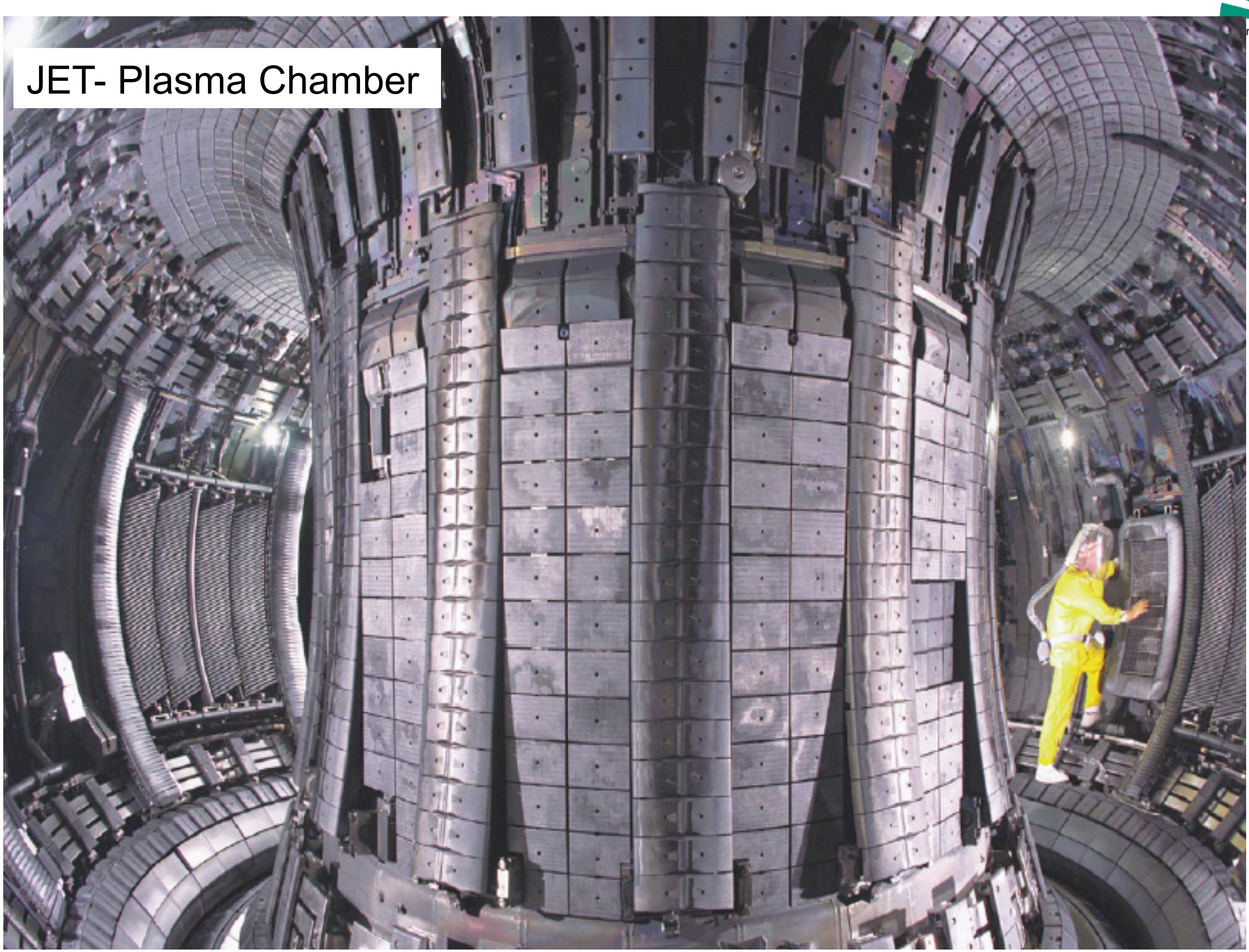
FRANCE

F4E
SPAIN

and joined universities

Additional Slides

Tokamaks

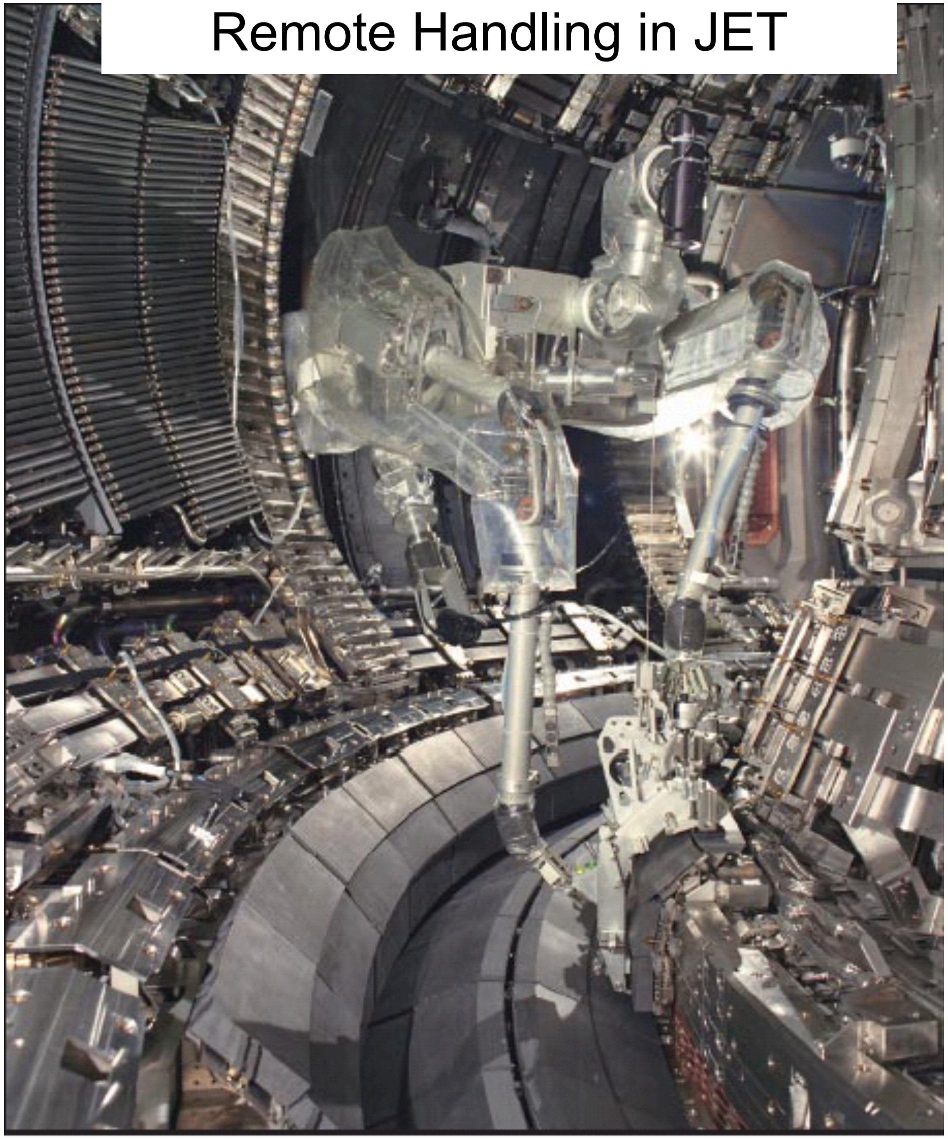


JET- Plasma Chamber

Tokamaks

Plasma Operation in JET

Remote Handling in JET

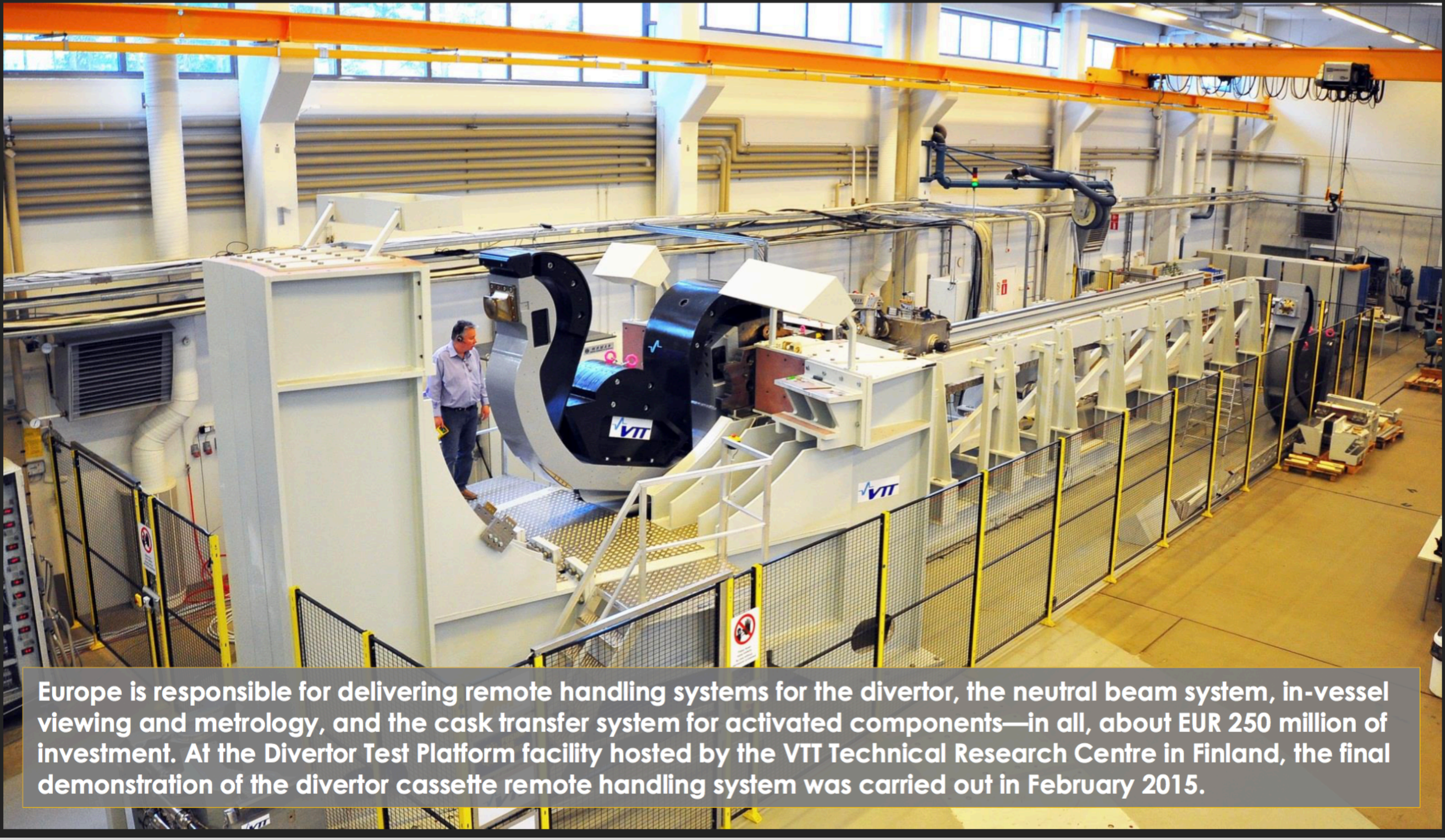


Worksite progress

September 2015

Manufacturing progress

Europe



Europe is responsible for delivering remote handling systems for the divertor, the neutral beam system, in-vessel viewing and metrology, and the cask transfer system for activated components—in all, about EUR 250 million of investment. At the Divertor Test Platform facility hosted by the VTT Technical Research Centre in Finland, the final demonstration of the divertor cassette remote handling system was carried out in February 2015.

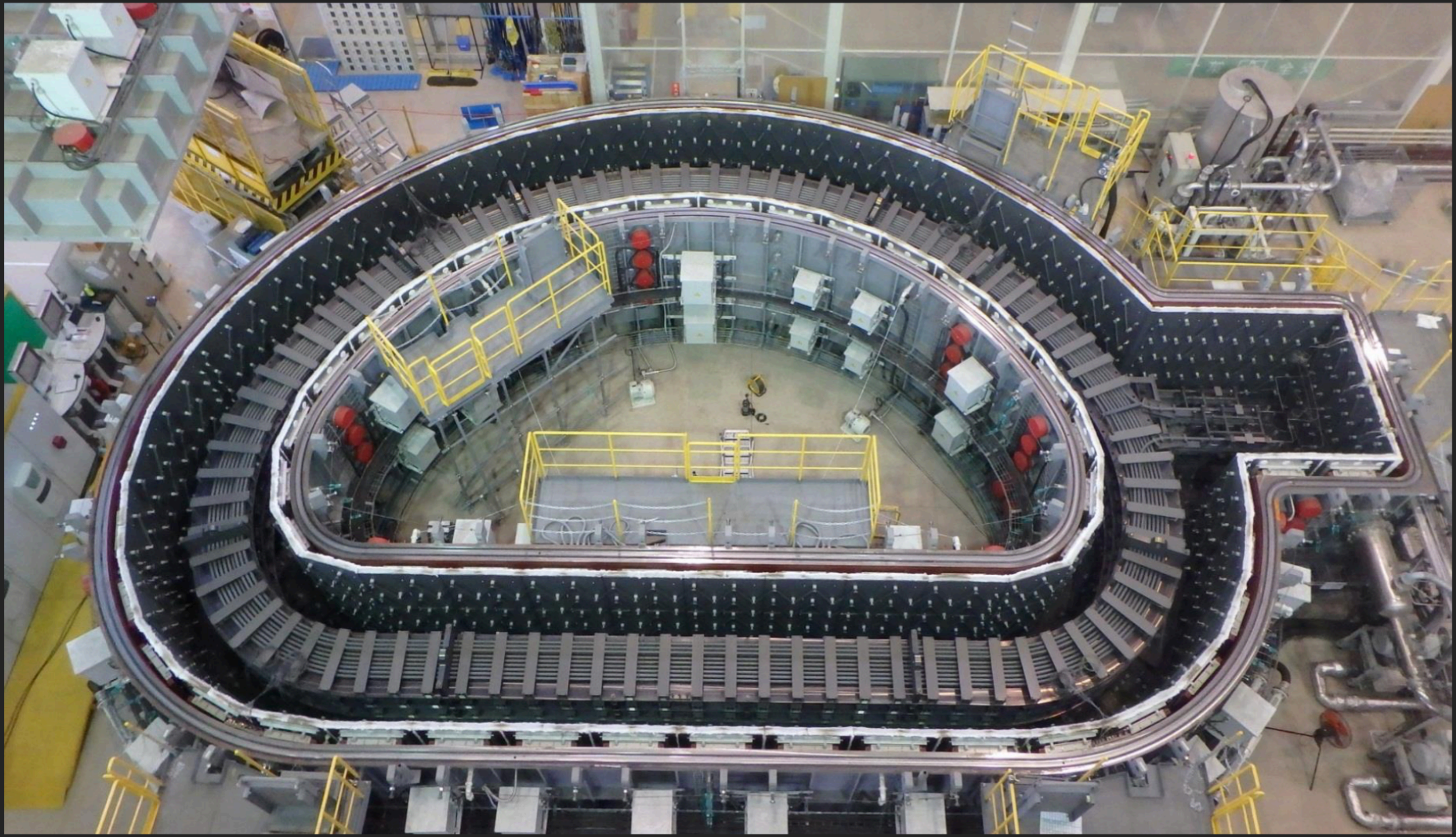
Manufacturing progress

India

India is responsible for the fabrication and the assembly of the 30 x 30 m. ITER cryostat. Pictured, six 60° base plates are temporarily assembled at the factory in order to check tolerances prior to shipment to ITER. The first cryostat elements are scheduled to arrive at ITER in November 2015.

Manufacturing progress

Japan



Japan is manufacturing half of the 18 giant toroidal field coils needed for ITER. Here, the D-shaped pancake windings are heat treated at 650 °C for 100 hours to react tin and niobium to form the superconducting compound niobium-tin.