ITER Superconducting Magnets

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Table of Content

Introduction

1) Basic superconductivity concept

- Certain metals become perfect conductors of electricity when cooled down to cryogenic temperatures in the range of 4-80 K.
- The superconducting state appears quite abruptly below a critical temperature *Tc* typical for each material.
- Not only the electrical resistance of the base material is very small, but below Tc is absolutely zero.
- But each material has different current-carrying capability (Jc = critical current density in A/mm^2) vs. applied magnetic field, stress and strain, etc.
- Adequate "temperature margin" shall be taken in the conductor design to control an abrupt phenomena called "quench", where the superconductor state suddenly changes back into resistive, with a fast large release of energy and heating of the coolant and conductor (protection system required).

2) Why superconductivity for fusion magnets?

- It allows steady state and pulsed operation at high magnetic fields with very low consumption of energy (except for refrigeration costs).
- Main developments for use of superconducting devices for accelerators (HEP) and MRI/NMR medical magnets started in the 1970s.

Main Types of Superconducting Materials

Low Temperature Superconductors (LTS) – Main applications: fusion, high energy physics, MRI/NMR magnets (~70% of production), etc.

- **NbTi**, operation up to 6-7 T, no need for heat treatment
- **Nb_3Sn**, operation up to 14 T, heat treatment at 650 °C for 100-200 h required to become superconductor (before or after winding)
- **Nb_3Al**, operation up to 14 T, no need for heat treatment, base material & manufacturing process very expensive due to special technology

→ Nb3Sn wires: four competing technologies

- Bronze route
- Internal tin diffusion
- Powder in tube
- Sn-Ta route

** Even 50 years after the discovery of Nb3Sn, there is still potential to improve Jc*

High Temperature Superconductors (HTS) – Main applications: small research or MRI magnets, high energy cables, switches, transformers, current leads, etc.

- **Bi-2212:** round wire (RW), operation up to 10-15 T at 20 K operating temperature
- **YBCO:** coated conductor, operation up to 16 T at 77 K operating temperature
- **MgB2:** operation still limited to a few T, 20-30 K operating temperature
- **RE Iron Arsenides:** fairly new material

The Discovery of Superconductivity 1911

The Nobel Prize in Physics 1913

"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"

Heike Kamerlingh Onnes

the Netherlands

Leiden University
Leiden, the Netherlands

b. 1853
d. 1926

•http://www.nobel.se/physics/laureates

LOW TEMPERATURE STUDIES: LIQUID HELIUM 321

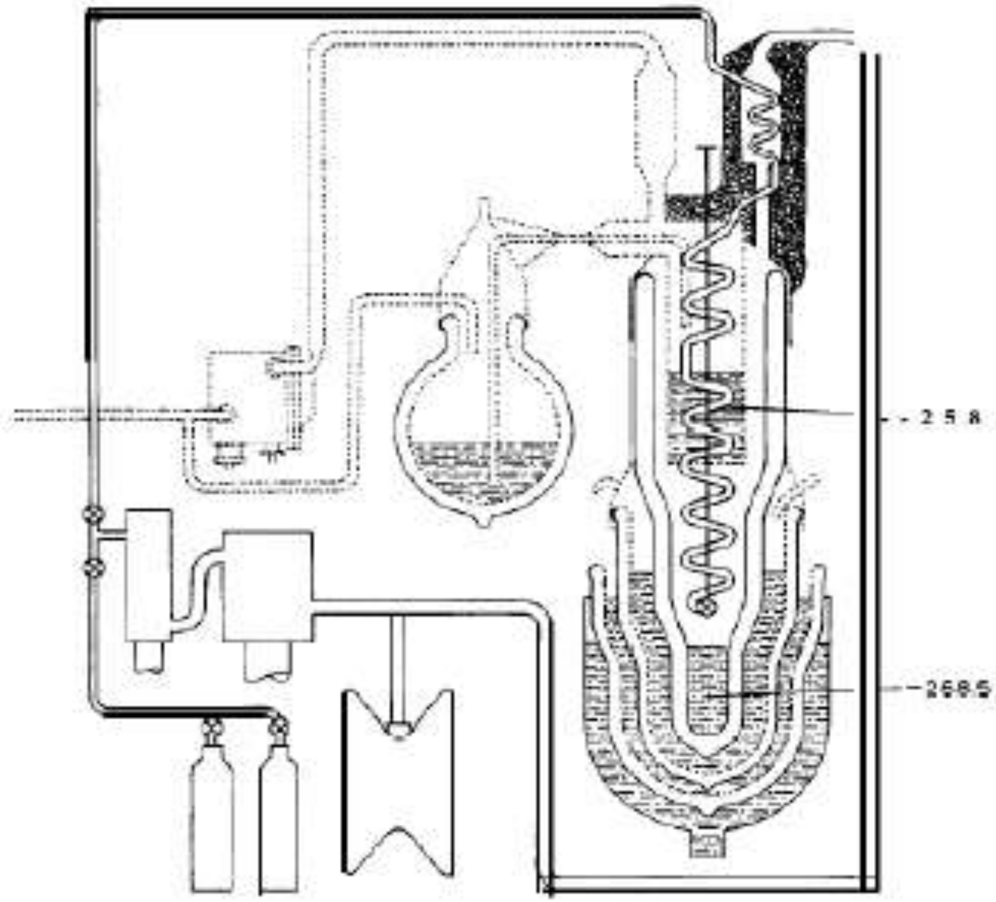


Fig. 7.

Section 1.

Superconductor Applications for Fusion

Superconductivity for Fusion Magnets

- The development of superconducting magnets for fusion has been started in the 1970s (i.e. T-7 and T-15 at Kurchatov Institute with forced flow and flat cables embedded in Cu)

➔ In the quest to achieve higher magnetic fields and longer pulses

- Tore Supra and other superconducting devices with NbTi conductors have started operation in 1980s-1990s.

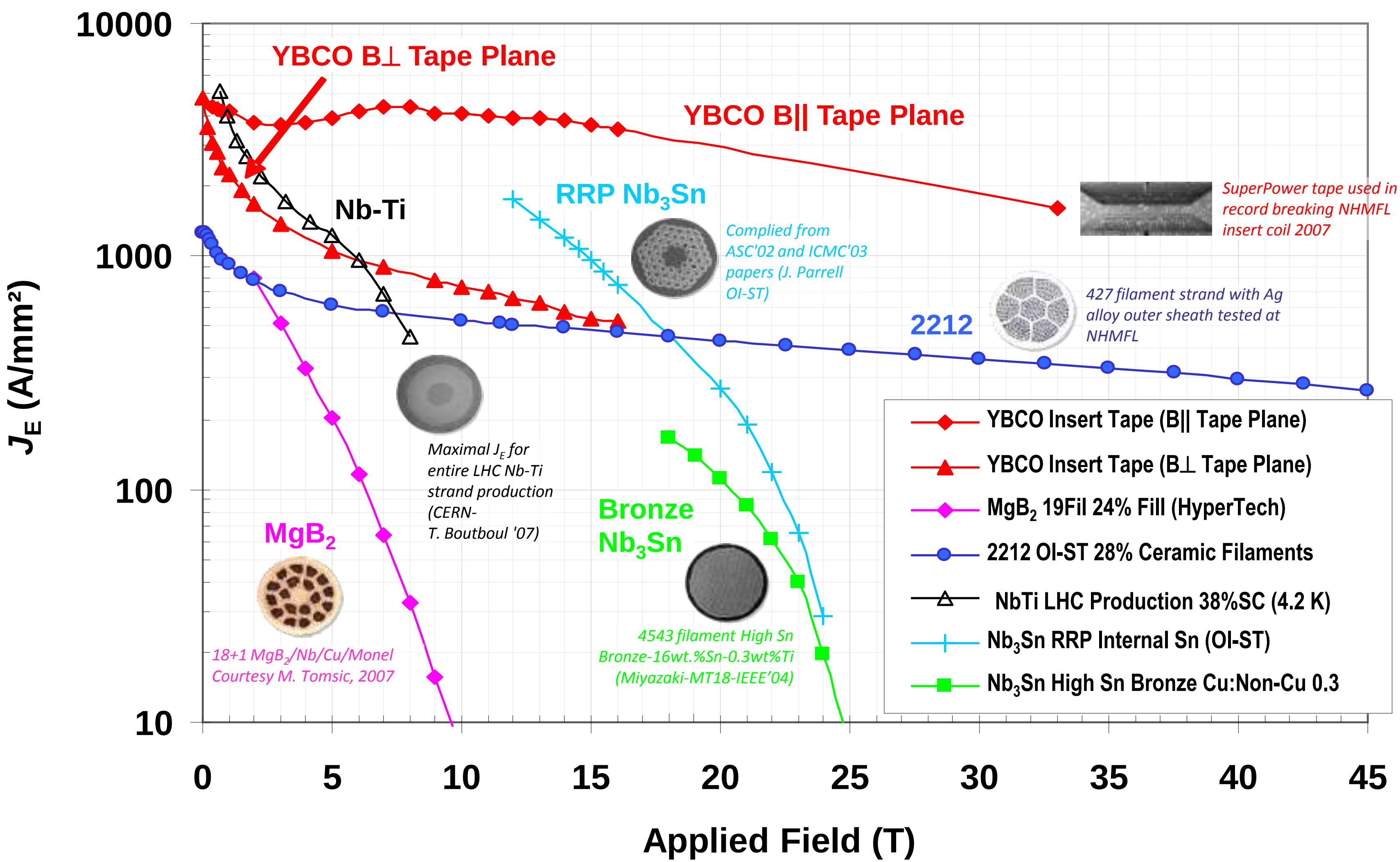
- Advanced multi-strand Nb_3Sn have been used to increase the operating magnetic fields.

- Cable-in-conduit conductors have been developed due to the large volume, energy and required stability for these magnets.

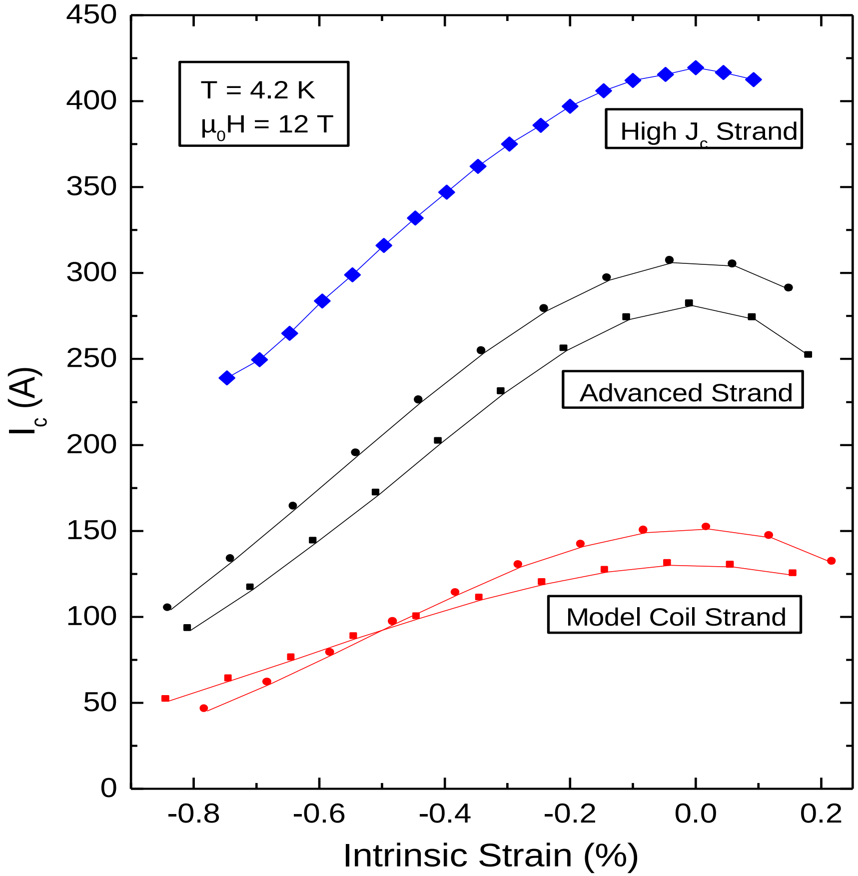
- The development of magnets for steady-state fusion devices has included, in between others, the 6 LCT coils in the 1980s, the POLO (EU) and DPC (JA-US) coils, and the ITER Model Coils in the 1990s.

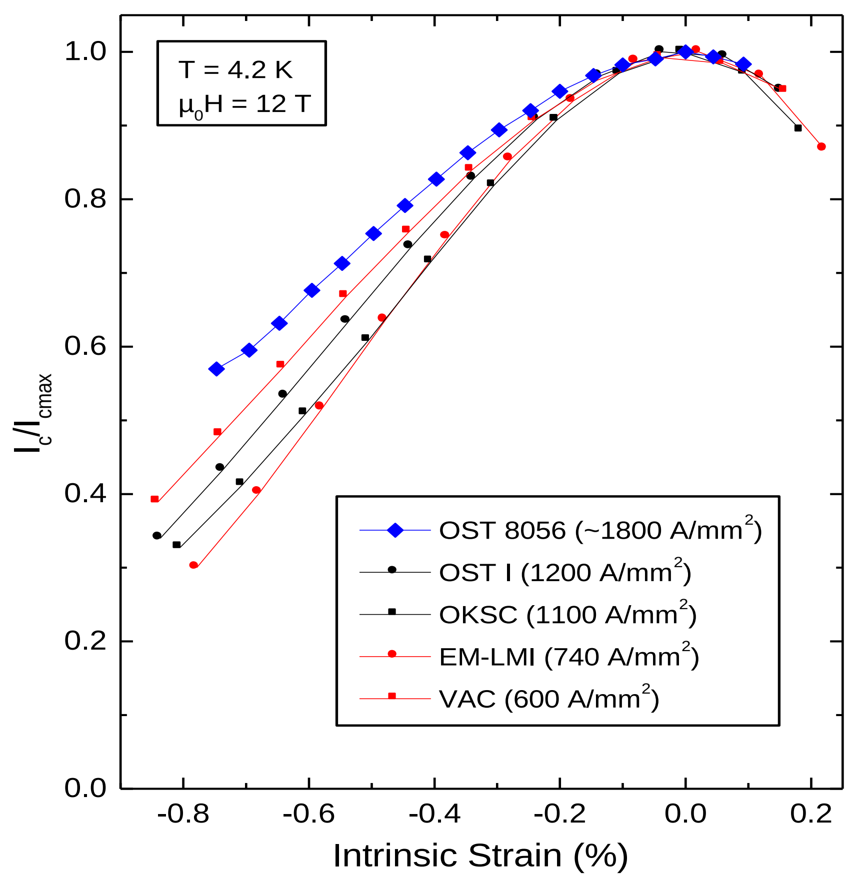
FUSION FOR ENERGY

Jc Improvement



Nb_3Sn Conductors: J_c Strain Sensitivity





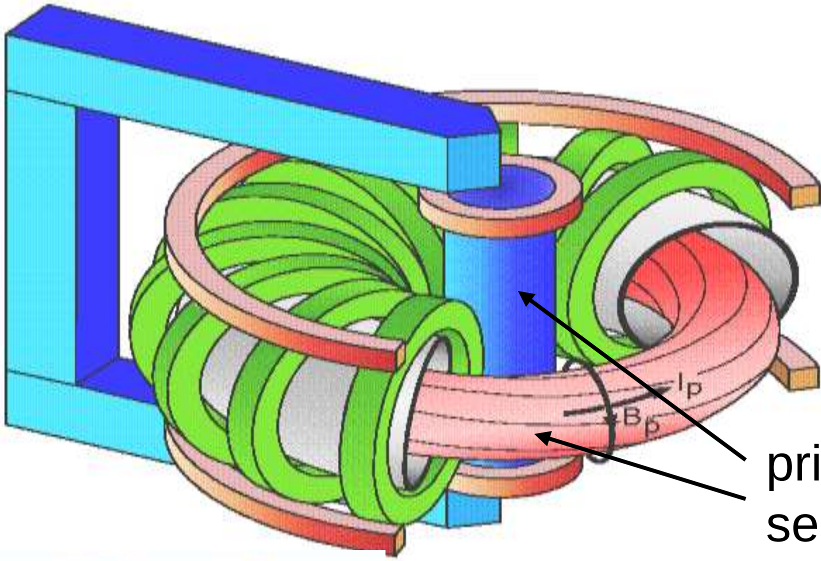
Courtesy of Durham Univ.

Section 2.

Magnetic Confinement Concepts

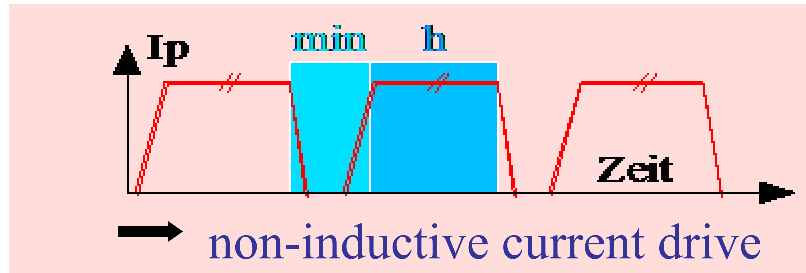
Toroidal Confinement Systems

Tokamak (ITER)



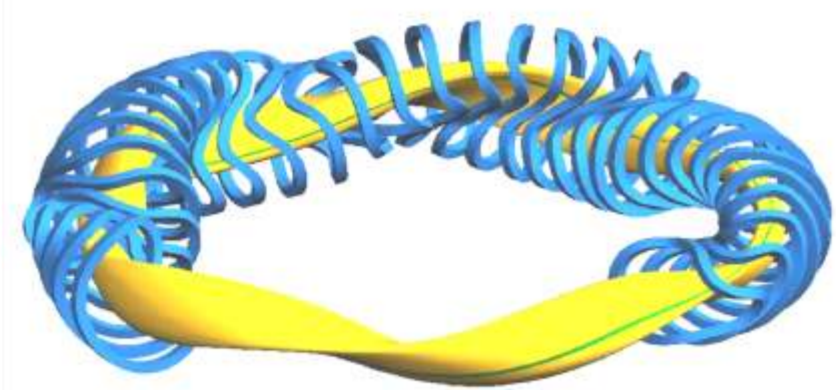
primary
secondary
winding

Transformer principle
Plasma current is induced
Discharges are pulsed



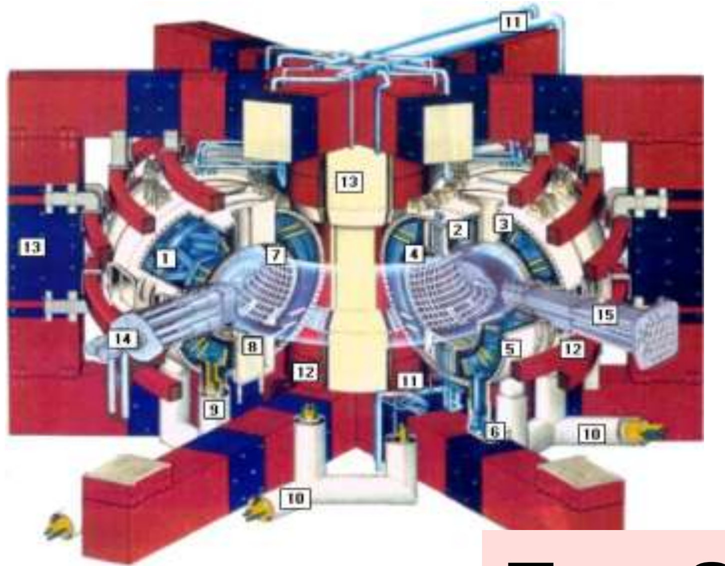
JET tokamak
(resistive)

Stellarator (W7-X) 3D



Steady-state configuration
No plasma current

Major Superconducting Tokamaks in the Worldwide Programme

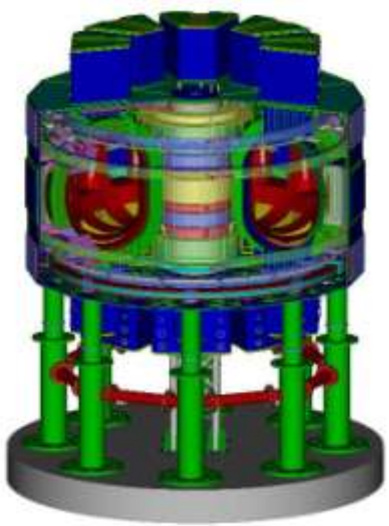


KSTAR

(Nb_3Sn/NbTi coils)

Tore Supra

(TF coils only)



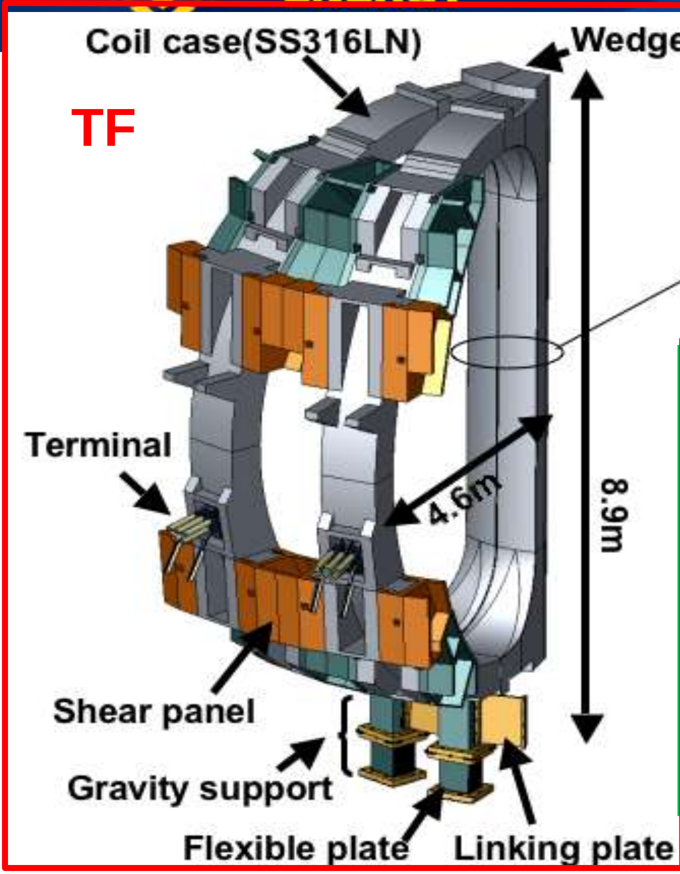
SST-1

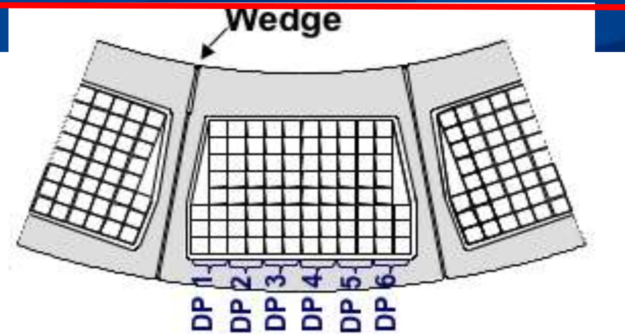
(NbTi coils)

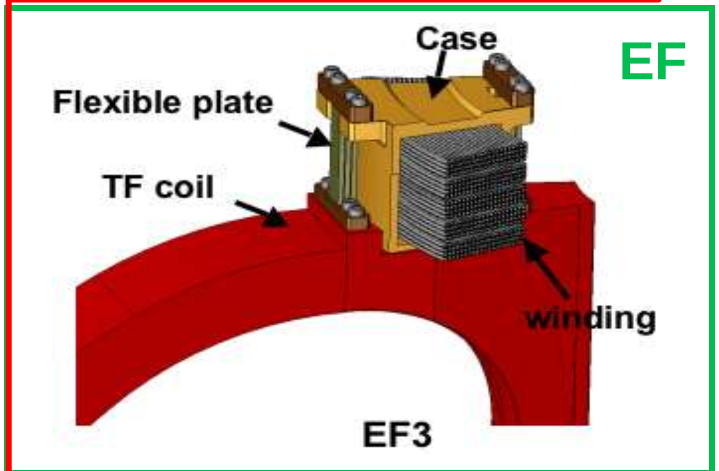
EAST

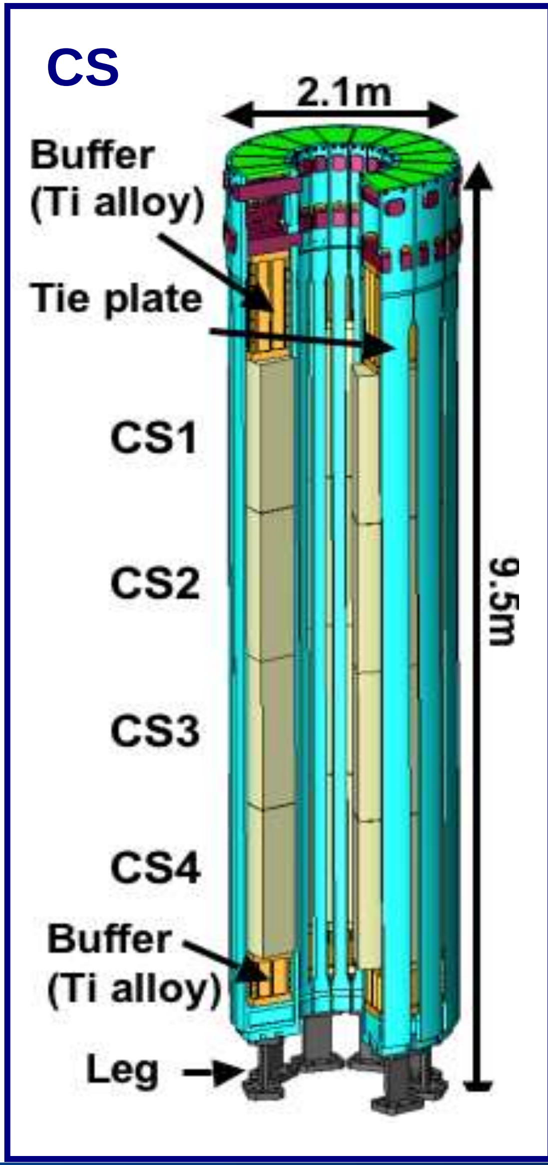
(NbTi coils)

JT-60SA Magnet System







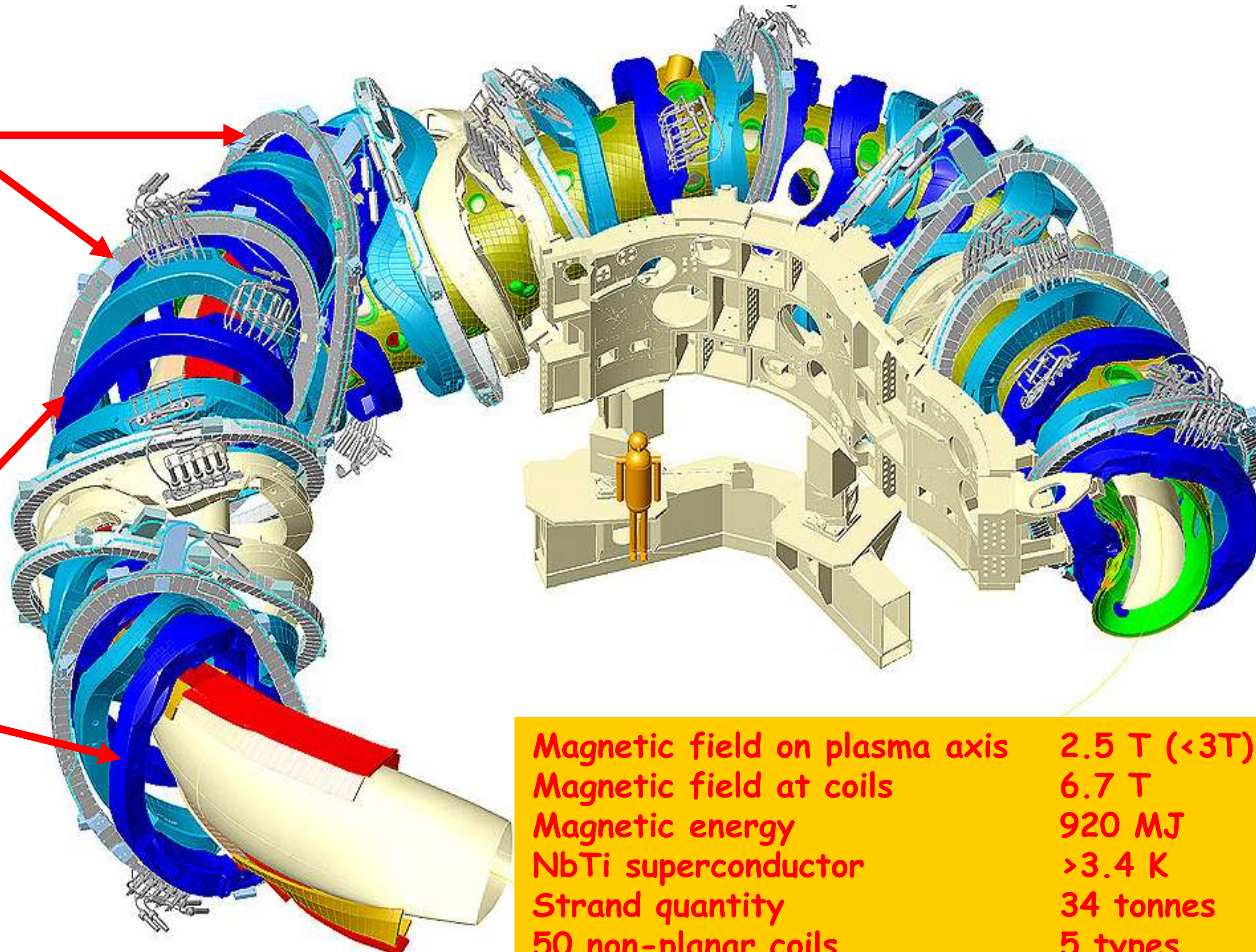


	TF	CS	EF
strand	NbTi	Nb_3Sn	NbTi
conductor	cable-in-conduit		
B_{max} (T)	5.7	8.9	6.2
T_{op} (K)	4.9	5.1	5.0
I_{op} (kA)	25.7	20	20

Bilateral EU_JA Collaboration (Broader Approach) ITER Satellite Tokamak, Naka (J)

W7-X Stellarator Magnet System

Planar coils
Nom. current 16kA@4K@6T



Non-Planar Coils
Nom. current 18.2kA@4K@6.7T

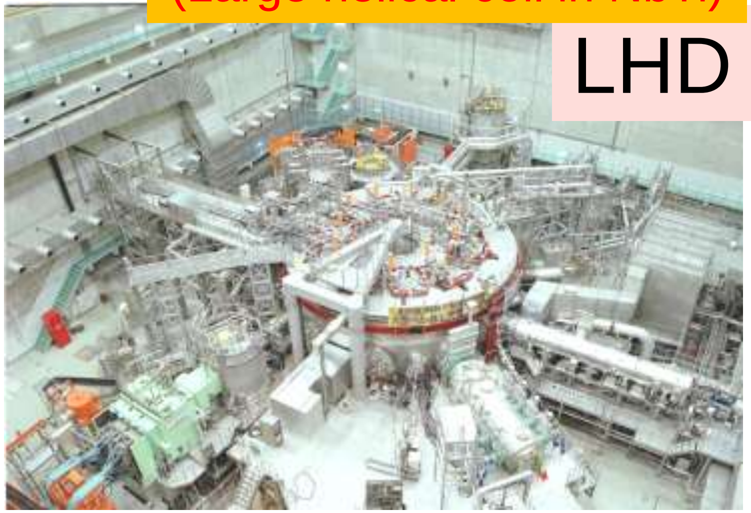
Magnetic field on plasma axis	2.5 T (<3T)
Magnetic field at coils	6.7 T
Magnetic energy	920 MJ
NbTi superconductor	>3.4 K
Strand quantity	34 tonnes
50 non-planar coils	5 types
20 planar coils	2 types

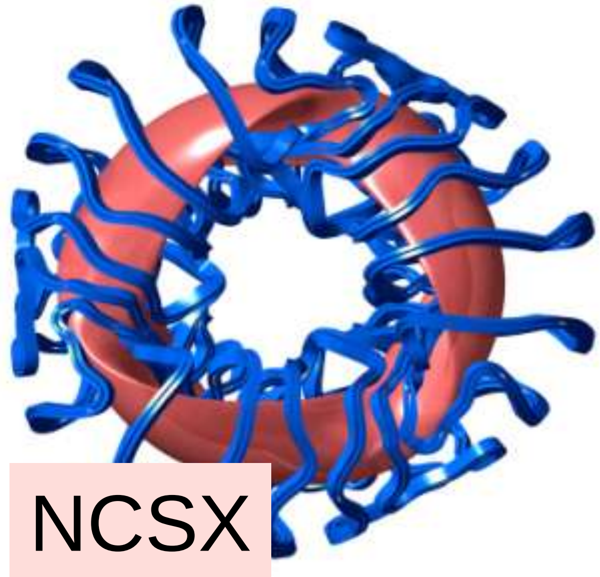
Under Assembly at IPP Greifswald (D), Operation in 2014

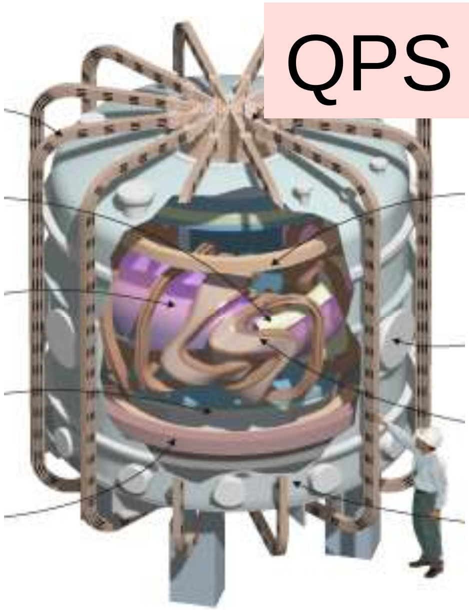
Courtesy of IPP

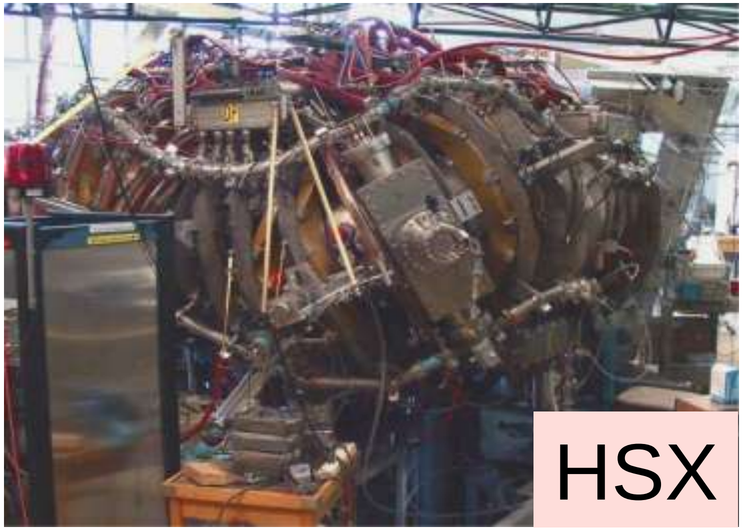
Major Stellarators in the Worldwide Programme

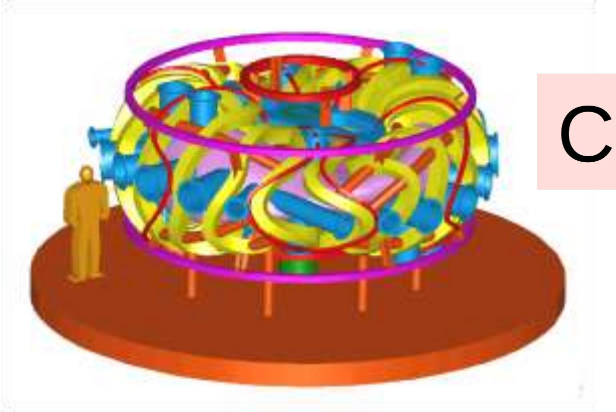
(Large helical coil in NbTi)











Section 3.

ITER Magnet Design

ITER Magnet Design Features

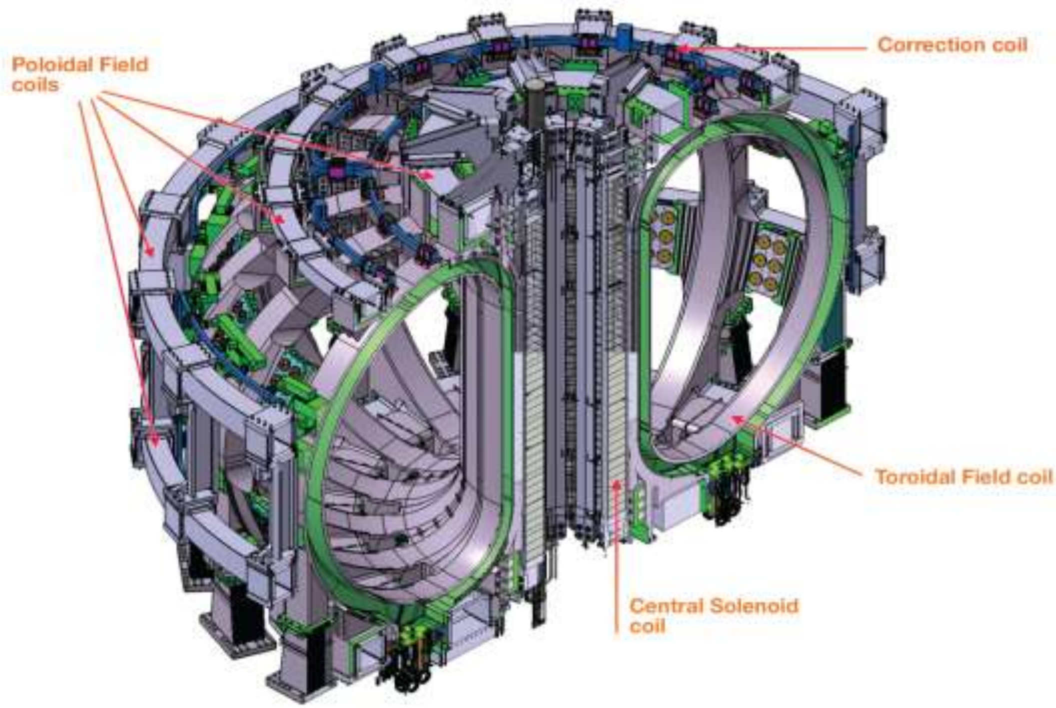
- TF & CS Coils use Nb_3Sn "cable-in-conduit" superconductor due to large operating field (TF 11.8 T, CS 13.0 T)
- TF Coils wound in double pancakes, thin wall circular conductors embedded in radial plates
- CS Coils wound in hexa- or quadru-pancakes with thick wall square conductors
- PF Coils are manufactured in NbTi, since operating field is <6.5 T, wound in double pancakes with square conductors
- Stainless Steel Jackets are used in the superconducting coils and they are designed to operate at high operating fields and for a large number of cycles (60,000)
- Stainless Steel TF Coil Cases with their intercoil structures form the main support structure of the magnet system
- Composite Pre-compression Rings at the inner leg of the TF coils to reduce tensile stresses and fatigue in the structures
- High Strength Insulated Shear Keys and Bolts for the mechanical connection at the inner and outer intercoil structures

ITER Magnet System

48 Superconducting Coils:

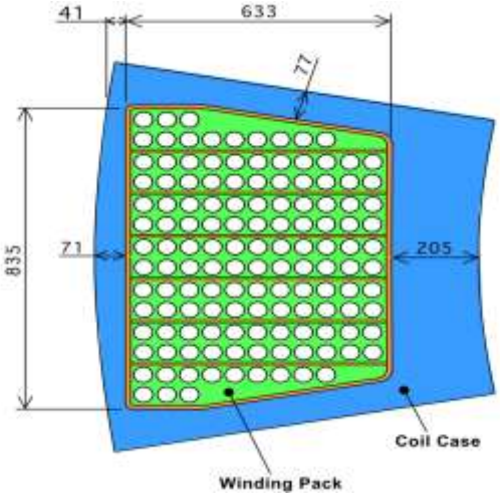
- **18 TF coils**
- **6 CS modules**
- **6 PF coils**
- **9 pairs of CC**
- **Feeders**

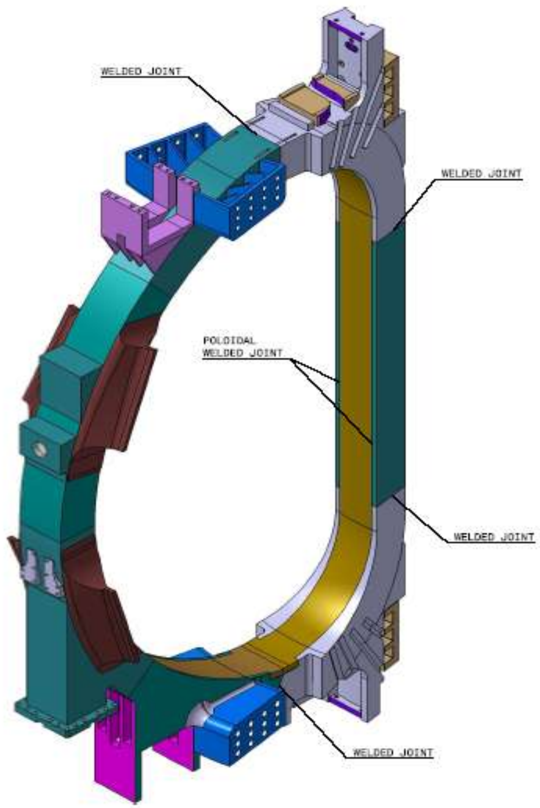
System	Energy GJ	Peak Field T	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85



(i.e. 41 GJ vs. 10.5 GJ magnetic energy in the 27 km tunnel of the Large Hadron Collider at CERN)

Toroidal Field Coils

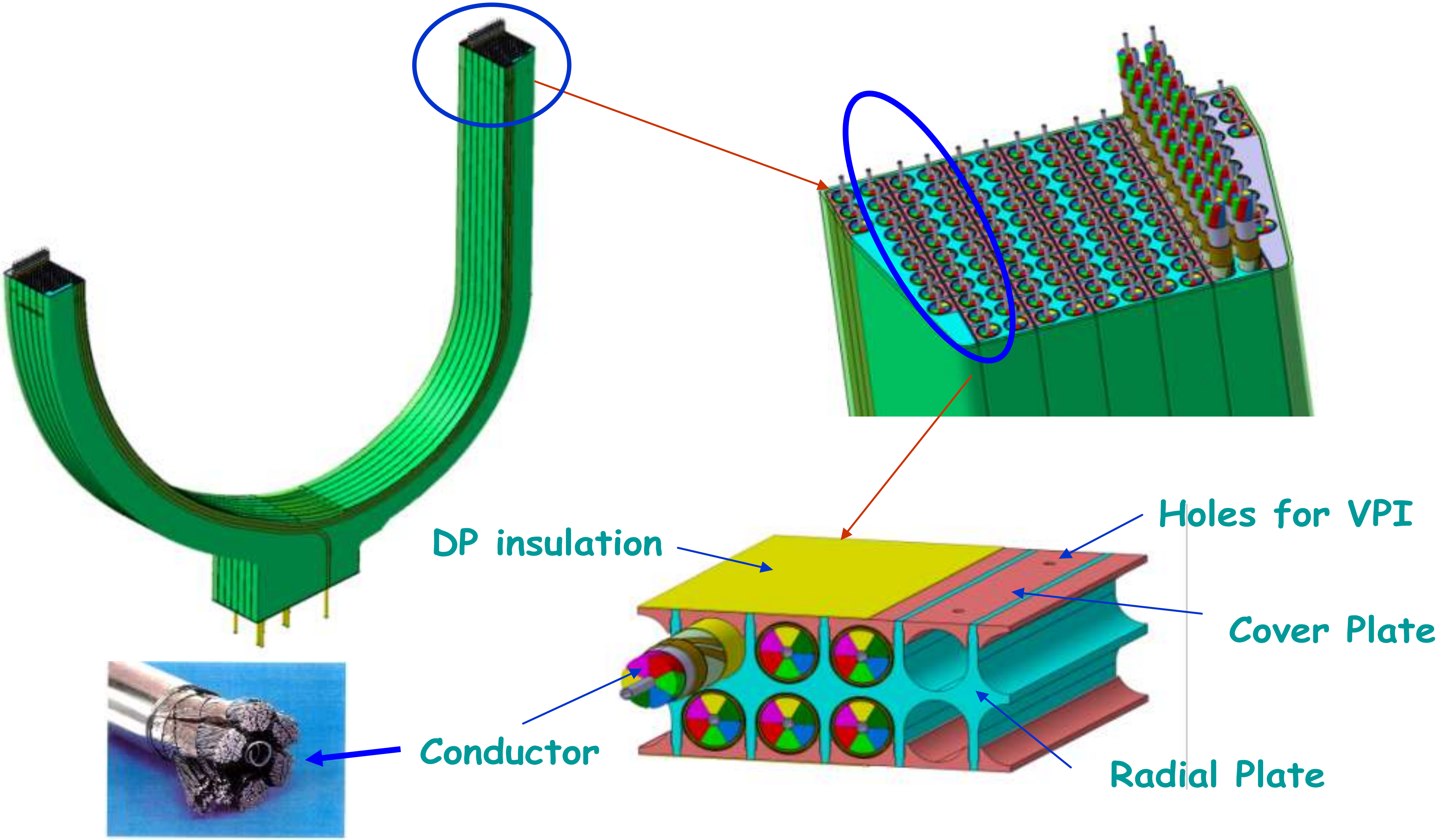




Number of coils	18
Total stored energy (GJ)	**~41**
Max. conductor field (T)	11.8
Superconductor	**Nb_3Sn**
Operating current (kA)	**68**
Operating temperature (K)	5
Number of turns	134
Height (m)	12.6
Weight (t)	~310
Centering force per coil (MN)	~400
Discharge time constant (s)	11
Max. voltage (kV)	7

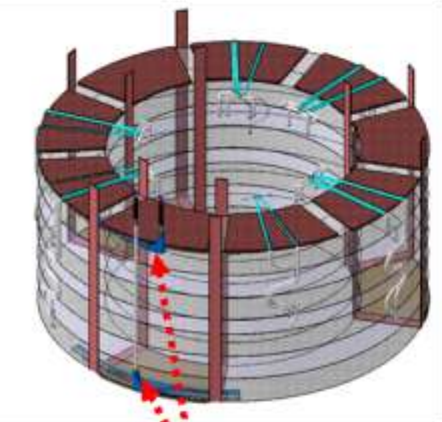
Design confirmation by Model Coil project launched in 1996

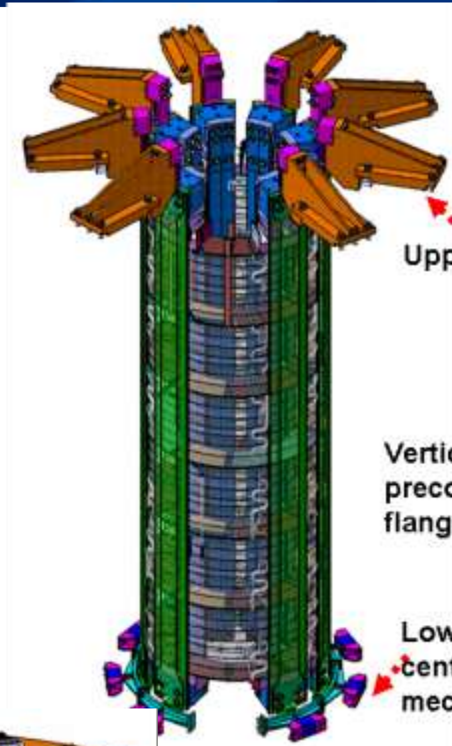
Construction of TF Winding Pack



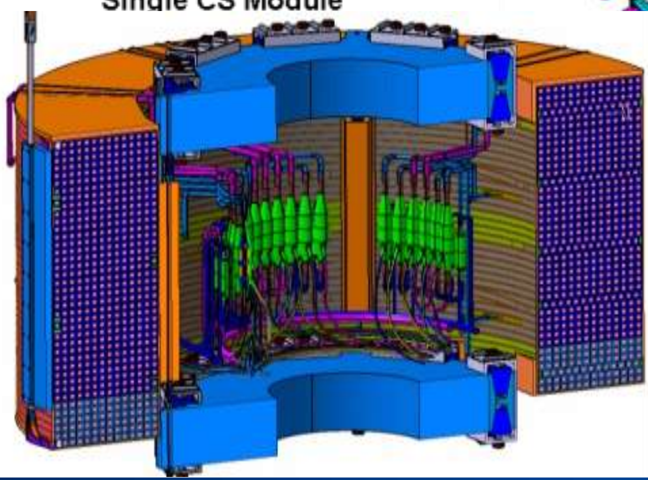
Fusion for Energy

Central Solenoid Coils





Single CS Module



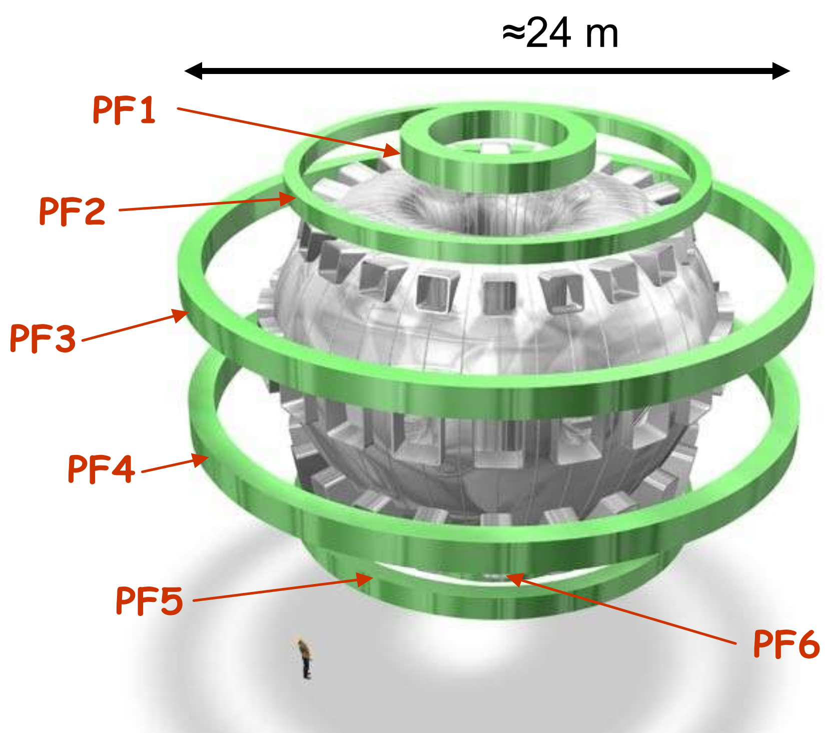
Number of modules	6
Total stored energy (GJ)	~6.4
Max. conductor field (T)	13
Superconductor	Nb_3Sn
Operating current (kA)	45
Operating temperature (K)	5
Turns per module	535
Total weight of all modules (t)	~980
Max. voltage to ground (kV)	20

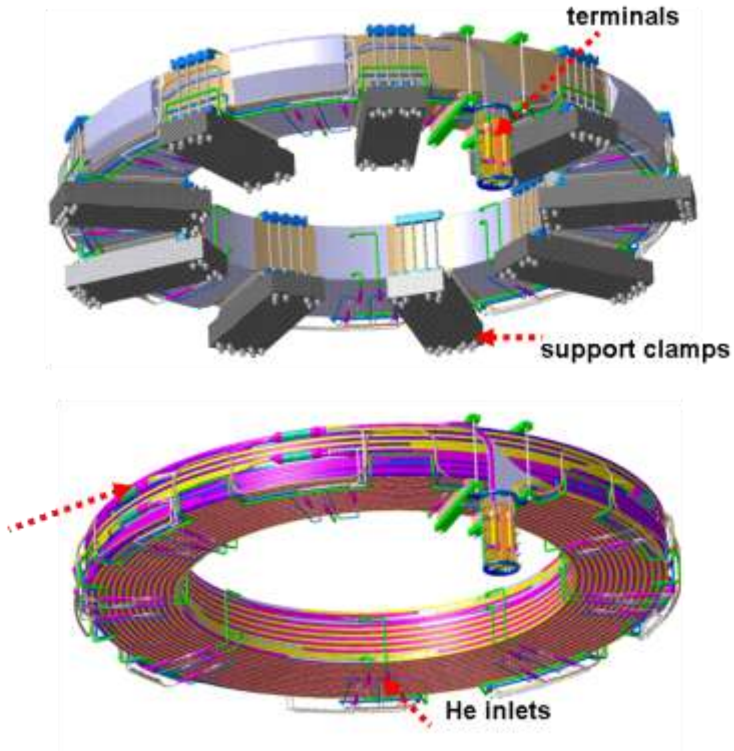
CS stack composed of 6 independently powered modules wound in hexa-pancakes

Detailed design phase in progress

Design validation through CS Model Coil tested in 2000, but new CS Insert required to confirm conductor performances under tensile hoop load conditions

Poloidal Field Coils





- **6 PF coils independently powered, wound in double pancakes**
  - Confine and shape the plasma
  - PF1 & PF6 control plasma vertical displacement
  - Conductor field limited to 6.5 T → **NbTi**, three grades of conductors depending on max. field
  - Coils are large (24 m diameter) but use of NbTi simplifies construction

Design validation through PF Insert Coil tested in 2008

Section 4.

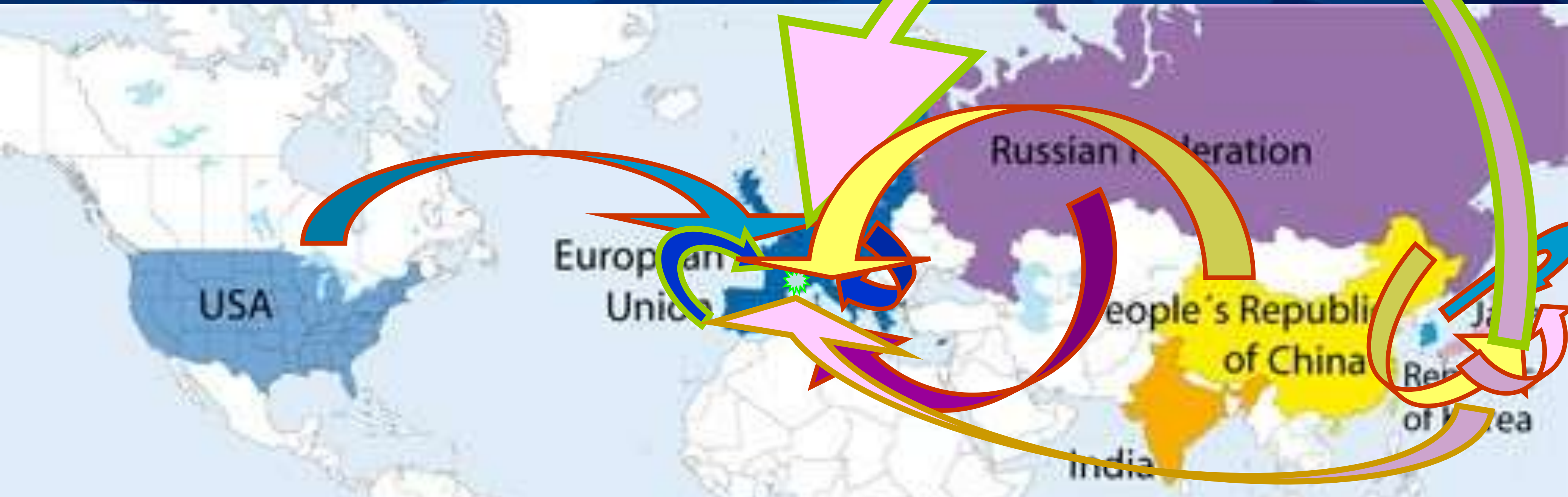
ITER Magnet Procurement Sharing

FUSION FOR ENERGY

Magnet Procurement Sharing

Component	IO	CN	EU	KO	JA	RF	US
TF Conductors		7%	20%	20%	25%	20%	8%
TF Windings + Insertion			10 coils		9 coils		
TF Case Sections					100%		
Pre-compression Rings			100%				
TF Gravity Supports		100%					
CS Conductors					100%		
CS Coils + Structure							7 coils
PF Conductors		65%	21%			14%	
PF Coils			5 coils			1 (PF1)	
PF Supports		100%					
CC Conductors		100%					
CC + Supports		18 coils					
Magnet Feeders		100%					
Instrumentation	100%						

19 Procurement Arrangements between ITER Organization (IO) and Domestic Agencies signed up to now, last one to be signed in Feb. 2011



TF Coil
- Japan
- Europe

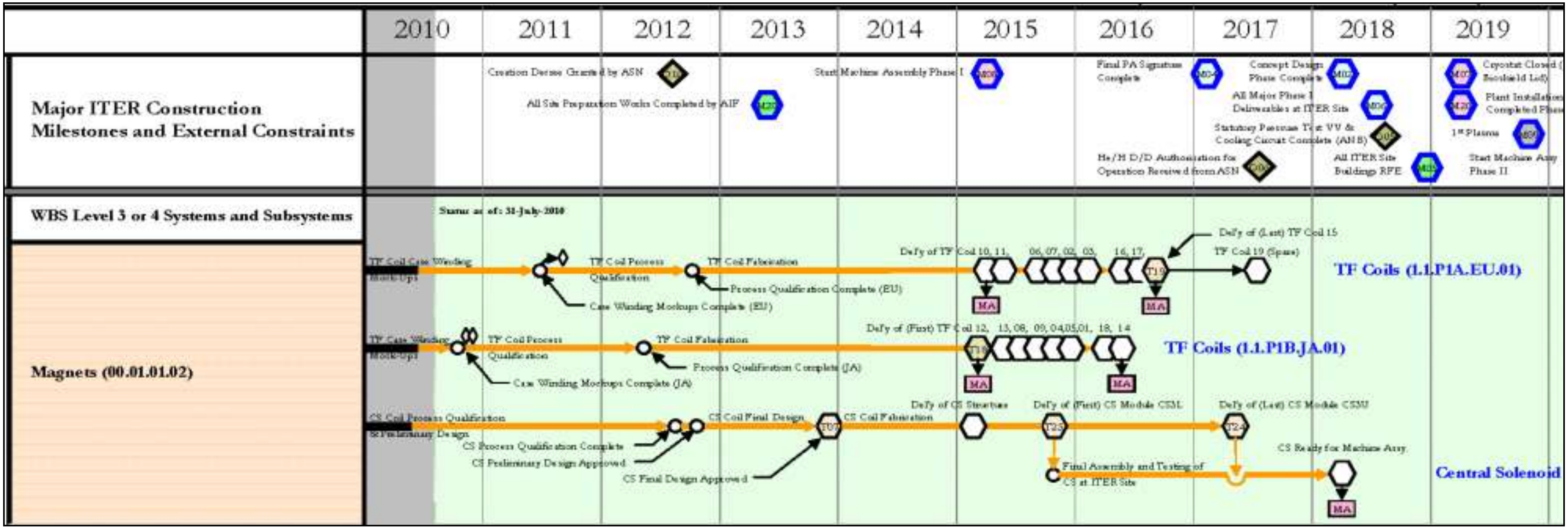
TF coil cases
- Japan

Conductor
- China
- South Korea
- Japan
- Russia
- United States
- Europe

TF Coil Sharing

(A Project Management Challenge…)

Another Big Challenge: the ITER Schedule



- 2 years qualification programme with the manufacture of mock-ups and dummy windings
- Delivery of the first conductors in 2010
- Start of installation of the first PF and TF coils in 2015
- Completion of the deliveries with the last PF coil and CS coils in 2017

➔ ***A true managerial and technological challenge ...***

Section 5.

Main Design Issues for Fusion Magnets

Main Design Issues for Fusion Magnets

- **Very high magnetic fields** (up to 13 T) with large operating currents (40-70 kA) → impact on **superconductor design and amount**

- **Large forces**:
  → Robust structural components
  → **Large steel fabrication** (welding, forging, etc.) with **tight tolerances**

- **Large nuclear heating** on conductor → impact on cooling requirements

- **Neutron irradiation** → impact on insulation selection

- **Large stored energy** → impact on conductor and design voltages

- **High electric voltage (in vacuum)** → impact on insulation selection and quality control procedures

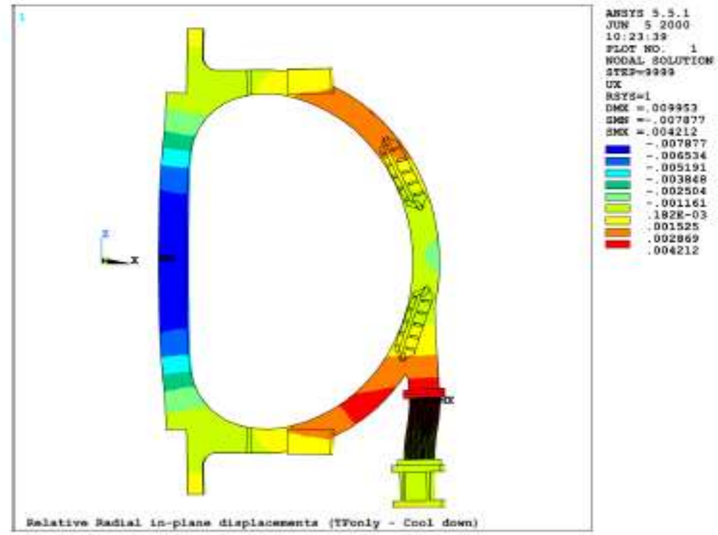
Mechanical Forces

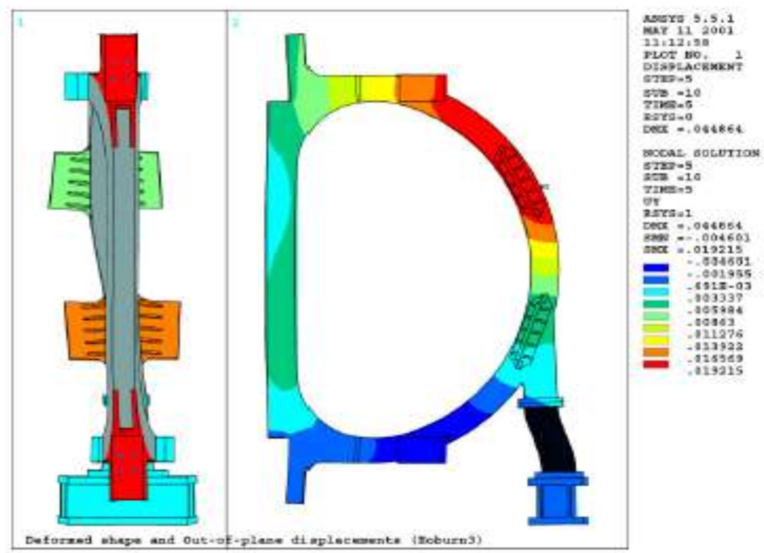
Very large electromagnetic forces on all magnets, i.e. for TF coils:

- In-plane forces:
  - 403 MN centripetal force
  - Wedged inner legs, outward forces in the outboard leg which induce an outward movement
- Out-of-plane forces:
  - Overturning moments

⇓

- TF radial expansion is mainly determined by the structure
- Mostly steel cross section
- Critical current density of superconductor at operating conditions has minor impact on the structure size





Bending Free Shape in a Toroid

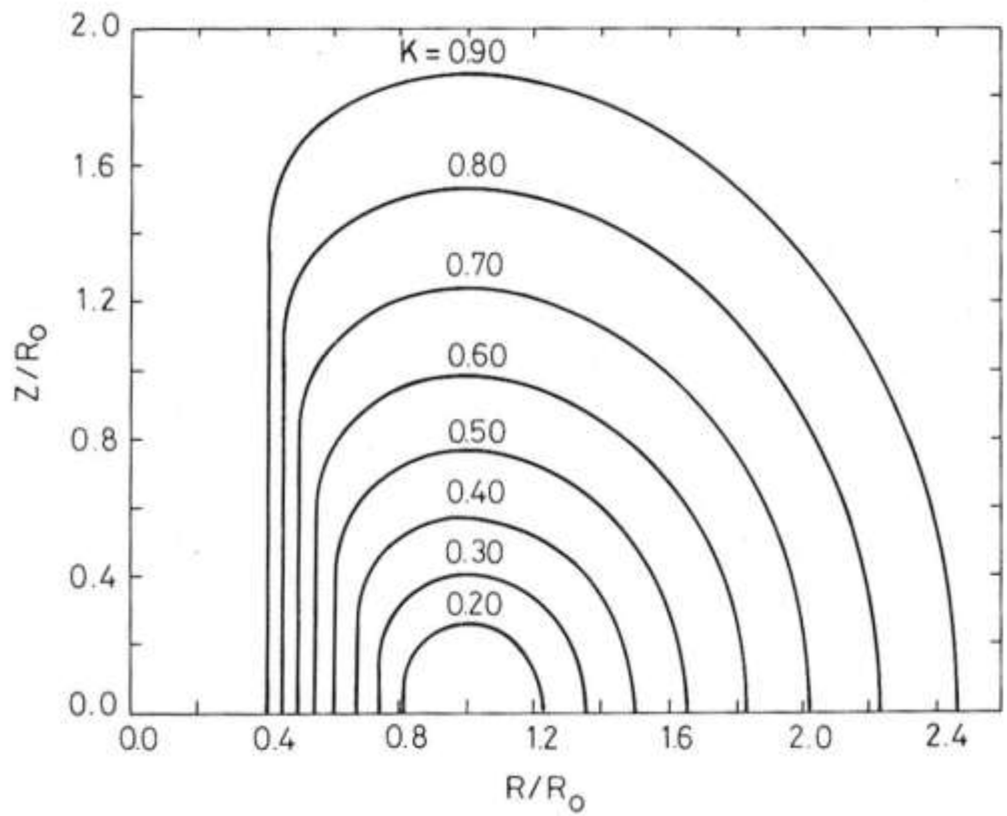
- In a toroidal system the field varies inversely to R → large bending stresses

- Since the field is equal to B(R)= BoRo/R, where R is the distance from the center of the torus, a way to maintain a constant tension along the coil is to shape it with the local radius of curvature ρ inversely proportional to B

- This reduces the bending effect to zero, plus allows to develop the tokamak TF coils into a D-shape and give more space to elongated plasmas

- Pure tension can be achieved on filaments, but on real coils with a finite thickness the approximation has to be refined to minimize the bending stresses

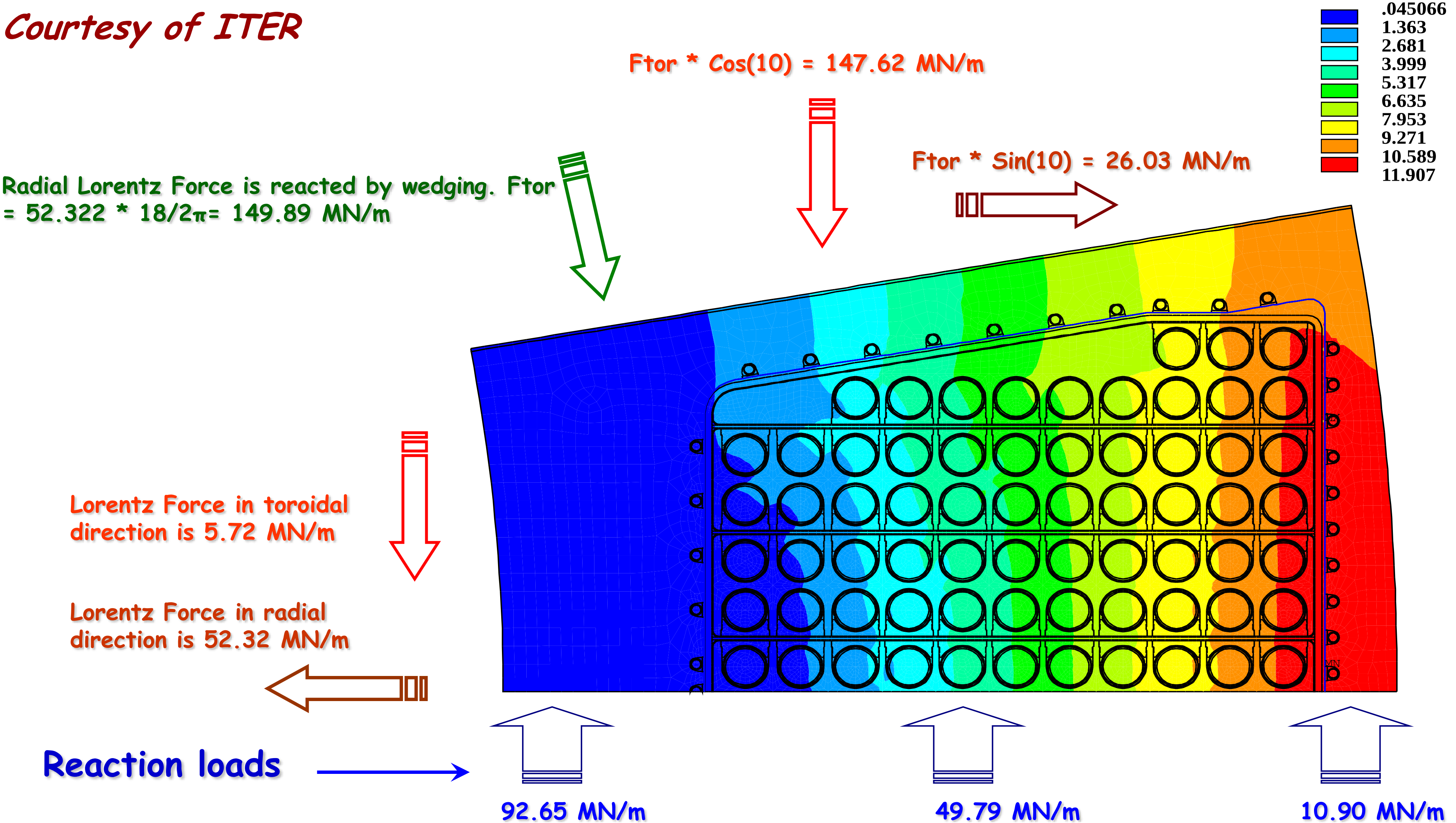
$$\rho = \left\{1+\left(\frac{dR}{dz}\right)^2\right\}^{3/2} \Big/ \frac{d^2R}{dz^2} = \frac{TR}{B_0R_0I} = KR$$



Inner Legs can be Wedged or Bucked against Central Coil to react net centripetal loads developed in the toroid

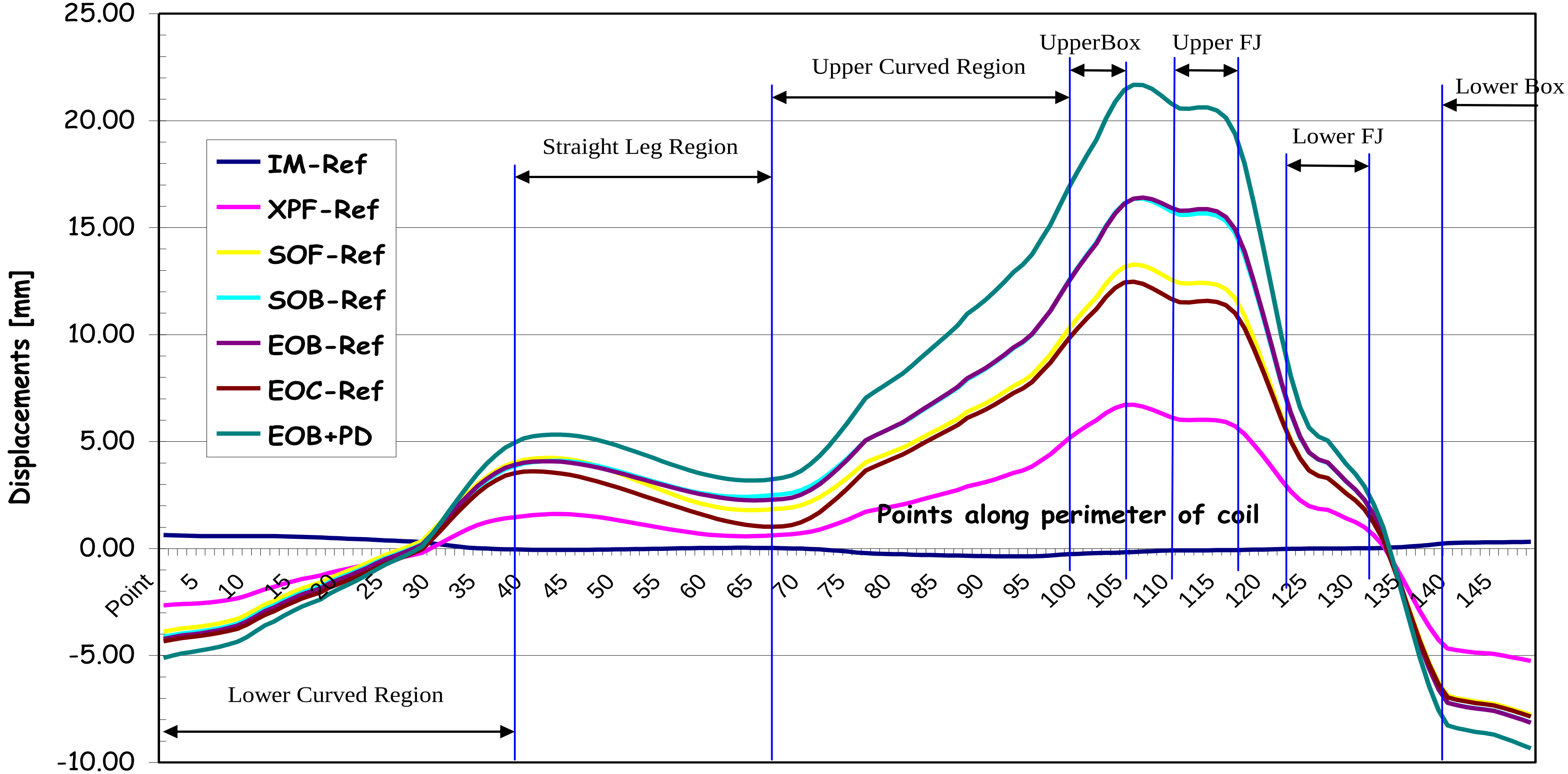
Force Equilibrium (Wedged)

Courtesy of ITER



Out-of-Plane Displacements

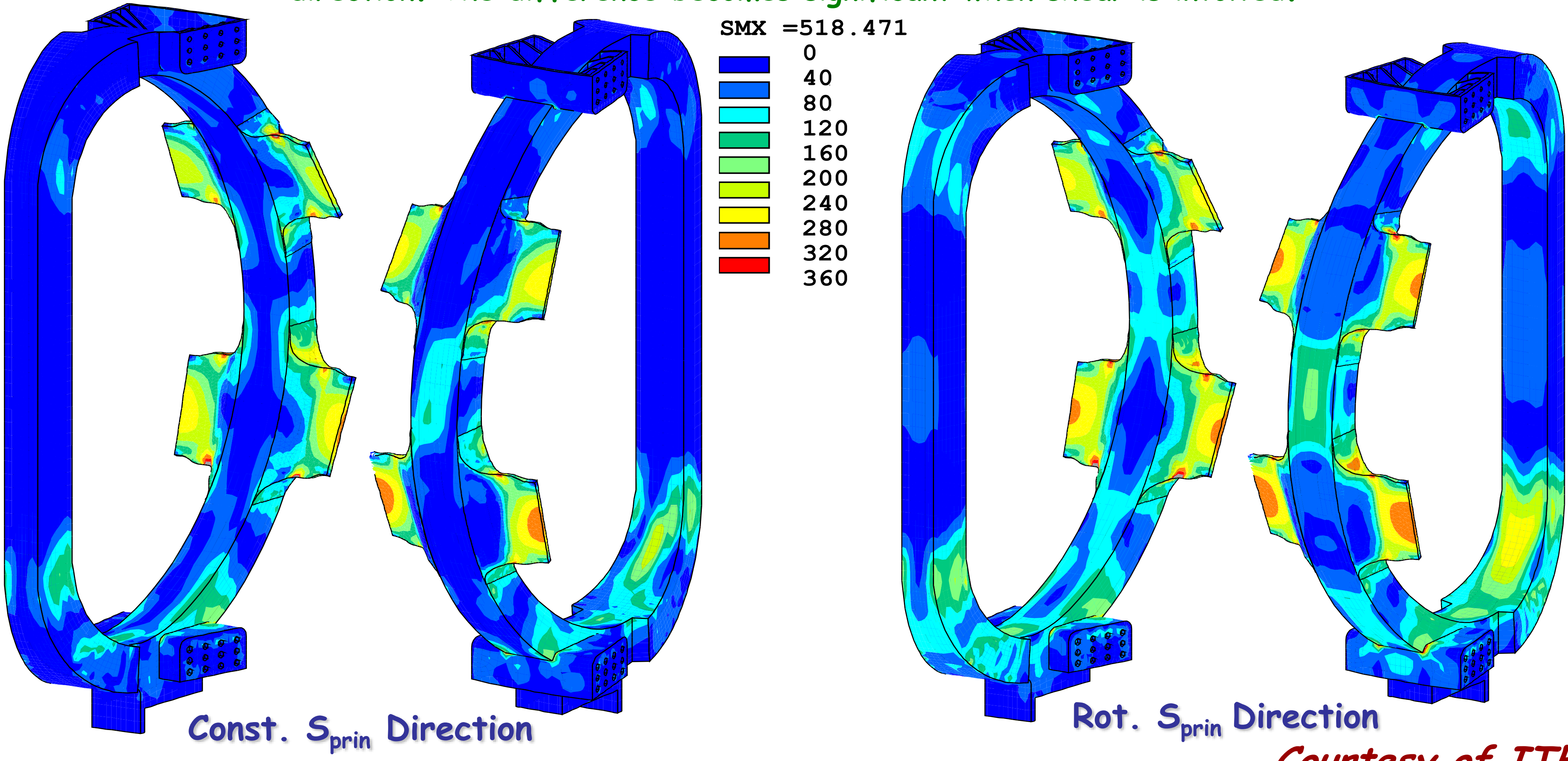
Out-of-plane displacements along the perimeter of the coil casing for all load cases of the Reference Scenario



Courtesy of ITER

Stress Range in TF Coil Case

The cyclic principal stress range is required for the crack growth analysis (LEFM) and for the assessment according SN data. Due to the cyclic loading the direction of the principal stresses is not constant. Therefore two procedures are used to calculate the cyclic stresses, i.e. constant direction and rotating direction. The difference becomes significant when shear is involved.



Courtesy of ITER

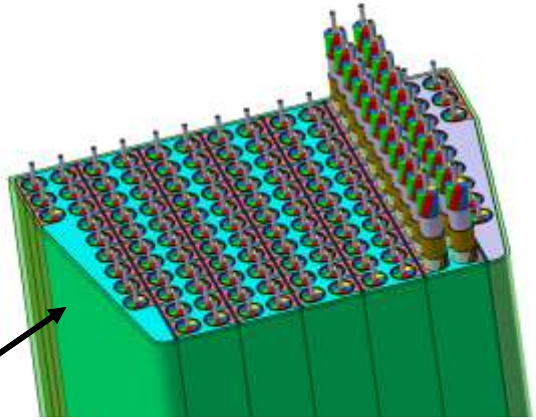
Electrical Insulation

- Four simultaneous constrains:
  - High radiation
  - Large stress on insulation
  - Presence of high voltages (tens of KVs)
  - Magnets are operated in vacuum
- Preferred design solution:
  - Glass-polyimide tapes
  - Vacuum pressure impregnation with resin

The impact of high voltage… selection of insulation type

Voltage during TF coil operation

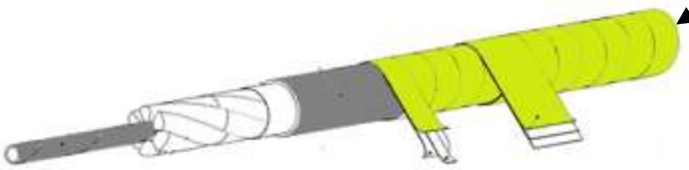
	Normal Operation (fast discharge) V_n (kV)	Fault scenario V_f (kV)
Turn to RP	0.6 (1.2 for a few ms)	1.2
DP to DP	1.2 (2.4 for a few ms)	2.4
WP to ground	3.5 (7 for a few ms)	18
Co-wound QD tape to conductor	0.01	0.1



17 layers of Glass/Polyimide

…has driven decision to use polyimide barrier ….

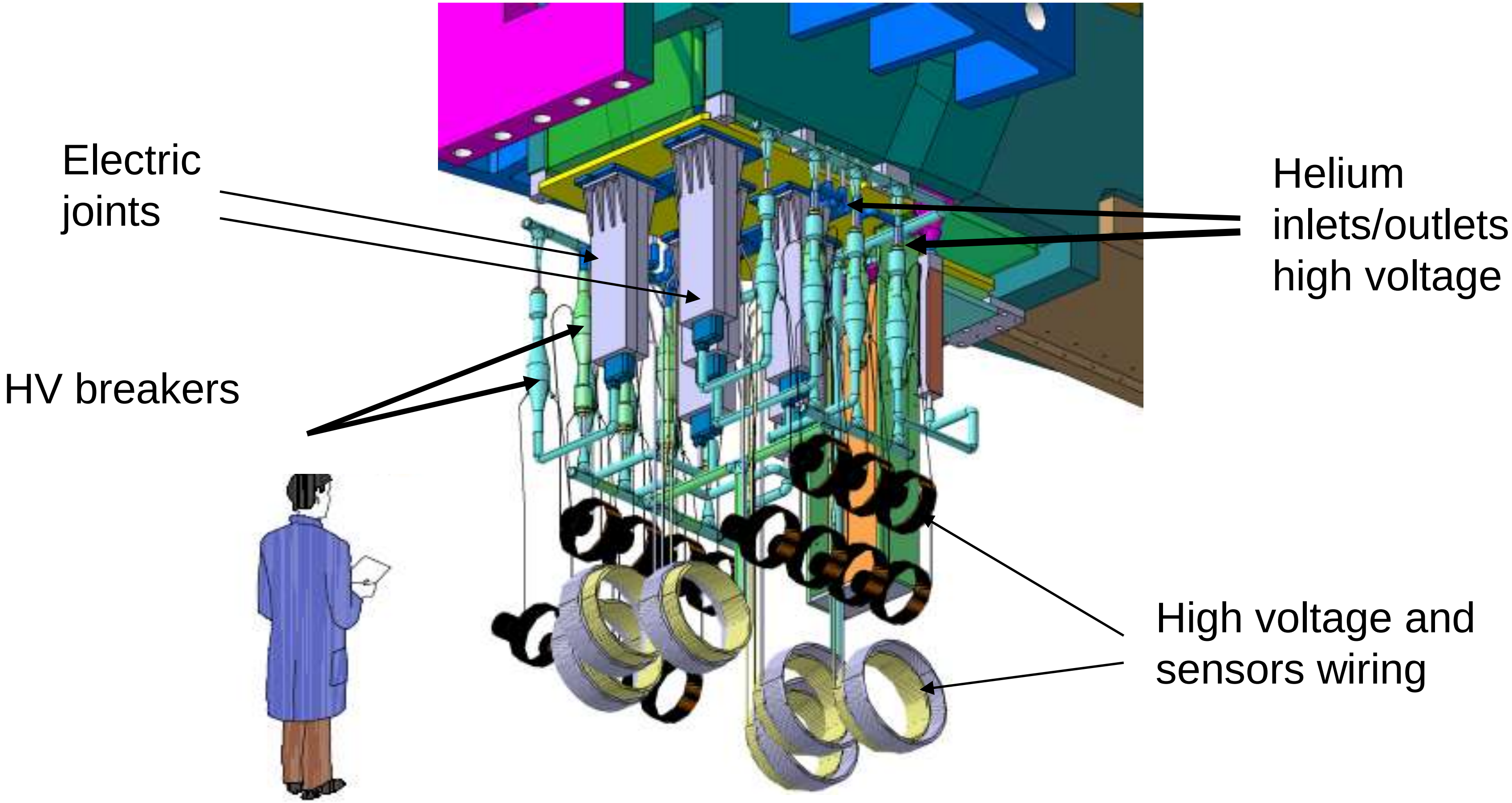
TF Coil Conductor



>3 layers of Glass/Polyimide half lapped

For Nb_3Sn coils (TF and CS) the insulation must be applied after the heat treatment

Joints and hydraulic connections region in the ITER TF coil



Very stuffed region, insulation must be applied by hand, typically resin wet glass/polyimide & pre-made G10 sleeves… high risk area… intermediate Paschen tests (or equivalent) needed to check quality of insulation between assembly steps

Section 6.

Superconductor Design

FUSION FOR ENERGY

Conductor Concept

Requirements

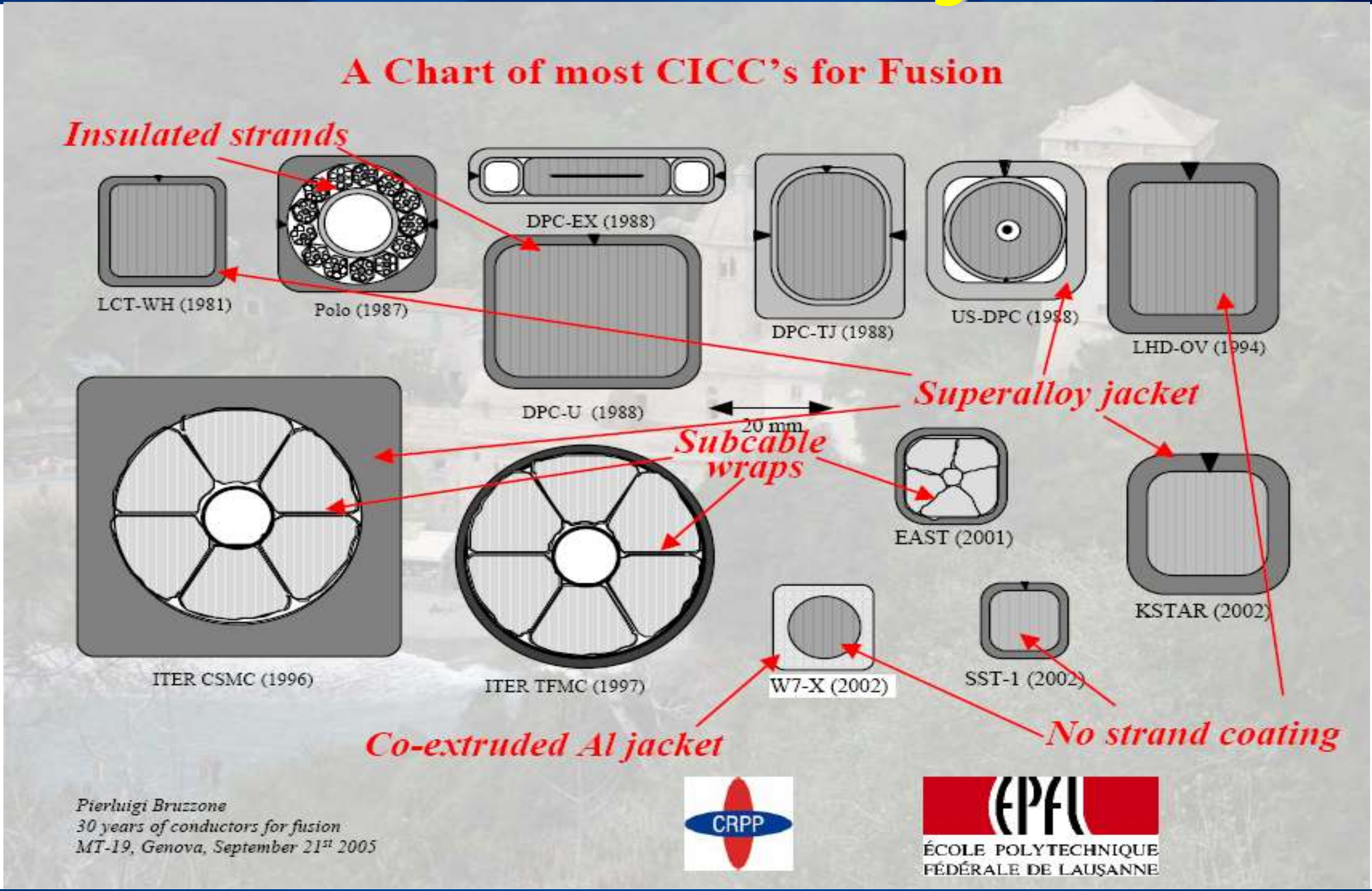
- High amperage conductor
  (large ampere turns and acceptable voltages)
- Large heat removal capability (nuclear heat, AC loss, …)
- High stability (local disturbances and peak loads)
- High mechanical strength (hoop and out-of-plane forces)
- Quench protection (hot spot limitation)

Solution

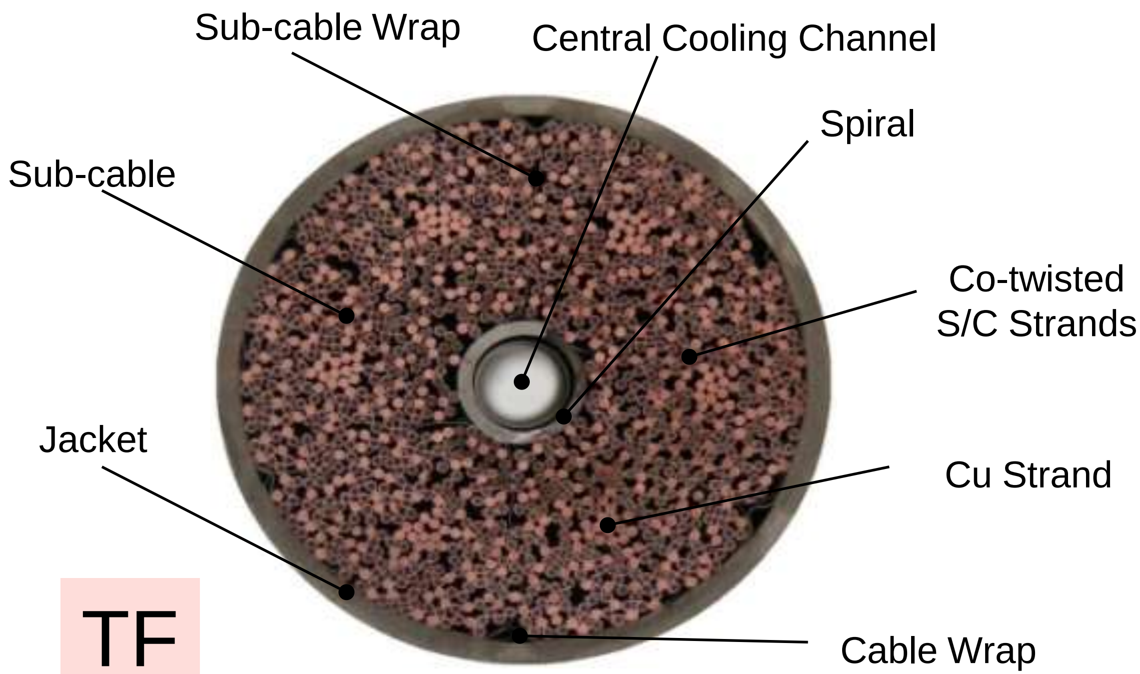
- Large number of parallel superconducting strands to enable high currents
- Cabling with ~1/3 void between strands for coolant (supercritical He)
- Outer jacket of high strength material to withstand large cyclic loads
- Flexible design: variable currents by scaling the amount of strands

→ *Cable-in-Conduit Conductor (CICC)*

CICC is the most used option in fusion magnets



ITER CICC Design

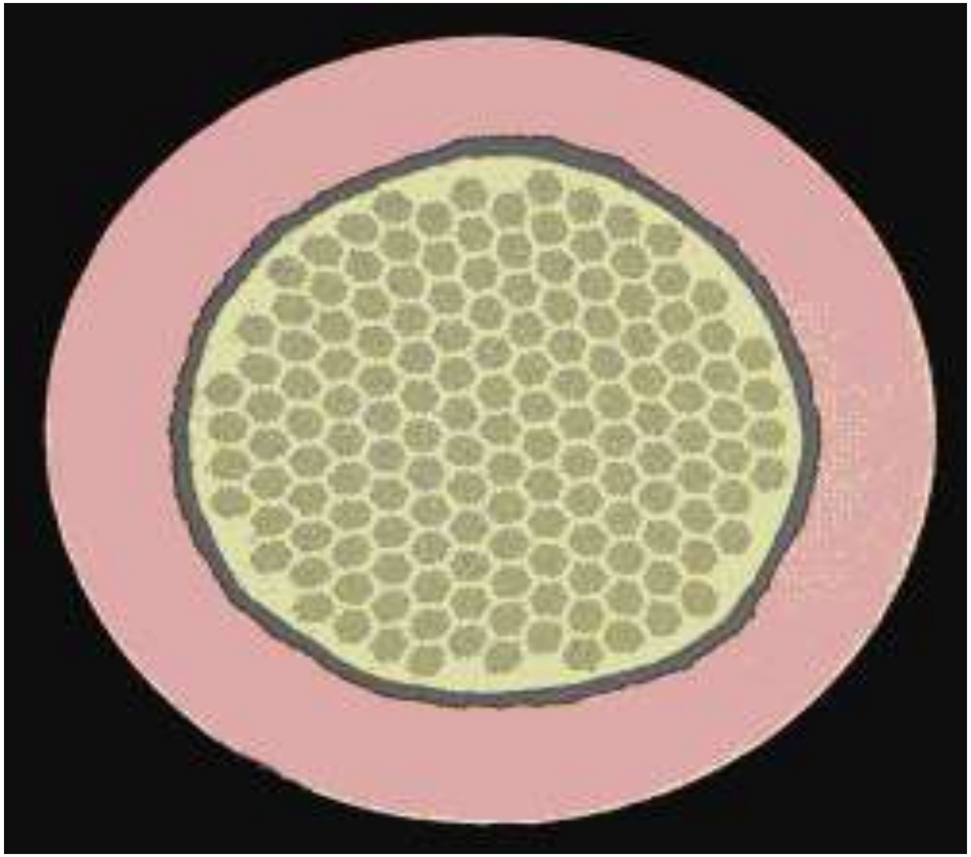


TF

CS, PF, CC

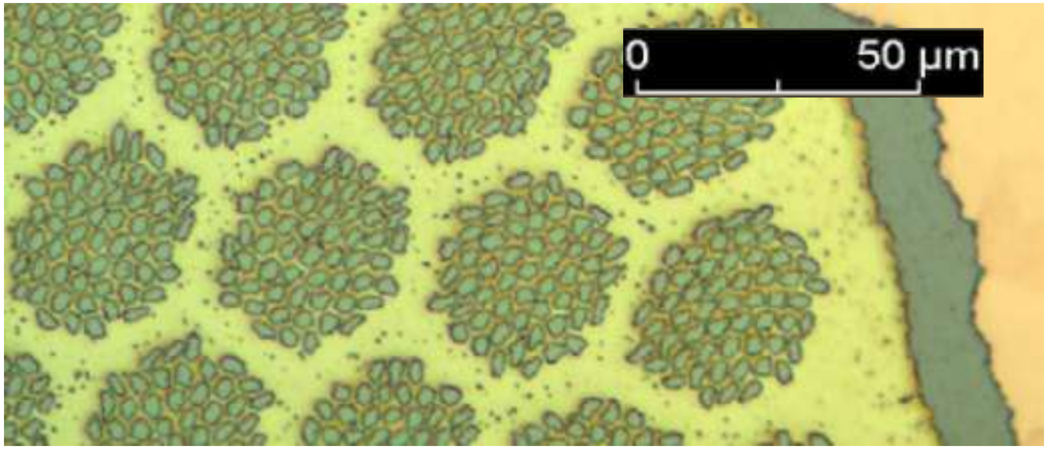
- All four magnet systems (TF, CS, PF and CC) are using the same concept
  - Strand type (NbTi or Nb_3Sn) defined by max. field
    - Number of strands defined by nominal current
- Outer conduit material and shape (steel, round) defined by magnet design
- Production started in 2008 by six ITER Members (strand, cabling & jacketing)

Typical Strand Design (Bronze Route)



[A. Szulczyk, EAS 2005]

- 0.81 mm quaternary strand
- 8035 Nb**Ta** filaments
- CuSn**Ti** bronze (~15wt% Sn)
- J_c ~**790 A/mm²**
- Non-Cu losses **200 kJ/m³**
- Unit length > 20 km



Section 7.

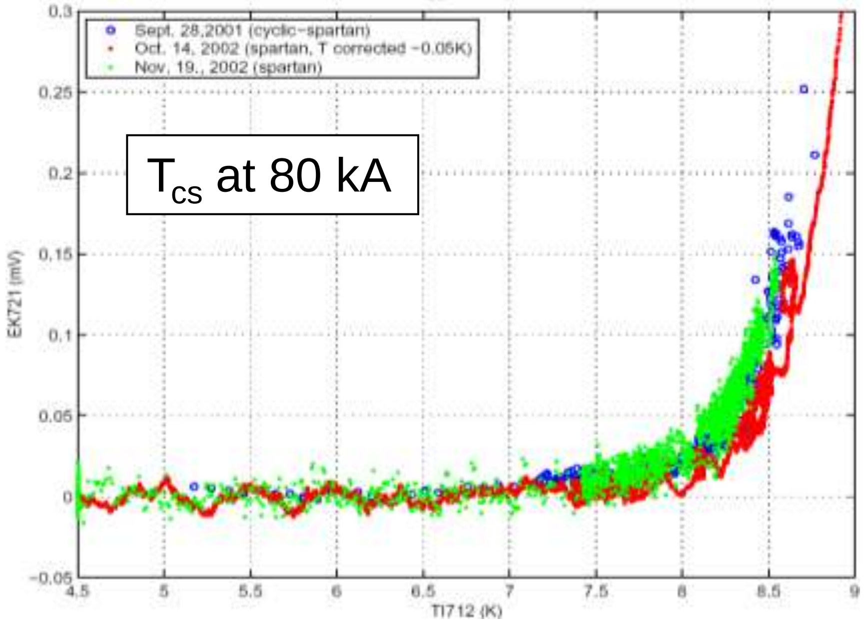
R&D Carried out to Support the Design and Manufacture of the ITER Magnets

TF Model Coil

TFMC inserted into TOSKA facility (FzK) for Phase II testing

TFMC Results

	ITER TF	TFMC
Peak field (T)	11.8	9.9
Conductor current (kA)	68	80
Number of turns	134	98
No. of double pancakes	7	5
Stored magnetic energy (MJ)	41,000	337
Coil height (m)	12.6	4.6
Total coil weight	310	40

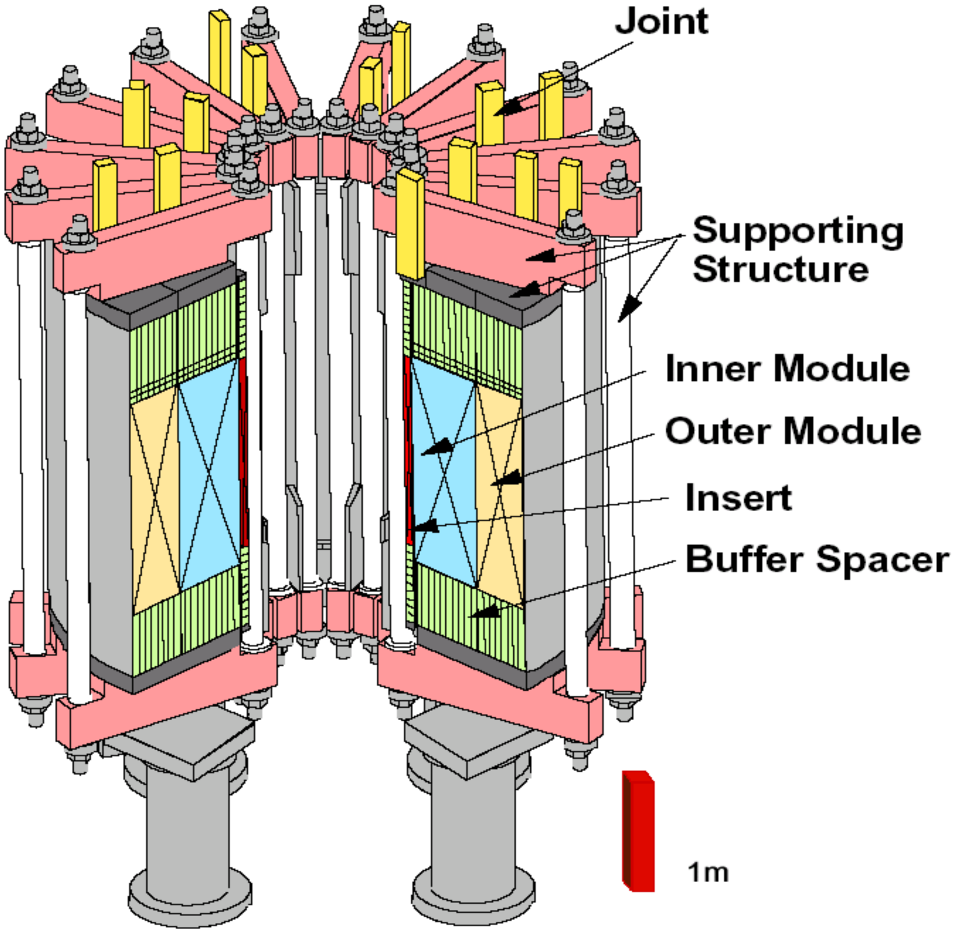


- TFMC exceeded design values
- No degradation with cycling
- Conductor performance in coil lower than expected from short sample tests

→ **conductor upgraded to recover margin**

[A. Ulbricht et al., Fus. Eng. Des. 73, 189-327 (2005)]

CS Model Coil



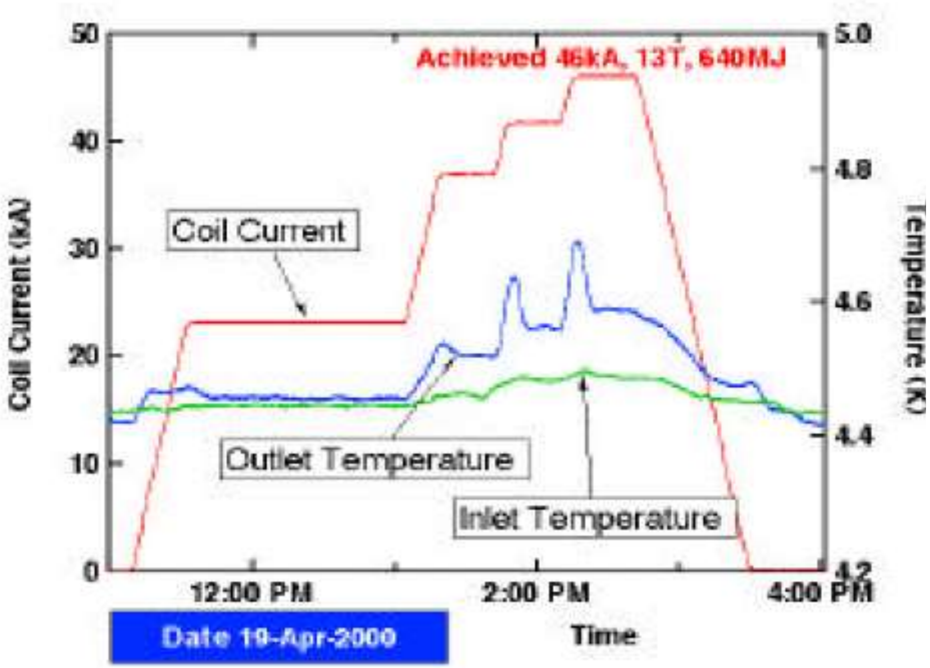
[H. Tsuji et al., Fus. Eng. Des. 55, 153-170 (2001)]

Coil Design Parameters

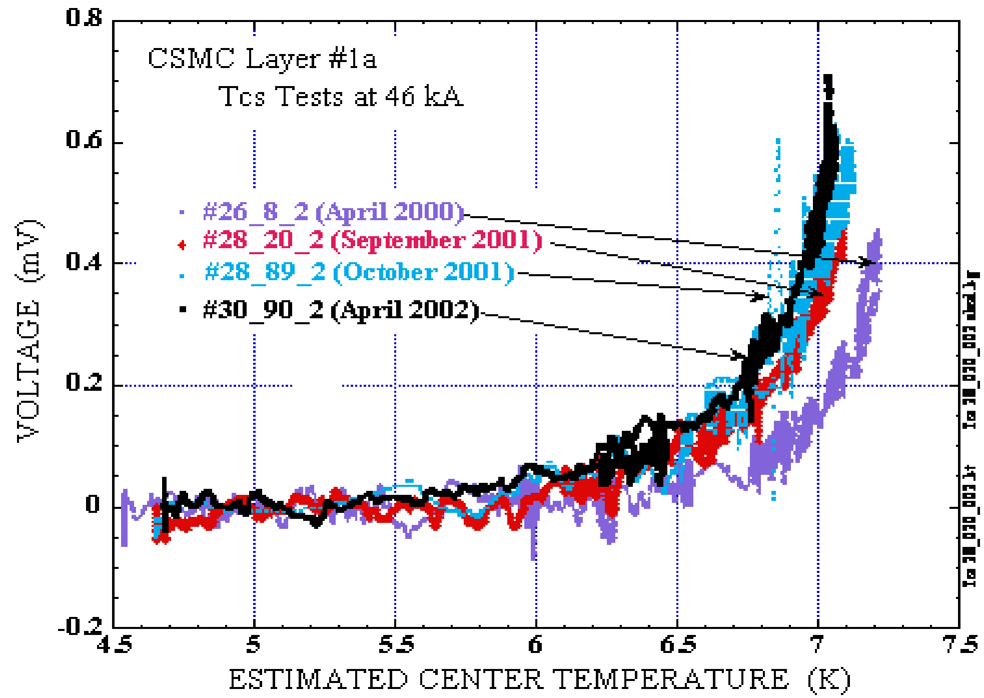
	CSI	CSMC IM	CSMC OM
Maximum Field	13 T	13 T	7.3 T
Operating Current	40 kA	46 kA	46 kA
Outer Diameter	1.57 m	2.71 m	3.62 m
Height	2.80 m	2.80 m	2.80 m
Weight	7.7 t	49.3 t	52 t
Stored Energy	11 MJ	640 MJ	

Coil installed and tested in Naka, Japan

CSMC Results



CSMC successfully achieved design values



Small degradation (0.1 to 0.2 K) saturated after few cycles

- **Differences to present design**

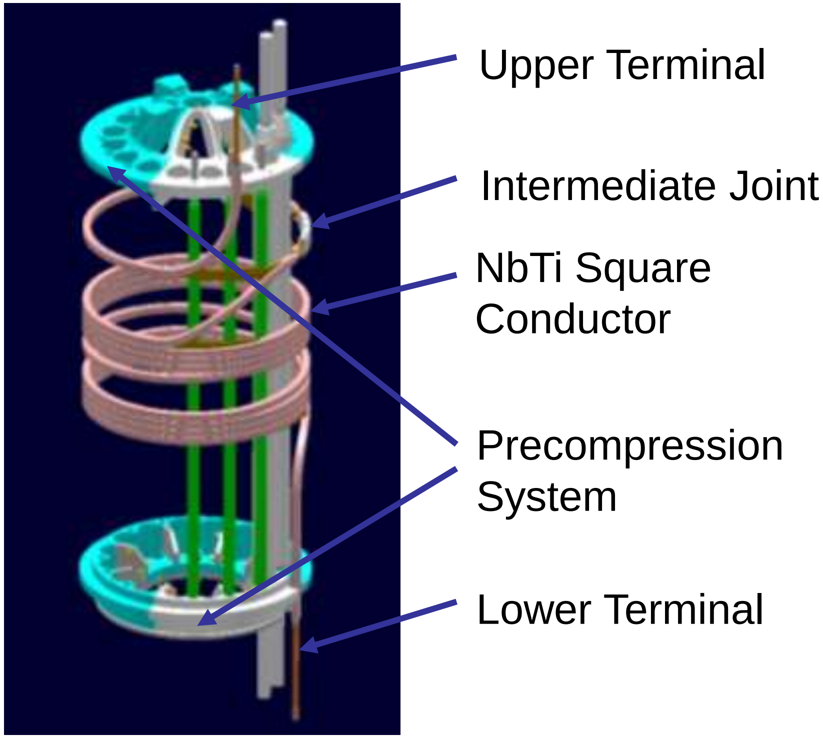
  Pancake winding (not layer winding)

  Jacket material: high Mn steel or SS (not Incoloy)

[Tsuji et al.,]

PF Insert Coil

[Nunoya et al, presented at ASC 2008]
[Zanino et al, presented at IAEA 2008]

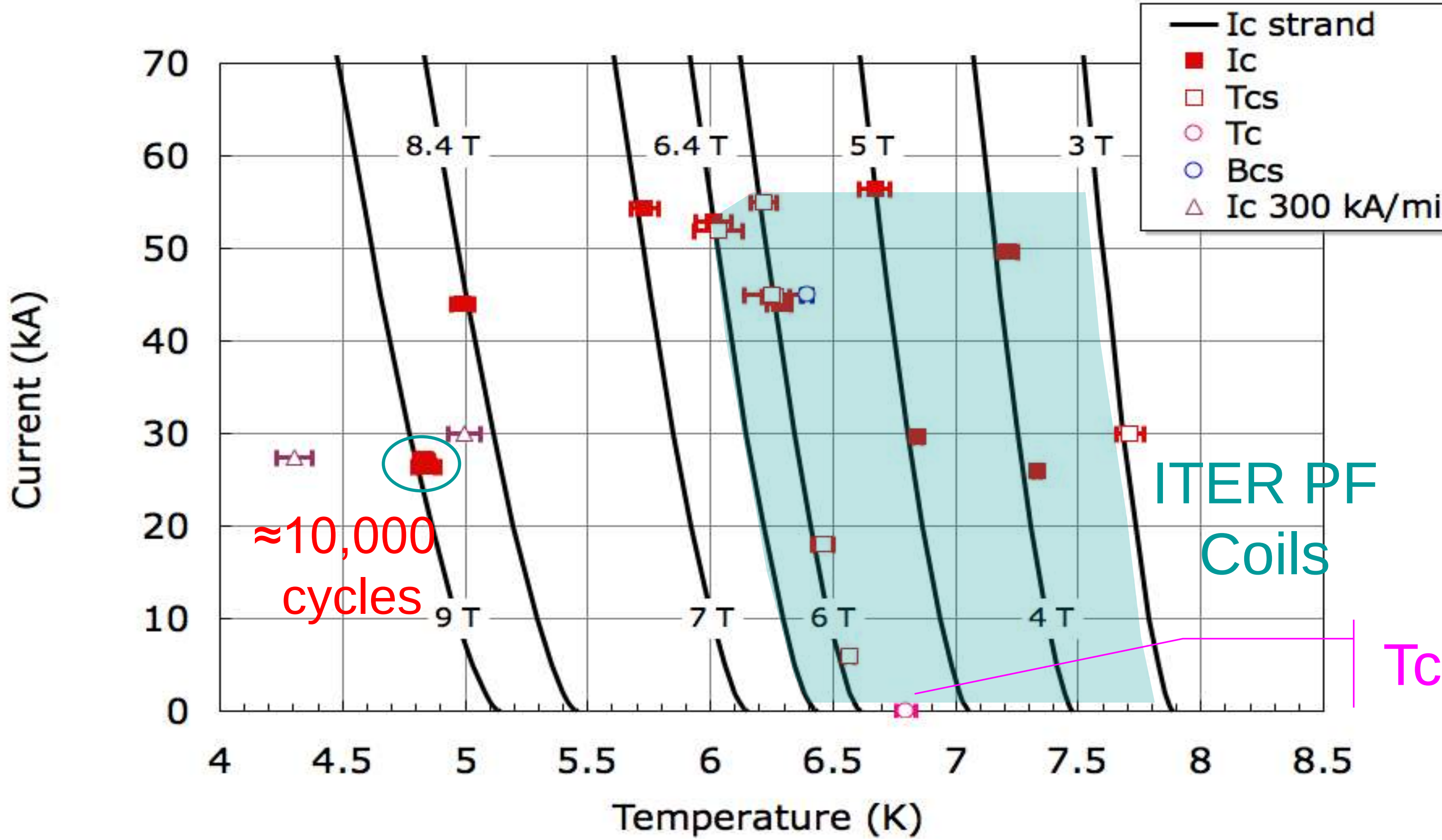


Coil Design Parameters

		PFI
Maximum Field		6.3 T
Maximum Operating Current		50 kA
Maximum Field Change		2 T/s
Conductor length		49.50 m
Main Winding Envelope	Outer Diameter	1.57 m
	Inner Diameter	1.39 m
	Height	1.40 m
Height		1.40 m
Weight		6 t

Test carried out in June-Aug. 2008

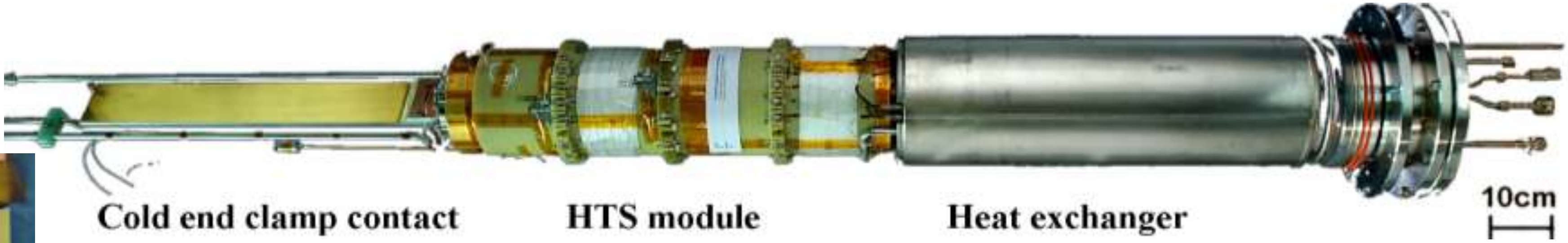
PF Insert Coil Result

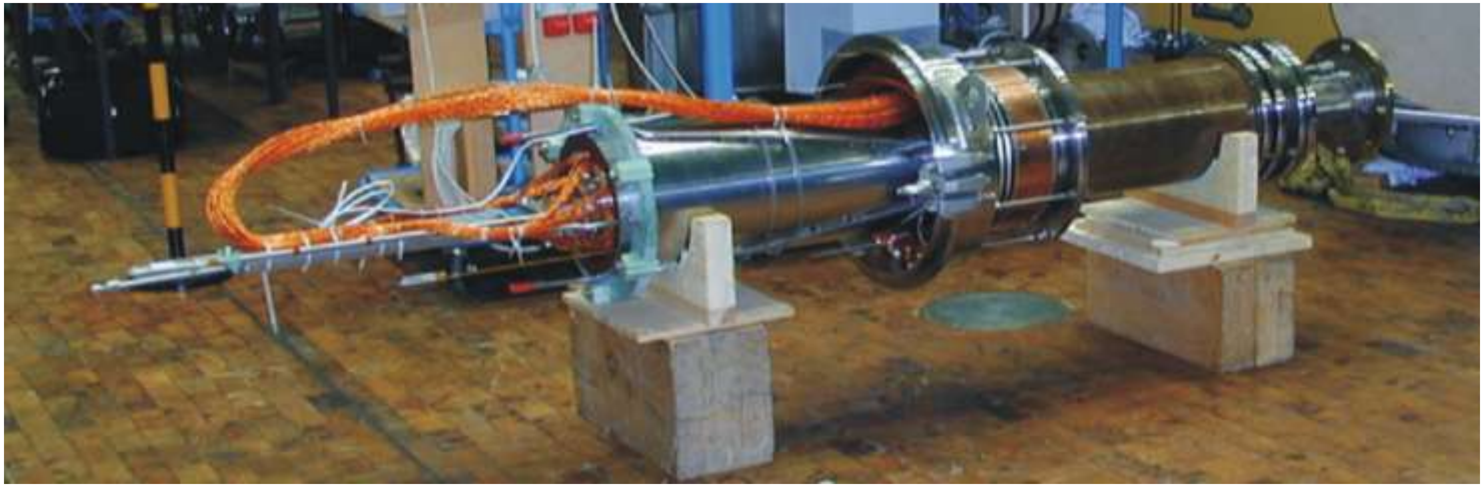


Excellent DC performance according to strand

HTS Current Leads

- Application of HTS current leads saves ~ 25 % of the total cryogenic power needed (18 kW at 4.5 K)
- Large R&D program initiated in EU to develop a 70 kA HTS current lead
- Program successfully completed in 2005 by test of a 1:1 prototype in the TOSKA facility (Karlsruhe)





[R. Heller et al., IEEE Trans. Appl. Supercond. 15, 1496-1499 (2005)]

Section 8.

Manufacturing of ITER Conductors

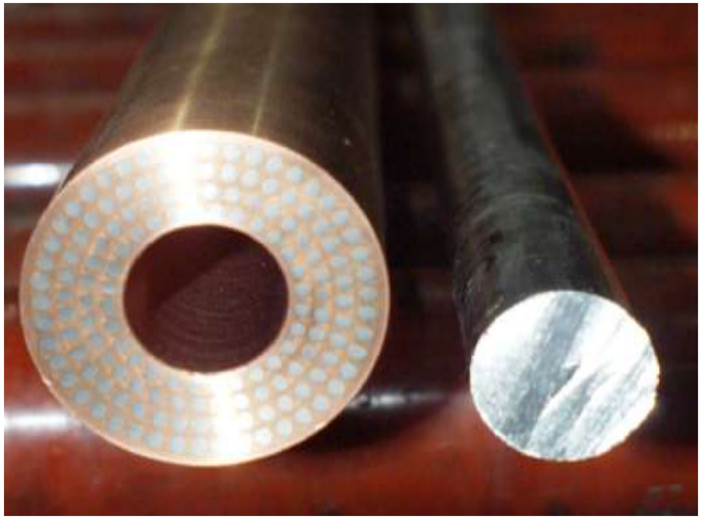
Internal Tin Strand

- Most commonly employed technique with largest potential
- No limitation of Sn content (additional tin rods)
- Strands properties achieved by several suppliers:
  - J_c: **1000 – 1200 A/mm²** (4.2 K, 12 T)
  - non-Cu losses: **400 – 1000 kJ/m³**
  - unit lengths (0.81 mm): **3.5 – 13 km**
- Ta and/or Ti added to improve J_c field and strain dependence
- After Sn insertion, extrusion is not possible, only cold drawing
- Final billet sizes:
  - 40 kg standard (20 kg for TFMC)
  - **100 kg** billet successfully drawn to final diameter

→ In the past, production of Nb_3Sn has been limited to a few tons/year worldwide, ITER has required a scale-up to industrial scale production of ~100 tons/year

Low Loss Internal Tin – Subelement

Sub-element Processing



1.) Deep hole drilling for Nb rods

2.) Insertion of Nb rods into holes

3.) HIPing

4.) Extrusion (80 mm)

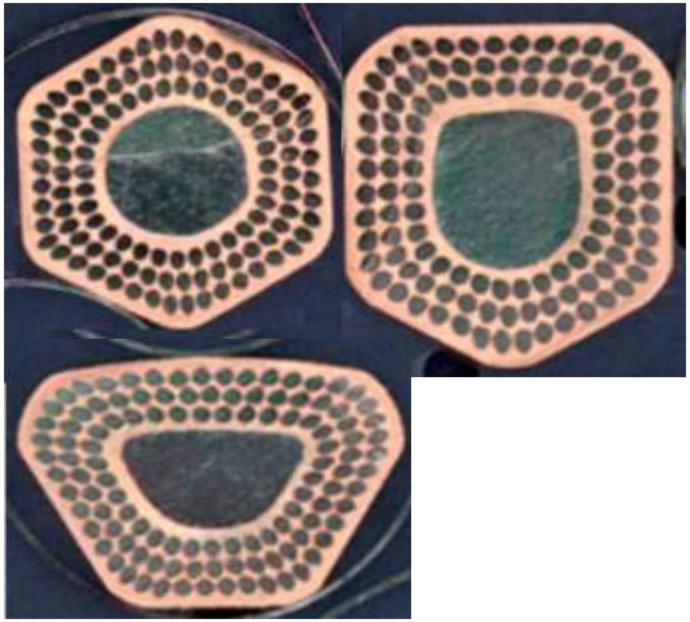
5.) Straightening

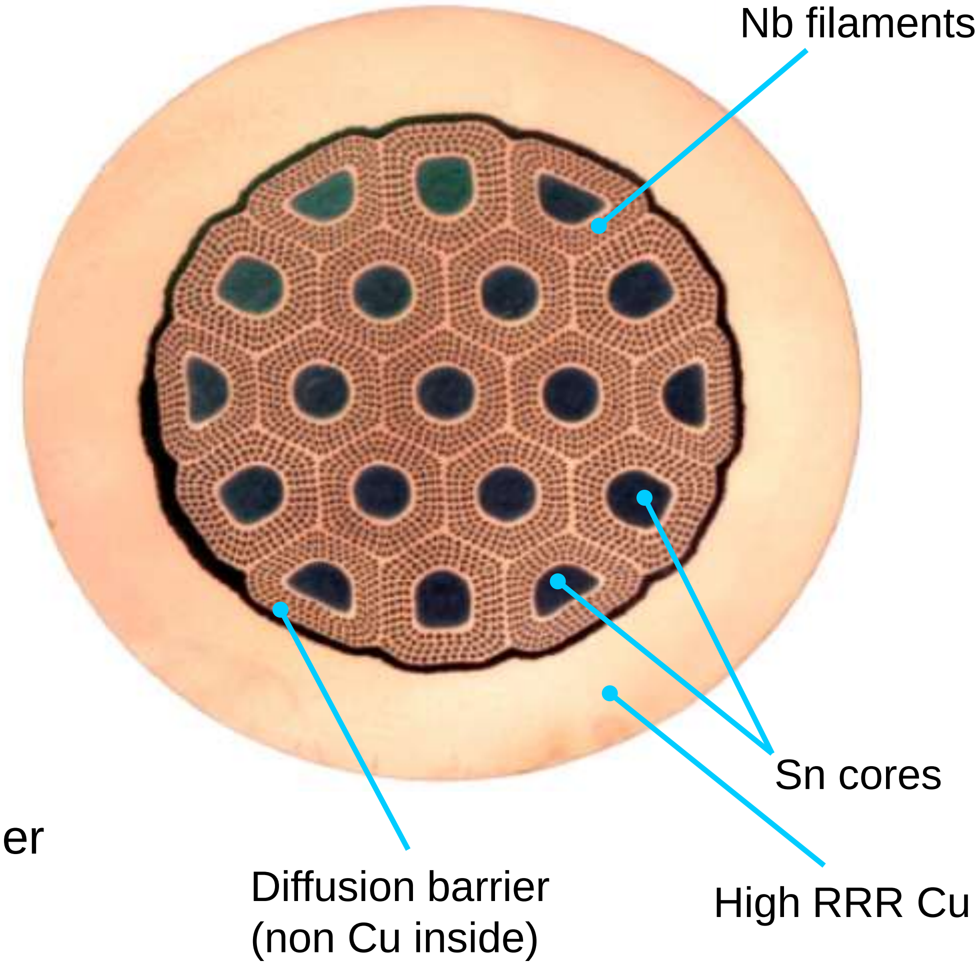
6.) Deep hole drilling for Sn rod

7.) Insertion of Sn rod into central hole

Low Loss Internal Tin – Restacking

Restack Billet Processing





8.) Draw subelement rod shapes

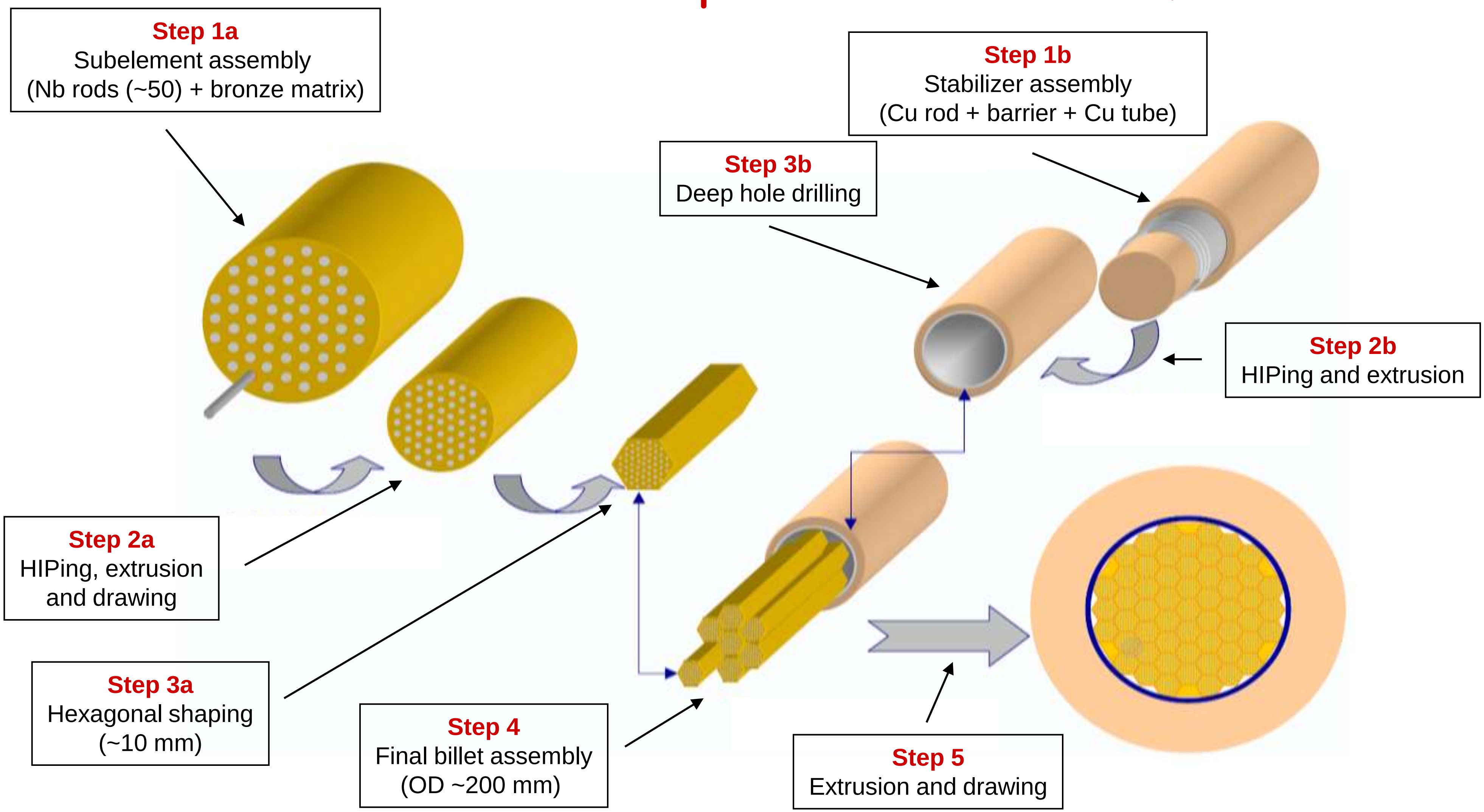
9.) Form barrier (Ta) into tube

10.) Assembly of restack, barrier, stabilizer

11.) Drawing and twisting (no extrusion!)

Bronze Route Manufacture

Complex and laborious manufacture …

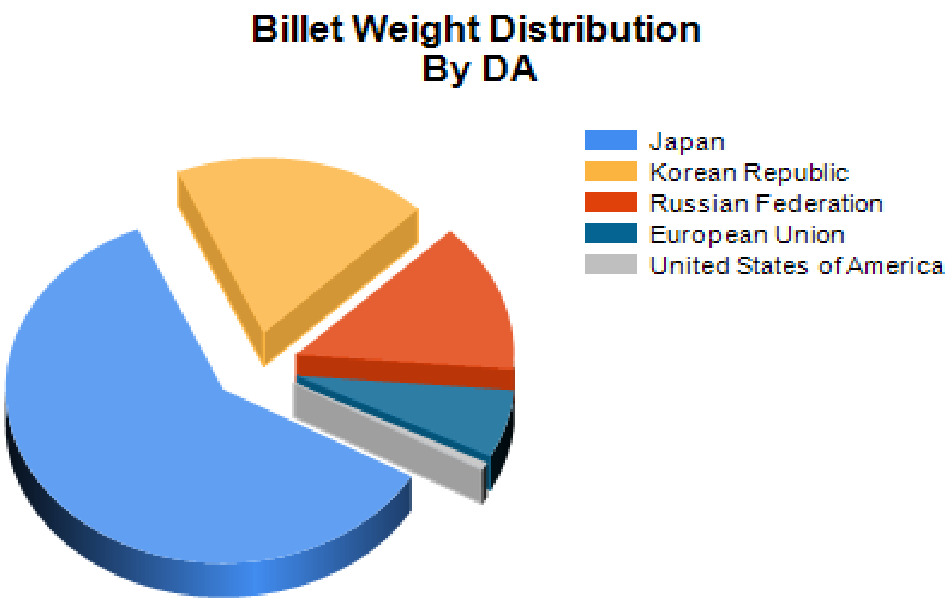


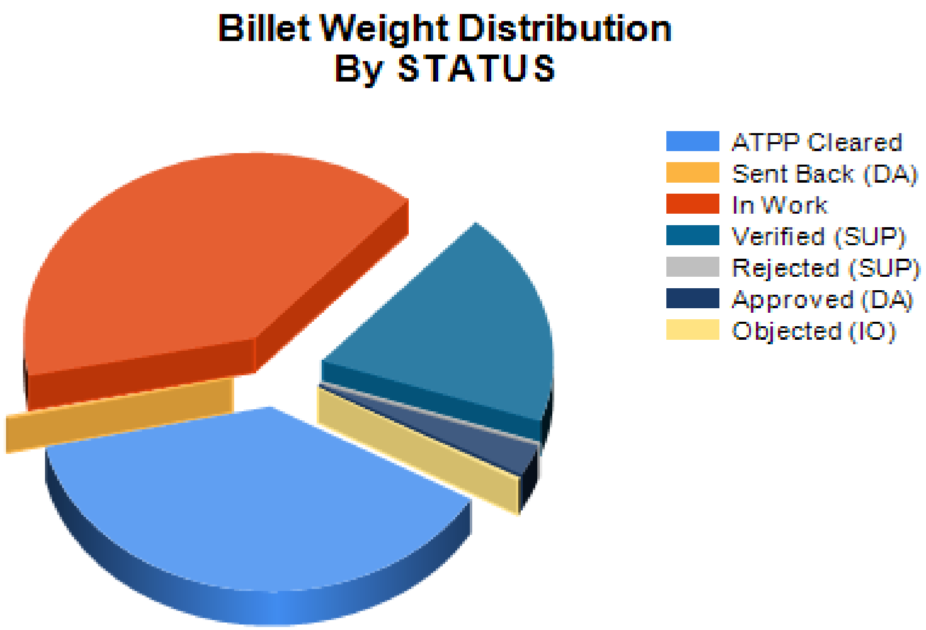
Strand Production: Status 2010

- More than **1,600 billets** (100 tons, all TF) produced by the end of 2010

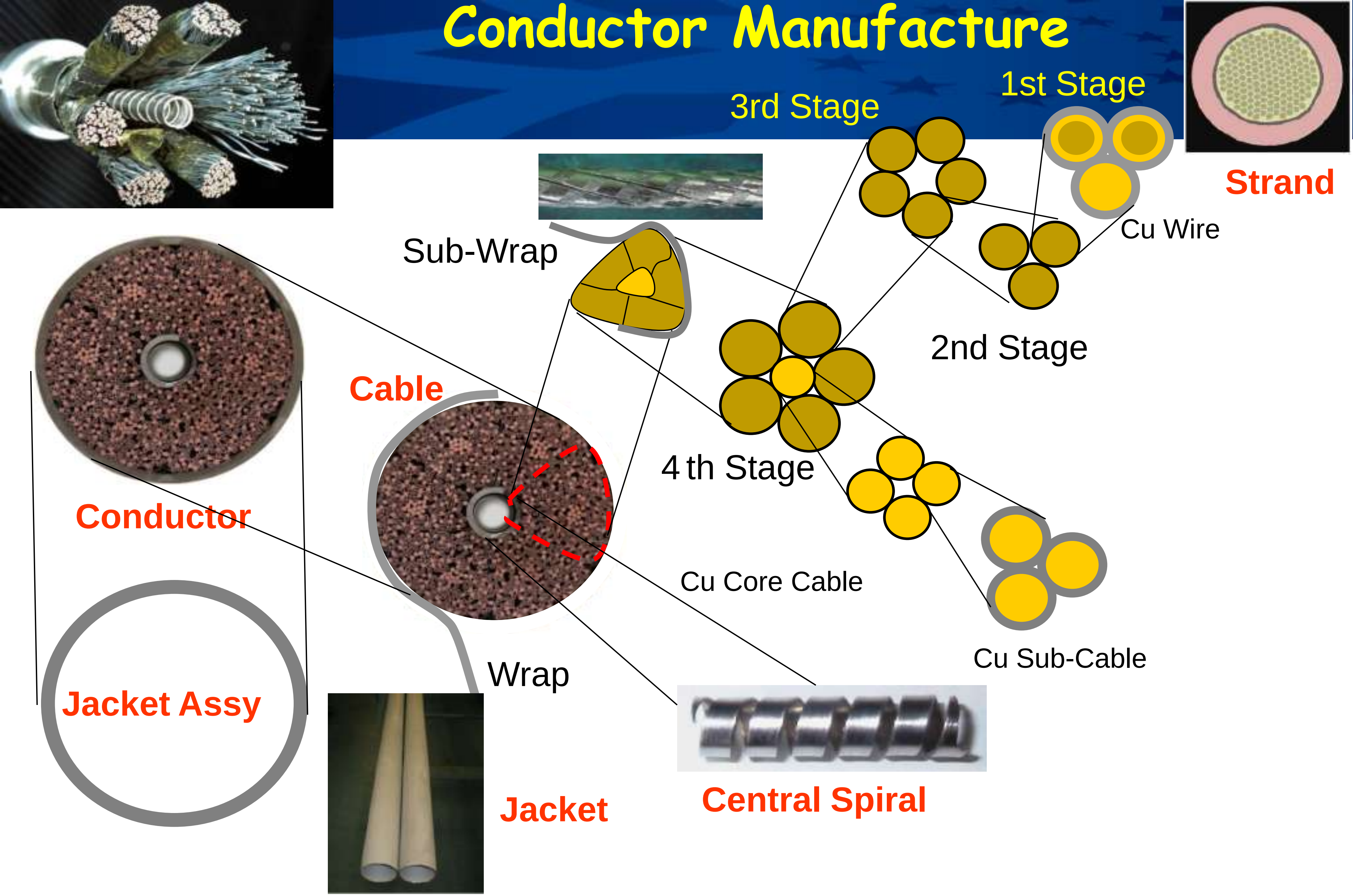
➔ about 50 t produced in 2 years, step up of one order of magnitude from previous Nb_3Sn worldwide production rate

- Most material from JA, followed by KO, RF, EU and US:



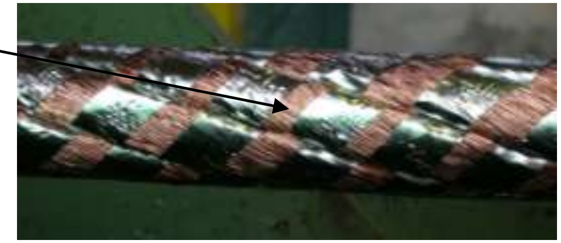


Conductor Manufacture

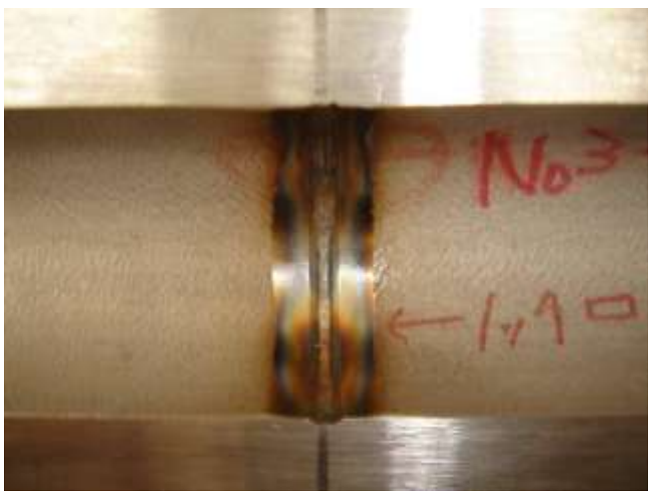


Cabling & Jacketing

- Final cable covered by steel wrap
- After final wrap, cable ready for insertion and compaction into jacket



Final stage (5th) cabling around central spiral

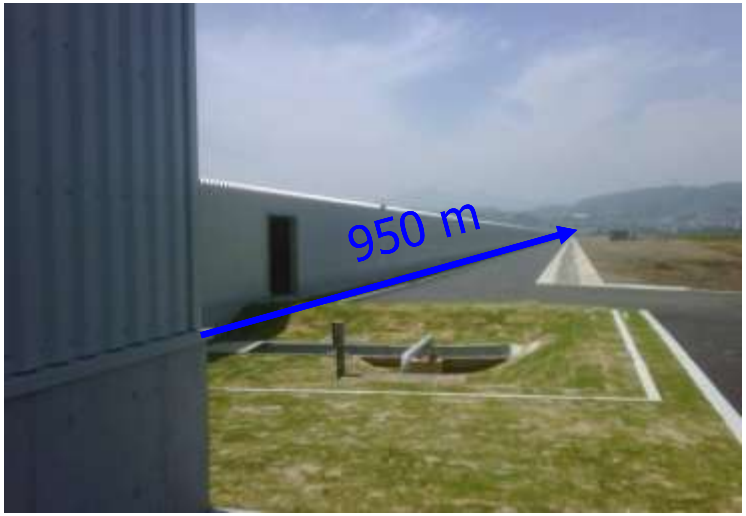


- Welding and inspection of circular and square extruded tubes

Thousands of tubes to be produced and welds to be made and inspected to find/repair defects…

TF and CS Jacketing in JA

First full length dummy conductor completed in 2010 by JA



TF Jacketing in RF

TF and PF Jacketing in CN

EU and US jacketing facilities being prepared, KO to get support from another Party

Section 9.

Manufacturing of ITER Magnets

Wind, React and Transfer

- The TF coils are made using W,R&T technique. The complex manufacturing technique, together with the large dimensions, make the **TF coil a huge technological challenge**.

➔ *Major issue is the permanent deformation of the superconductor winding during heat treatment which makes difficult transfer into radial plates*

Note: *up to 10 conductor supplies with different behaviour*.

- EU has chosen a multiple split procurement between radial plates, coil windings and insertion in the cases ➔ Contract for winding manufacture awarded to Iberdrola/ASG/Elytt.

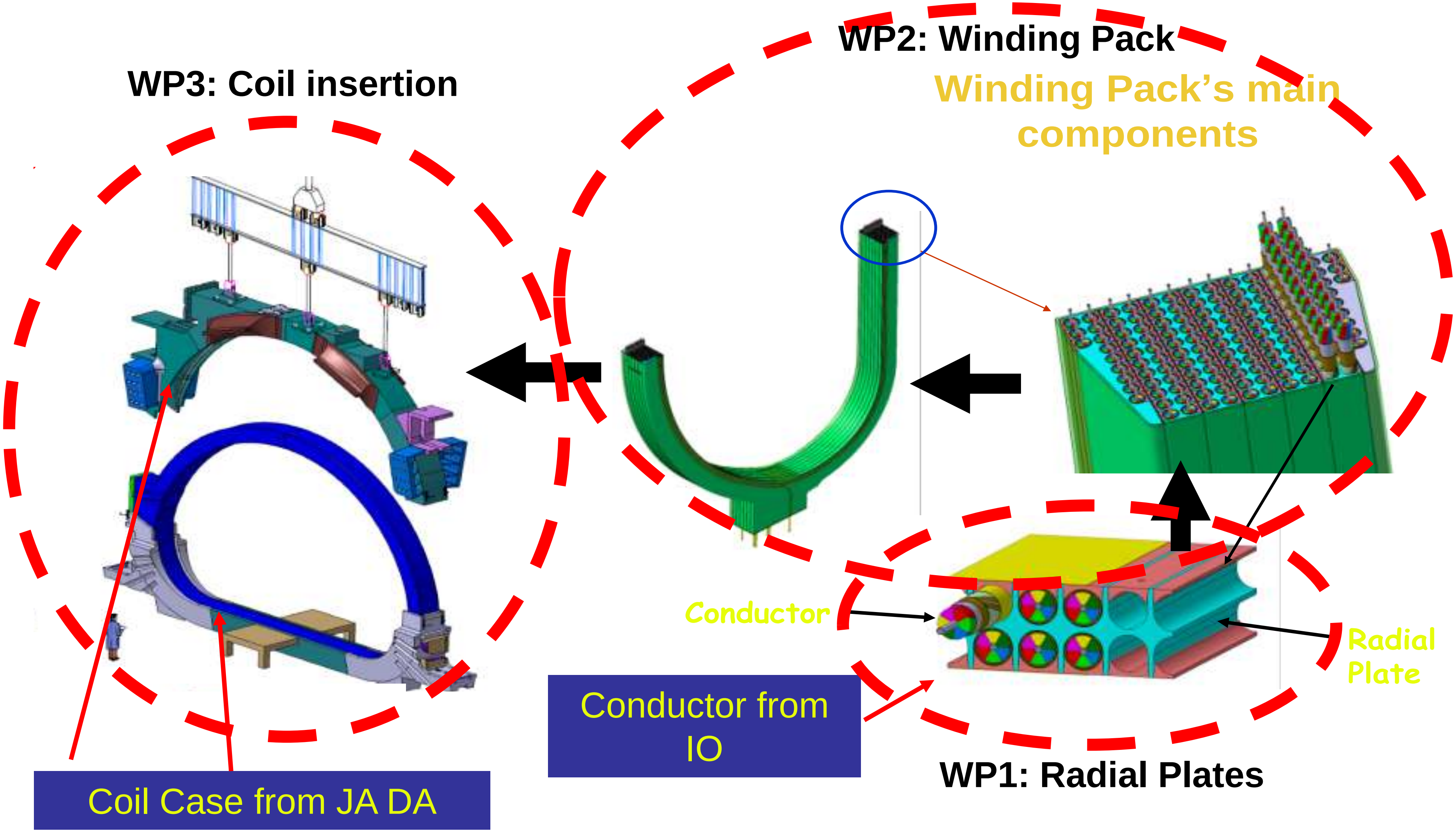
- JA to use one prime contractor, Toshiba, at least for the first two years of preparation phase, with the manufacture of prototypes of coil winding, radial plates and cases

1-3 scale winding table for TF coil prototype (JA)

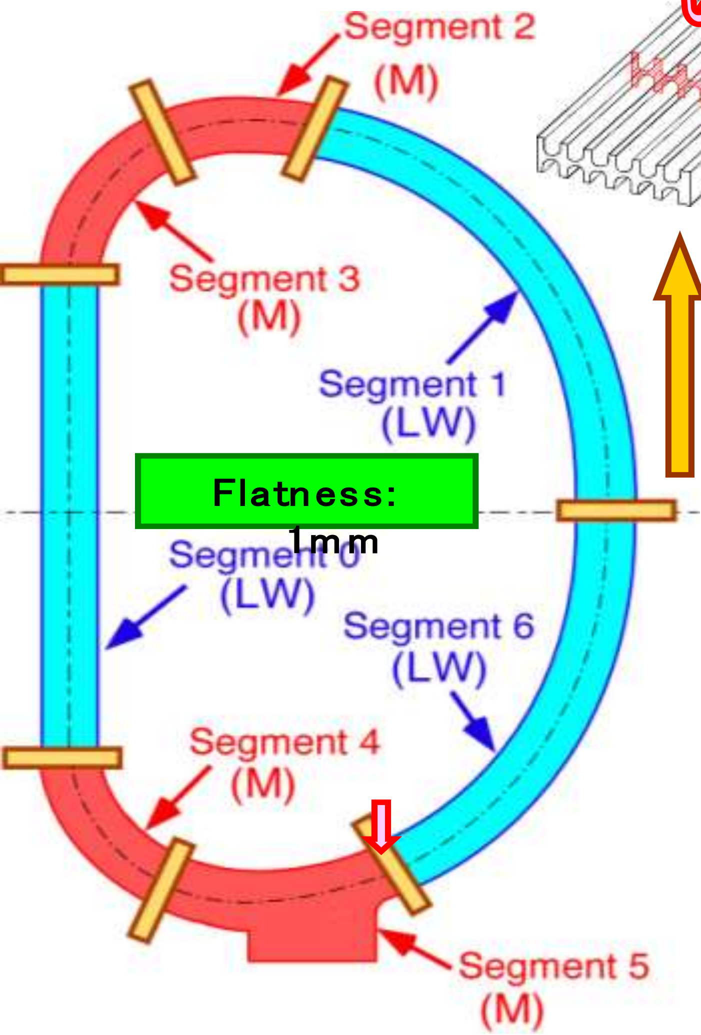
TF Coil Main Manufacturing Steps

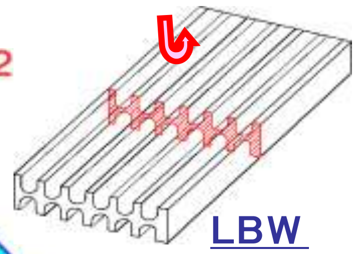
FUSION FOR ENERGY

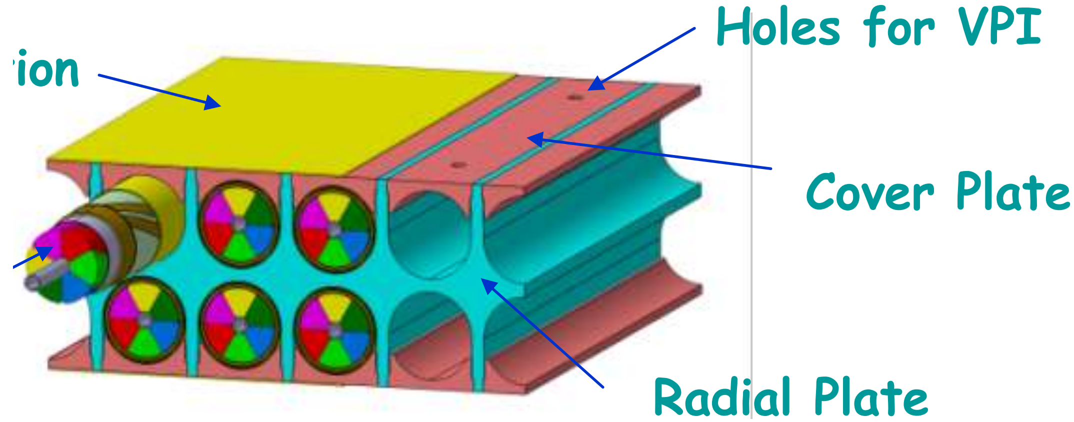
EU Procurement Strategy for TF Coils



Two options for machining of the radial plates







Machining Method (M)

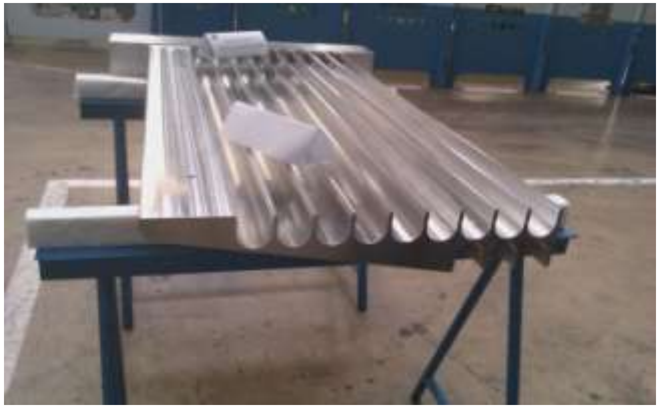
Laser Welded Method (LW)

Courtesy JA

Manufacture of Radial Plate Prototypes (EU)

FUSION FOR ENERGY

Forging of radial plate segmentt (CNIM)



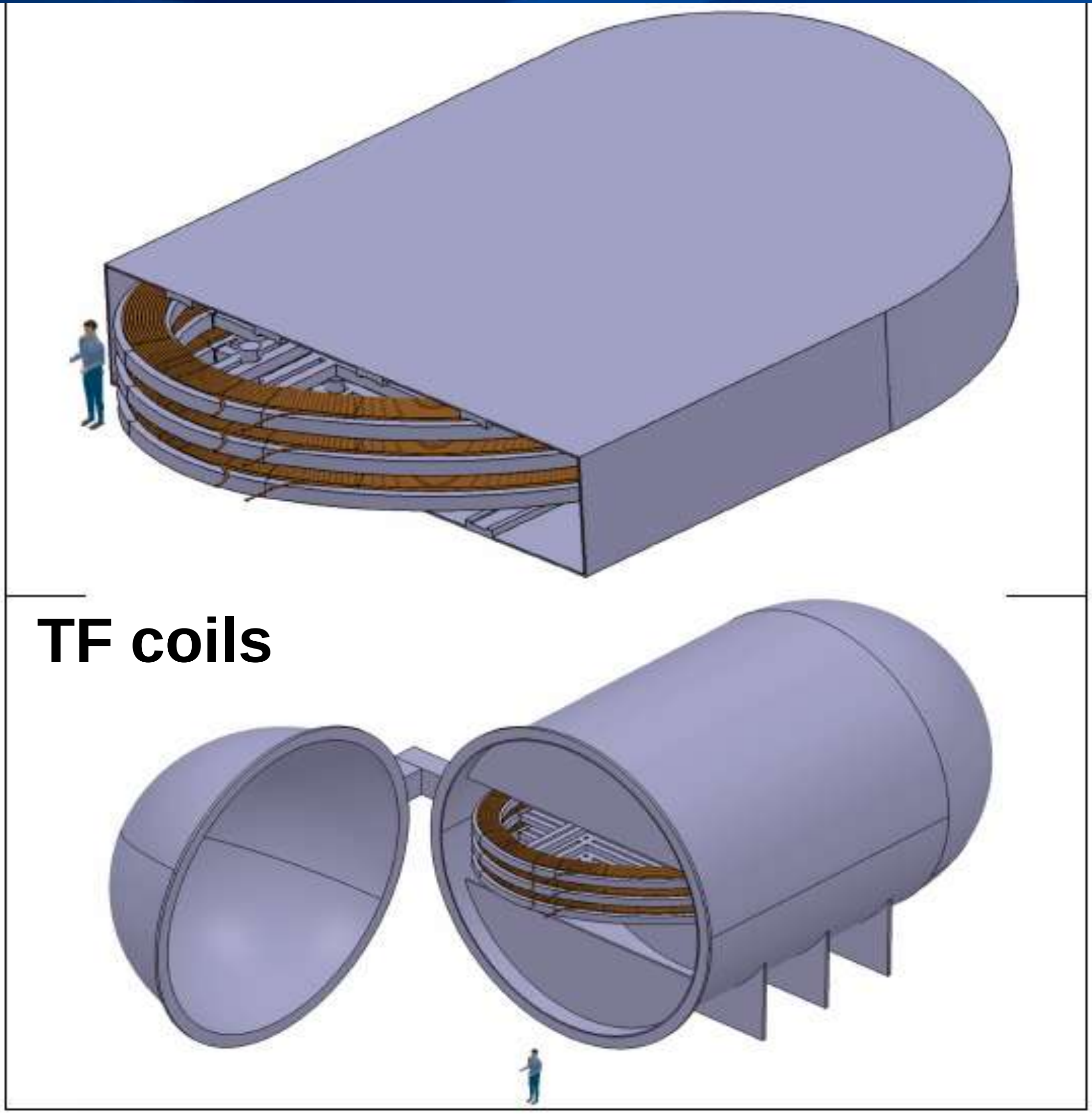
Machined side radial plate segment (CNIM)

Local vacuum Electro Beam welding machine (CNIM)

Radial plate segment produced by powder HIPping (SIMIC)

Assembly of radial plate with MAG welding (in progress at SIMIC)

Heat Treatment



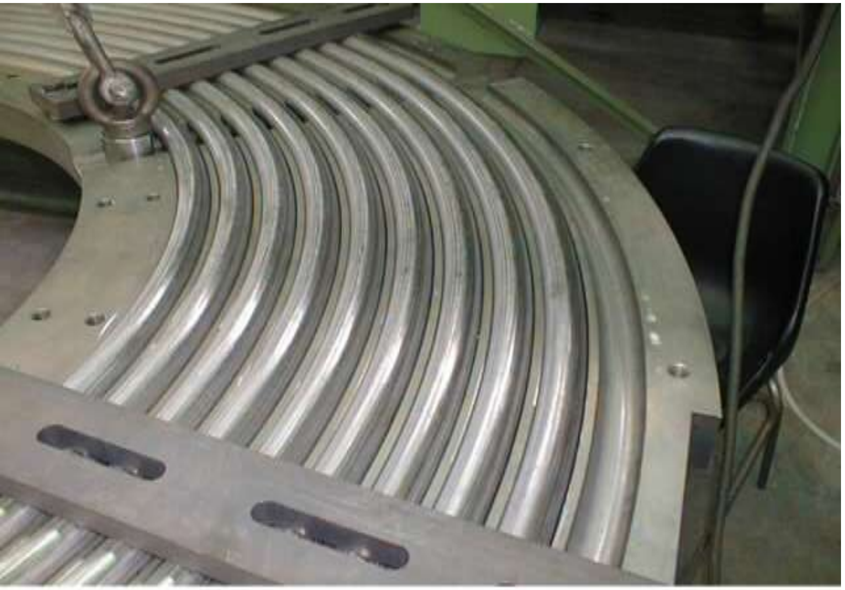
TF coils

TFMC

The experience on heat treatment gained on TFMC is quite relevant to the full size TF coils

A big challenge: the conductor change in length during HT

In the TFMC the measured change in length was +0.05%



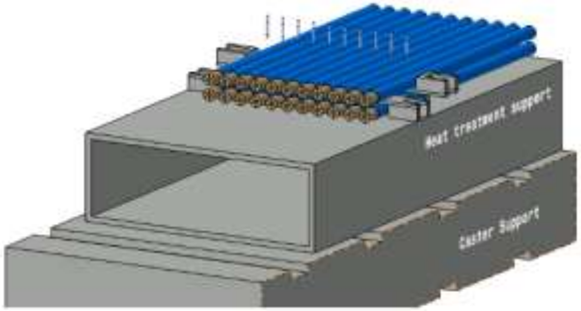
Before HT: Gap on <u>EXTERNAL</u> side of groove

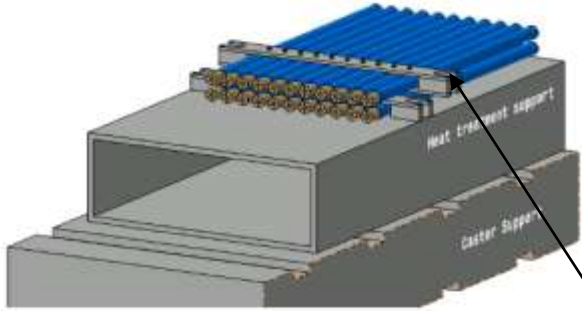
→ Heat Treatment

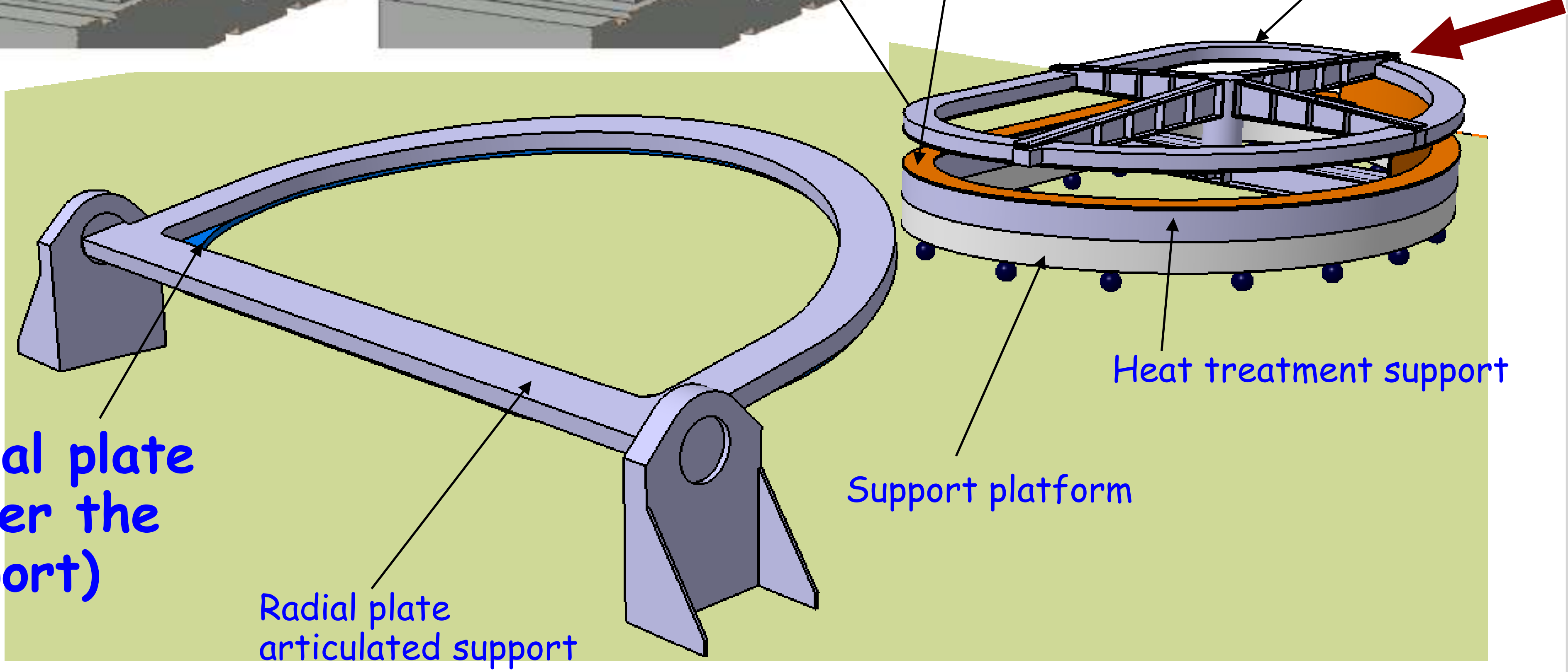
After HT: Gap on <u>INTERNAL</u> side of groove

Extrapolating to the full size TF coils = Elongation of 7 mm !

On paper we have a solution for the transfer process…







…DP insulation and impregnation of the DP modules…

…this is relatively straightforward operation…

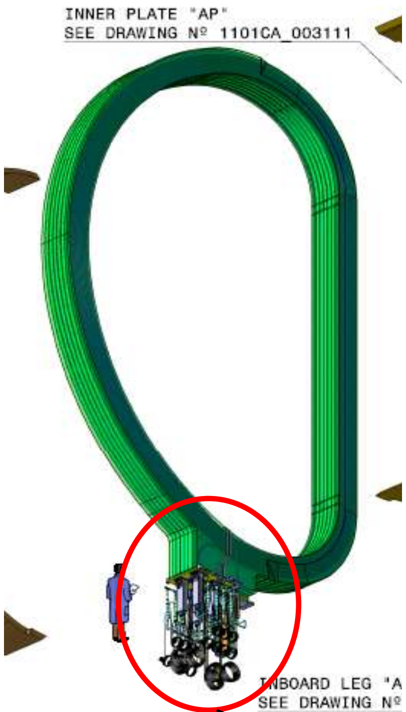
• Main challenge is to impregnate the turns inside the radial plates after laser welding of the covers

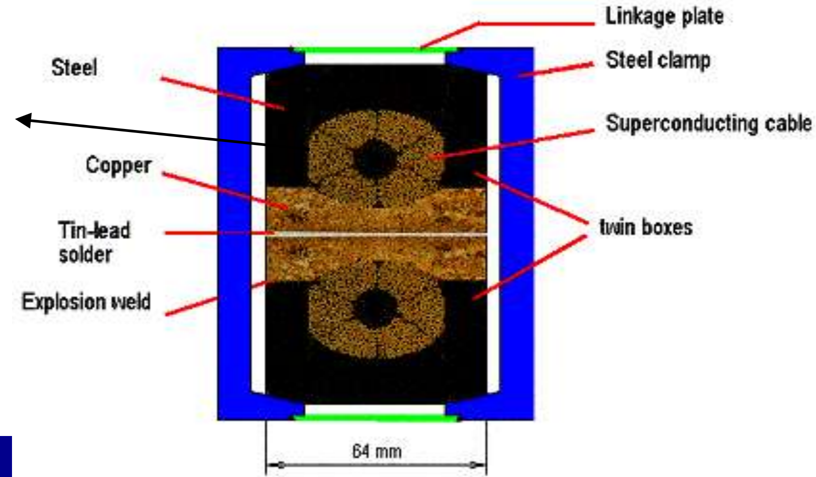
A section of the TFMC Dummy DP

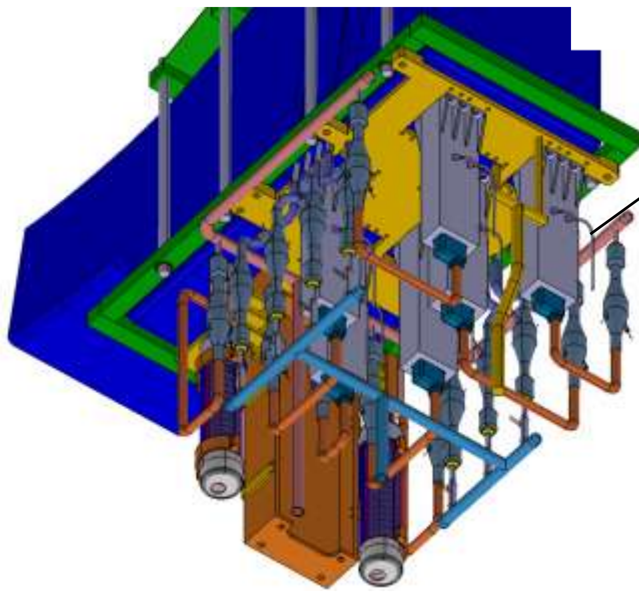
• The resin penetrates through holes in the covers. The distance between holes is determined with preliminary R&D

A fully impregnated TFMC DP

Electrical Joints



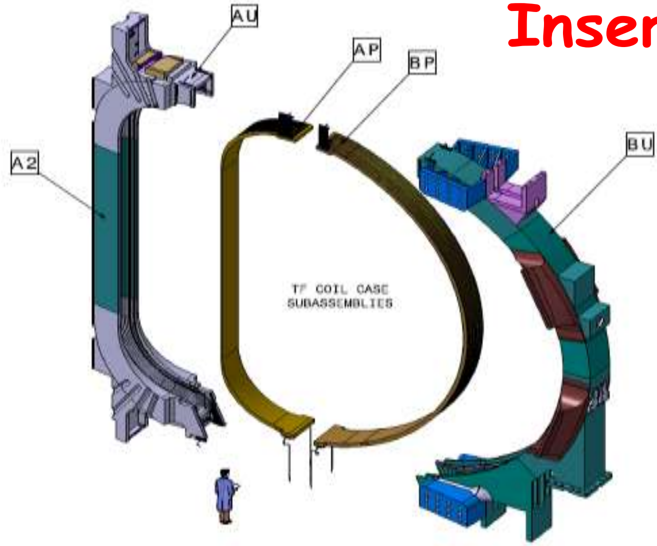


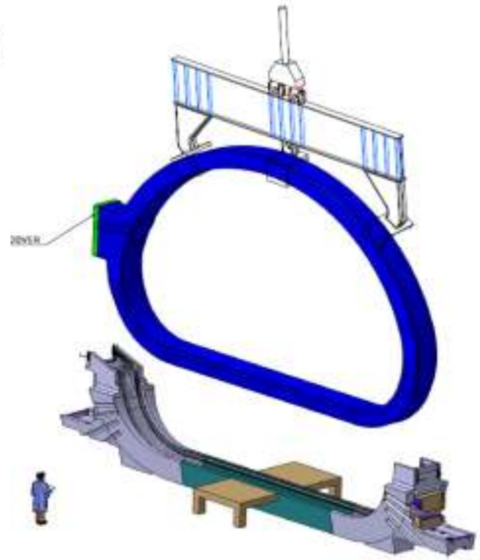


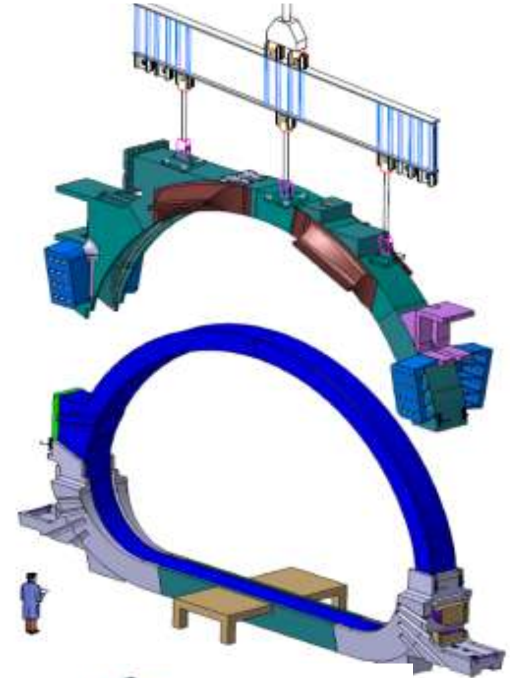
Very critical manufacture, joint resistance may have a severe impact on cooling requirements

Insertion of the WP in Case

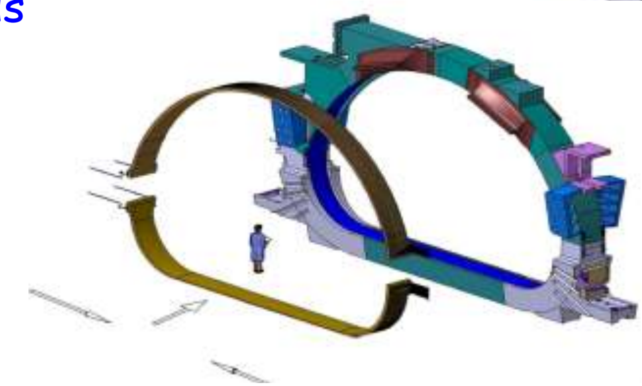
Insertion of Winding into Case



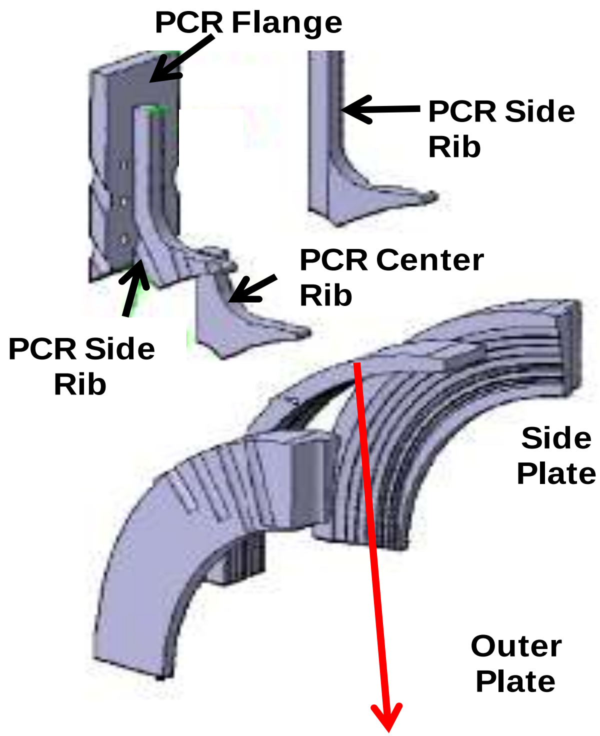




- High accuracy required to reduce error fields
- Reduce machining of huge components
- Fitting gaps carry stress penalty

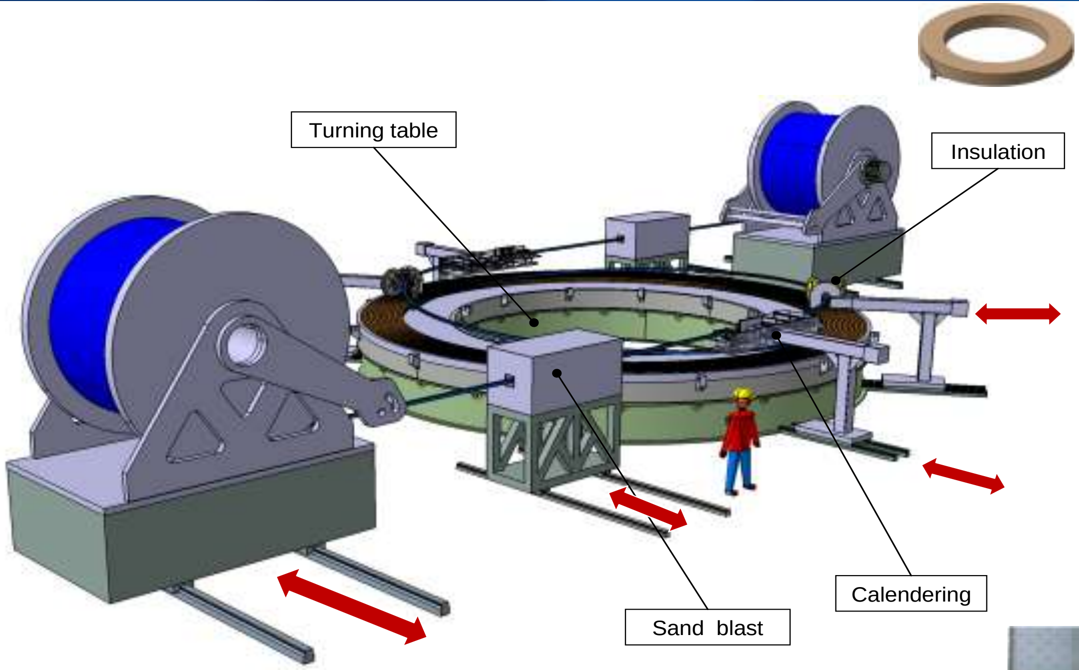


TF Coil Case Preparation Work (JA)



Prototype of side plate for TF coil case under forging process (above) and finished shape (below)

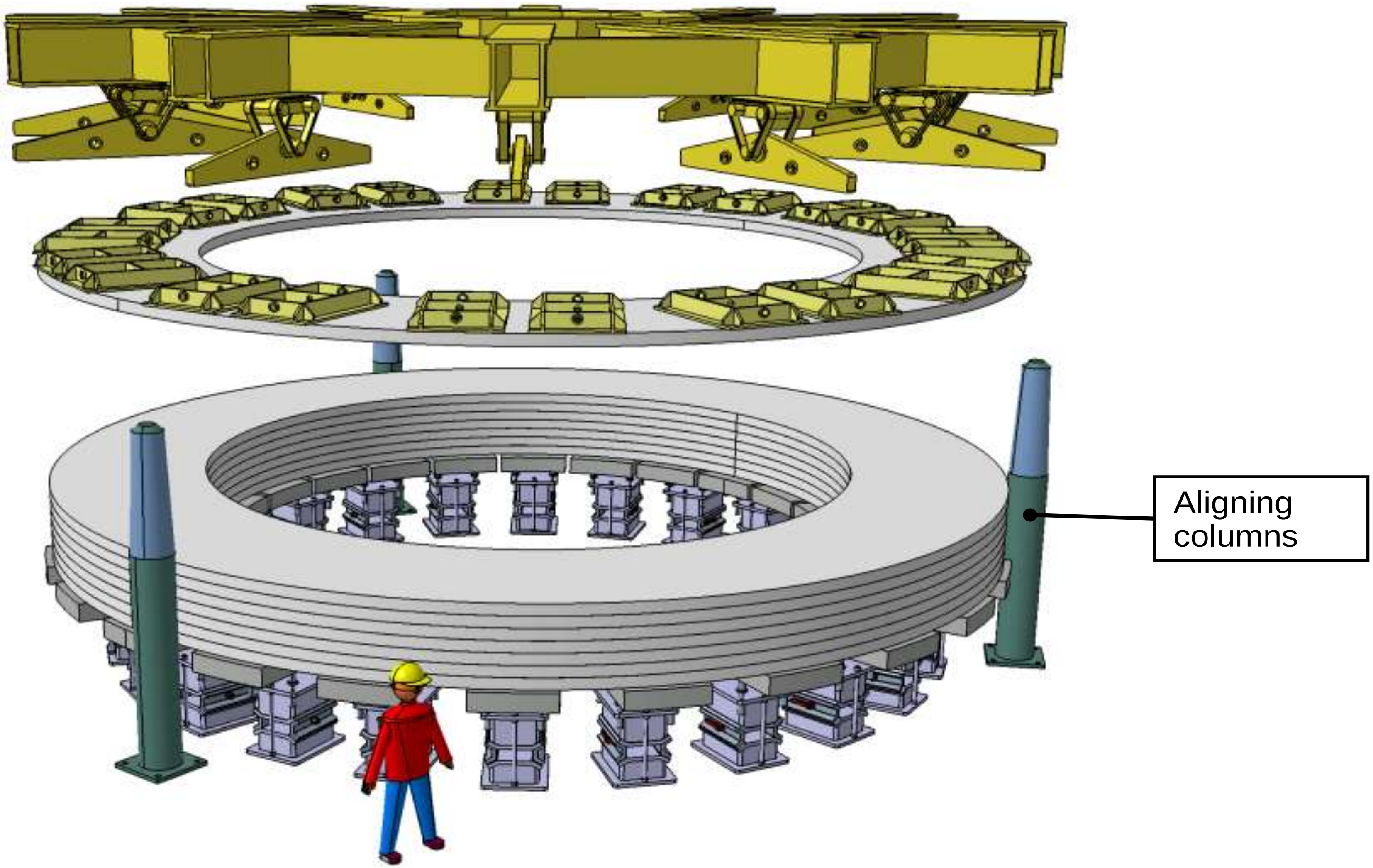
PF Coil Fabrication



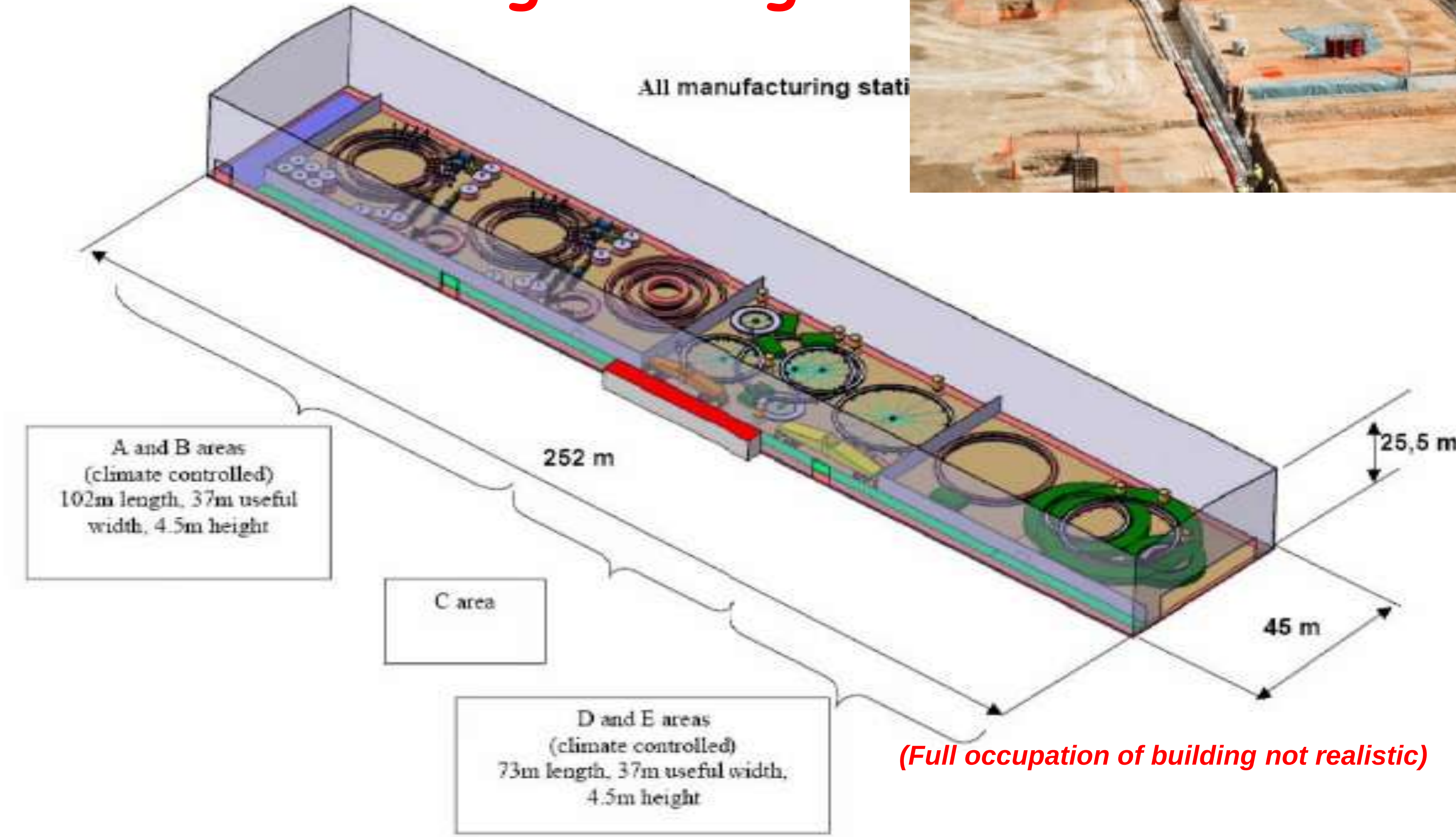
Proposed winding scheme by EU DA: call-for-tender for manufacture of PF2-PF5 is in progress, supply contract to be placed in early 2011

Winding tooling prepared by RF DA for PF1 double pancakes: insulating and impregnation equipment & devices have been designed and procurement is in progress

The DPs stacking



PF Coil On-site Manufacturing Building



(Full occupation of building not realistic)

Quality Assurance Programme

- Extensive quality control and quality assurance are foreseen throughout the manufacture of conductors and coils
- Extensive databases for strand and cable properties, winding geometry and all quality control test protocols
- Staged procurement and production-proof samples of the manufactured conductors are required
- A series of leak tests on conductors and coils during different stages of jacketing and winding
- High voltage tests throughout the coil manufacture, also in Paschen-minimum conditions
- Tight control of non-conformities
- *Cold testing of all magnets* is proposed down to 77 K to check leak and high voltage integrity and measure joint resistance with moderate current (TF windings before insertion and finished CS/PF coils)

Section 10.

Beyond ITER

Long Term Fusion Magnet R&D

ITER → **Demo / Proto** → **Commercial Fusion Power Plant**

≈ 2018 **≈ 2030** **≈ 2045**

Need for Efficiency

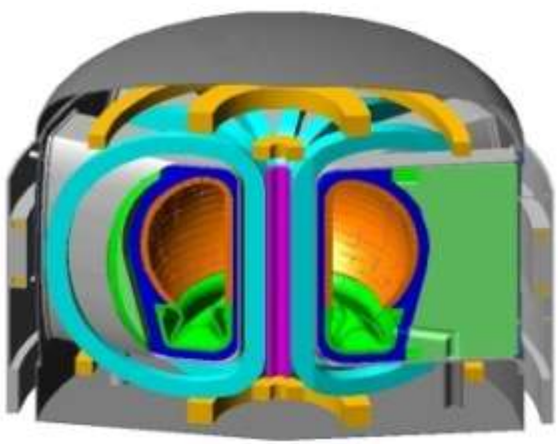
Scope of DEMO & DEMO Studies

Fusion Technology

Requirements for DEMO	• core dimension, comparable to ITER • steady state (year-long) • certain level of economic viability *AEC report, 2005*

Two conceptual DEMO designs proposed by JAEA and CRIEPI

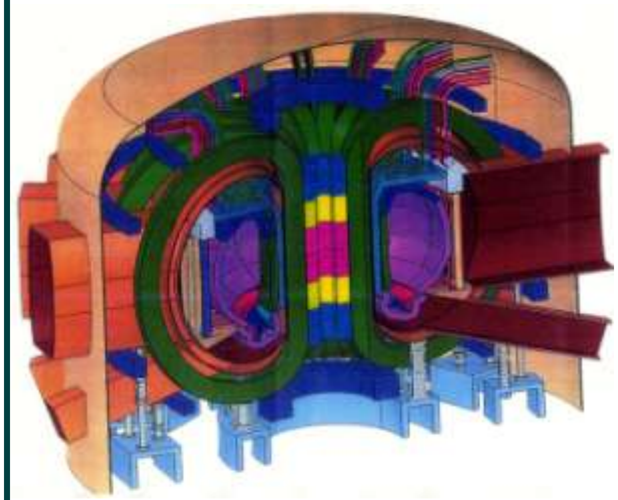
SlimCS — *JAEA*



R_p = 5.6 m
a = 2.1 m
P_{fus} = 2.95 GW

- **compact low-A DEMO with reduced-size central solenoid**
- **potentially economic & low-A merit in design margins**

Demo-CREST — *CRIEPI*



R_p = 7.25 m
a = 2.1 m
P_{fus} = 2.97 GW

- **in-life upgrade strategy to bridge the gap between ITER and economic CREST**

Possible Conductor Options

Three possible operating scenarios for fusion reactors beyond ITER

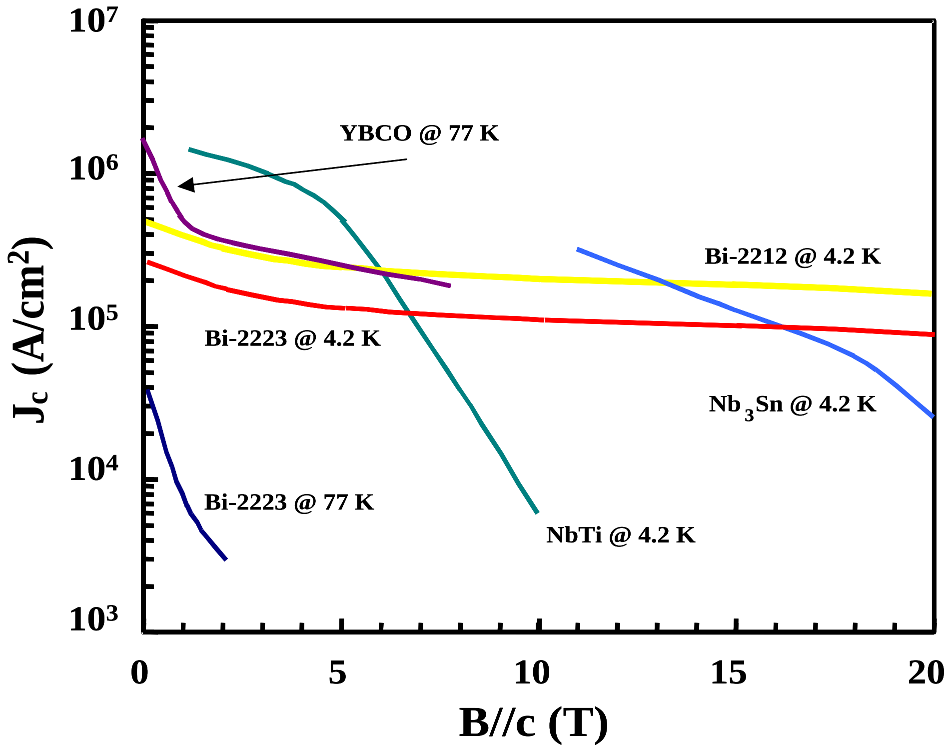
1) **High Field Option**
   Operating temperature at 5 K, but toroidal field at 13 – 17 T

2) **Intermediate Temperature Option**
   Operating temperature at 20 - 30 K, ITER like fields
   HTS basic material performance ok, increased efficiency but vacuum and He still required

3) **High Temperature Option**
   Operating temperature at a level where no thermal shield and maybe no He is required (T > 65 K)
   Simplification of reactor, significant increase of efficiency and reliability.
   HTS performance to be confirmed
   → YBCO only viable option

HTS for Fusion Applications

HTS show enhanced superconducting and irreversible properties compared to the established LTS (NbTi, Nb_3Sn):



- Much higher superconducting transition temperatures up to 135 K
- Very high upper critical fields of the order of 100 T
- High irreversible (operating) fields at higher temperatures
- Excellent critical current densities up to high temperatures and magnetic fields

Suitable HTS compounds: **Bi-2212**, **Bi-2223**, **Y-123** and for PF- **MgB_2**

Research projects already started to manufacture samples and prototype coils

Section 11.

Summary

Summary

- Main drivers for fusion magnets design are:
  - Large forces & stresses
  - Radiation on windings
  - Large stored energy
  - Operation in vacuum
  - Large heating in the conductor
- The magnets being manufactured for ITER present many challenges
- The Model Coil programs have addressed many issues, but because of the size scaling some major manufacturing issues of full scale coils still need to be addressed
- The magnet program is very aggressive because it does not foresee construction and testing of full scale prototypes of the coils
- Technical solutions have to be developed directly on the real coils
- Therefore, a preliminary 2 year qualification phase is foreseen to tackle some of the manufacturing issues (i.e. dummy double pancake construction)

Summary - 2

- The ITER project sets new limits for conductor and coil dimensions, quality assurance and project management:
  - Currents up to 68 kA
  - Coils up to 13 m (Nb_3Sn) and 24 m (NbTi) in diameter
  - More than 530 t of Nb_3Sn strands for TF and CS coils
  - About 300 t of NbTi strands are required for PF and CC
  - Complex coils with a total weight of up to 350 tons
- HTS current leads using Bi-2223 tapes up to 68 kA

The ITER magnet system will be a challenge for industry, worldwide…

Thank you
for your attention