The ITER Magnets
at
MATEFU

6 Apr 2009

N. Mitchell

ITER IO, Cadarache, France

Structure of Presentation

Design Overview

- TF coils PF coils CS coils Correction coils Feeders
- Conductor
- Cooling
- Forces

Design Focus 2007-9

- Tolerancing of magnet system

Procurement Arrangements

- How ITER is procured
- Status

Procurement and Qualification Status

Overall Features

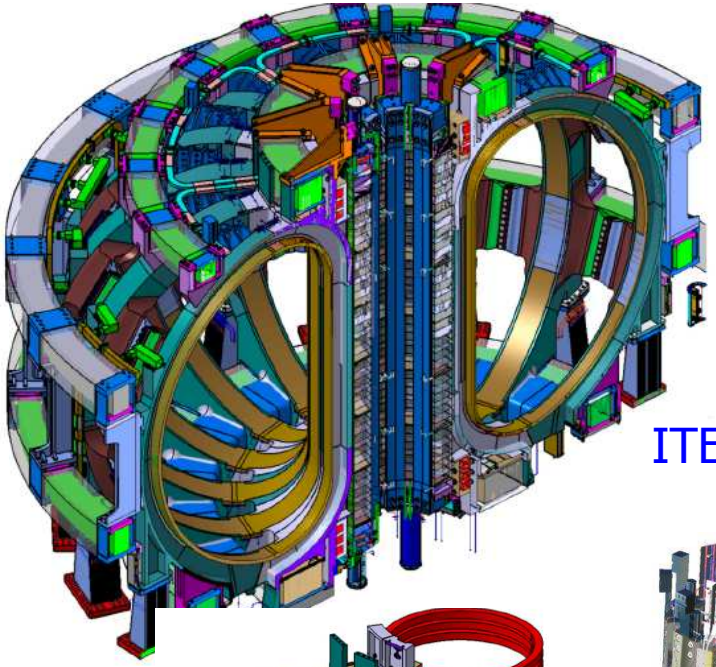
4 Main Systems, all superconducting

System	Energy GJ	Peak Field	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

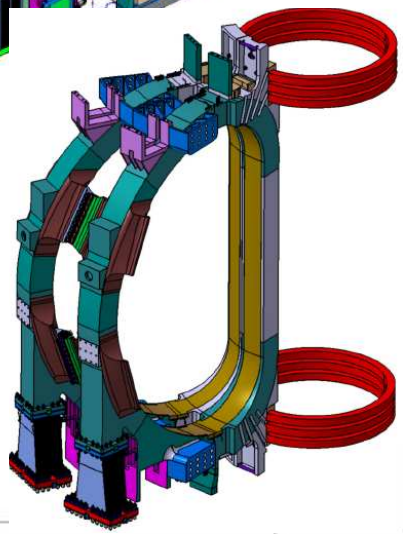
FUNCTIONALITY

TF 18 coils	Field to confine charged particles in the plasma
CS 6 coils	Inductive flux to ramp up/drive plasma Plasma shaping Plasma vertical stability
PF 6 coils	Radial position equilibrium of plasma Plasma shaping Plasma vertical stability
CC 18 coils	Correction of error field harmonics

- The ITER magnet system is made up of
  - 18 Toroidal Field (TF) Coils,
  - a 6-module Central Solenoid (CS),
  - 6 Poloidal Field (TF) Coils,
  - 9 pairs of Correction Coils (CC).

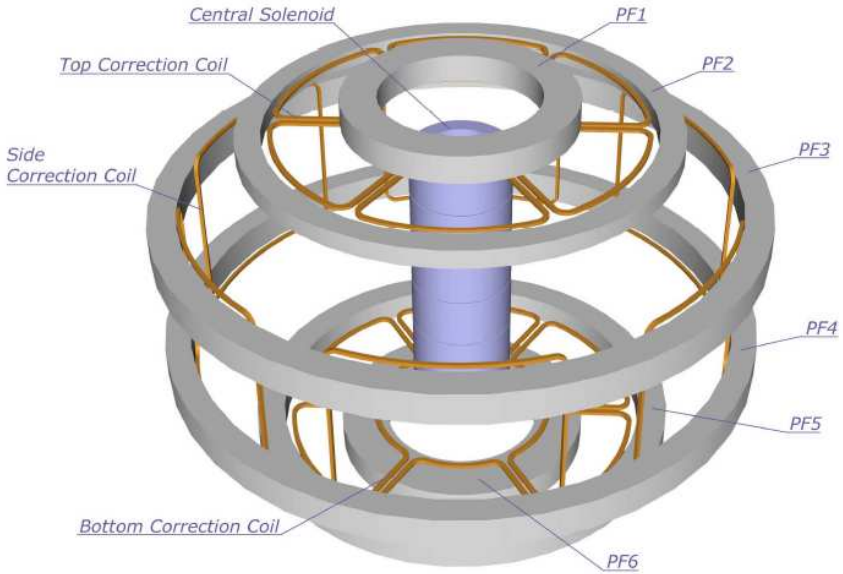


ITER Magnet System



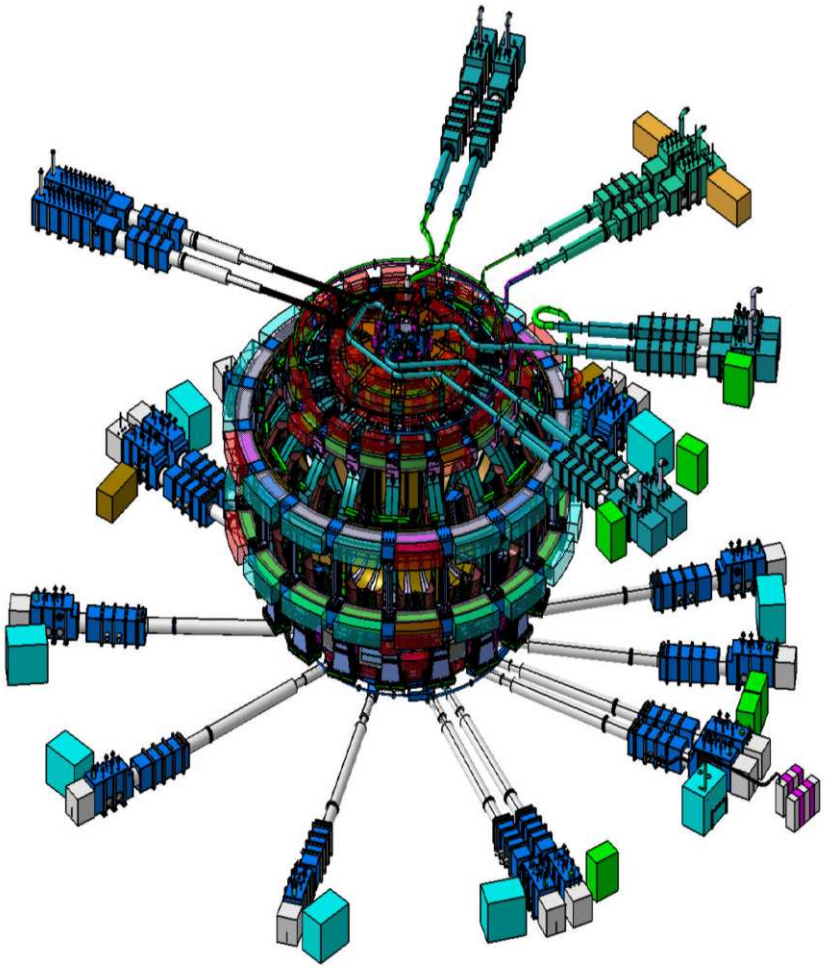
Pair of TF Coils

CS Coil

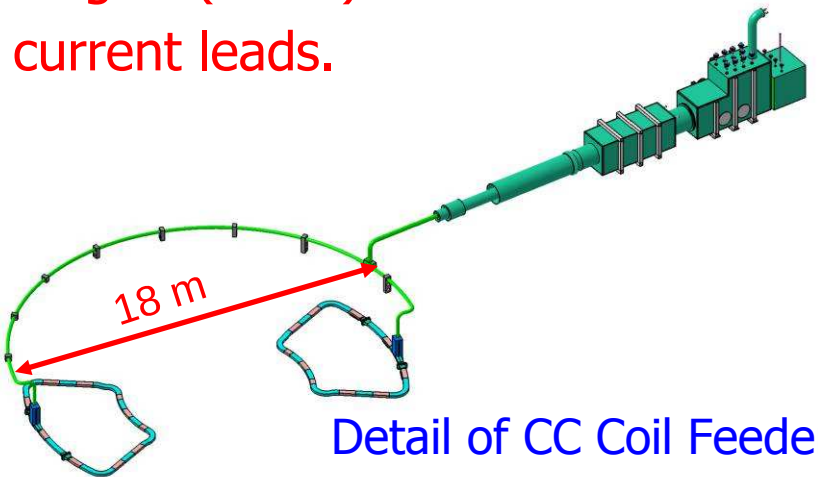


PF & CC Coils

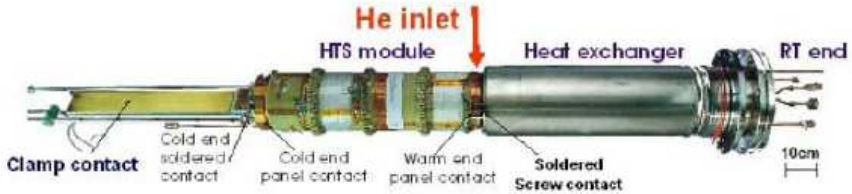
- Magnet Feeders include
  - Containment ducts,
  - NbTi CICC busbars,
  - Supplies (instrumentation, He lines)
  - expansion boxes and terminal boxes
  - Ag-Au(5.4%) BiSCCO 2223 HTS current leads.



ITER Feeder System



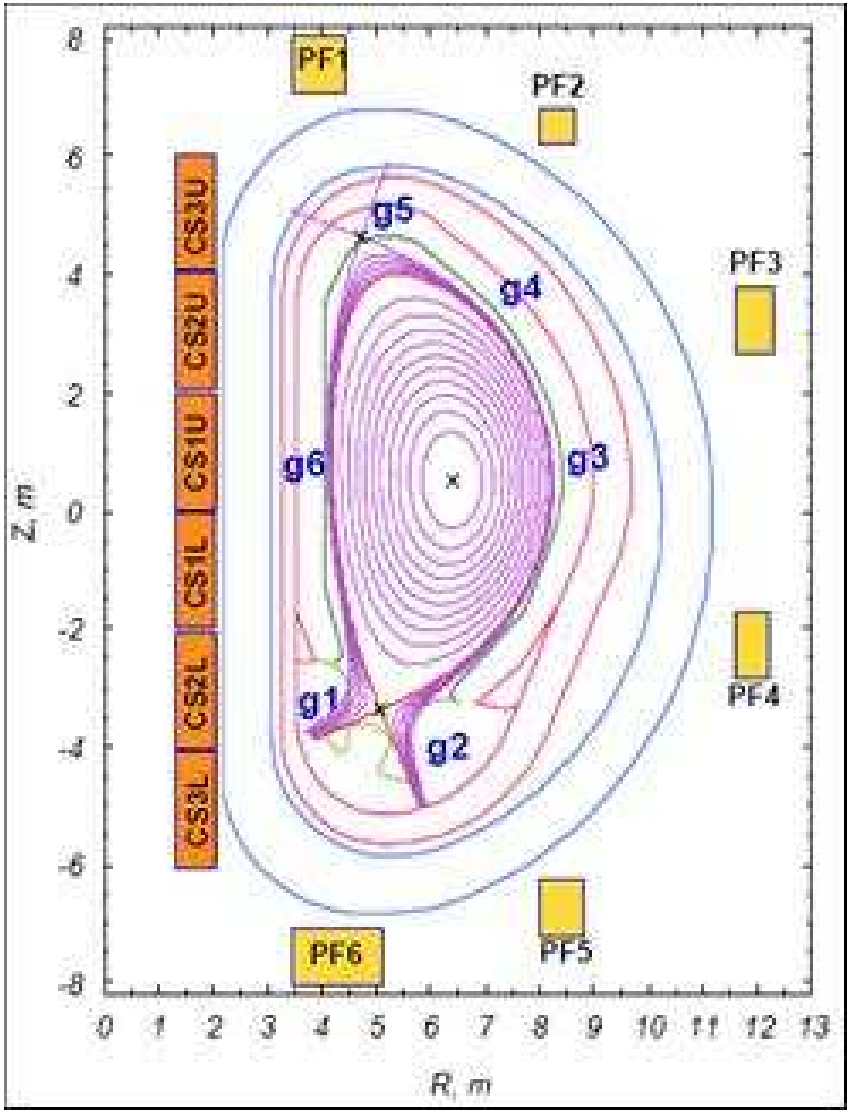
Detail of CC Coil Feeder



68 kA HTS Prototype Lead Developed by FZK

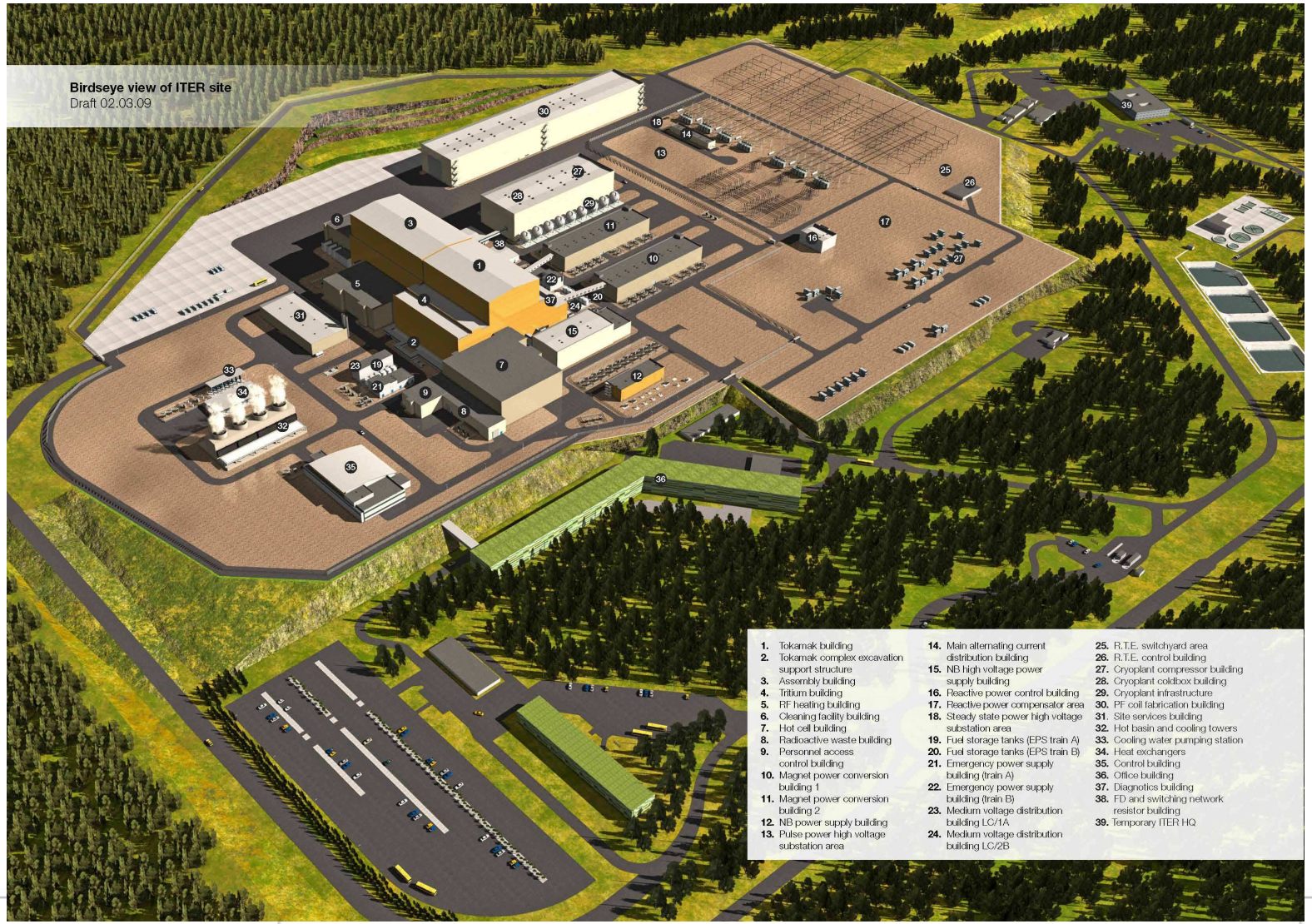
Plasma magnetic control:

1) **plasma initiation**
2) **control of plasma current**
3) **control of positions and shape (six plasma-wall gaps). Slow feedback loop is used, timescale of 5-10 s.**
4) **Vertical stability control. Fast feedback loop is used, timescale <1 s with P2-P5 and possibly CS2U,L**

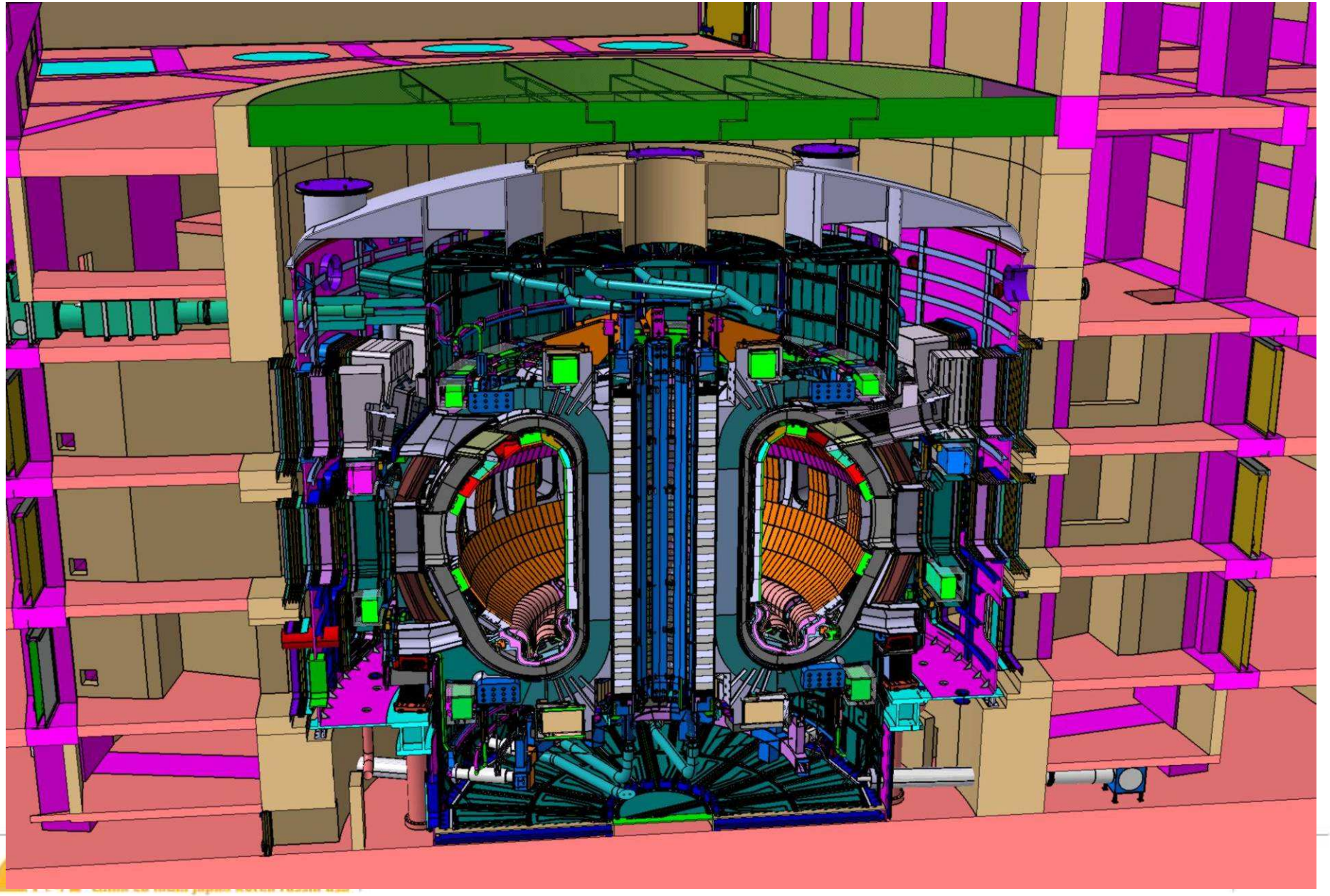


The plasma position is controlled at the points g1-g6 to keep the first wall and diverter heat loads to acceptable values

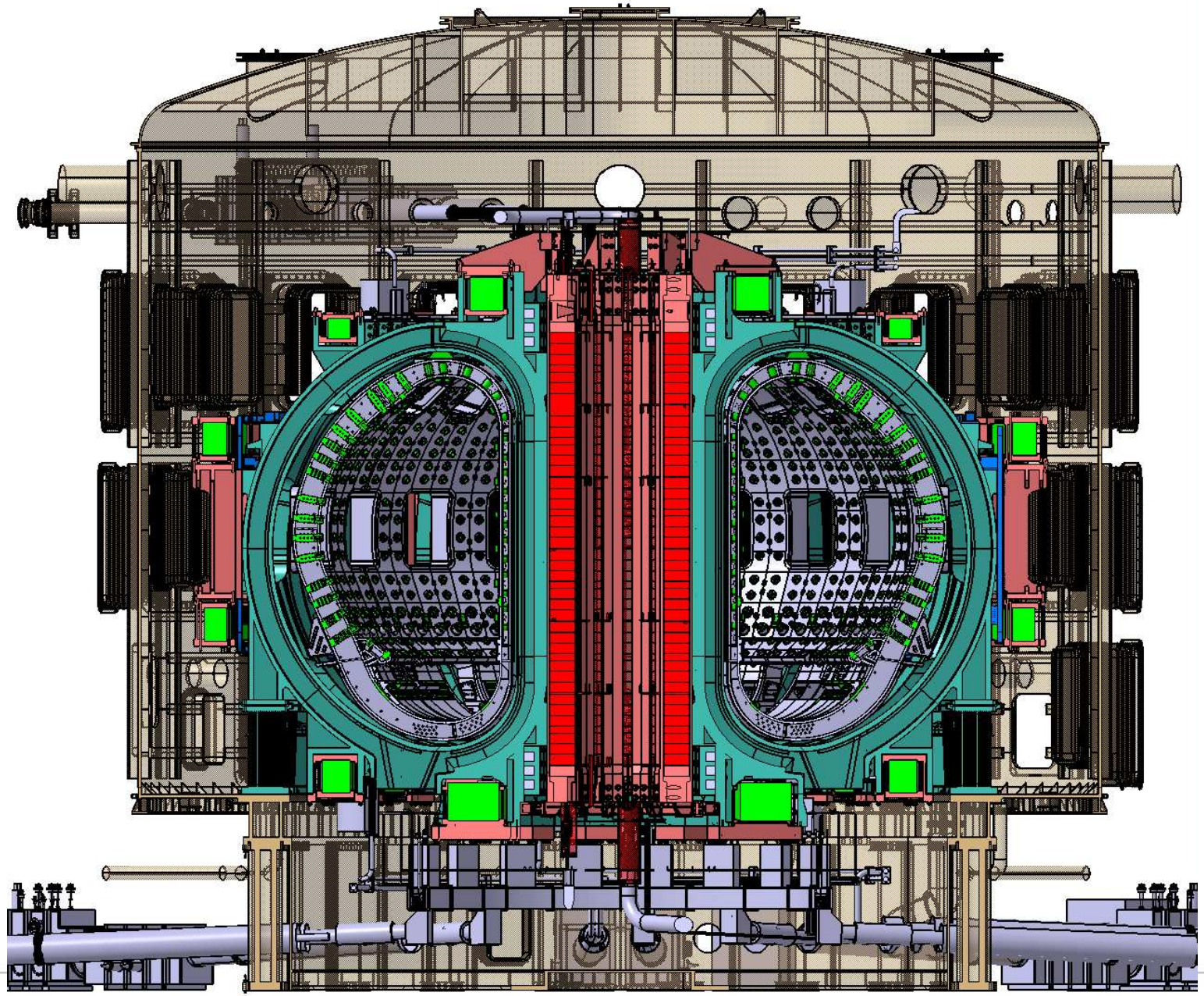
ITER Project Site Layout: 3-D graphics view

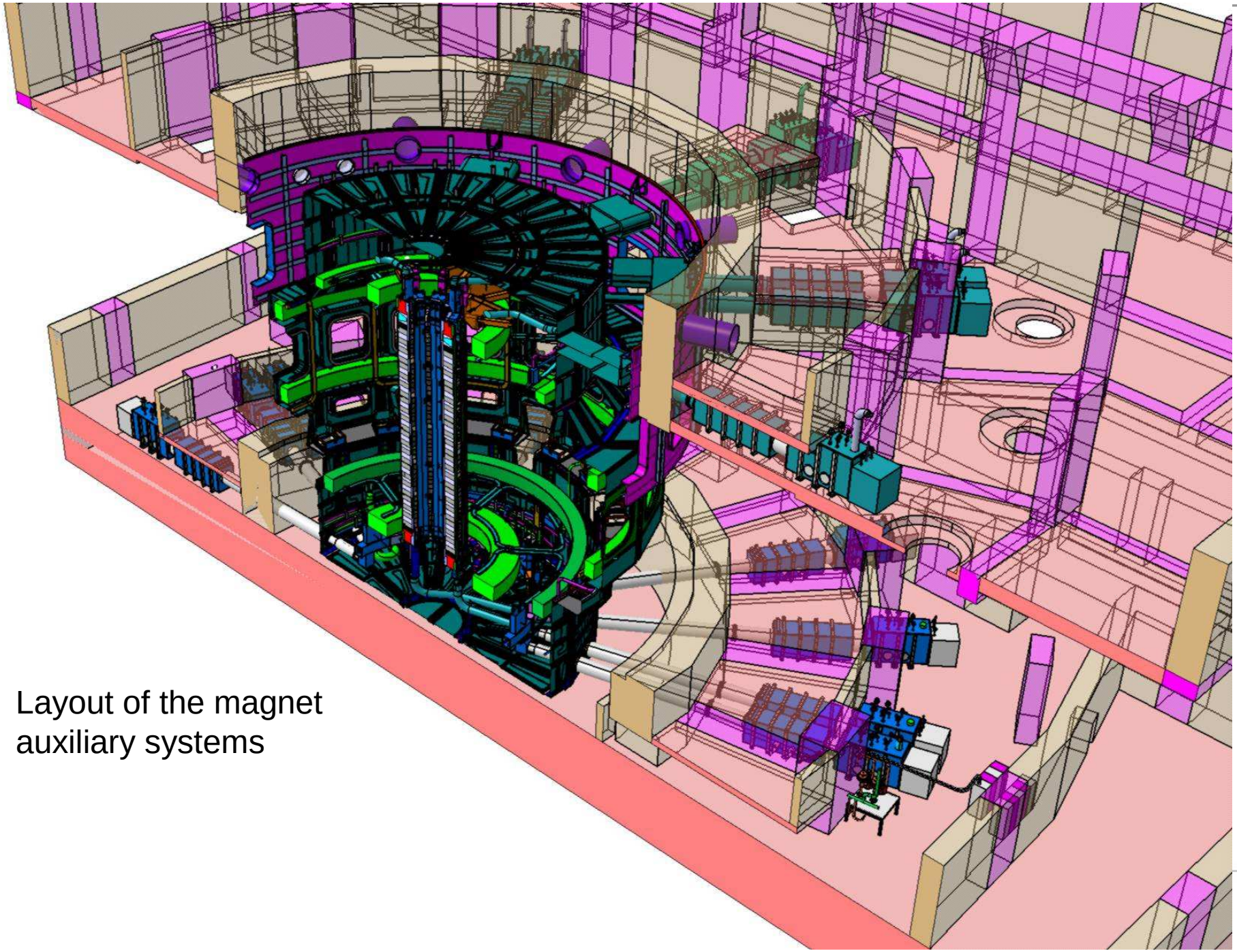


ITER Tokamak (Basic Machine) and the Surrounding Building



Cross-section of the basic machine with Vacuum Vessel



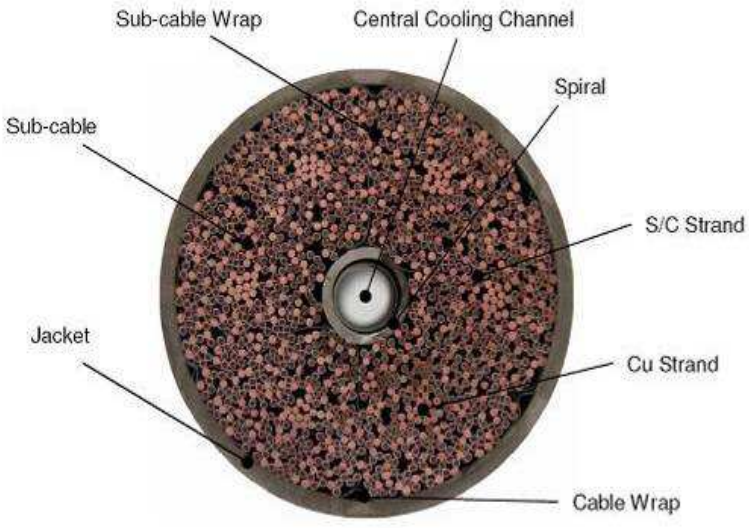


Layout of the magnet auxiliary systems

Main Magnet Features

Conductor	**Circular Cable in Conduit, about 1000 strands, 45-70kA** **Nb3Sn for CS, TF, NbTi for PF and CC** **TF thin circular jacket. CS and PF thick square jacket**
Cooling	**Supercritical Helium, inlet temperature 4.5K**
Insulation	**Glass-polyimide with epoxy/ cyanate ester resin**
TF	**D shaped, massive case surrounding winding** **Radial plates to protect conductor insulation, double pancakes**
CS	**Stack of 6 circular coils, vertical pre-compression structure to hold coils in contact, no case, hexapancakes**
PF	**Circular coils, double pancakes, no case, supported on TF. 2 in hand windings, no inner joints**
CC	**Square coils around circumference, correction of error fields from tolerances on TF, CS, PF**

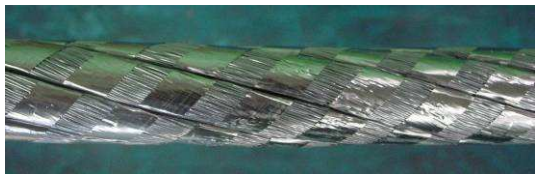
ITER Conductors-1



X-section of 70kA ITER TF Conductor (CEA)

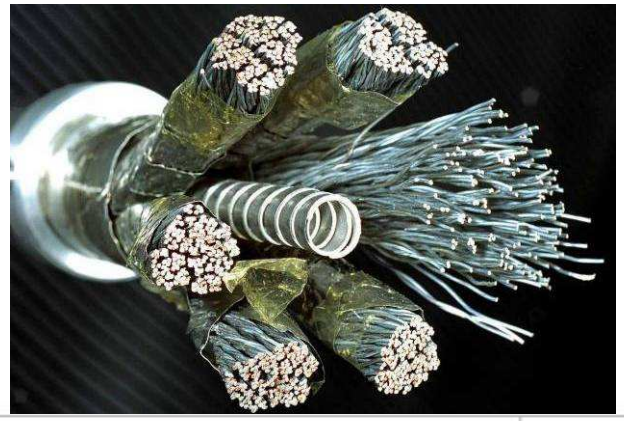
- ITER coils are wound from Cable-In-Conduit Conductors (CICC's), relying on superconducting multifilament composite strands mixed with pure Cu strands/cores.
- The strands are assembled in a multistage rope-type cable around an open central cooling spiral.
- The cable and its spiral are inserted inside a stainless steel conduit which provides helium confinement.

Cooling Spiral



Final-Stage Cable (NFRI)

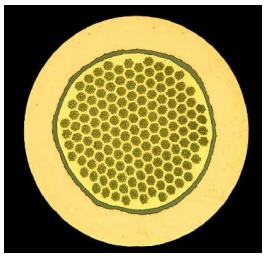
Stainless Steel Conduit (ASIPP)



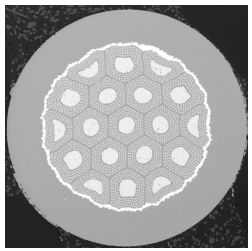
ITER Conductors-2

TF Conductor

- TF coils rely on Nb_3Sn strands and a modified 316LN, round-in-round jacket,
- CS coil modules rely on Nb_3Sn strands and a JK2LB (high Mn), round-in-square jacket.

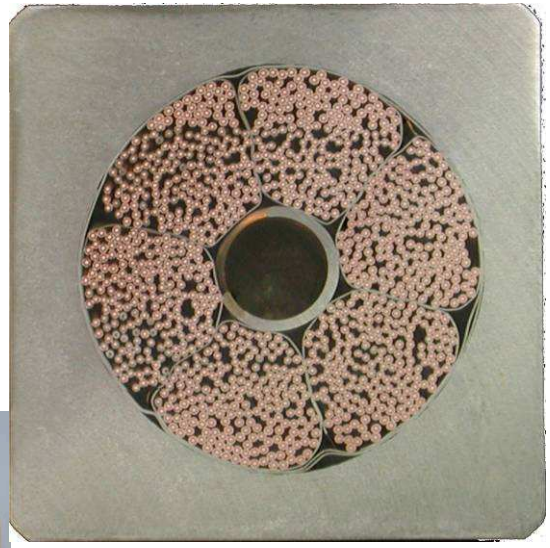


Bronze Nb_3Sn strand developed by EAS, EU



Internal-tin Nb_3Sn strand developed by OST, US

PF Conductor

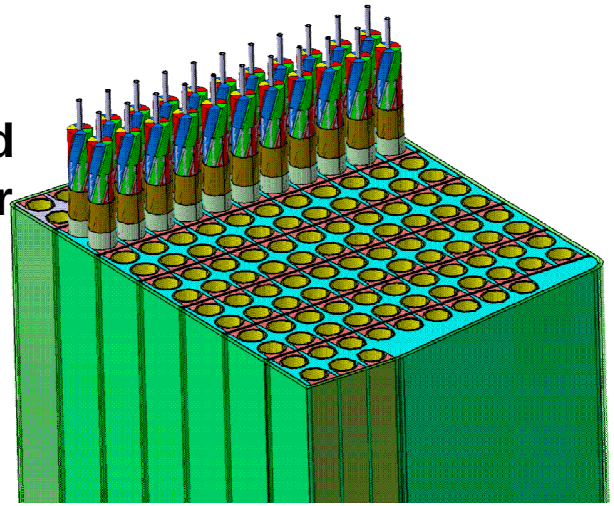


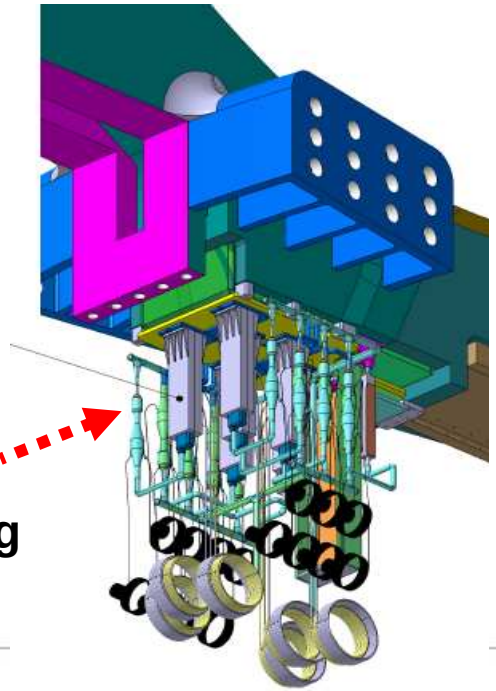
- PF coils rely on NbTi strands and a 316L, round-in-square, jacket.

NbTi strand developed by VNIINM, RF

TF Coils

Radial plates and conductor

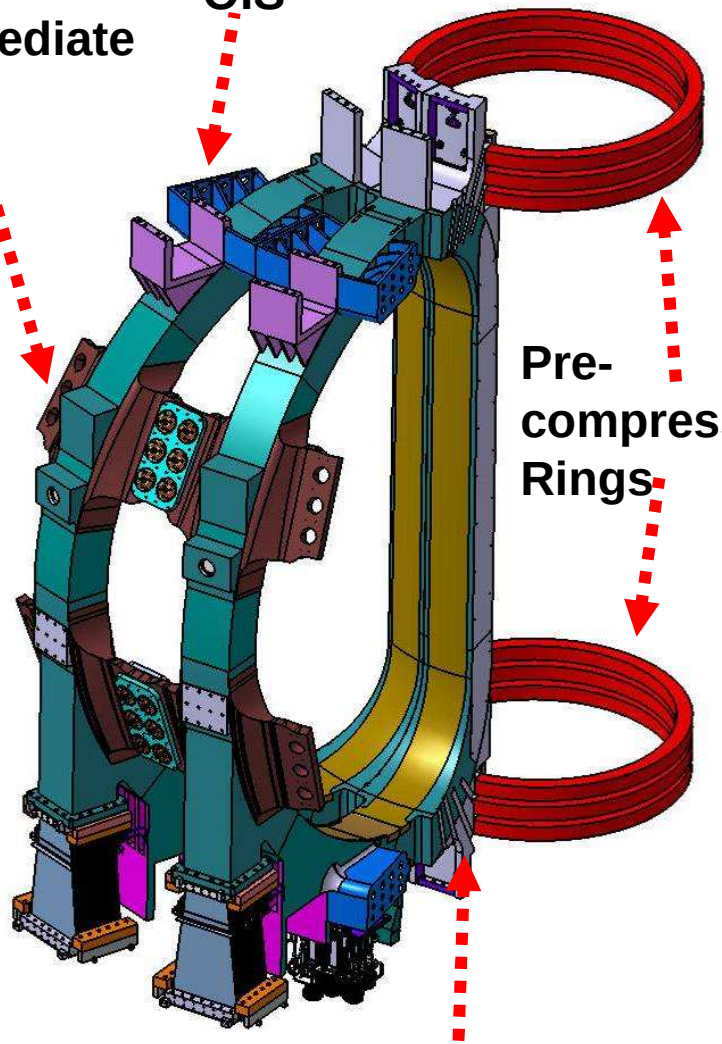




Joint and manifolding region

Upper OIS

Intermediate OIS

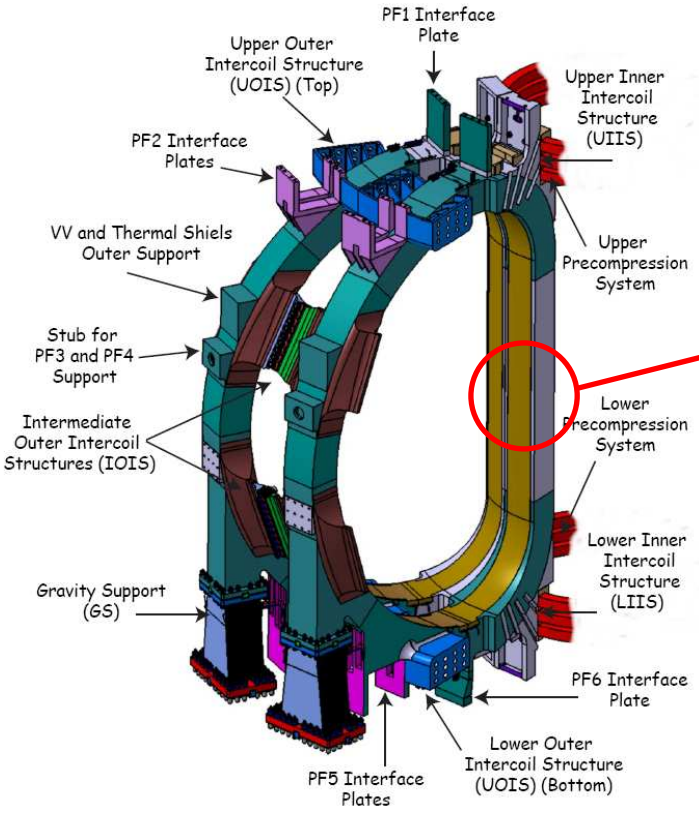


Pre-compression Rings

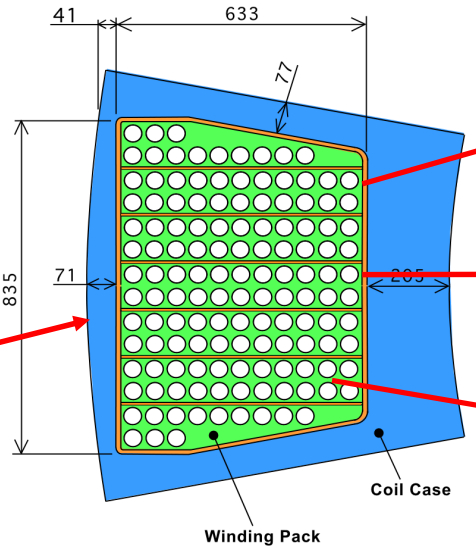
Gravity support leg

Inner poloidal keys

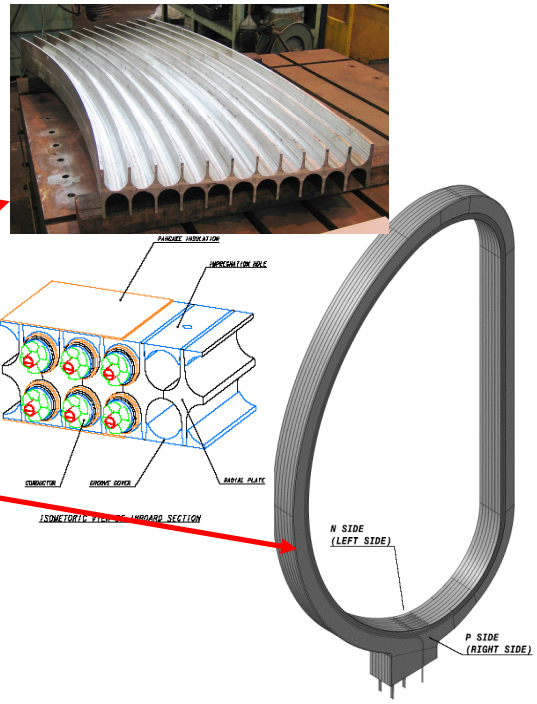
TF Coil Winding Pack



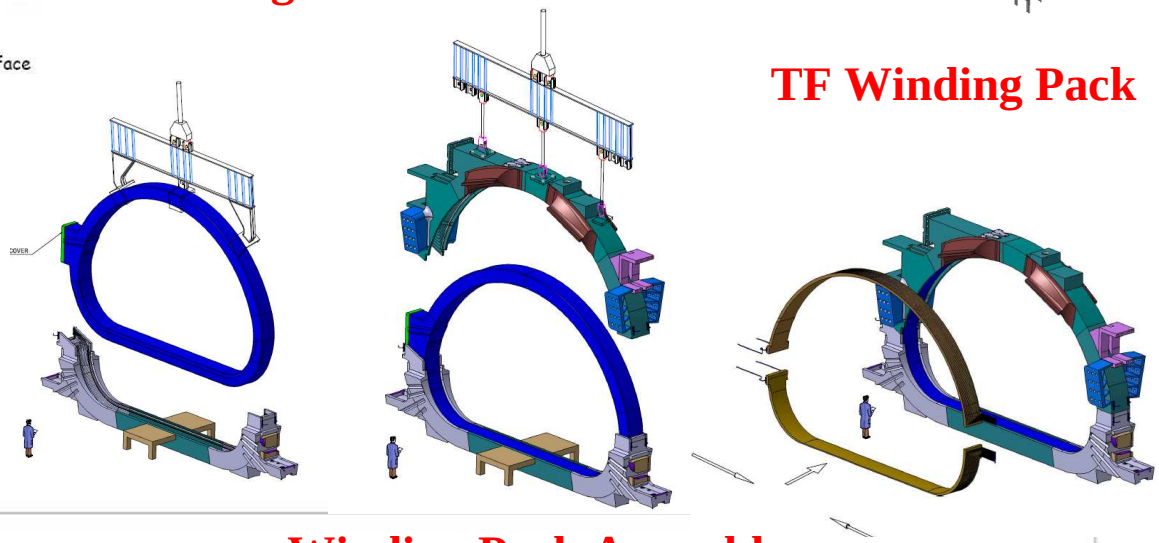
TF Coil



Inner Leg Cross Section



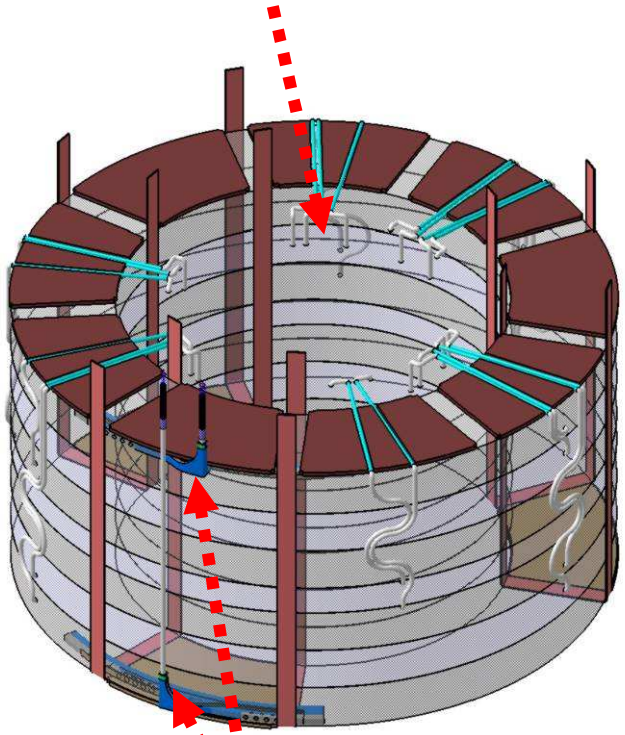
TF Winding Pack



Winding Pack Assembly

CS Coils

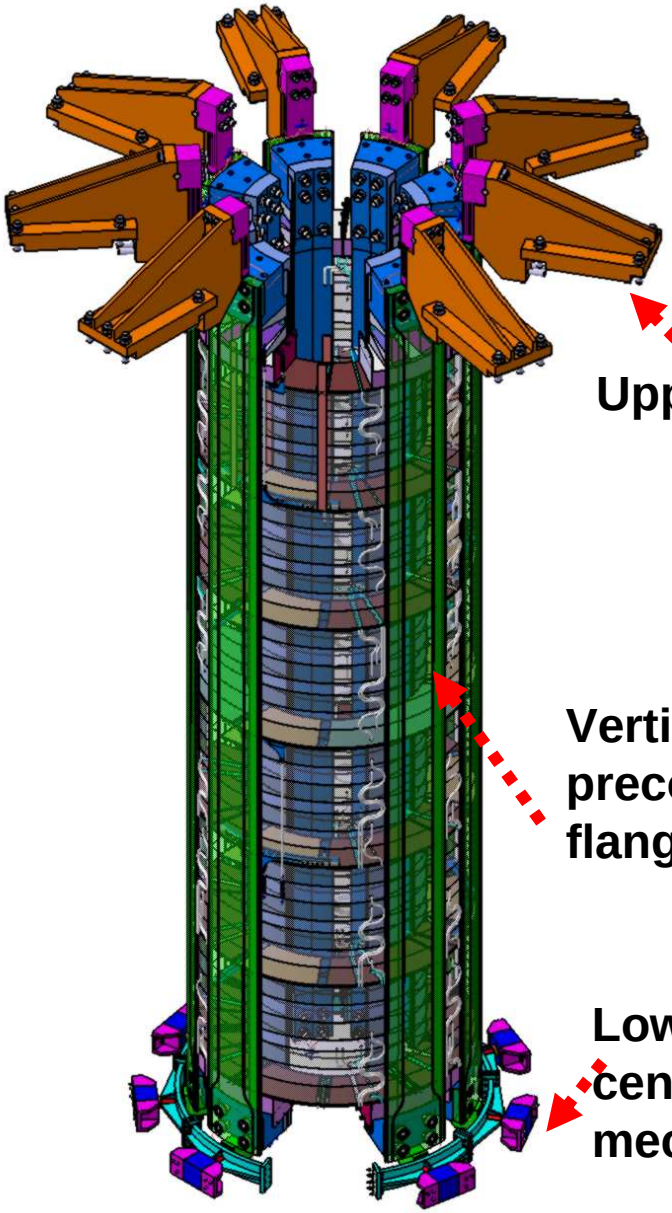
He inlet manifolds



terminals and busbars

Single CS Module

CS stack, 6 modules, supports and precompression flanges



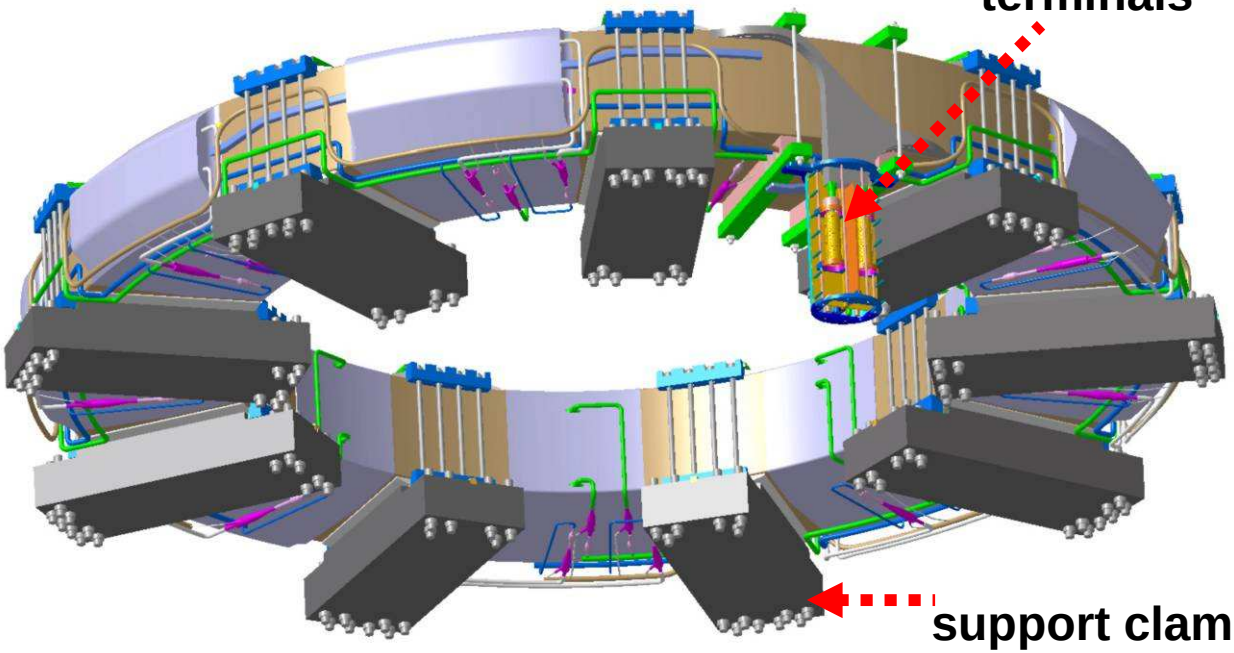
Upper hangers

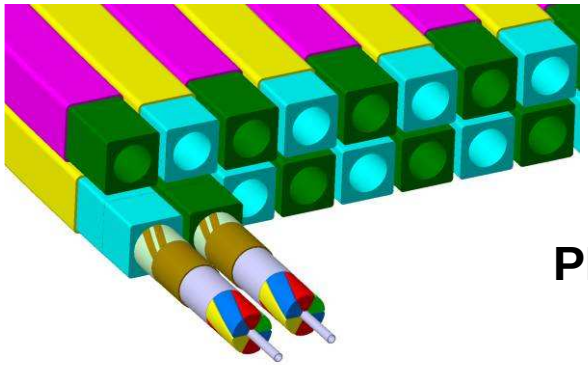
Vertical precompression flanges

Lower centring mechanism

PF Coils

P6 coil
and
supports

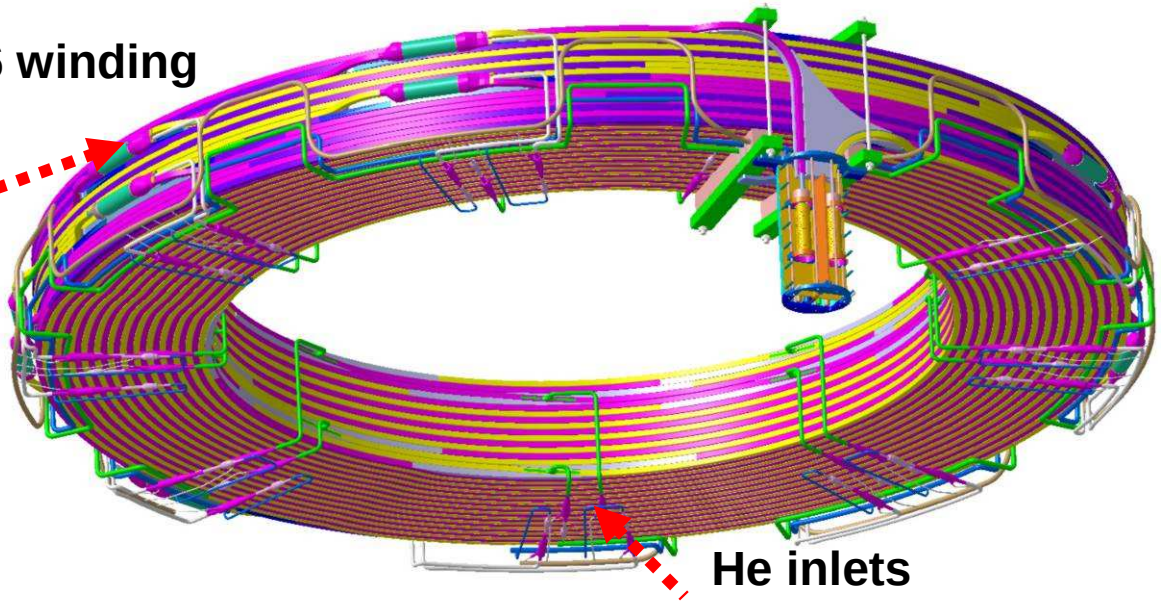




2 in hand
conductor
winding

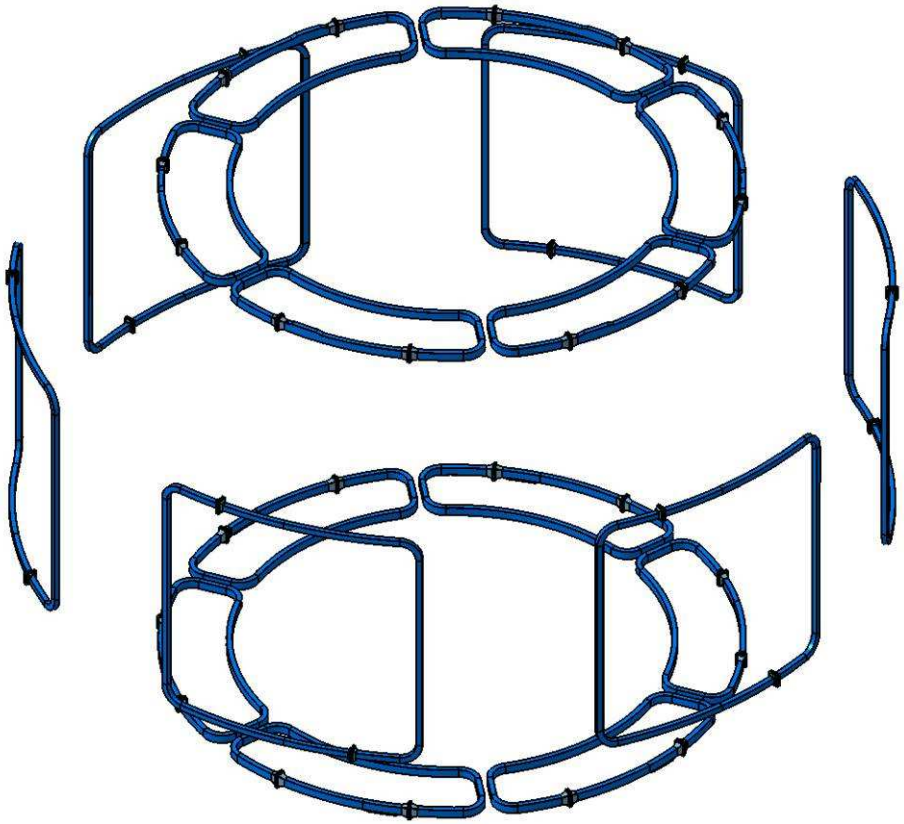
PF 6 winding

pancake
joints



Correction Coils

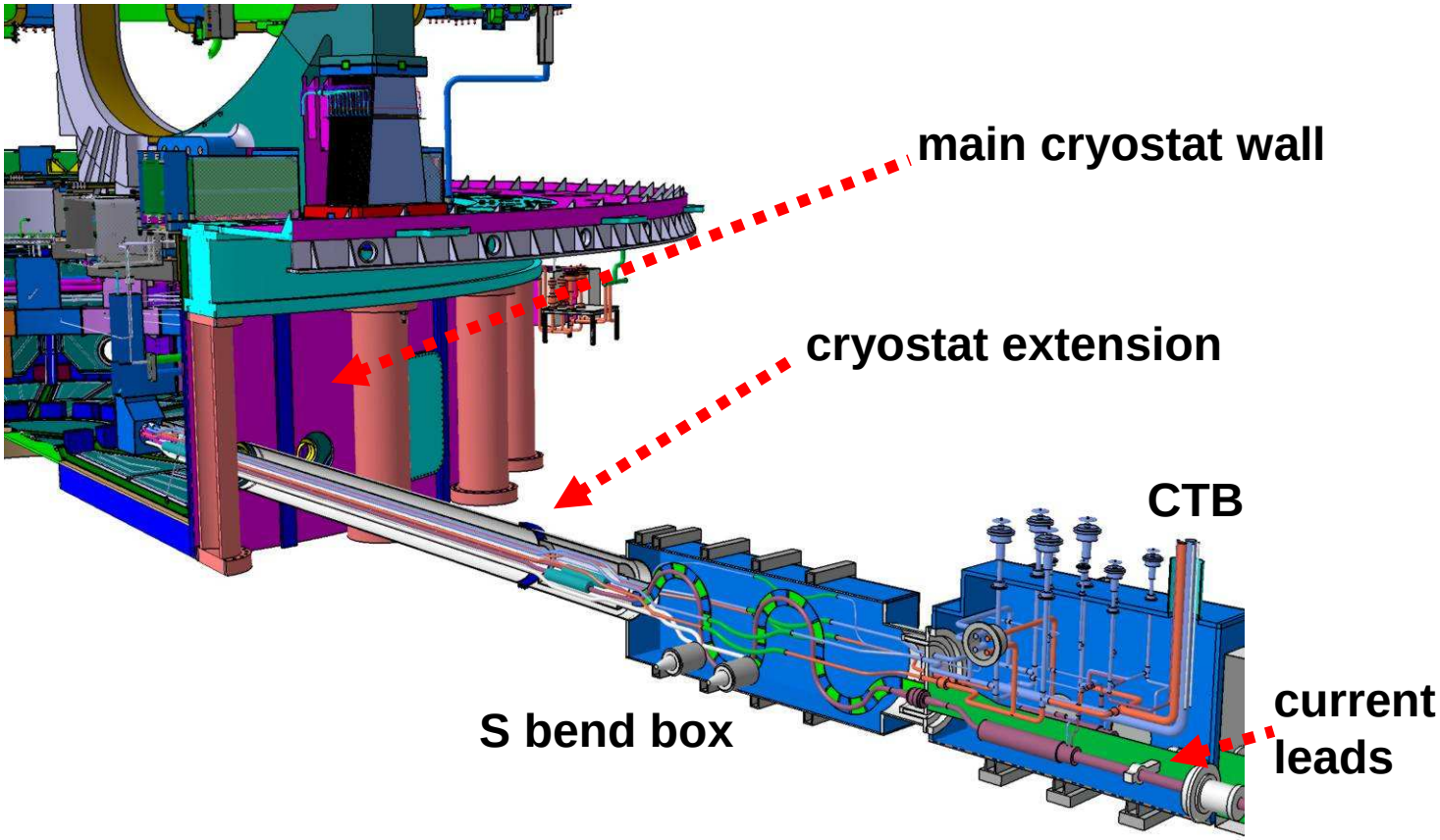
320kAT

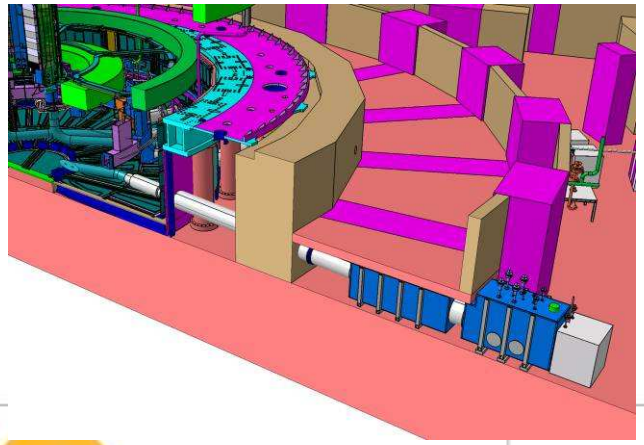


200kAT

320kAT

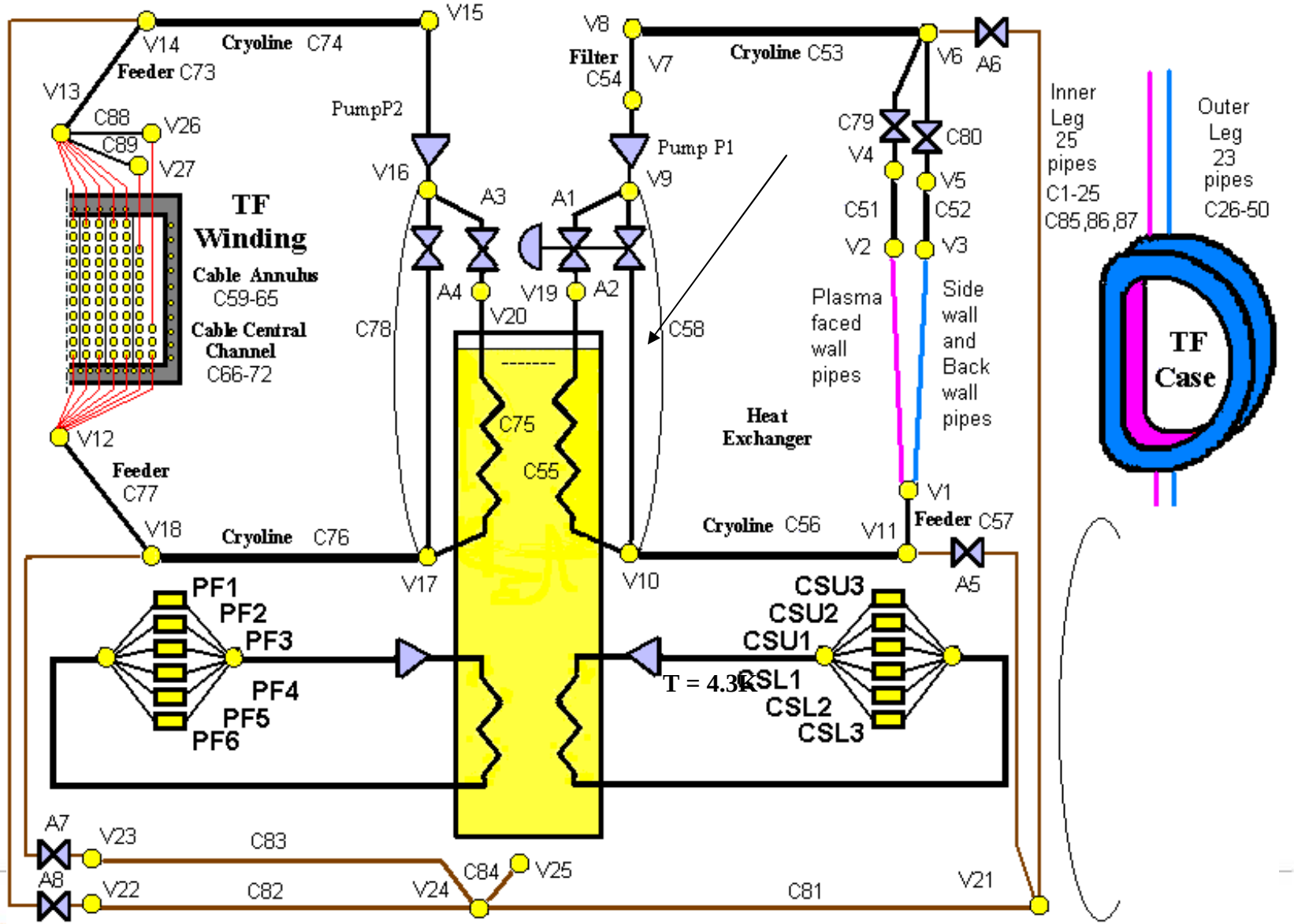
- opposite pairs in anti-series
- 9 independent sets
- correct toroidal and poloidal harmonics in poloidal field



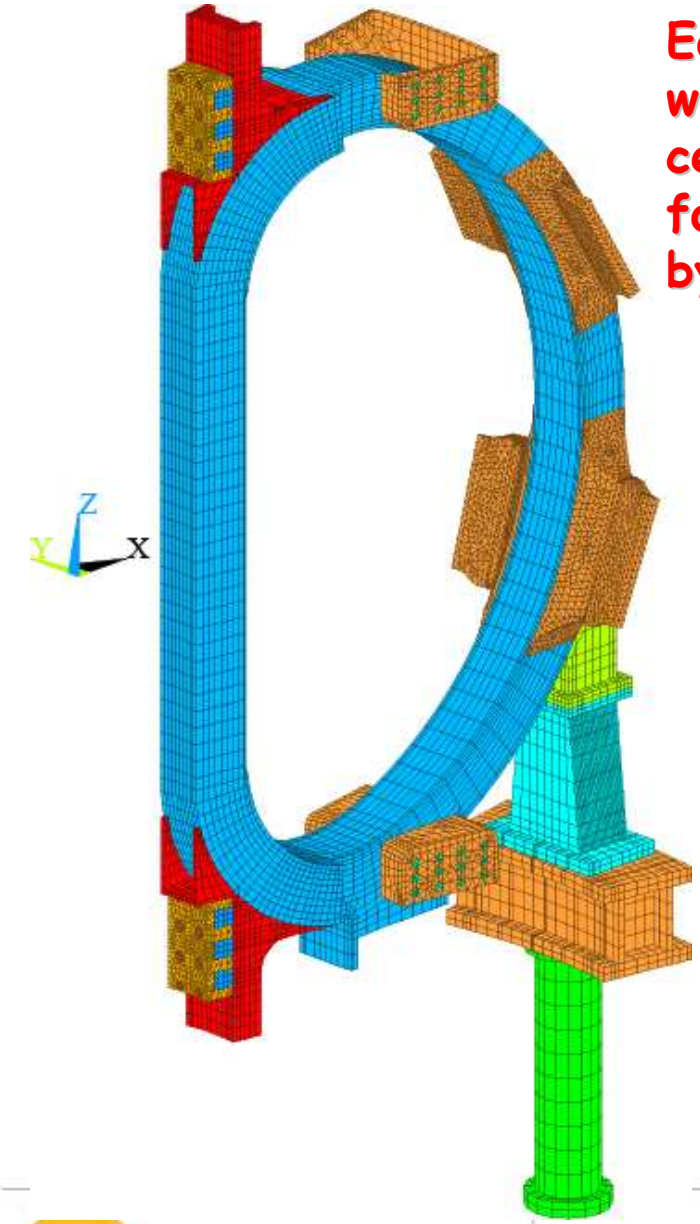


Feeder Terminations

4 large He cooling loops for the ITER magnets: TF casing, TF winding pack, PF & cc, CS.



TF In-plane Magnetic Forces

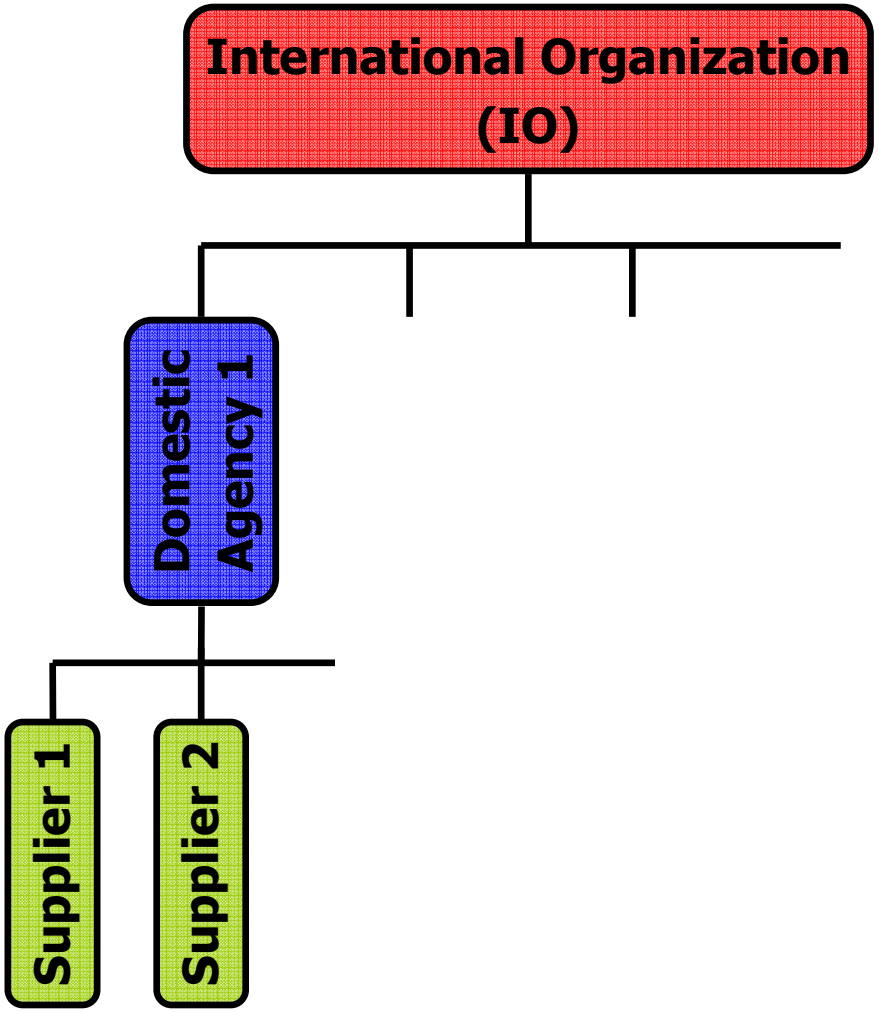


Each TF coil experiences a bursting force (Fz) as well as a resultant centring force (Fx) towards the centre of the machine. The resultant centring forces are reacted by the cylindrical vault formed by the inboard straight legs of the TF coils.

ΣFx	**- 402.8.** ***-201.4/ -201.4***
ΣFy	**0.0** ***0.0/0.0***
ΣFz	**0.0** ***+205.3/ -205.3***
ΣMx	**0.**

Top half/bottom half

ITER In-Kind Procurement -1



- Most ITER components are contributed *in-kind* by the seven ITER Parties through their respective Domestic Agencies (DA's).
- The IO is responsible for overall design and integration and for defining the technical requirements.
- The DA's are responsible for procuring the components and for delivering them to the IO.

- In-kind procurement sharing was negotiated among ITER Parties and is cast in the so-called ITER agreement.

ITER In-Kind Procurement -2

- In-kind Procurement process is in two steps:
  - First step is the issuance of the so-called Procurement Arrangement packages (PA's) between the IO and the DA's (within framework of ITER agreement),
  - Second step is the issuance of contracts between the DA's and their suppliers (following DA rules).
- Issuing PAs between IO and DA is proving very time-consuming
  - DAs reluctant to commit to schedule but IO cannot resolve interface issues between DAs without this
  - Procurement system does not favour competitive tenders. Das concerned about costs but locked in system that prevents effective reduction

Total Value of Magnets

- 48 coils / 6 major systems

Procurement Arrangements

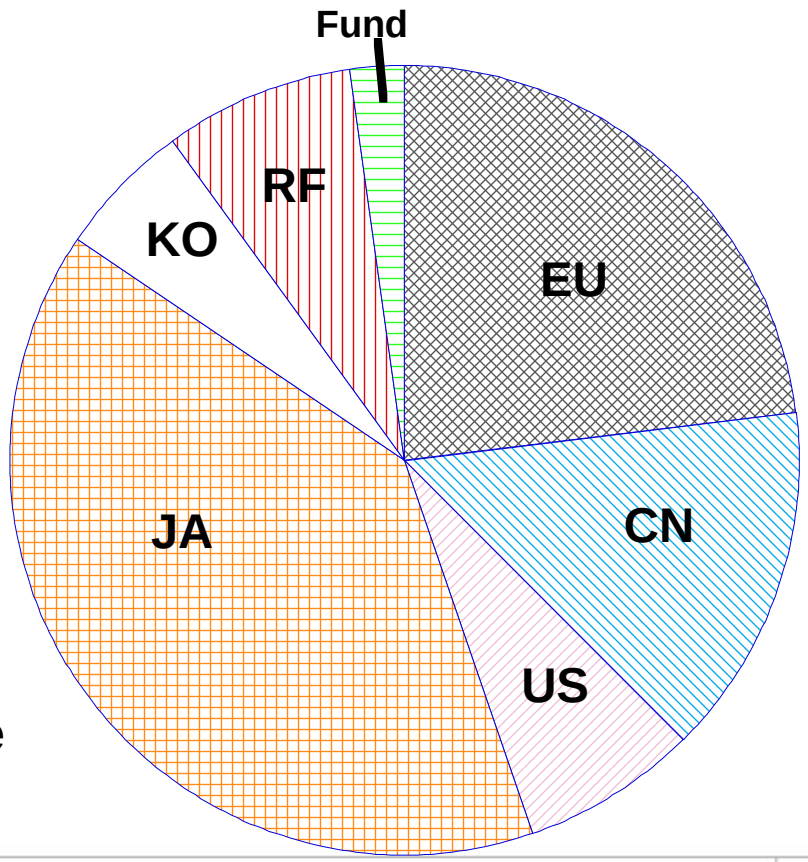
- TF Conductors –215kIUA
- PF Conductors -74kIUA
- CS Conductors – 90kIUA
- TF Winding -168kIUA
- TF Structures -99kIUA
- PFMagnets 1&6 -13kIUA
- PFMagnets 2,3,4,5 -33kIUA
- Correction Coils – 3 kIUA
- Central Solenoid – 40kIUA
- Feeders & Sensors – 44kIUA

TOTAL ~779kIUA = 1000MEuro

ITER In-Kind Procurement -3

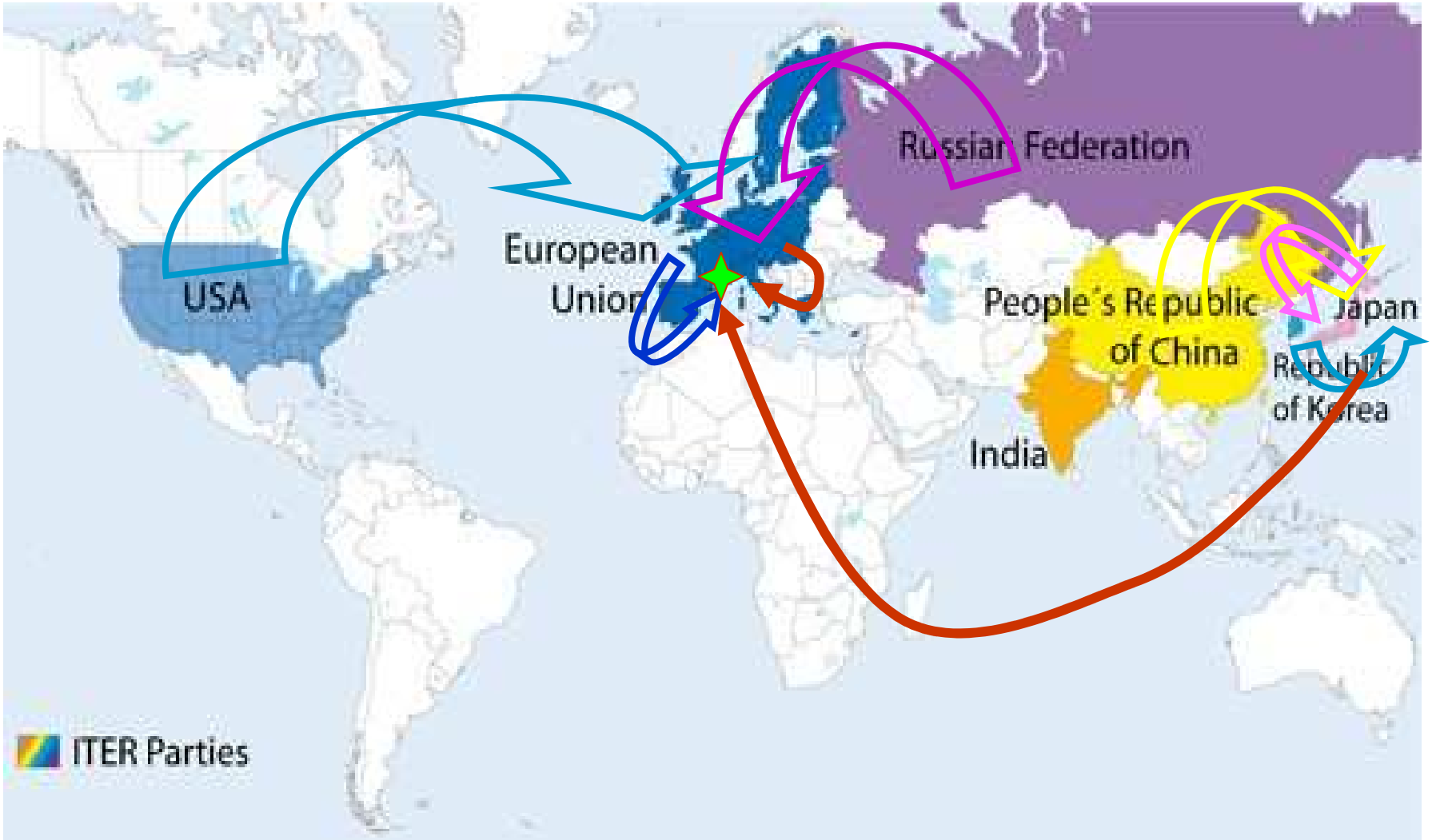
In magnets we have

TF coils EU, JA (conductor CN, EU, JA, KO, RF, US)
PF coils EU, RF (conductor CN, EU, RF)
CS coils US (conductor JA)
Correction Coils CN
Feeders CN



Procurement distribution by value

TF Coils: a Worldwide collaboration



conductor coils

Present Status of Magnet Procurement Arrangements
and industrial contracts

TF Conductor
Signed with CN, EU, JA, KO, RF (93% of supply). US waiting for sign from heaven.
JA in production, RF in production, KO contracts placed
TF Coils
Signed with EU and JA. JA contract placed
TF Structures
Signed with JA. JA contract placed
PF Conductor
Signed with CN, EU due to sign start May
CN contract placed
PF Coils
EU due to sign end May
RF due to sign Sept
CS Conductor
JA due to sign in July
CS Coils
US not yet ready to sign

Design Finalisation and Preparation for Manufacturing

Objective of Design Work 2007-9

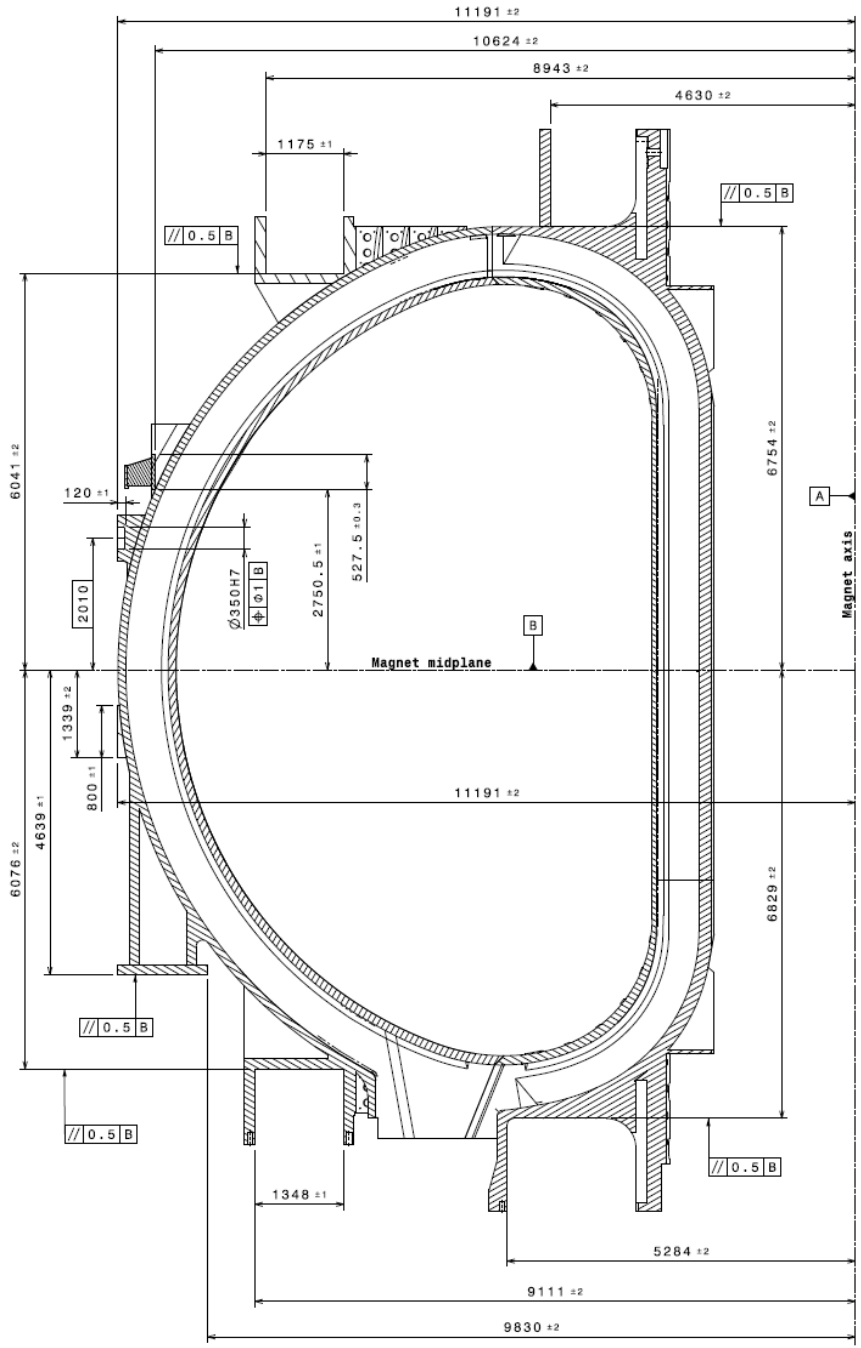
Complete design and analysis....achieve an approved design....detailed at the level of 'build to print'

- **All major features defined**
- **Contains sufficient detail to allow manufacturing drawings to be done**
- **Checked for design integration (major task due to complexity of in-cryostat systems)**
- **Major structural features analysed**
- **Interfaces defined**
- **Assembly procedures reviewed**
- **Tolerances defined (between magnets and other systems and within the magnets themselves, between systems and between subcomponents)**
- **Manufacturing concepts available and assessed as feasible**

Status
TF Coils complete
PF Coils complete
CS Coils complete
CCs and supports complete Sept 2009
Feeders and CTBs complete early 2010

Example of ‘after manufacture’ outer surface tolerances for a single TF coil

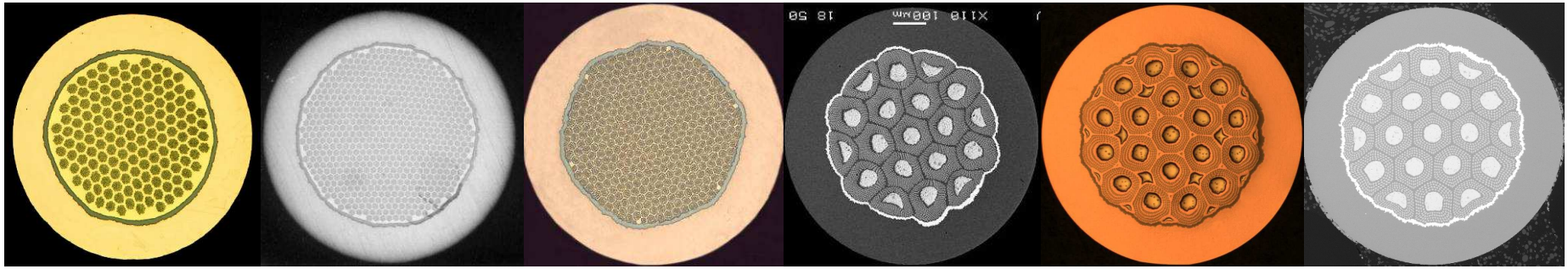
ON ASSEMBLY each sector (including a TF Coil pair) will be aligned relative to its best-fit nominal position with the following total tolerances:
radial ± 3 mm
vertical ± 2 mm
toroidal gap in the wedged region of the inner leg 2 ± 0.5 mm
toroidal (outer region) ± 3 mm



Examples of Industrial Production and Design Qualification

TF Strand Specifications

- Nb_3Sn strand specifications are functional and call for
  - Diameter (un-reacted, Cr-plated) 0.820 ± 0.005 mm
  - Cu-to-Non-Cu volume ratio 1.00 ± 0.10
  - I_C at 4.22 K and 12 T (ITER Barrel) > 190 A
    (at 4.2 K and 12 T on ITER barrel)
  - Hysteresis loss per strand unit volume < 500 mJ/cm^3
    (± 3 T at 4.2 K cycle on a sample longer than 100 mm)
  - RRR (after Cr-plating & heat treatment) > 100



EAS	Hitachi	VNIIBM	NIN&WST	KAT	OST
(Br; EU)	(Br; JA)	(Br; RF)	(IT; CN)	(IT; KO)	(IT; US)

(Br: Bronze; IT: Internal Tin)

TF Conductor cross-section (KODA)

Multistage twisted cable

Contained in a steel jacket

Jacket pre-assembled by butt welding (in a straight line ~800m long) and then pulling the cable inside. A compaction machine then pushes the jacket onto the cable

Status of RF Jacketing Line, Jacketing & Spooling

RF Jacketing Line under construction at High Energy Physics Institute in Moscow

Status of RF Jacketing Line, Jacketing & Spooling

Workshop inside

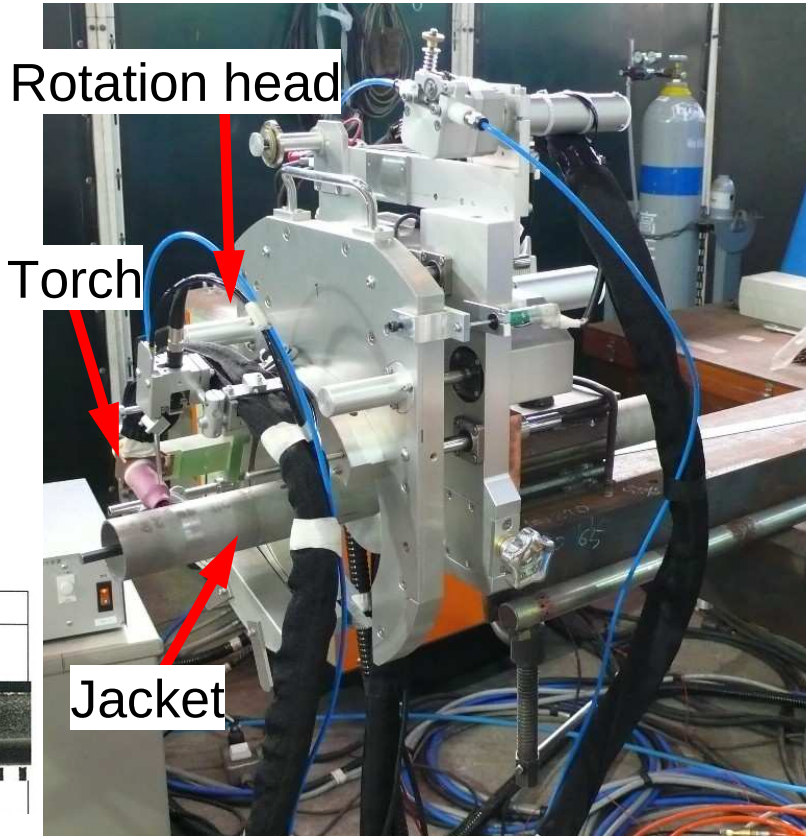
TF & PF Conductor Activities in Heifei, China

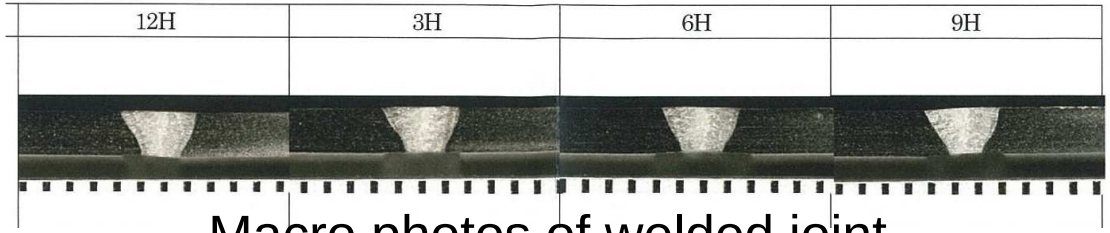
JA Compaction machine

Status of building construction for JA jacketing line
(9 March 2009)

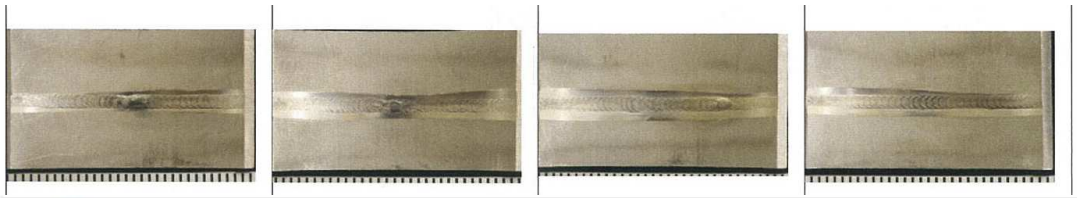
Status of JA jacketing facility preparation

- First automatic orbital TIG welding machine has been completed.
- Preliminary welding test using TF jacket with a thickness of 1.9mm was started.

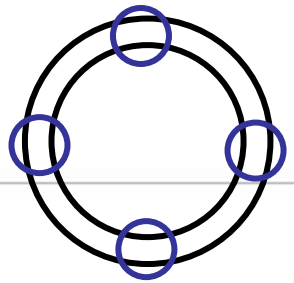




Macro photos of welded joint



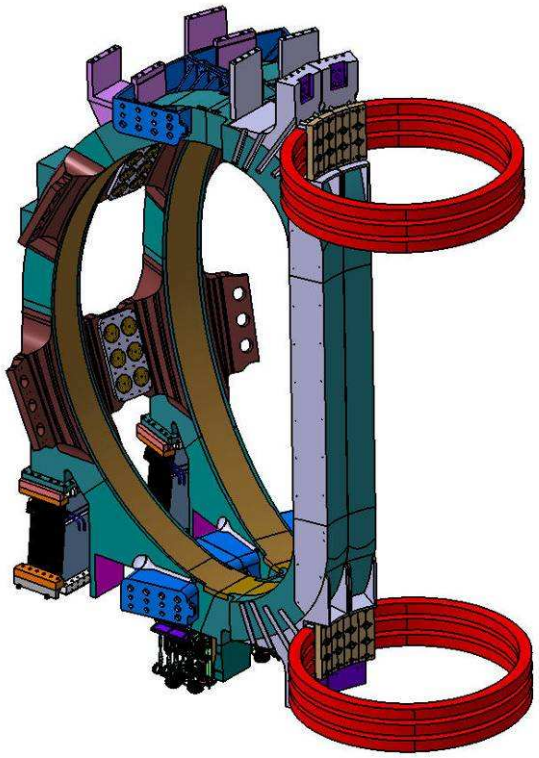
Inside surface of welded joint



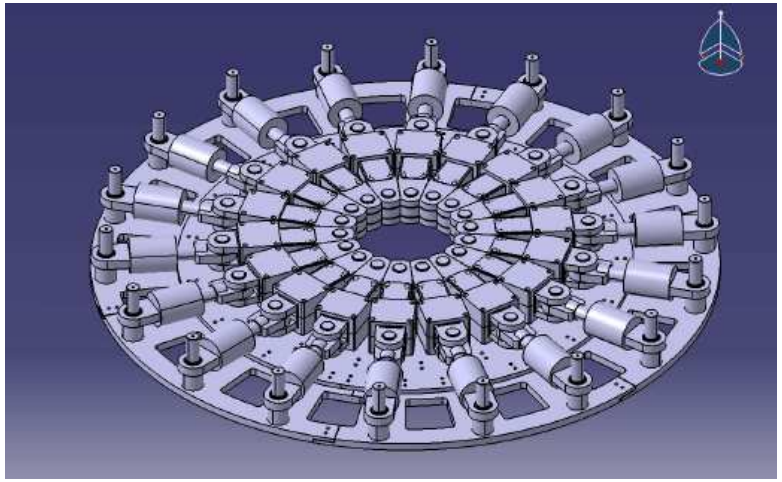
Precompression Ring R&D
(EU and ENEA Frascati)

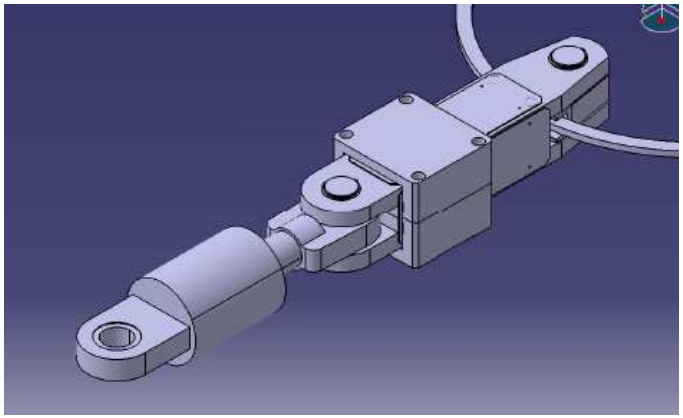
OBJECTIVE

- **To confirm that a uniaxial glass fibre precompression ring can meet the pre-loading requirements (about 0.4% strain, 440MPa stress) at room temperature with a factor of ~4 to failure**
- **To confirm absence of creep**



ENEA PCR test facility (1/5 full scale rings)

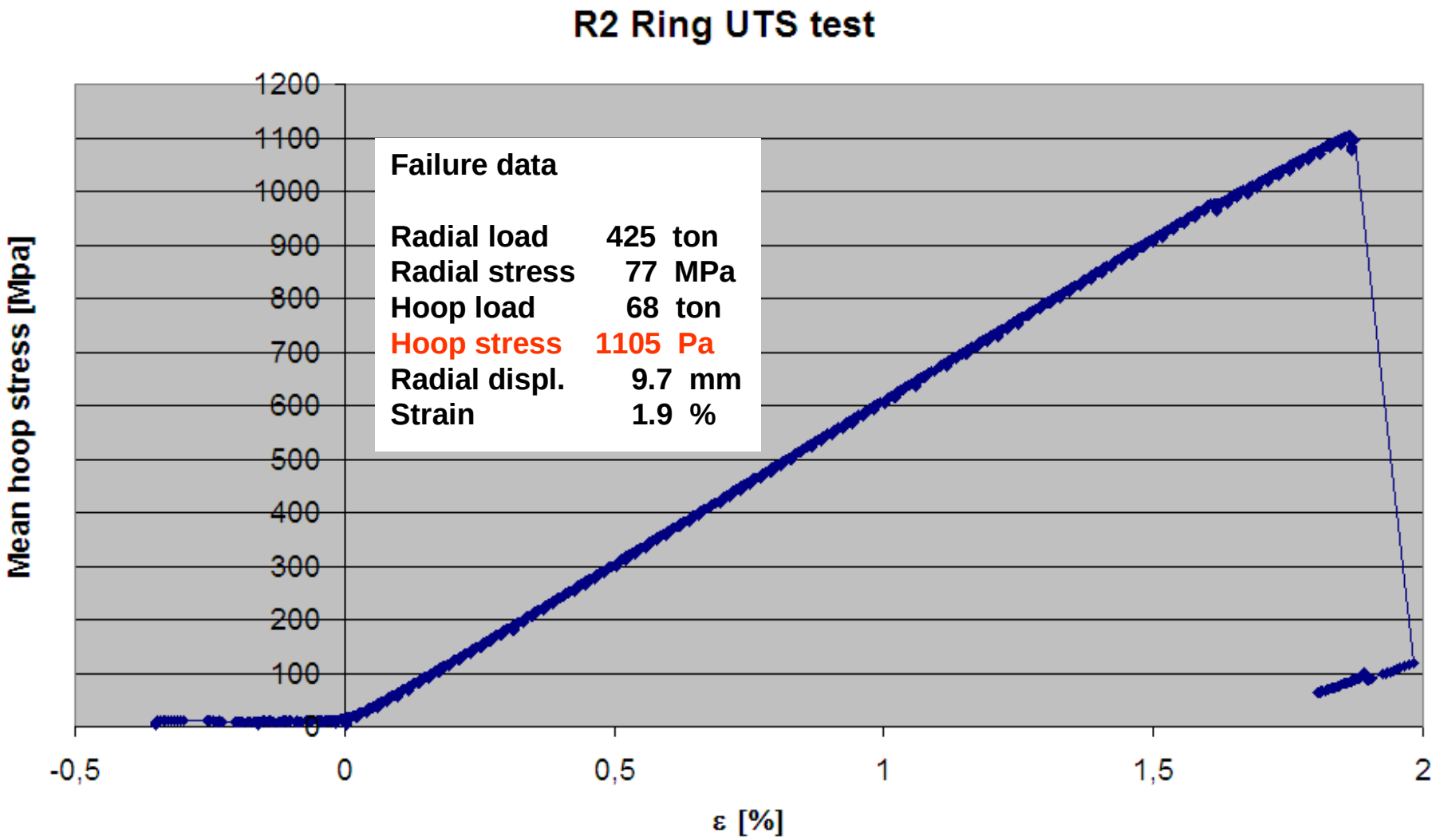




18x58t hydraulic cylinders

Position sensors accuracy 0.1mm

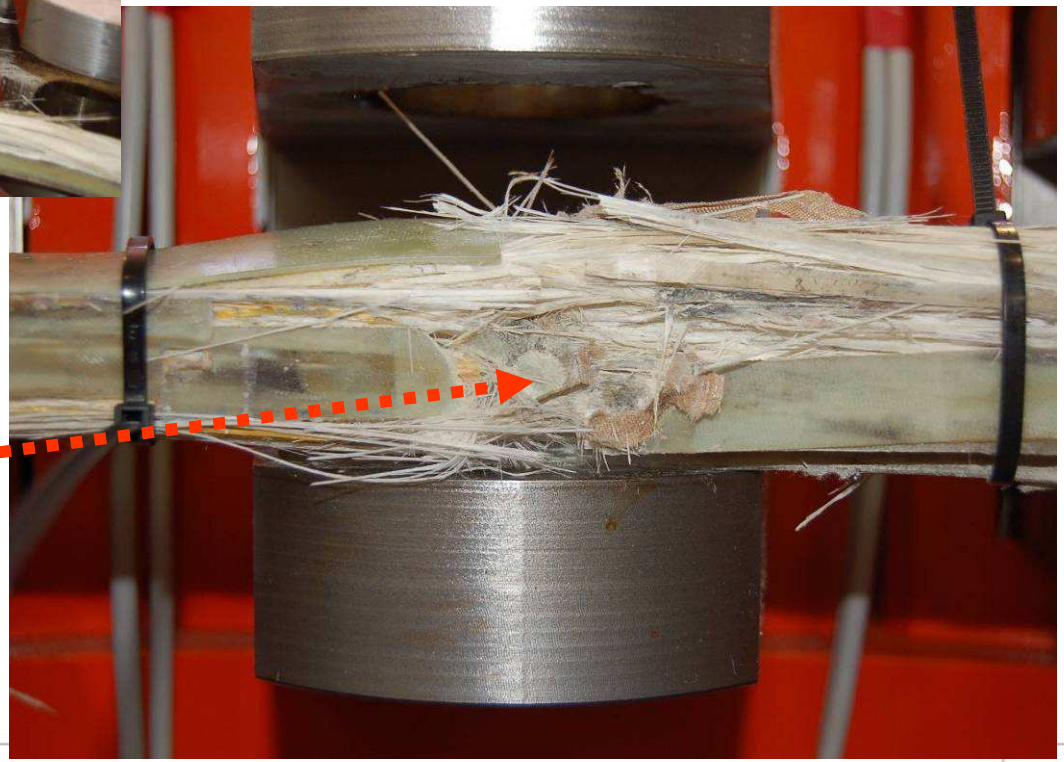
Test of second ring



Failure mechanism

FAILURE DATA

Radial load	**425**	**ton**
Radial stress	**77**	**MPa**
Hoop load	**68**	**ton**
Hoop stress	**1105**	**Pa (design 440MPa)**
Radial displ.	**9.7**	**mm**
Strain	**1.9**	**%**



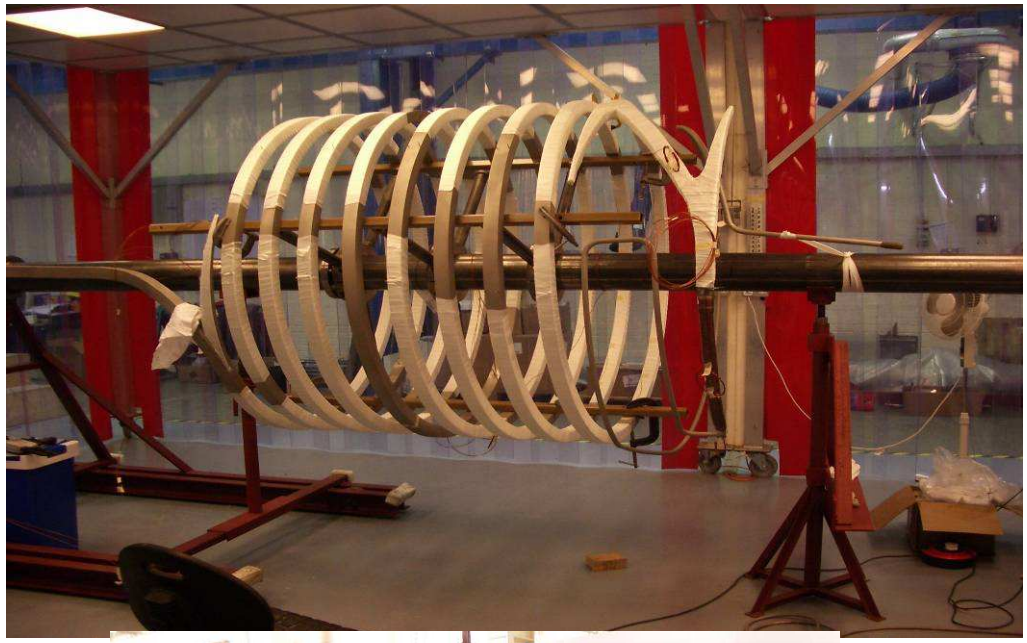
Glass fibre winding anchoring point embedded in ring was a crack initiator.

PF Insert Test
(EU, JA, RF DAs)

Single layer insert coil

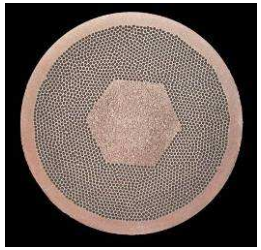
Closely corresponds to PF6 conductor (NbTi)

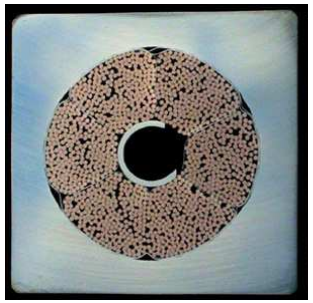
Tested in the bore of CSMC facility in Naka July 2008

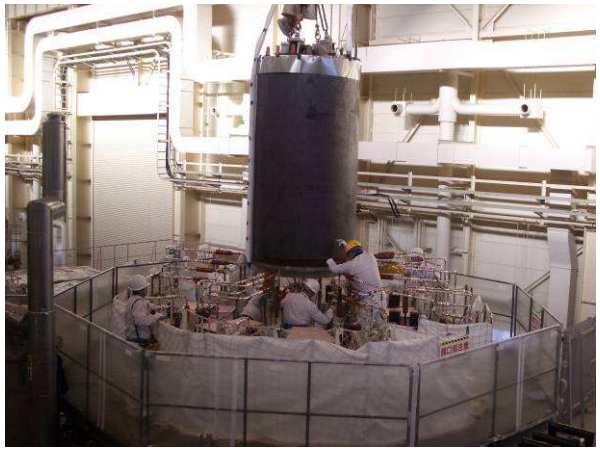


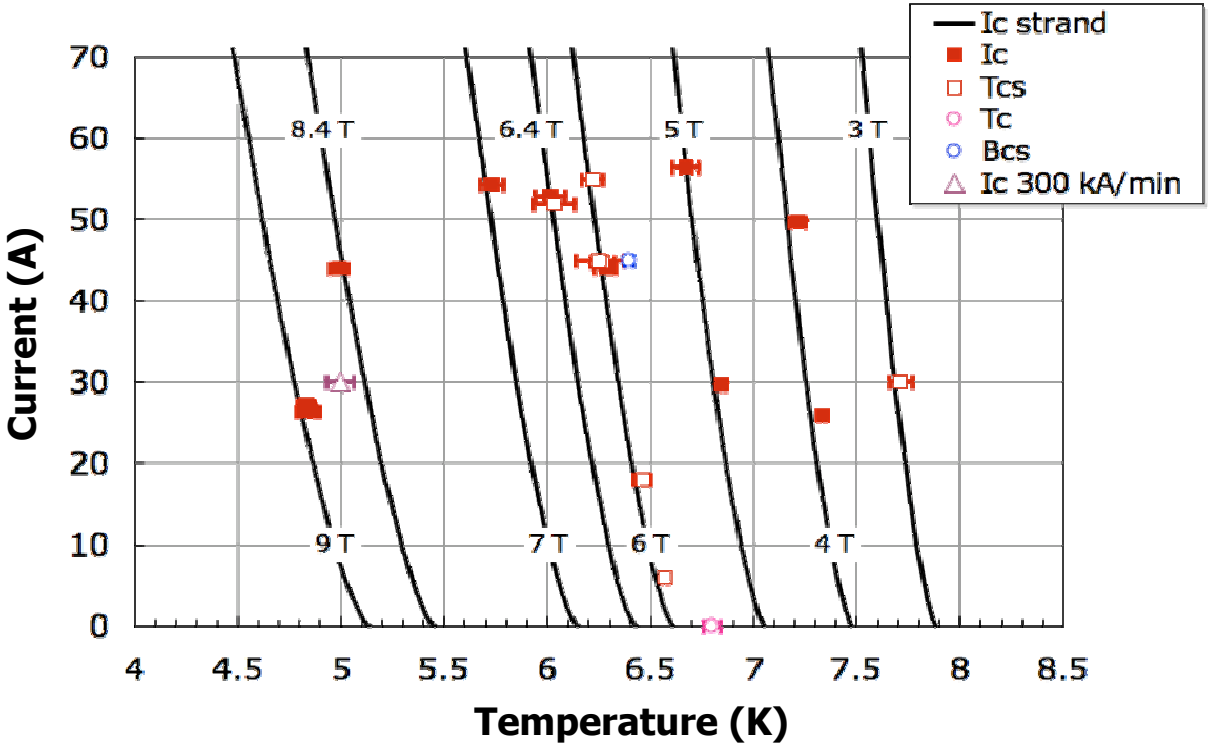
PF Conductor Status

- PF Insert (PFI) coil, manufactured by EU from a RF cable jacketed by EU.
- PFI performance conforms to extrapolated strand performance.



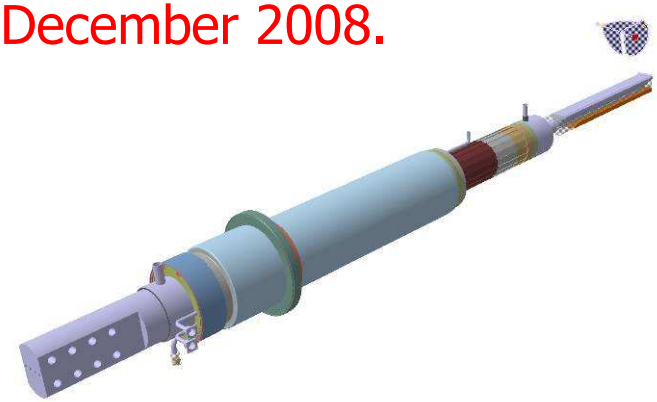


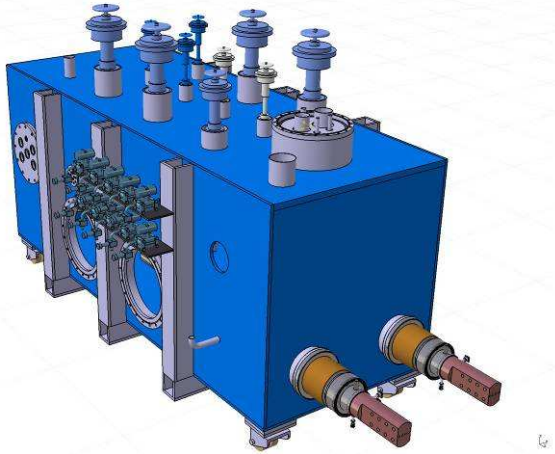




HTS Lead Status

- ASIPP, CN manufactured a pair of 60kA HTS trial leads, tested in December 2008.



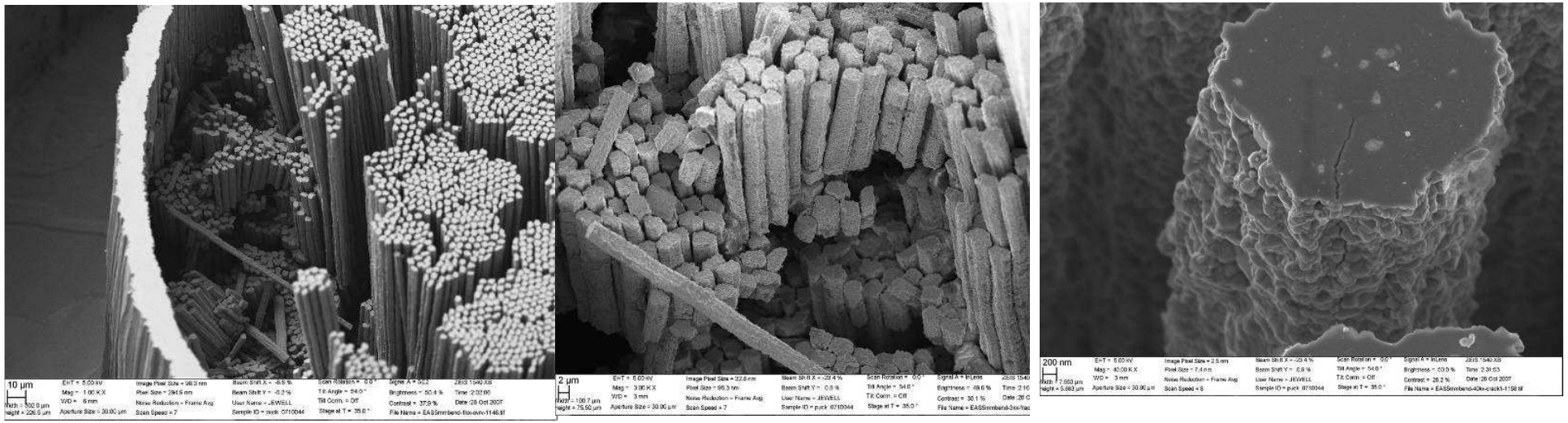


Views of 68 kA
ITER TF Trial Lead

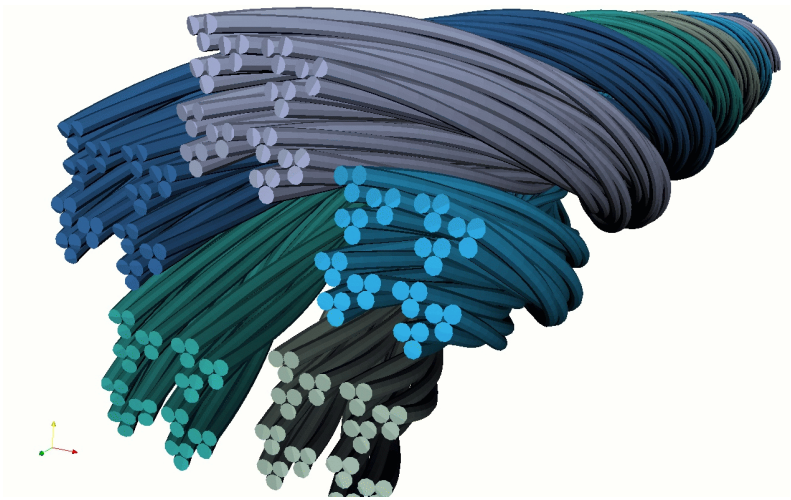
Views of Test CTB

See 2LPT06

ITER IO R&D Contracts (2/2)

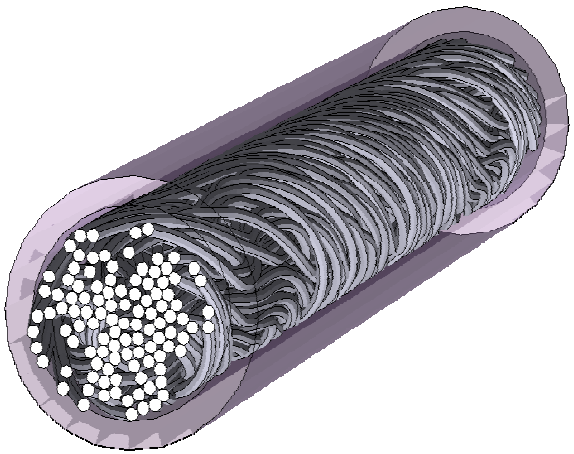


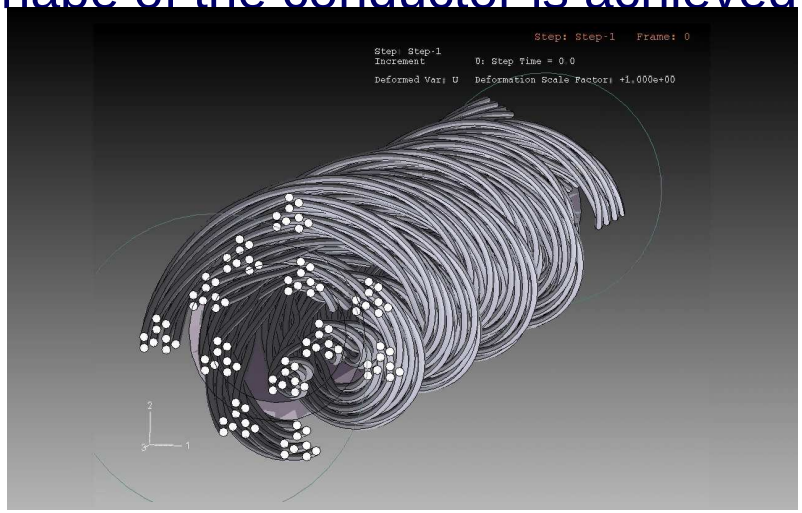
Micrographic Analyses of Bent Bronze Strand
(courtesy of M. Jewell)

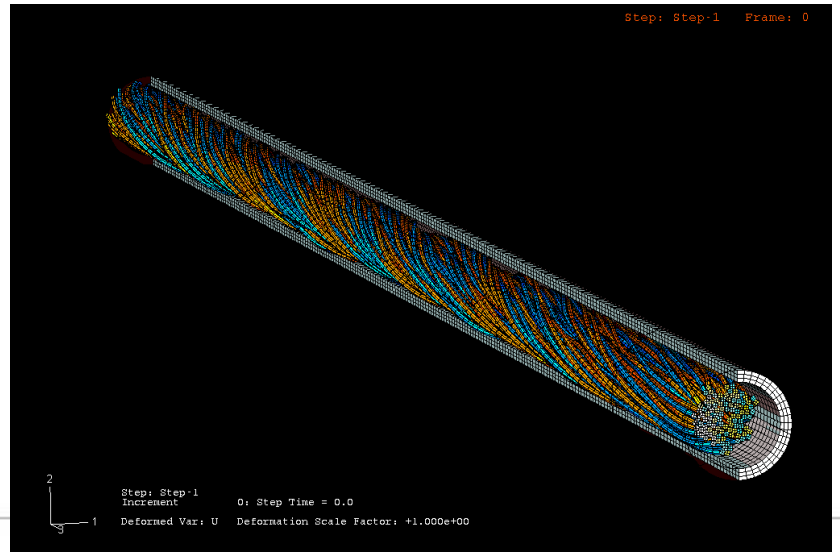


Cable Modeling
(courtesy of H. Bajas, ECP)

Finite element based model by LT Calcoli (L. Semeraro) 108 strands, each strand modeled with solid elements (and single equivalent properties), multiple contact surfaces to each other and compaction tool (jacket). Total length of 400 mm is modeled. The square shape of the conductor is achieved through a rolling process







Radiation Resistant Insulation
(EUDA, ATI, CEA)

Objectives

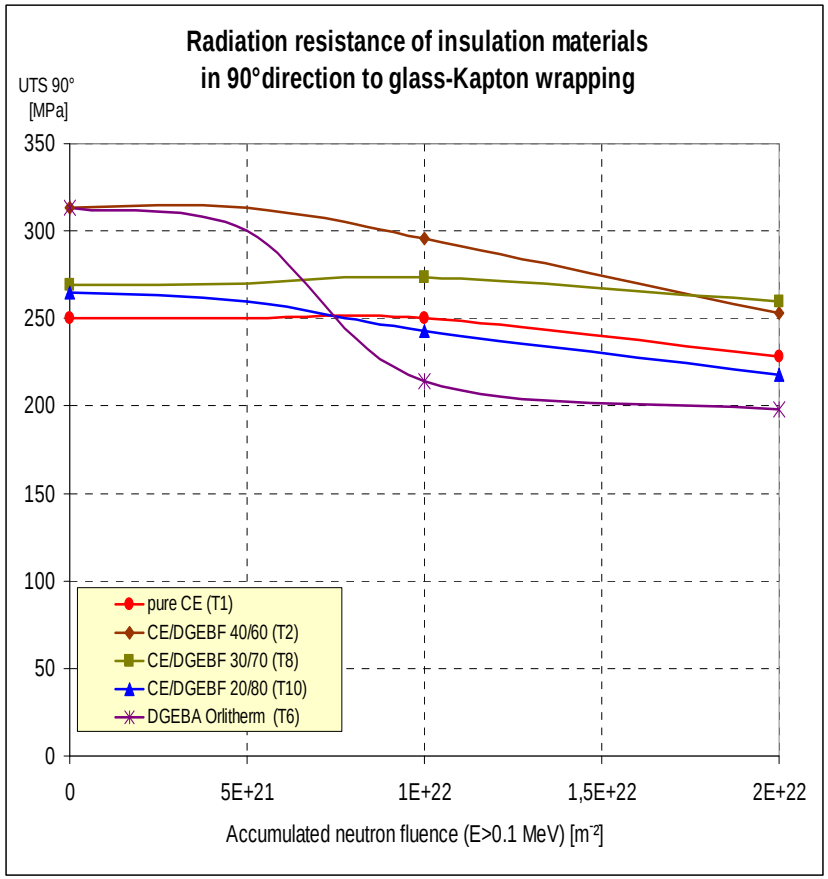
Epoxy resin is at the limits of its radiation resistance at the ITER fluence level of 10 MGy (10^{22} n/m^2). Higher resistance is available from cyanate ester based resins

Cyanate ester resins are expensive but cost can be reduced by blending with epoxy

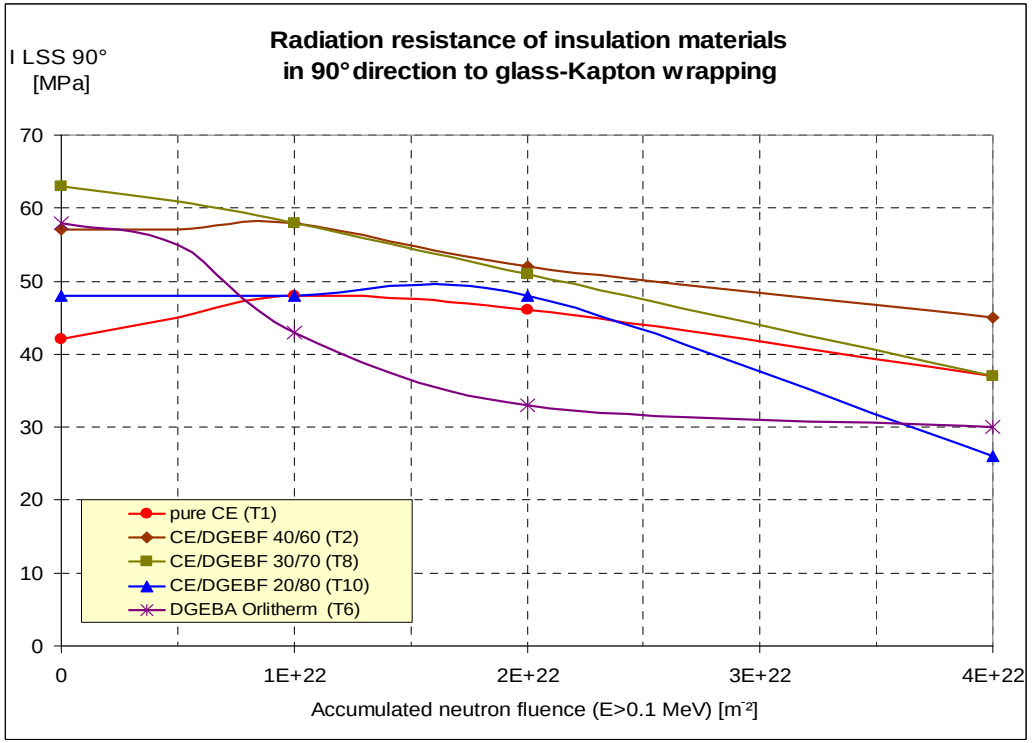
Incorrect curing of cyanate ester can lead to exothermic runaway reaction. Impregnation of a TF winding section under industrial conditions to demonstrate reaction can be controlled

Radiation Resistance of Epoxy and Epxoy-Cyanate Ester Blends

Tension



Shear



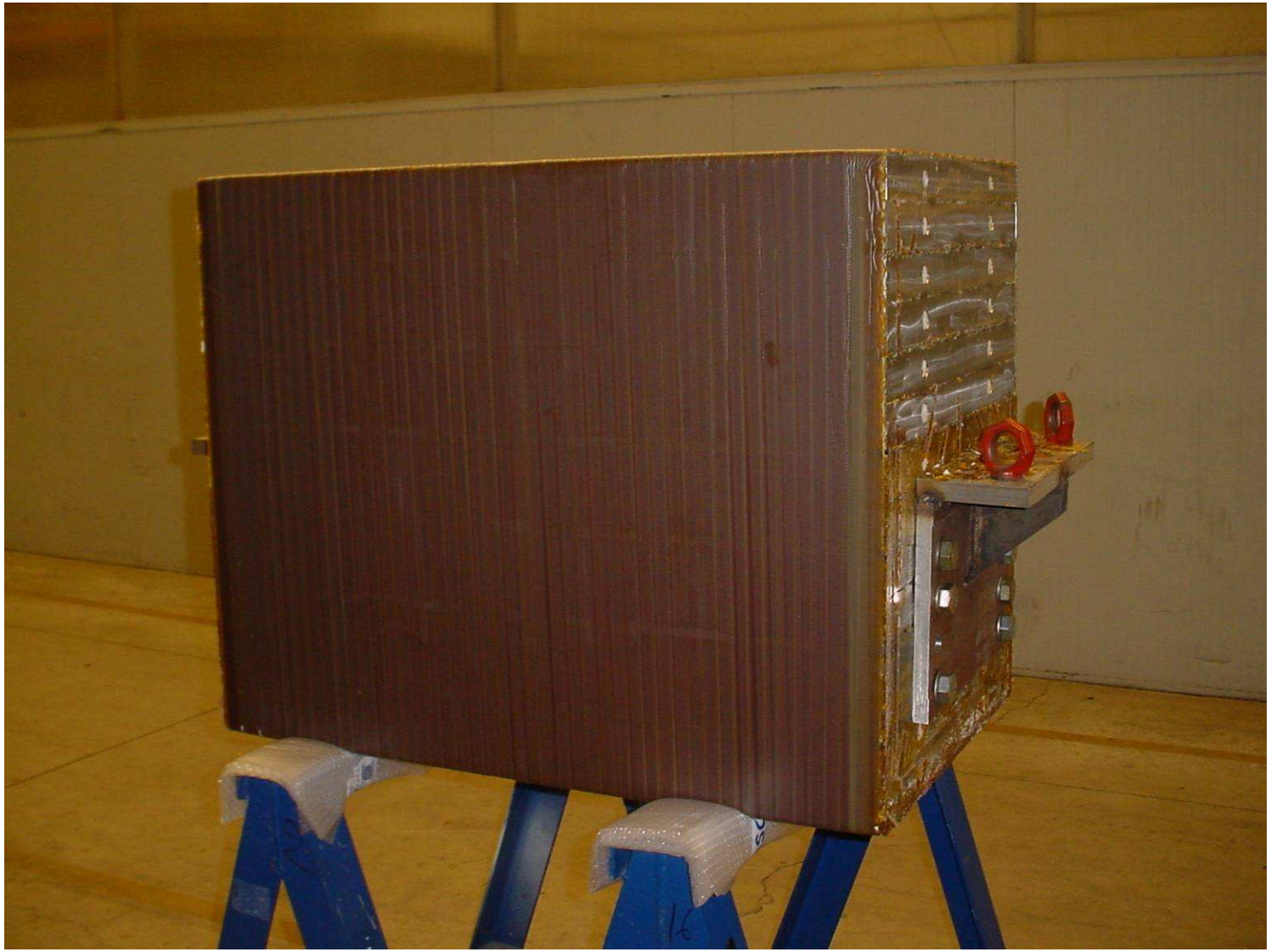
(from ATI)

The epoxy – CE blends can achieve about x2 the ITER design basis ($1x10^{22}$ n/m^2)

Fabrication of a Large Test Piece to Gain Industrial scale experience

(provided by CEA)

After Impregnation with CE - Blend



(provided by CEA)

Conclusions

Blended CE offers same radiation resistance as pure CE resin. Other features

- Pot life >>24hrs
- Implied cost increase ‘a few million’ euros for ITER TF coils

Impregnation on an industrial scale can be performed successfully