Status of Magnet Development for Fusion Machines and Applicable Design Criteria

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Materials & Manufacturing / 29

Introduction

- **Basic superconductivity concept**
  - Certain metals become perfect electrical conductors at 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 a phenomena called **"quench"**, where the superconductor state changes back into resistive, with large release of energy and heating of the coolant and conductor (quench protection systems are required).

- **Why superconductivity for fusion magnets?**
  - It allows steady state and long-pulse operation at very high magnetic fields with low consumption of energy (except for refrigeration costs).
  - Main developments for use in 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 16 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

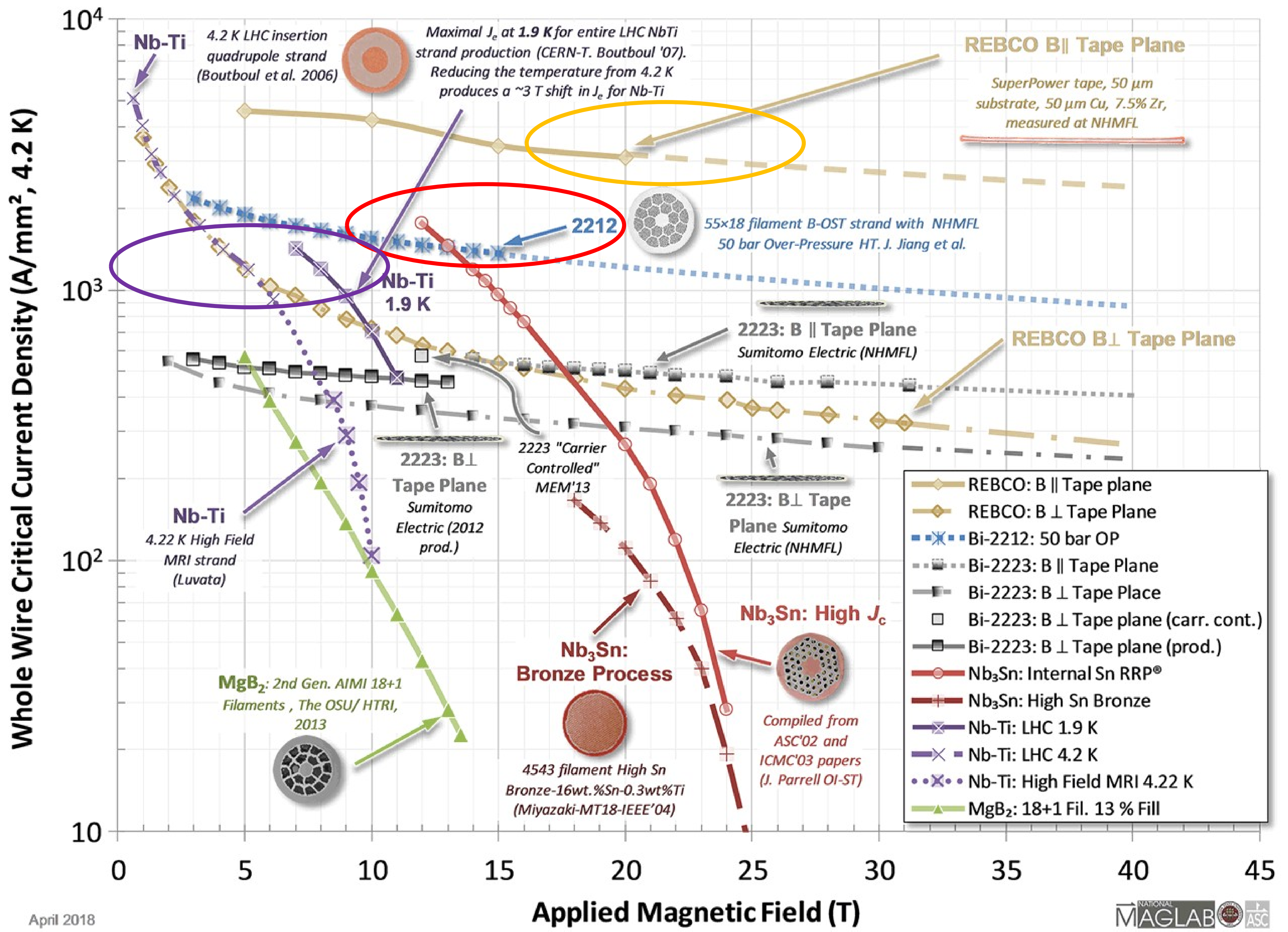
→ Nb3Sn wires: four competing technologies

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

***** Even 60 years after the discovery of Nb_3Sn, there is still potential to improve Jc***

High Temperature Superconductors (HTS) – Main applications: very-high field magnets for fusion and other applications, 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 limited to a few T, 20-30 K operating temperature
- **RE Iron Arsenides → REBCO:** big boost of development in recent years with large procurements for various fusion start-ups, able to operate up to 20-25 T in the range of 10-20 K operating temperature


Whole Wire Critical Current Density (A/mm², 4.2 K)
Applied Magnetic Field (T)
Nb-Ti
4.2 K LHC insertion quadrupole strand (Boutboul et al. 2006)
Maximal J_c at 1.9 K for entire LHC NbTi strand production (CERN-T. Boutboul '07). Reducing the temperature from 4.2 K produces a ~3 T shift in J_c for Nb-Ti
REBCO B|| Tape Plane
SuperPower tape, 50 μm substrate, 50 μm Cu, 7.5% Zr, measured at NHMFL
2212
55×18 filament B-OST strand with NHMFL 50 bar Over-Pressure HT. J. Jiang et al.
Nb-Ti 1.9 K
2223: B || Tape Plane
Sumitomo Electric (NHMFL)
REBCO B⊥ Tape Plane
2223: B⊥ Tape Plane Sumitomo Electric (2012 prod.)
2223 "Carrier Controlled" MEM'13
2223: B⊥ Tape Plane Sumitomo Electric (NHMFL)
Nb-Ti
4.22 K High Field MRI strand (Luvata)
Nb_3Sn: High J_c
Nb_3Sn: Bronze Process
MgB_2: 2nd Gen. AIMI 18+1 Filaments, The OSU/ HTRI, 2013
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)
Compiled from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)
REBCO: B || Tape plane
REBCO: B ⊥ Tape Plane
Bi-2212: 50 bar OP
Bi-2223: B || Tape Plane
Bi-2223: B ⊥ Tape Place
Bi-2223: B ⊥ Tape plane (carr. cont.)
Bi-2223: B ⊥ Tape plane (prod.)
Nb_3Sn: Internal Sn RRP®
Nb_3Sn: High Sn Bronze
Nb-Ti: LHC 1.9 K
Nb-Ti: LHC 4.2 K
Nb-Ti: High Field MRI 4.22 K
MgB_2: 18+1 Fil. 13 % Fill
April 2018
NATIONAL MAGLAB ASC

Development of Fusion Magnets

- The development of superconducting magnets for magnetic confinement fusion systems 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 (now WEST) 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.

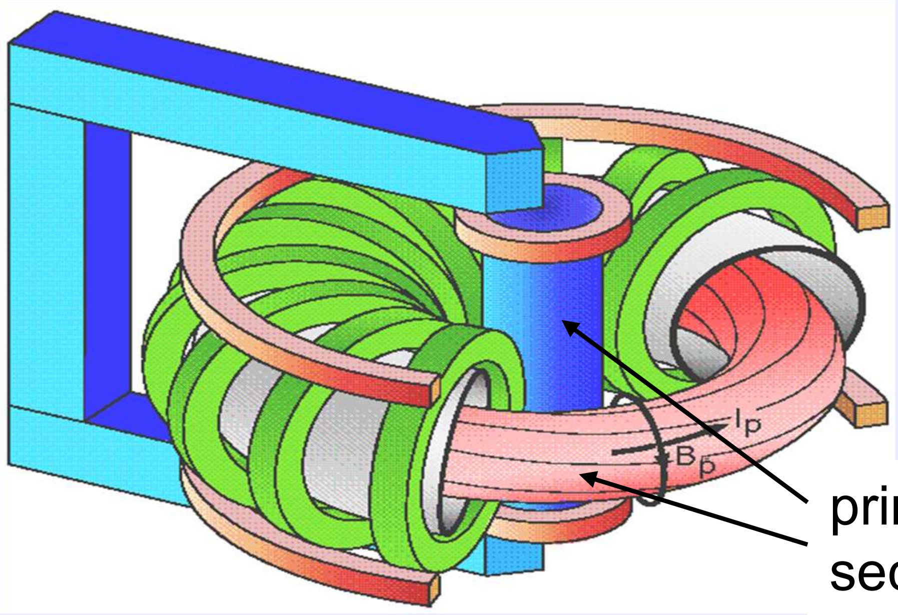
- **Cable-in-conduit conductors** have been developed due to the large volumes, current density, energy and required stability for these magnets.

- The development of magnets for steady-state fusion devices has included, in between others, the 6 LCT coils in the 1980s, POLO (EU) and DPC (JA-US) coils in early 1990s, ITER Model Coils in early 2000s and, more recently, the SPARC Model Coil in early 2020s.

- Construction of W7-X, ITER, JT-60SA, DTT, SPARC, and other devices has given a big boost to the large-scale production of novel superconductors, in particular, Nb_3Sn and the recent development on REBCO-based HTS tapes.

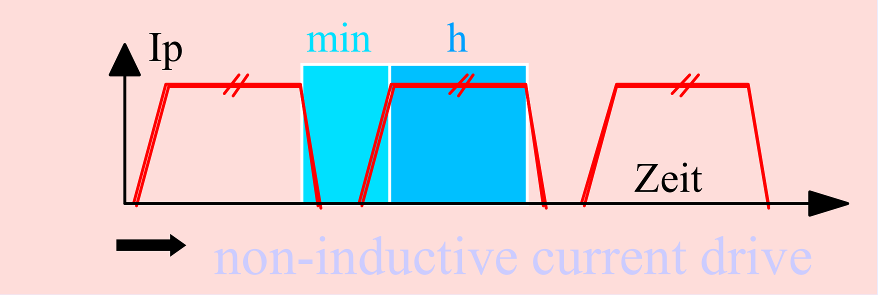
Magnetic Confinement Systems

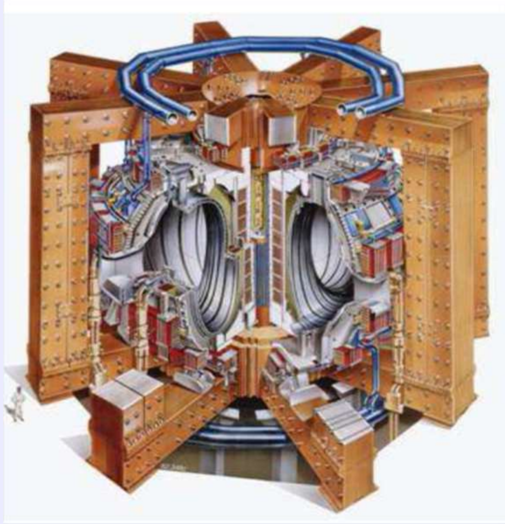
Tokamak (ITER, SPARC)



primary
secondary
winding

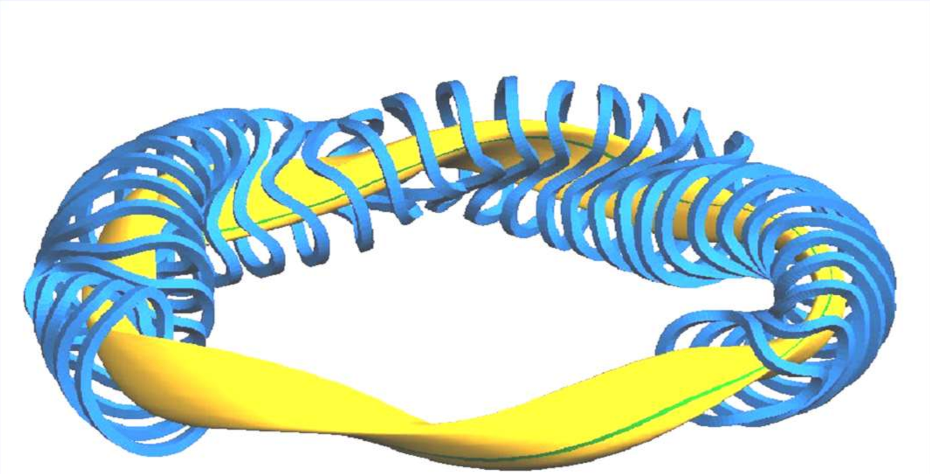
Transformer principle
Plasma current is induced
Discharges are pulsed



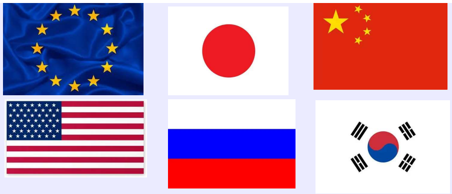


JET tokamak
(resistive)

Stellarator (W7-X)



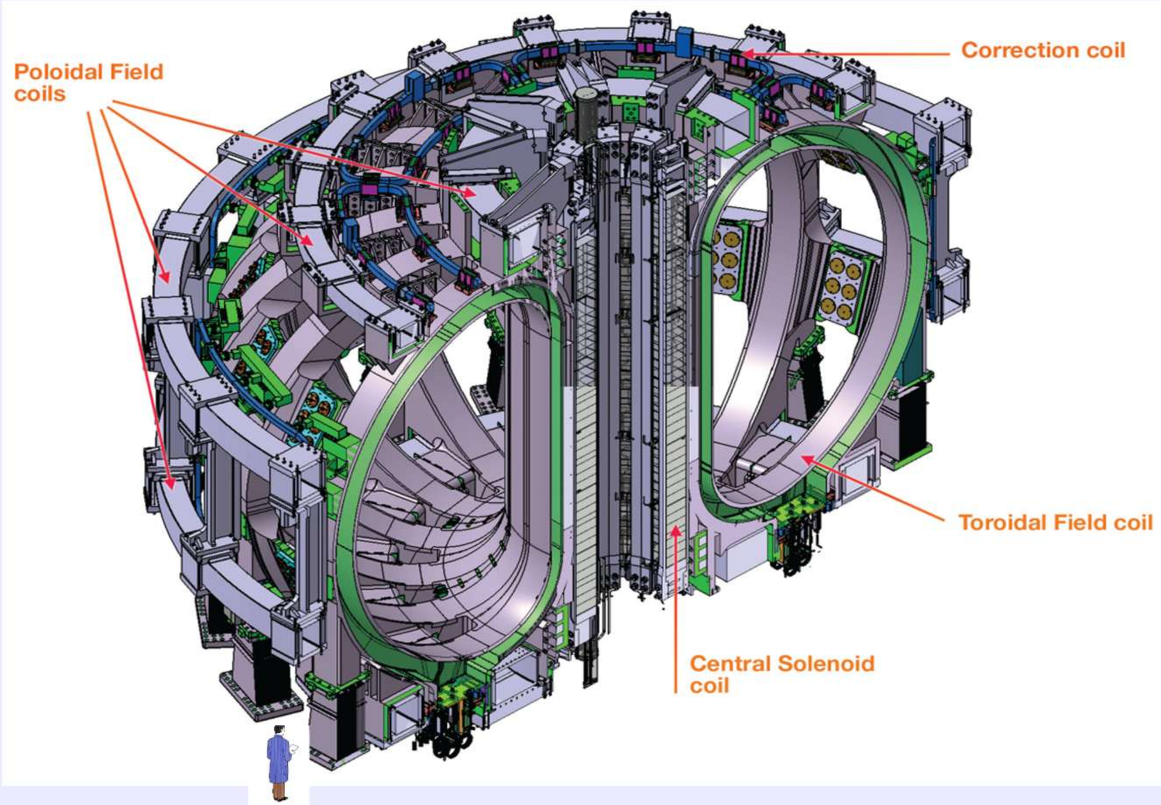
Steady-state configuration
No plasma current



ITER Magnet System

(under assembly at IO Cadarache, F)

(~41 GJ in TF system vs. 10.5 GJ stored magnetic energy in the 27 km tunnel of the Large Hadron Collider at CERN)



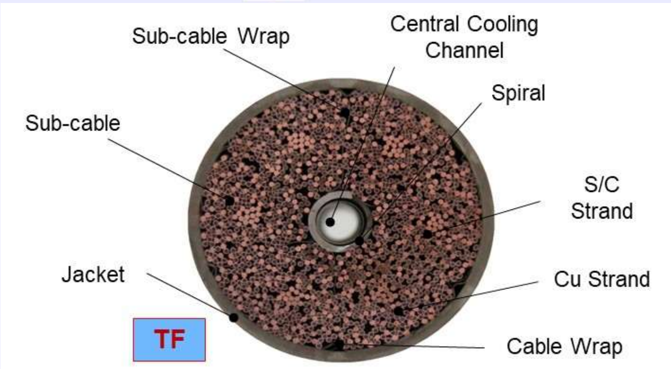
48 Superconducting Coils:

- 18 Toroidal Field (TF) coils - Nb_3Sn
- 6 Central Solenoid (CS) modules - Nb_3Sn
- 6 Poloidal Field (PF) coils - NbTi
- 9 pairs of Correction Coils (CC) – NbTi
- 6 pre-compression rings

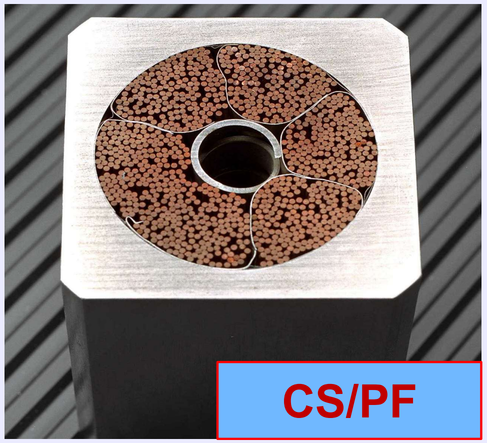
\+ NbTi feeder lines

\+ HTS current leads

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



Stainless Steel Jacket

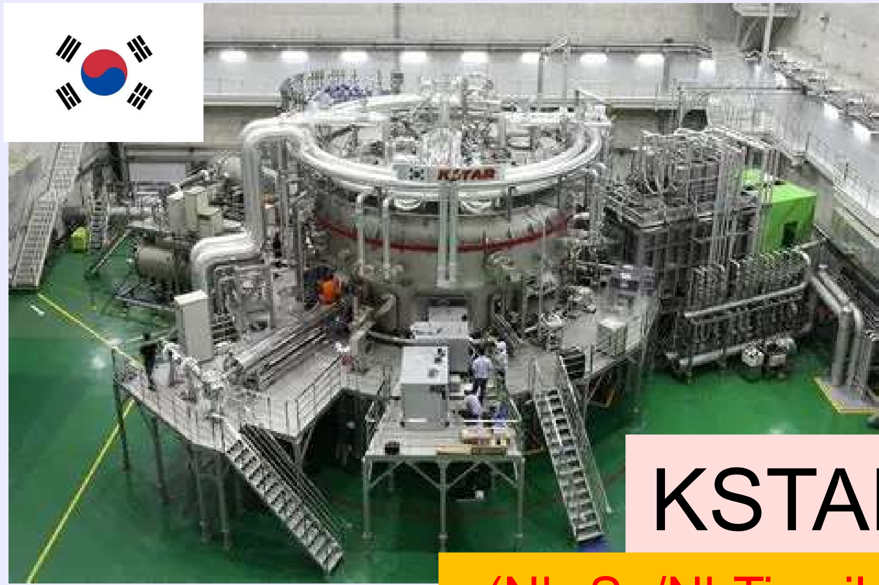


C. Sborchia et al. "The ITER magnet systems: progress on construction", Nucl. Fusion 54 (2014) 013006 (8pp), Dec. 2013 DOI/10.188/0029-5515/54/1/013006

Superconducting Tokamaks in Operation

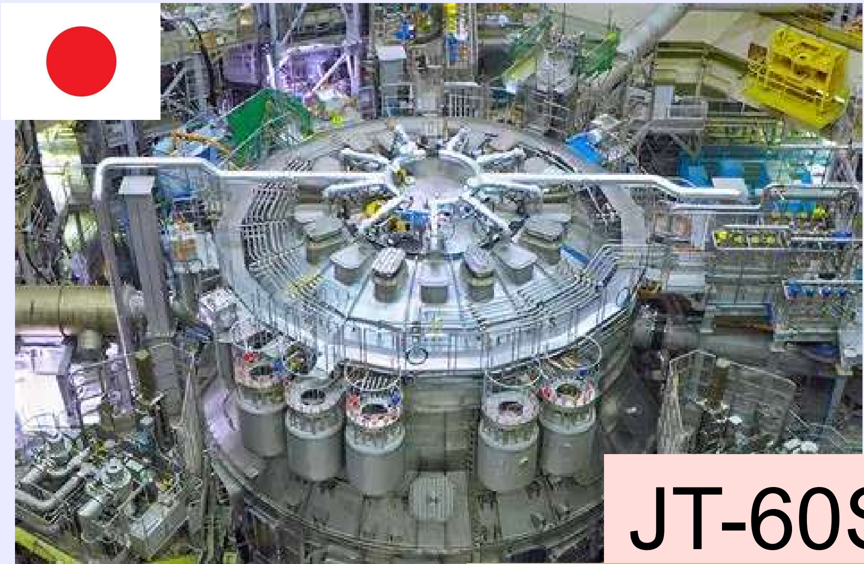
WEST

(TF coils only/NbTi)



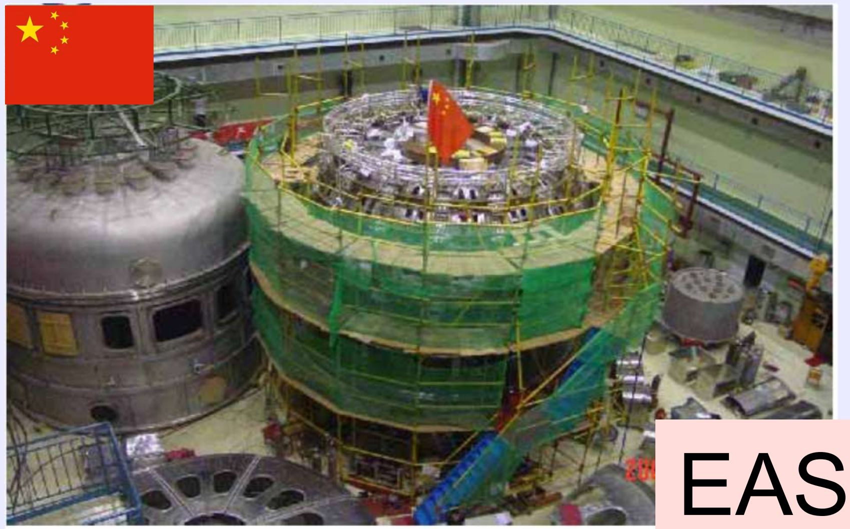
KSTAR

(Nb_3Sn/NbTi coils)



JT-60SA

(Nb_3Sn/NbTi coils)



EAST

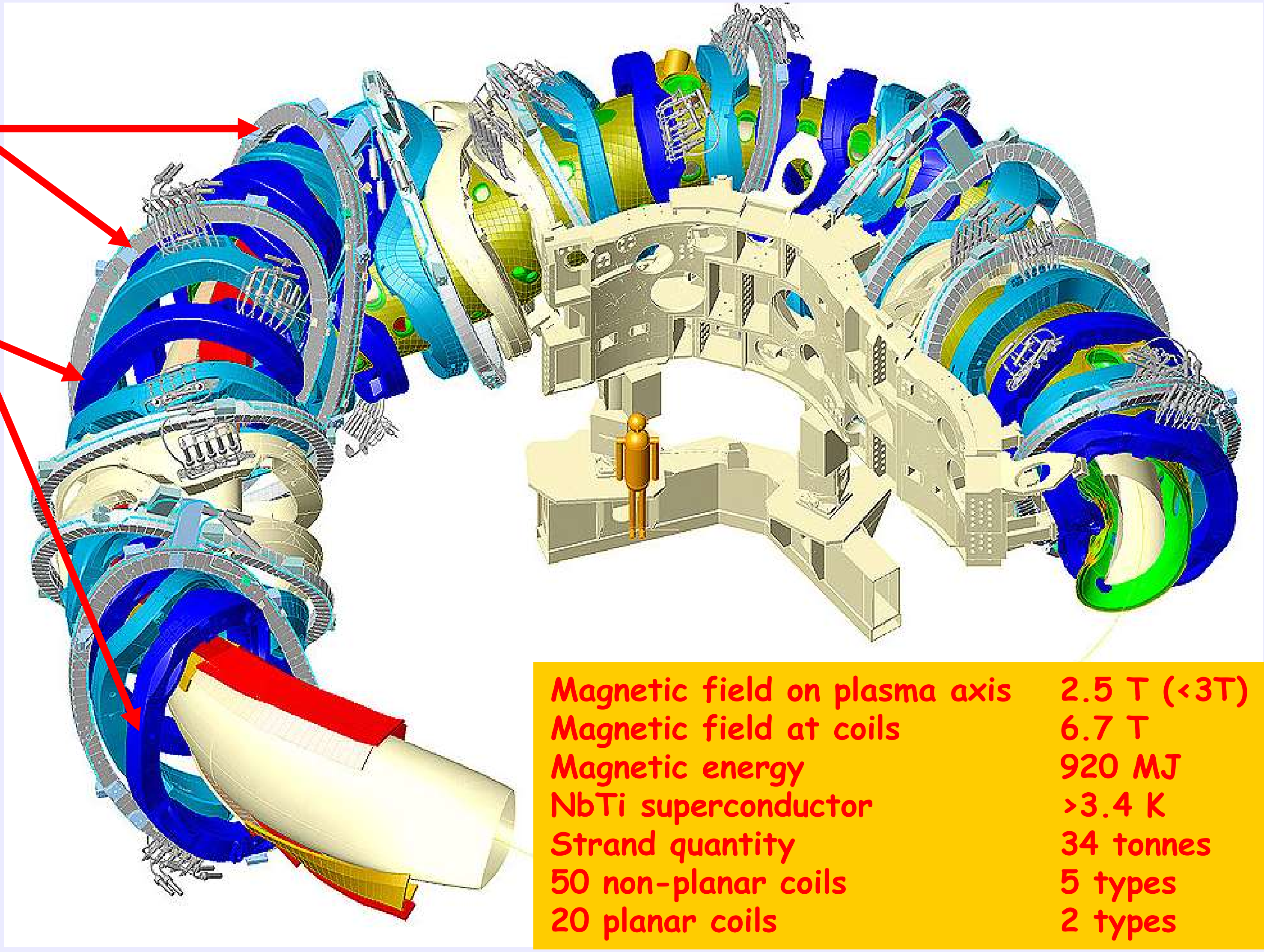
(NbTi coils)

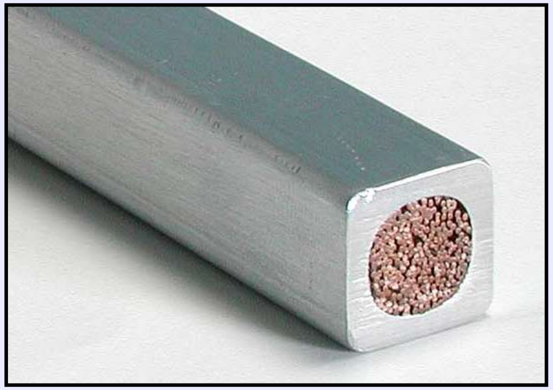
W7-X Stellarator Magnet System

(under operation at IPP Greifswald, D)

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

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





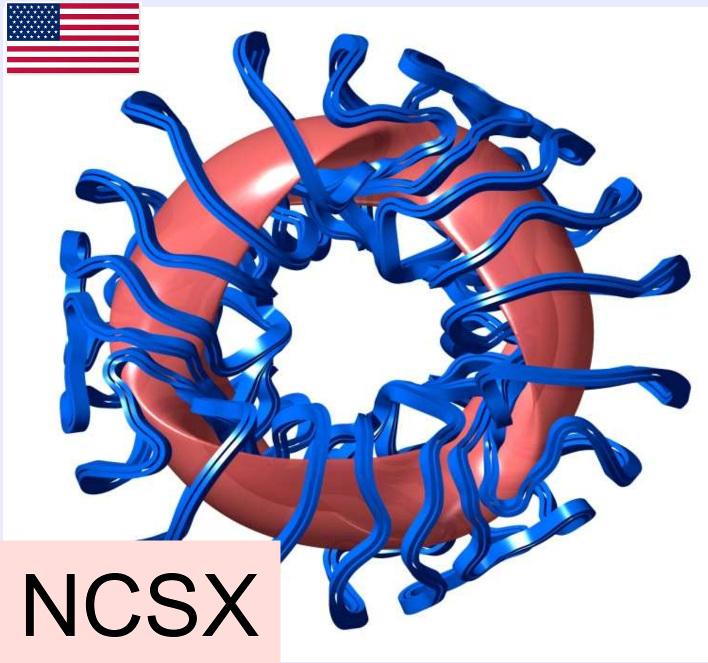
Aluminum Jacket

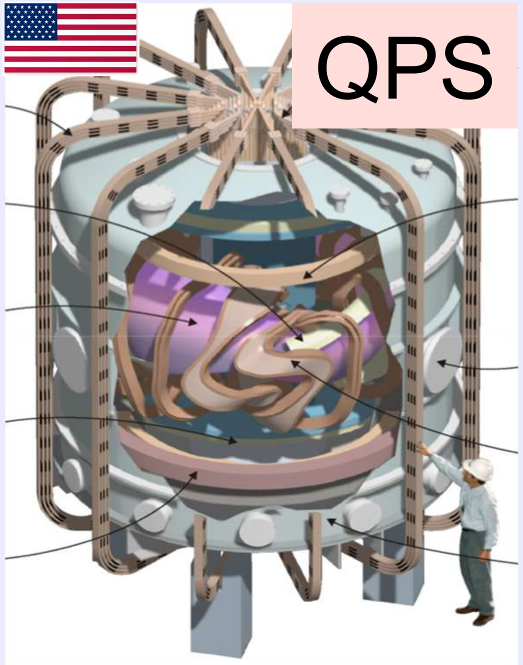
Magnetic field on plasma axis	2.5 T (<3T)
Magnetic field at coils	6.7 T
Magnetic energy	920 MJ
NbTi superconductor	>3.4 K
Strand quantity	34 tonnes
50 non-planar coils	5 types
20 planar coils	2 types

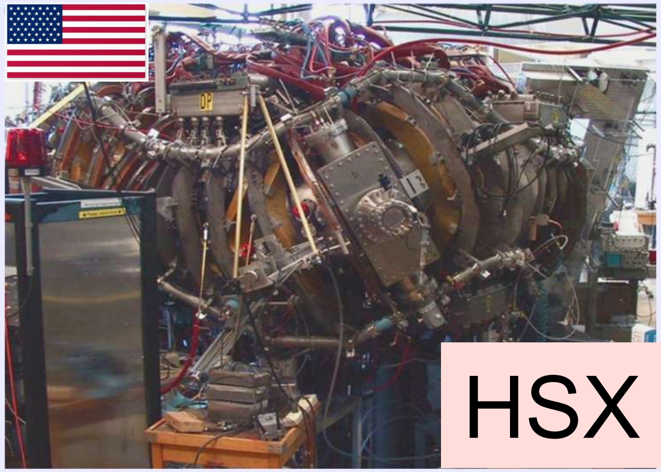
C. Sborchia et al., "Progress in the Design, Manufacture and Testing of the W7-X Superconducting Magnets," IEEE Trans. on Applied Superc., vol. 16, no. 2, pp. 848-851, June 2006
DOI/10.1109/TASC.2006.873345

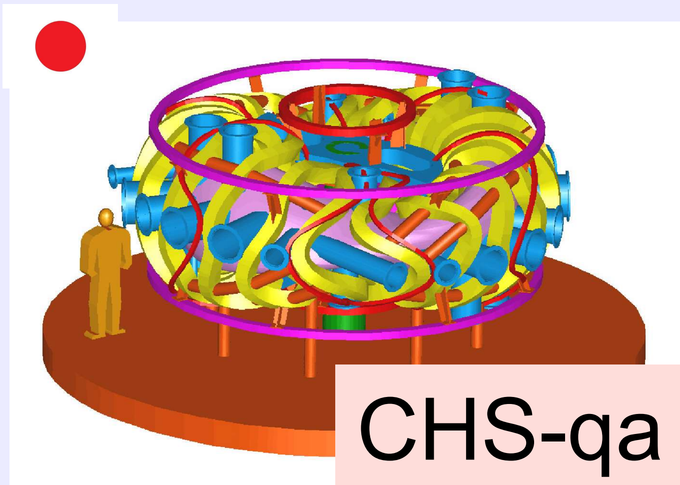
Some Helical Devices Worldwide

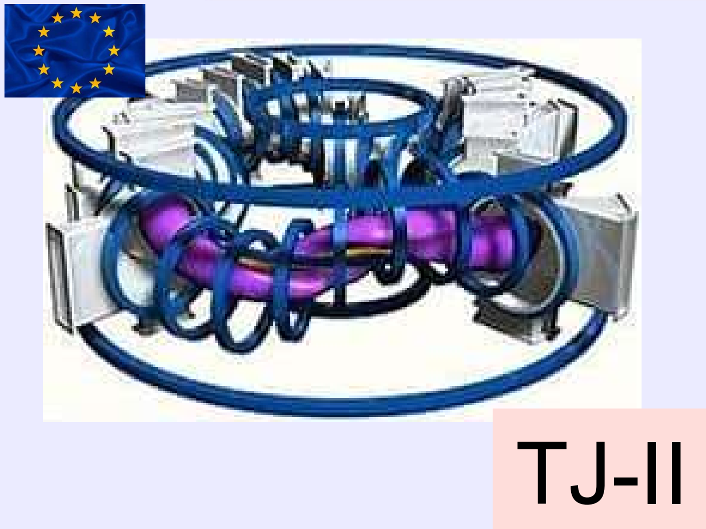
(Large helical coil in NbTi)











Key Design Criteria for Fusion Magnets

1) **Performance Requirements:** magnet systems and their main components (*conductors, structures and insulation*) must support long inductive burn times at very high magnetic fields and, in case of a tokamak, a large number of pulses ➔ these drive the design limits, material choice and the required mechanical, thermohydraulic and electrical properties.

2) **Superconducting Materials:** these allow for higher current capacity and stronger magnetic fields compared to conventional magnets.

3) **Integration and Reliability:** magnet systems have to be integrated with the main vacuum vessel and other components, maintaining tight tolerances and ensuring the structural integrity of the magnets under operational conditions (i.e. arc protection to the primary confinement boundary in case of electrical faults of magnets and feeders).

4) **Safety & Maintenance:** design criteria must also include provisions for safety and maintainability, ensuring that the system can be operated safely and efficiently over its lifespan. These include remote maintenance capabilities and robust safety features to handle the high neutron flux and activation expected during operation.

5) **Cost Effectiveness:** the design process must incorporate cost constraints aiming to deliver a reliable and effective magnet system within budgetary limits.

Note: *magnet systems are not part of the primary confinement barriers, but they must be classified as **QC-1** components for investment protection and safe operation.*

Main Design Issues for Fusion Magnets

- **Very high magnetic fields** (up to 20-25 T) with large operating currents (40-80 kA) → impact on **superconductor design and amount**

- **Large forces**:
  - → **Very robust** structural components
  - → **High-strength austenitic steels** with at least 1,000 MPa yield strength and 200 MPa·m fracture toughness in the operational range 4-20 K
  - → **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 layout and design voltages

- **High electric voltage (in vacuum)** → impact on insulation selection and quality control procedures (such as tests in partial vacuum/Paschen-minimum conditions)

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)

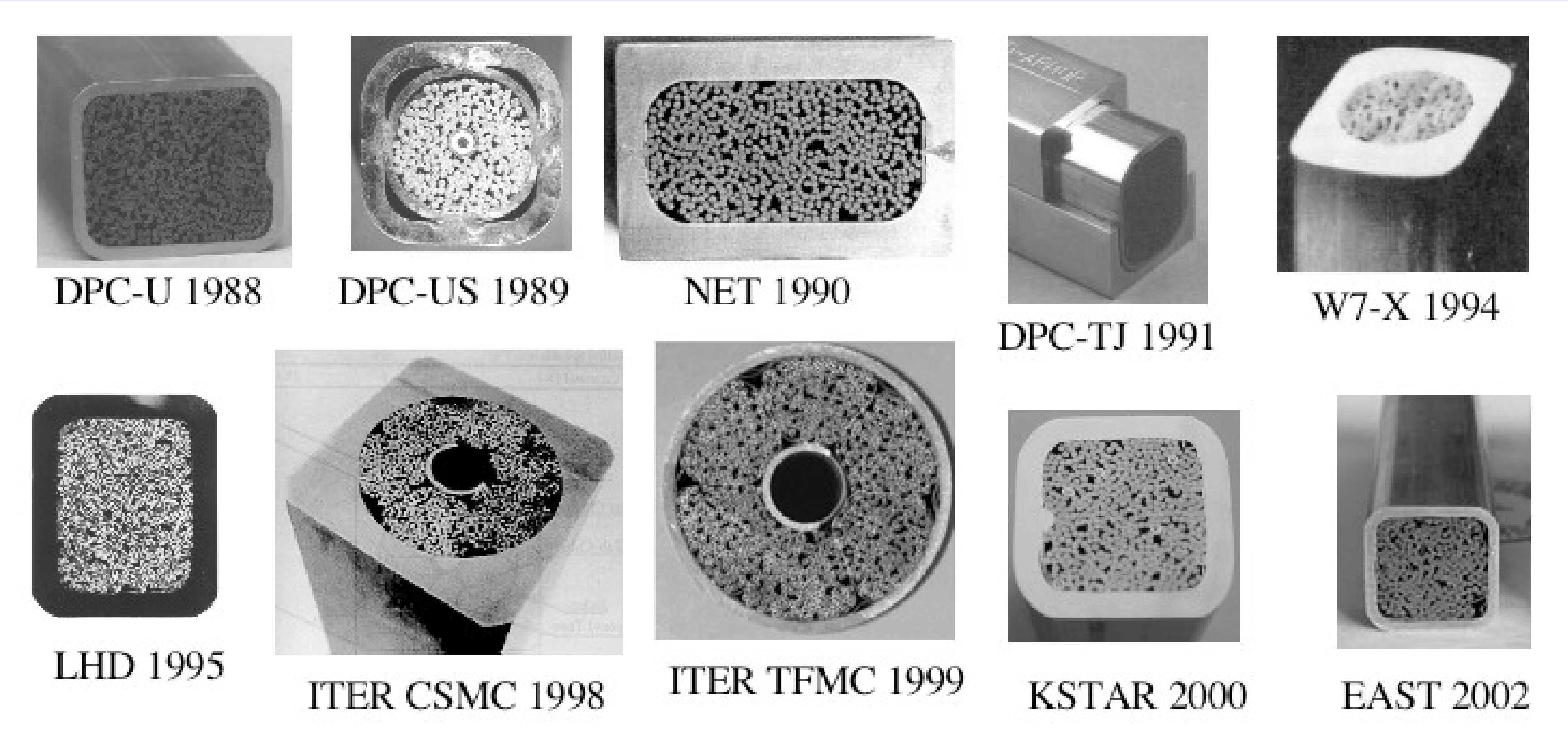
Solution

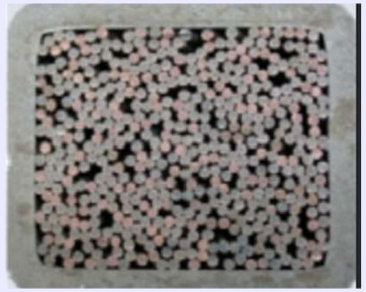
- Large number of parallel superconducting strands to enable high currents
- Cabling with ~1/3 void between strands for coolant (supercritical He)
- Outer jacket of high strength material to withstand large cyclic loads
- Flexible design: variable currents by scaling the amount of strands

→ *Cable-in-Conduit Conductor (CICC)*

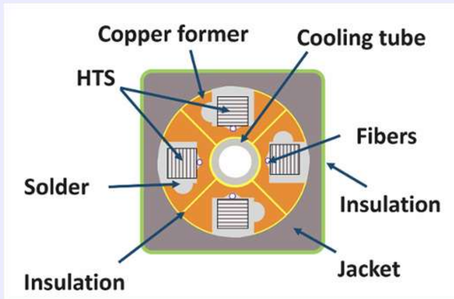
Cable-in-Conduit Conductors

Since about 40 years, *cable-in-conduit conductors* (CICC) has the monopoly in the design of forced flow conductors for fusion ….





JT-60SA 2012

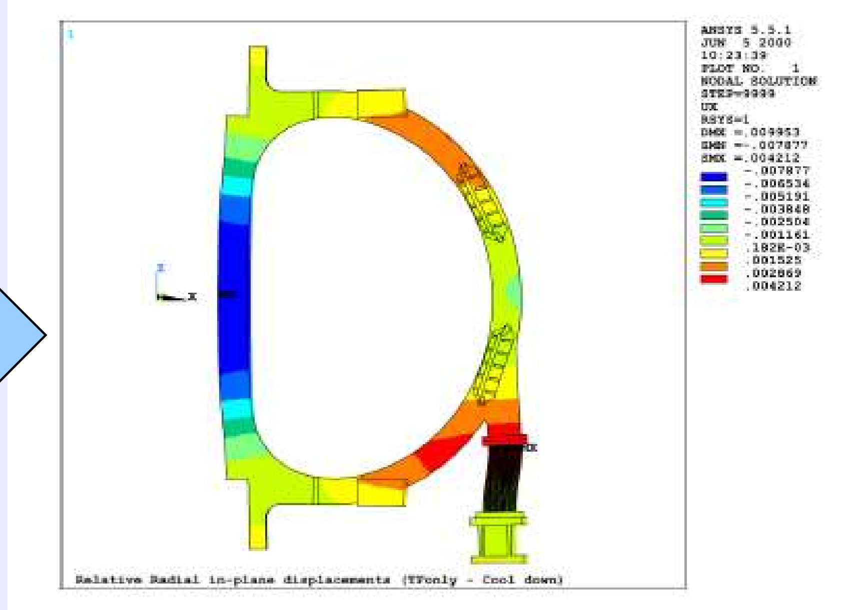


SPARC 2023

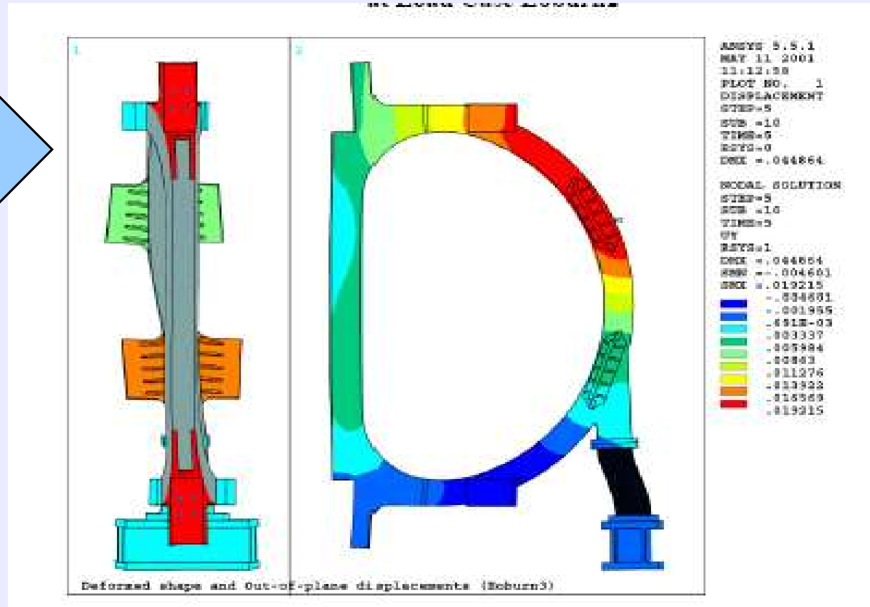
Mechanical Forces

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

  - In-plane forces:
    - ~400 MN centripetal force
    - Wedged inner legs, outward forces in the outboard leg which induce an outward movement



  - Out-of-plane forces (50,000 cycles):
    - Overturning moments



⇓

- TF radial expansion is restrained by the structures
- 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

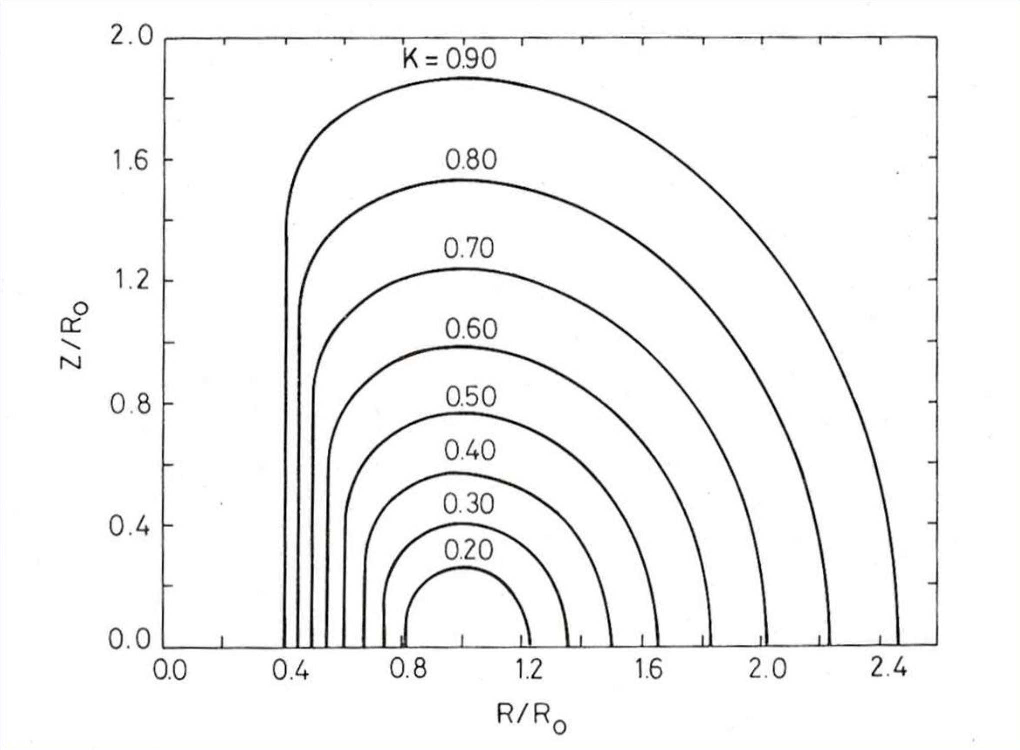
• In a toroidal system the field varies inversely to R → large bending stresses.

• Since the field is equal to $B(R)= B_0R_0/R$, 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.

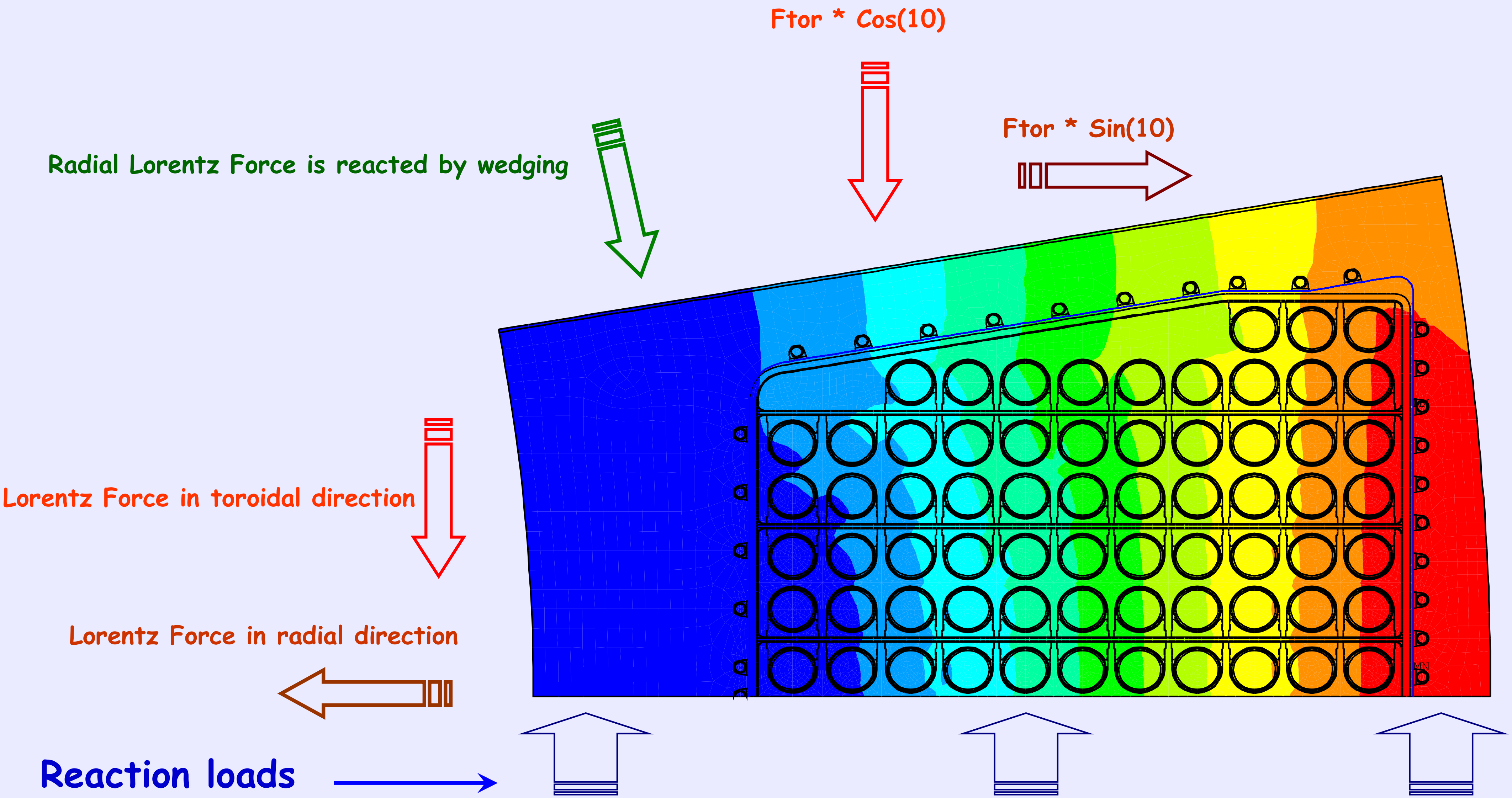
• Pure tension can be achieved on filaments, but on real coils with a finite thickness the approximation has to be refined to minimize the bending stresses.

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



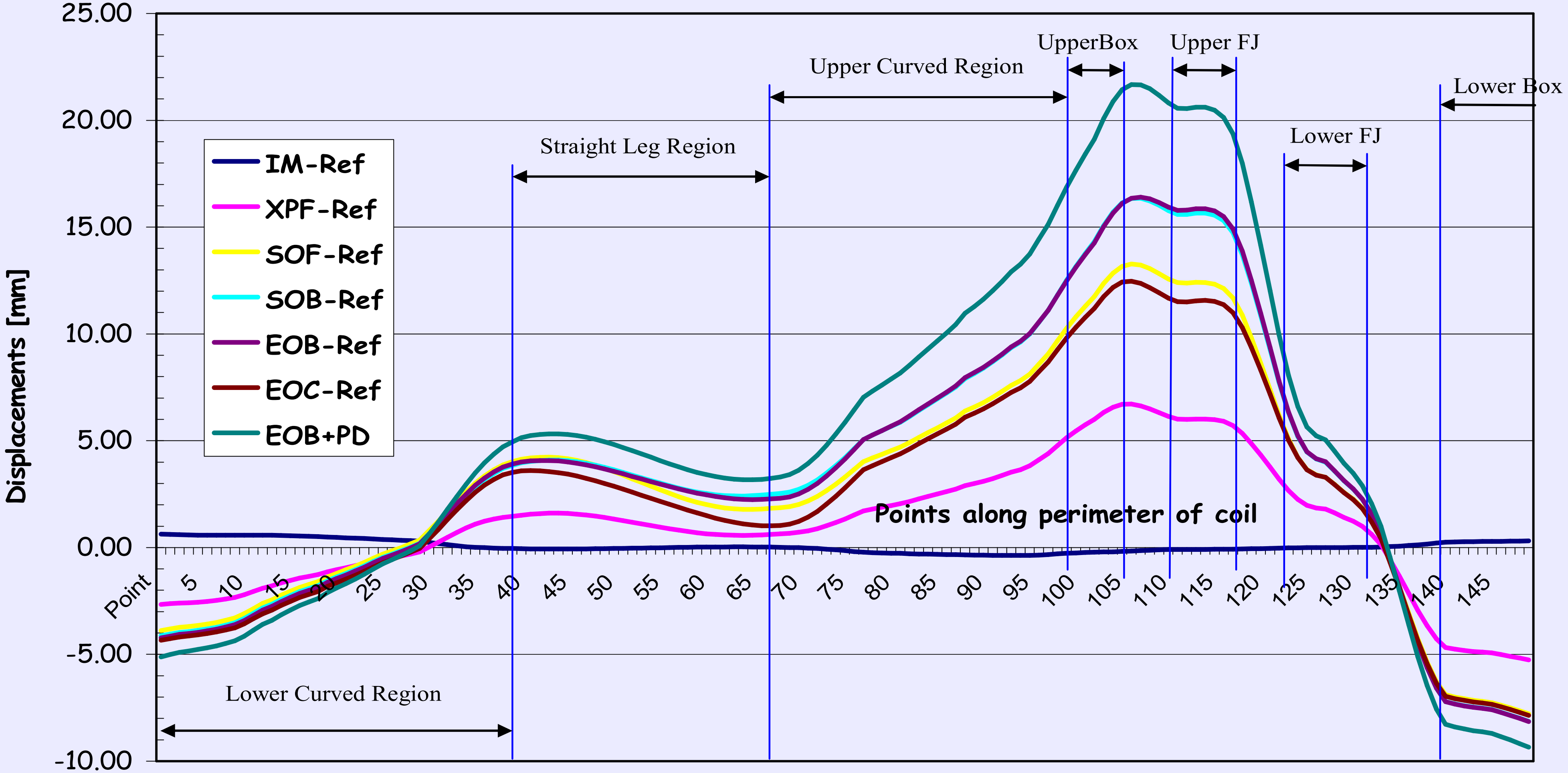
Inner Legs can be Wedged or Bucked against Central Coil to react net centripetal loads developed in the toroid

Force Equilibrium (Wedge)



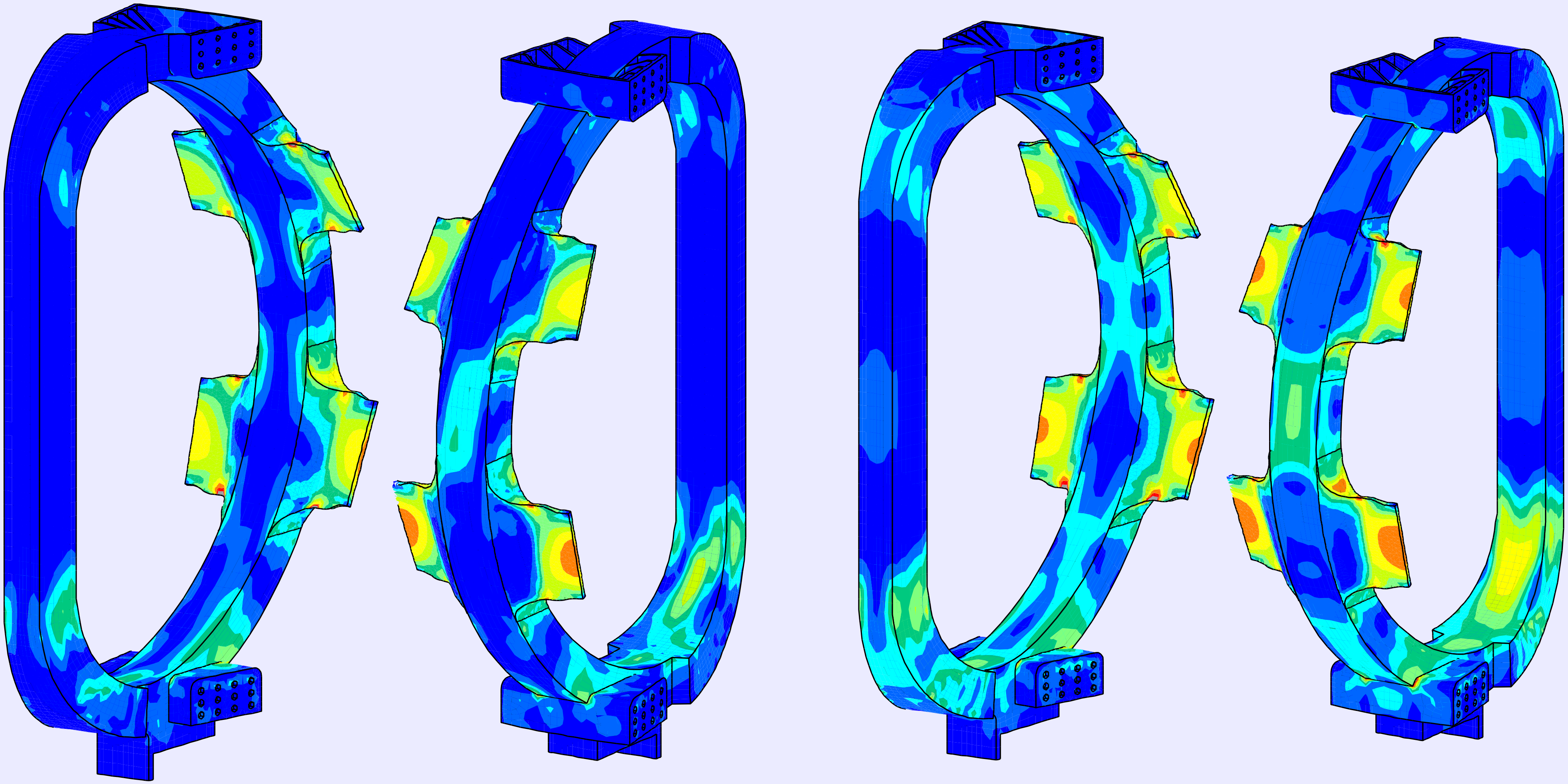
Out-of-Plane Displacements

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



Stress Range in TF Coil Case

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



Electrical Insulation

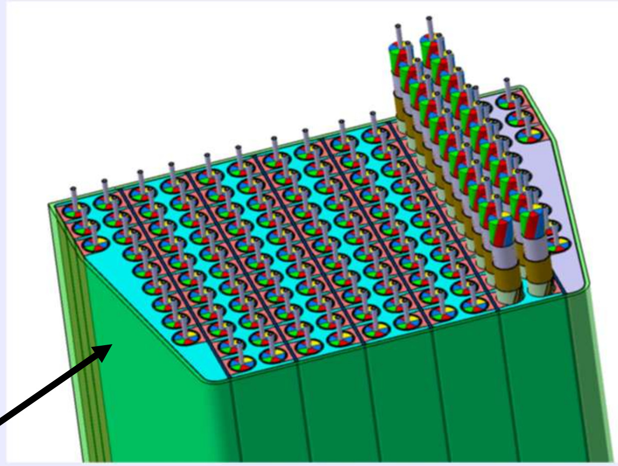
- Four simultaneous constraints:
  - High radiation
  - Large stress on insulation
  - Presence of high voltages (tens of KVs)
  - Magnets are operated in vacuum

- Preferred design solution:
  - Glass-polyimide tapes
  - Vacuum pressure impregnation with resin

The impact of high voltage… selection of insulation type

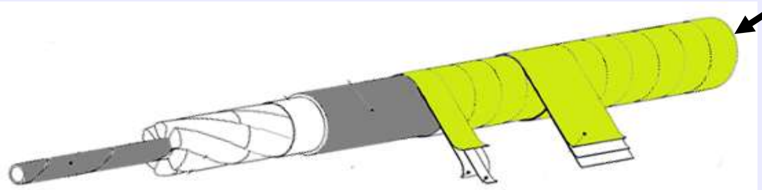
Voltage during TF coil operation

	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



…drives decision to use polyimide barrier ….

TF Coil Conductor



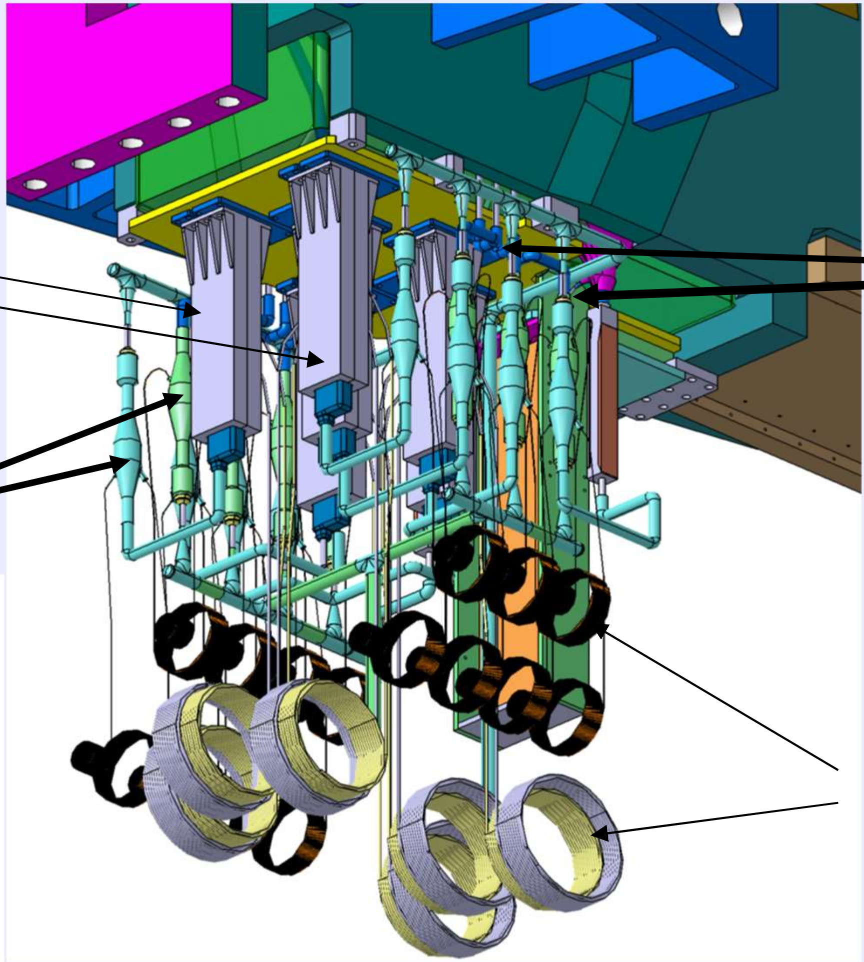
>3 layers of Glass/Polyimide half lapped

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

Joints and Hydraulic Connections

Electrical joints

HV breakers

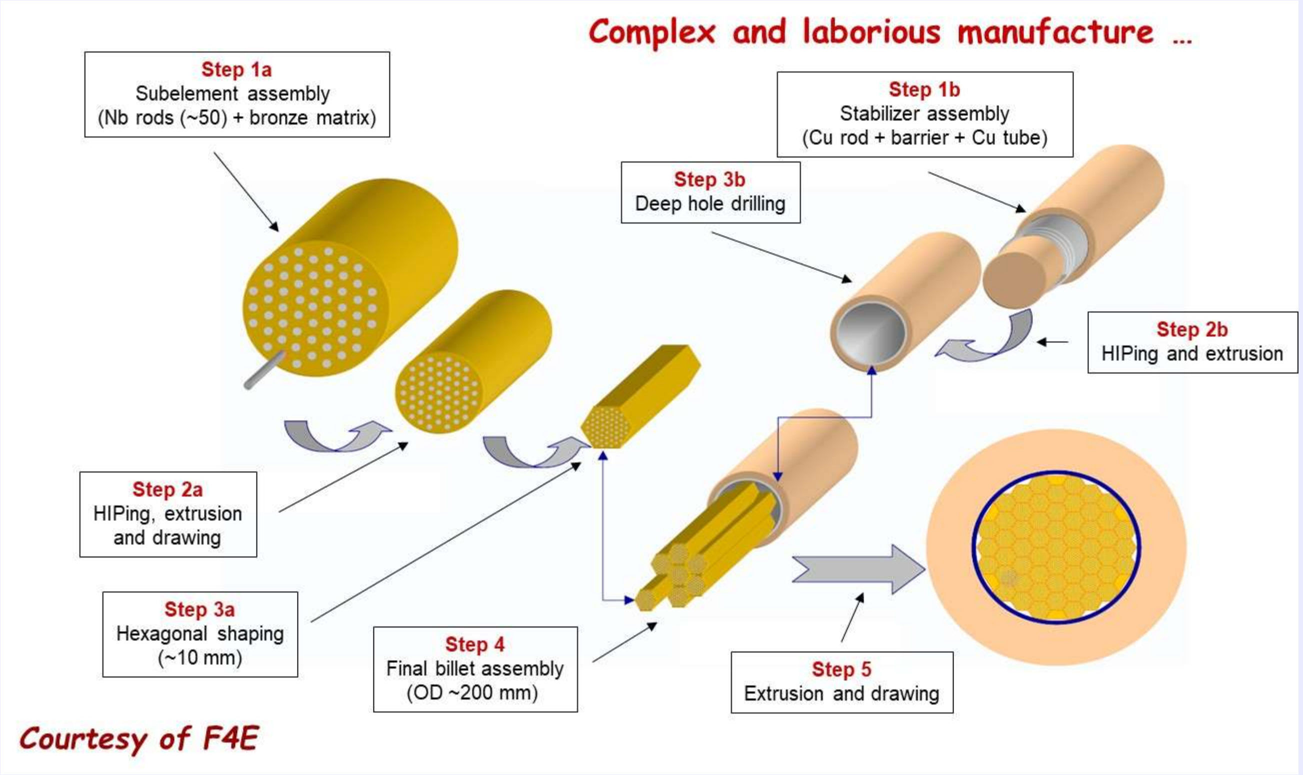


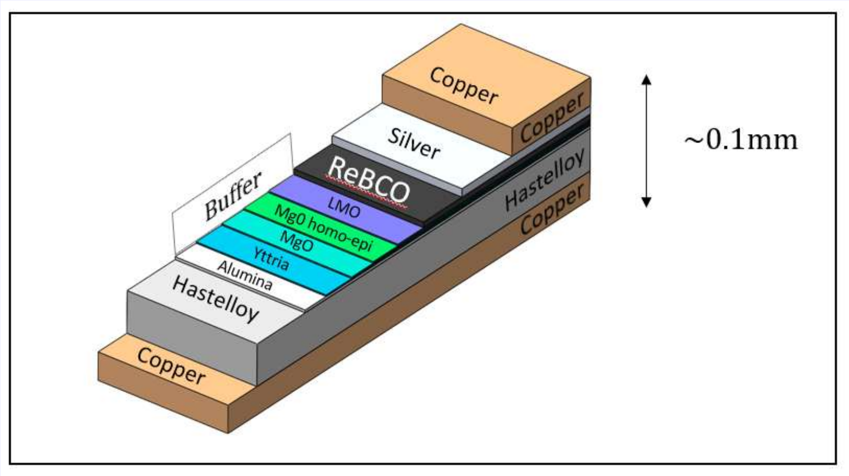
Helium inlets/outlets: high voltage

High voltage and sensors wiring

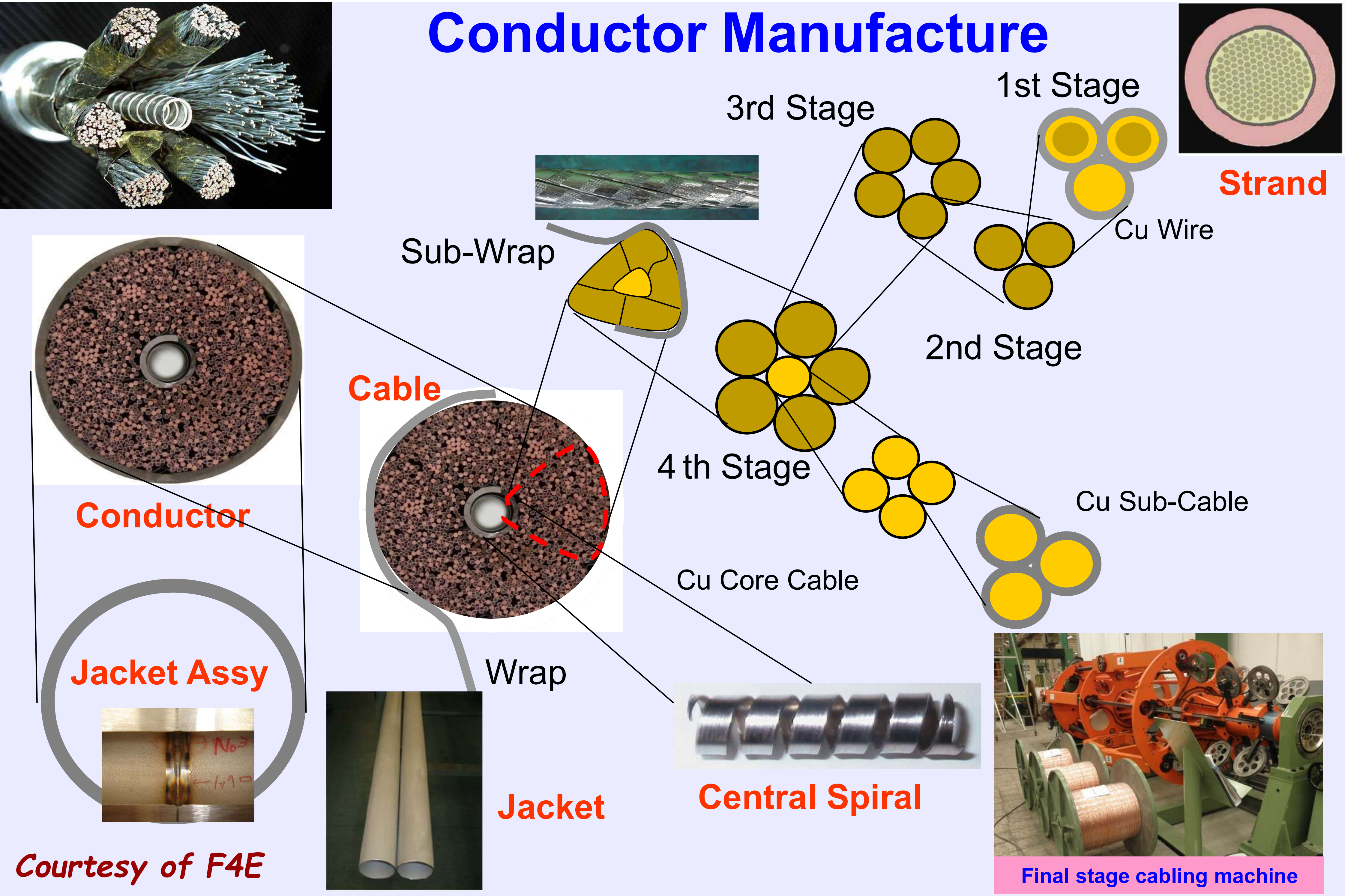
Very complex region, insulation must be applied by hand, typically resin wet glass/polyimide & pre-made G10 sleeves which need to be compacted… high risk area… intermediate Paschen tests (or equivalent) needed to check quality of insulation between assembly steps

Nb_3Sn wire vs. HTS tape





Conductor Manufacture

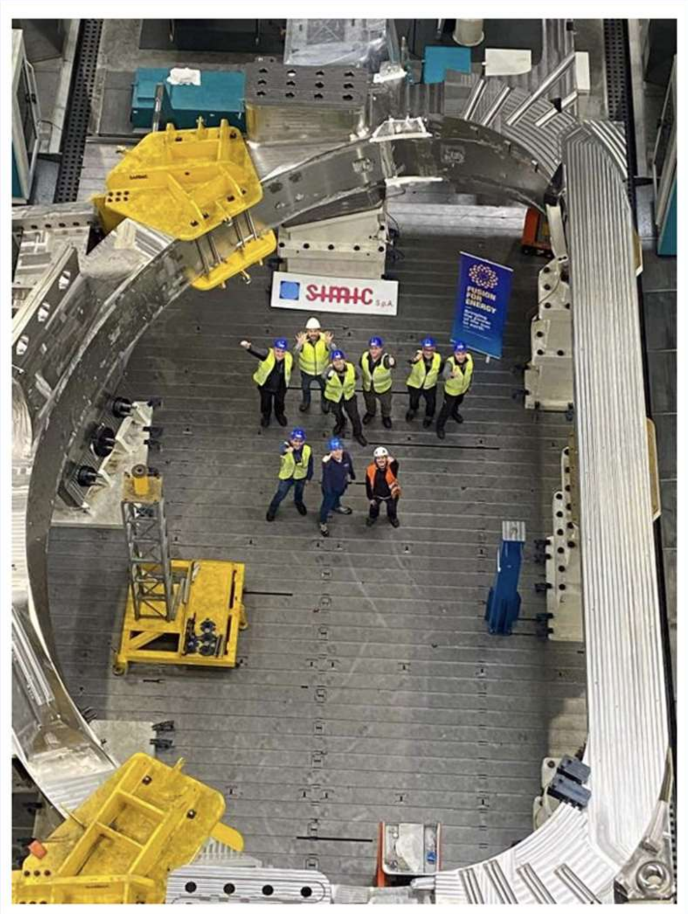


TF Coil Fabrication

Radial Plate

Double Pancake

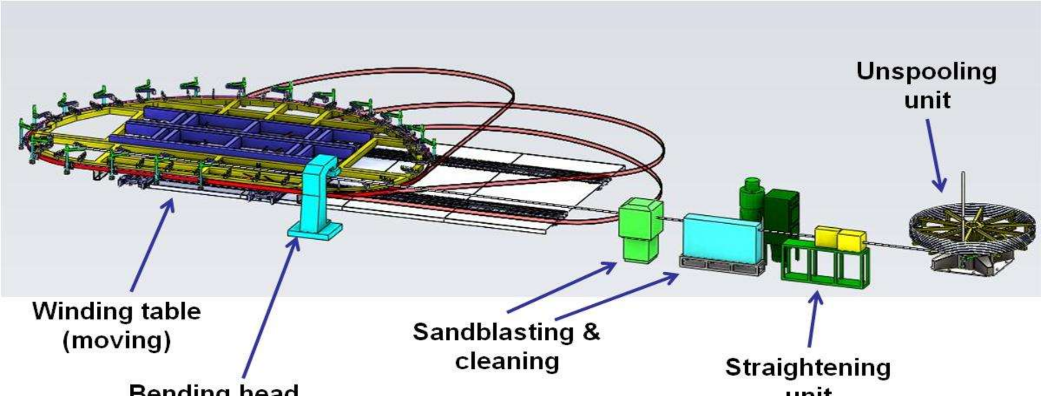
Winding Pack



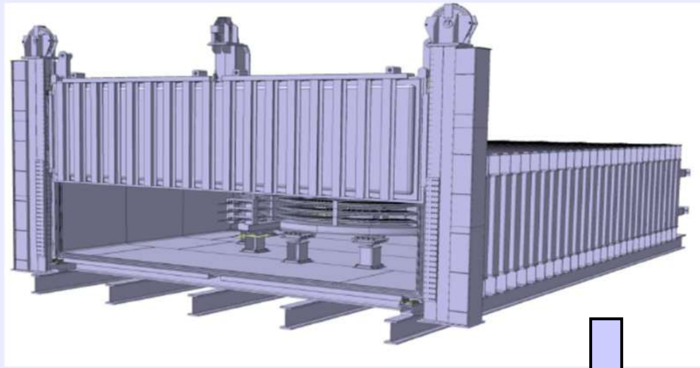
Final assembly into TF Case

Courtesy of F4E

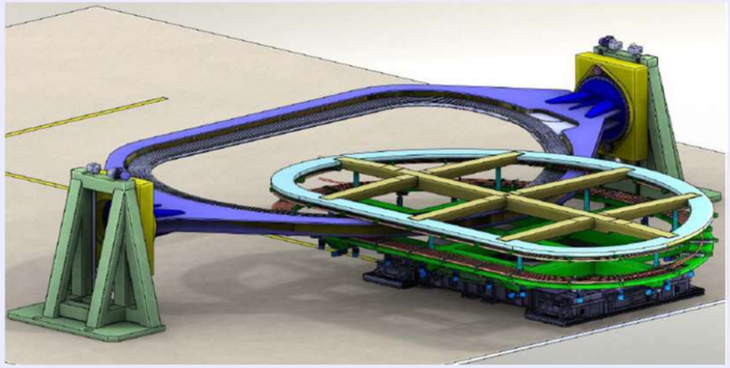
TF Double Pancake Manufacturing Steps



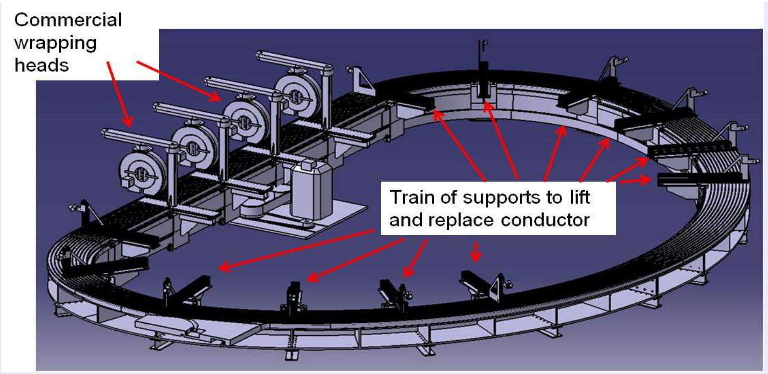
Winding



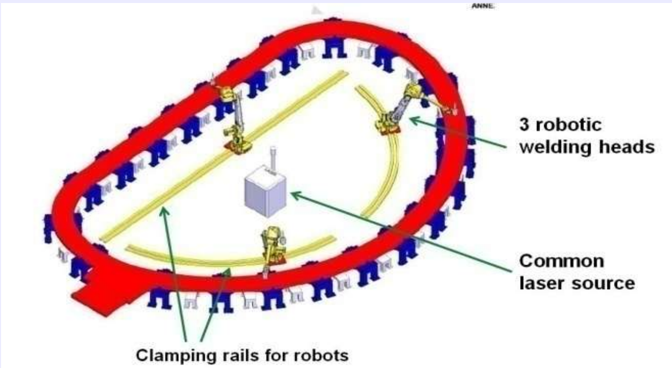
Heat Treatment of 2-3 DP



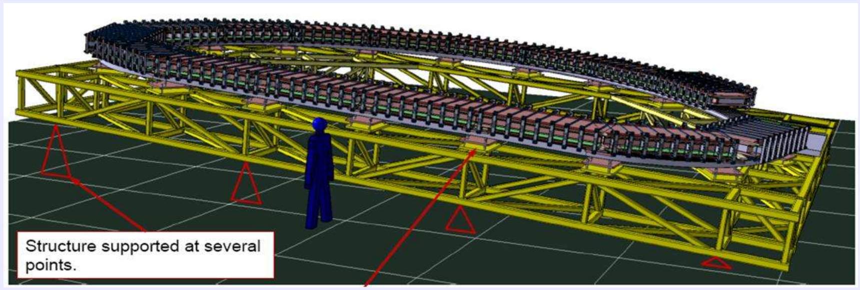
Transfer into Radial Plate



Turn Insulation

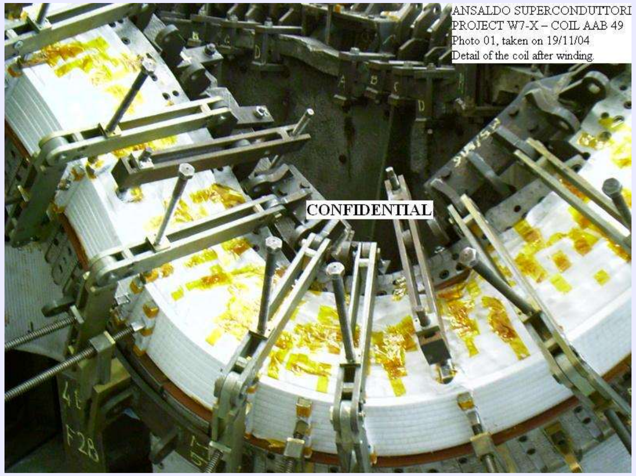


Cover Plate Laser Welding



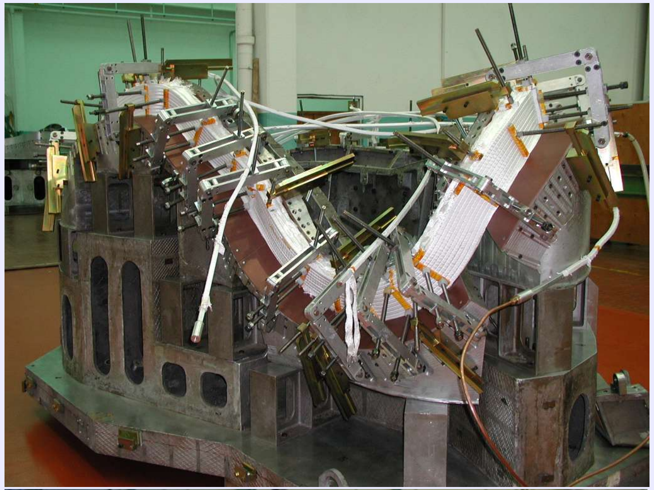
DP Vacuum Pressure Impregnation (VPI)

Non-Planar Coil Winding



ANSALDO SUPERCONDUTTORI

ABB

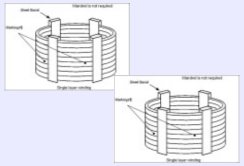


Winding of Coil Types 2, 3 & 4

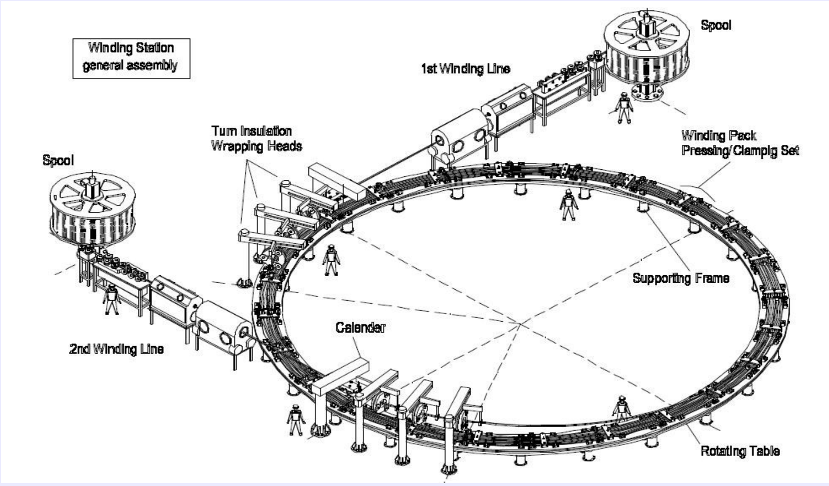
Winding of Coil Types 1 & 5

Courtesy of IPP

PF Coil Fabrication

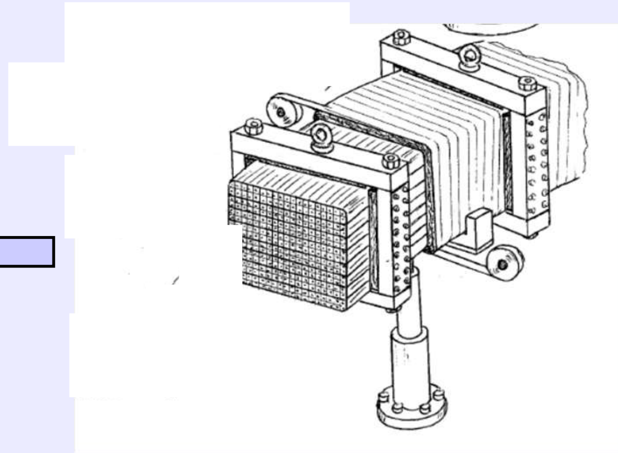


CICC Preparation

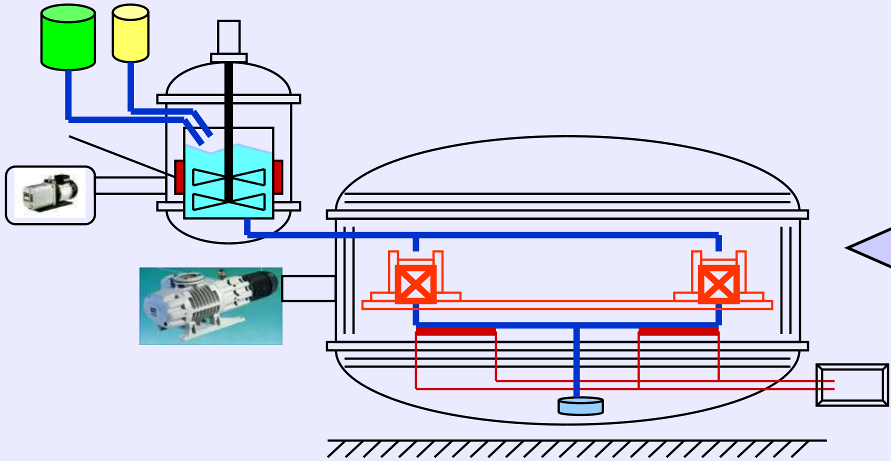


Winding & Insulation

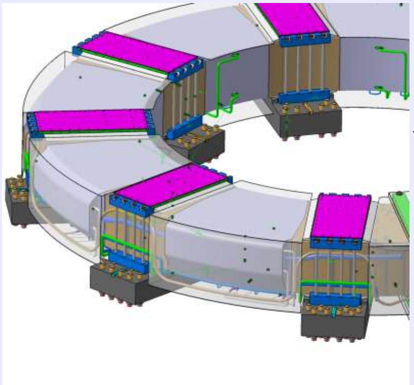
DP Impregnation



DP Stacking & Ground Wrapping



Final VPI



Assembly of Clamps & Covers

PF6 Coil (350 tons)

Winding Pack after impregnation

Final Assembly

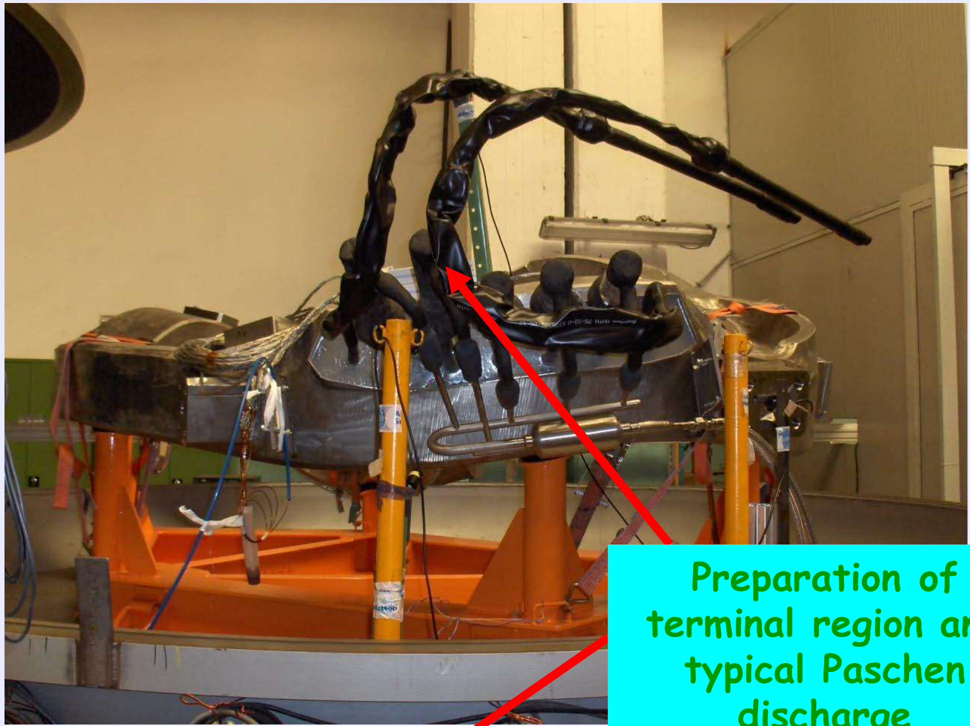
Courtesy of F4E

Quality Assurance Programme

- Extensive quality control and quality assurance should be 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 and joints are required → to be tested in a dedicated test facility.
- 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.
- Advanced metrology to control geometry and deviations and ease assembly and alignment of the magnets.
- Tight control of geometrical, electrical and manufacturing non-conformities.
- Cold testing of all magnets must be carried to validate their superconducting performance, leak and high voltage integrity and measure joint resistance at operating conditions.

Failures in high-voltage Paschen conditions

Paschen Tests Non-Planar Coils

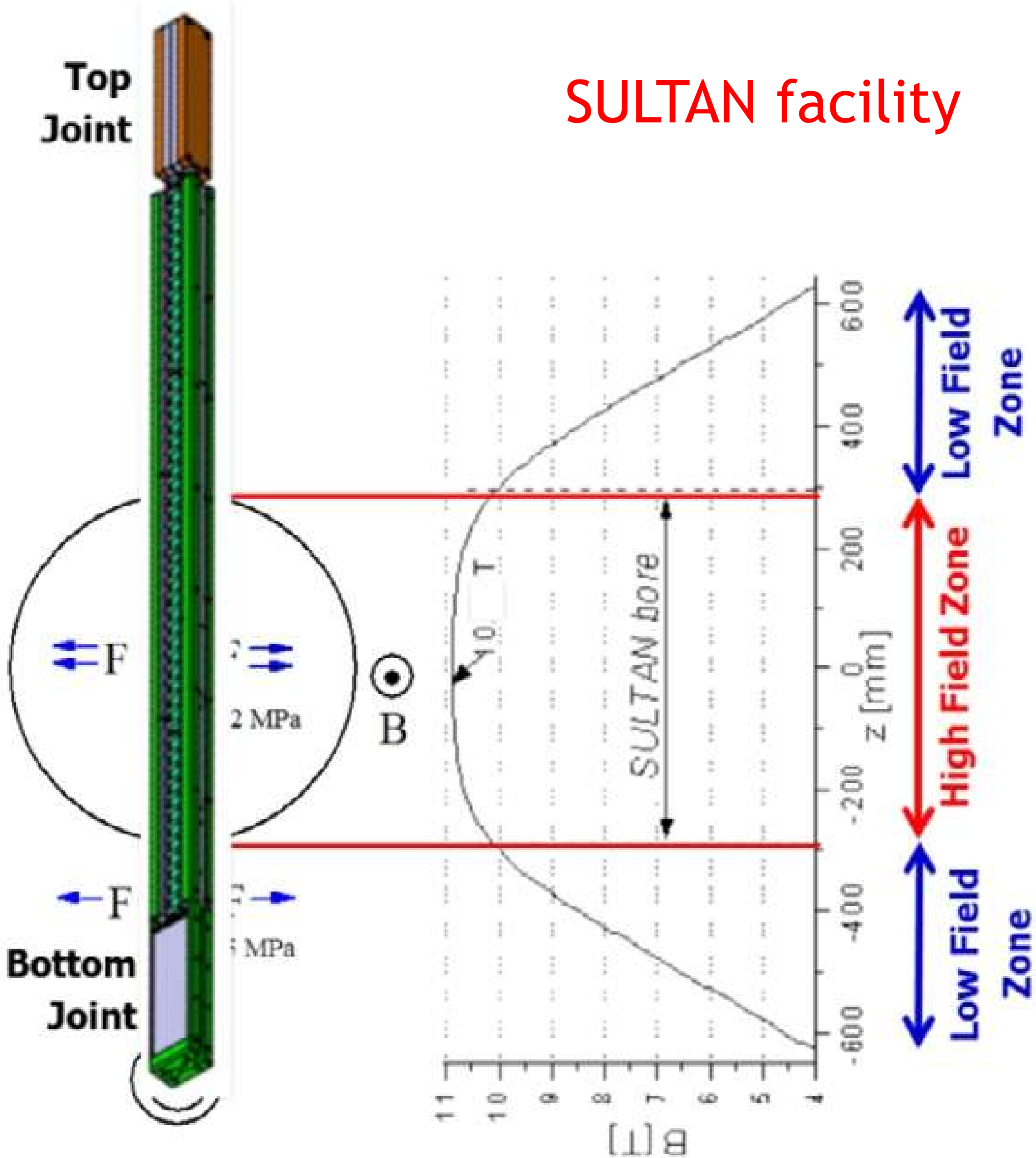


Preparation of terminal region and typical Paschen discharge

Cracks and cavities detected by Paschen tests

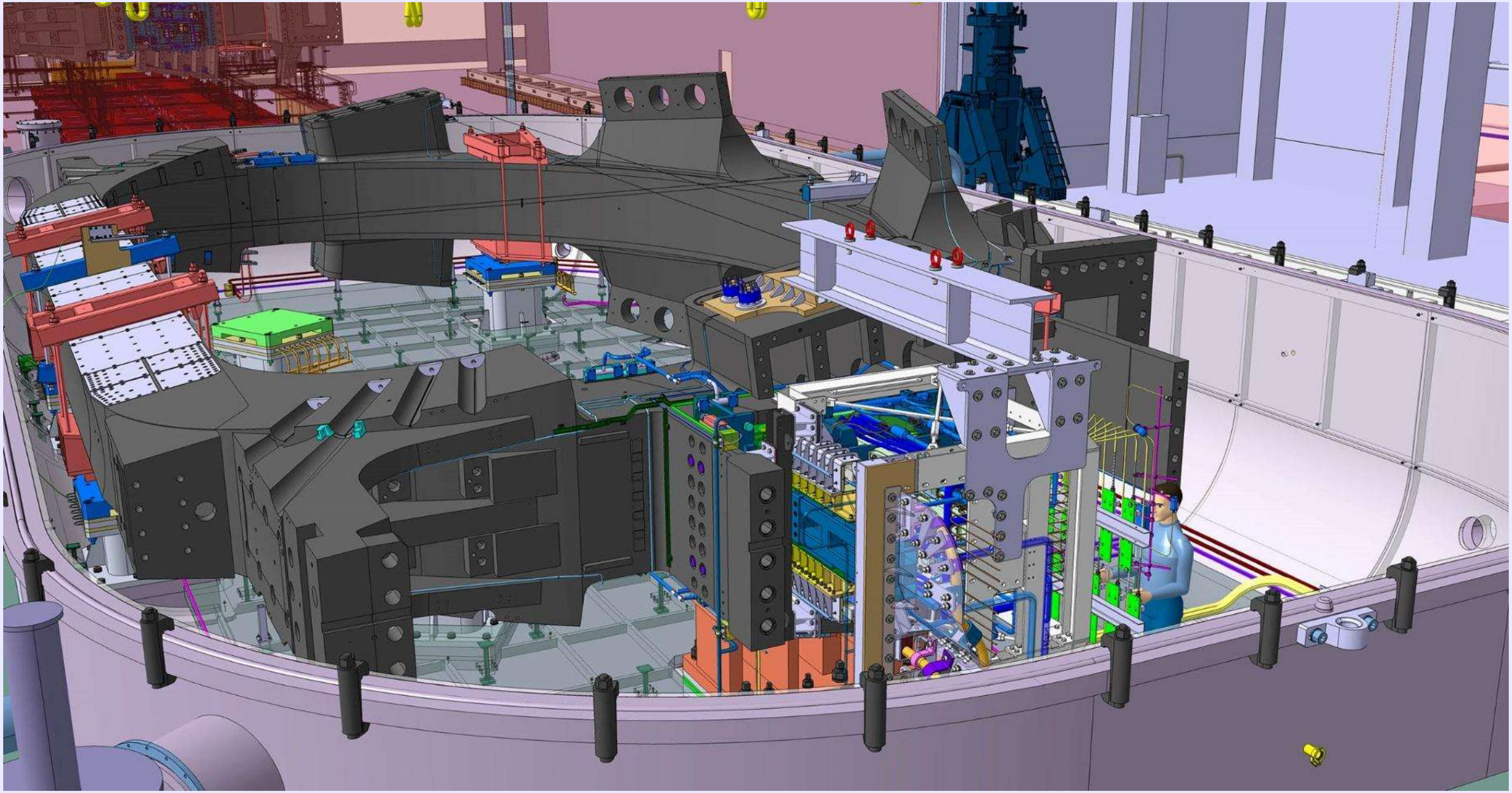
Courtesy of IPP

Test Facilities for CICC and Joints

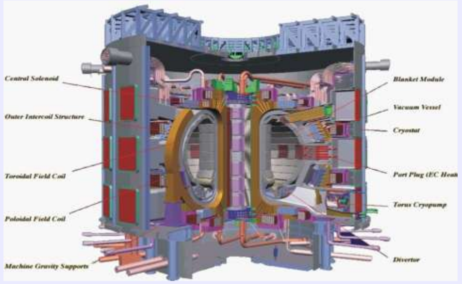


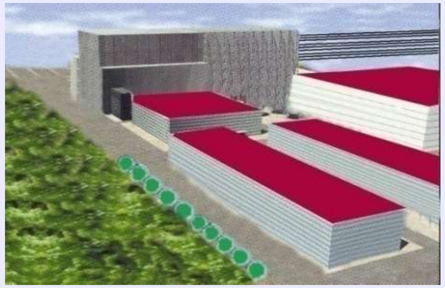
ITER Cold Test Facility

Under assembly, testing of a few TF & PF magnets at 4K foreseen after in-factory cooldown tests of all TF/PF magnet were carried out at 77K



Roadmap to Fusion Power Plant (FPP)

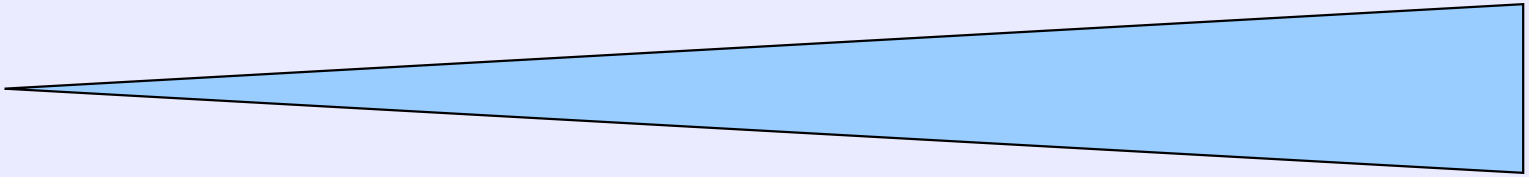




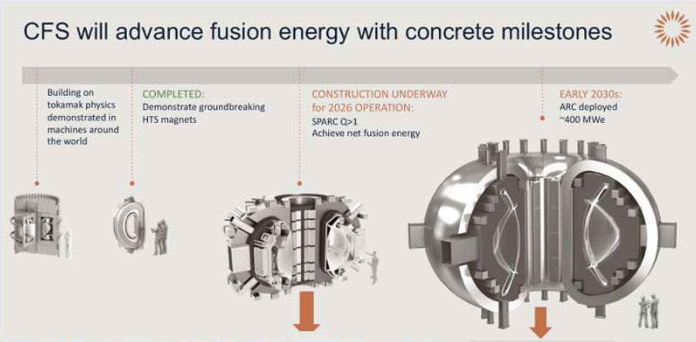
ITER → DEMO / Proto → Commercial FPP

(EU, UK, CN, JA, KO, IN, USA, etc.)

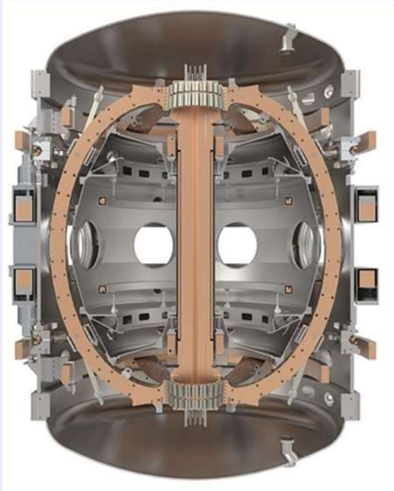
≈ 2030s ≈ 2040s



Some private initiatives on magnetic confinement

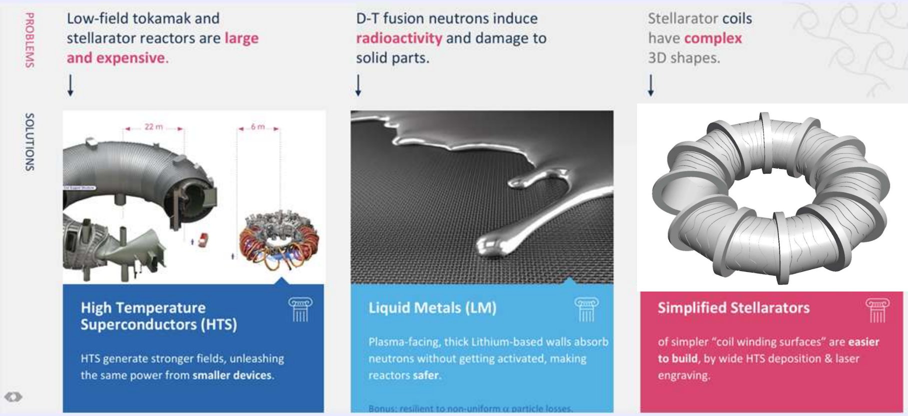


CFS (USA), HTS tokamak

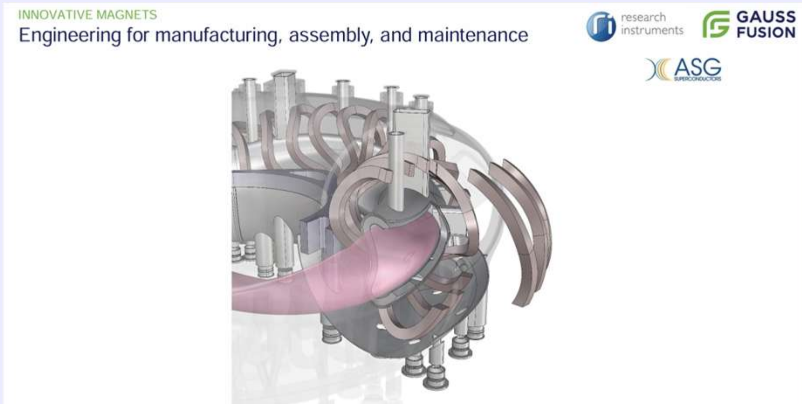


Tokamak Energy (UK), HTS spherical tokamak

Proxima Fusion (D), HTS stellarator



Renaissance Fusion (F), HTS stellarator



Gauss Fusion (D), Nb_3Sn stellarator

Summary

- **Main drivers for fusion magnets design** are:
  - Large forces & stresses, possibly under a large number of cycles
  - Radiation on windings
  - Large stored energy
  - Operation in vacuum
  - Large heating in the conductor

- **Model coils**, possibly in full-scale, should be foreseen to address the major design and manufacturing issues before starting full-scale production ➔ reduce risk associated with the development of technological solutions directly on the real coils

- The ITER project has set new limits for conductor and coil dimensions and performance, quality assurance and project management, which have been beneficial for following projects such as JT-60SA, DTT, SPARC, BEST, STEP, DEMOs, etc.:

  - 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 strand for TF and CS coils
  - About 300 t of NbTi strands for PF coils and CC
  - Complex coils with a total weight of up to 350 tons
  - HTS current leads using Bi-2223 tapes operating up to 68 kA

Thank you
for your attention

Disclaimer: ***the views and opinions expressed herein are personal and do not necessarily reflect those of ITER or other organizations referenced in the presentation.***