Tokamak Electromagnetics

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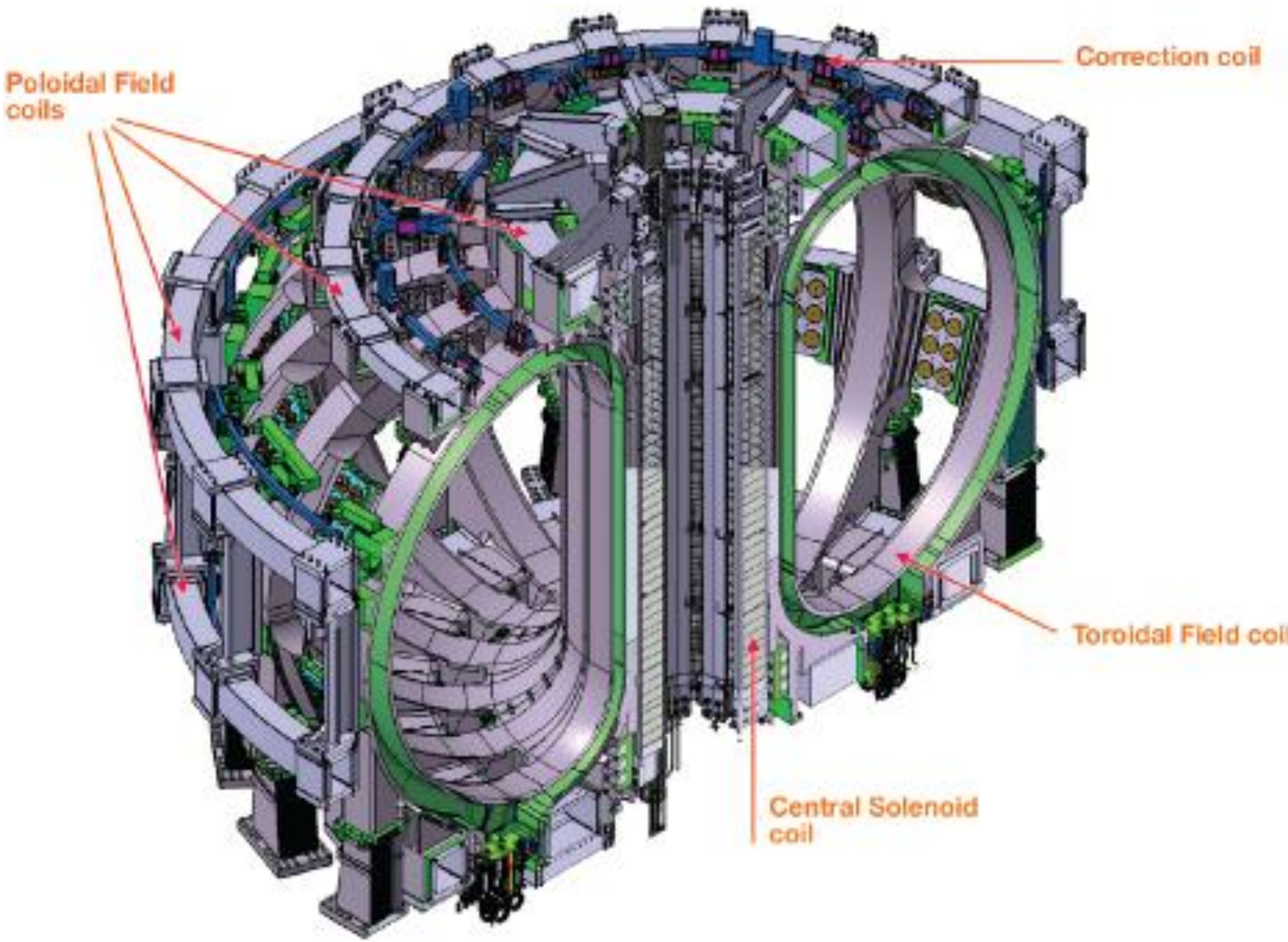
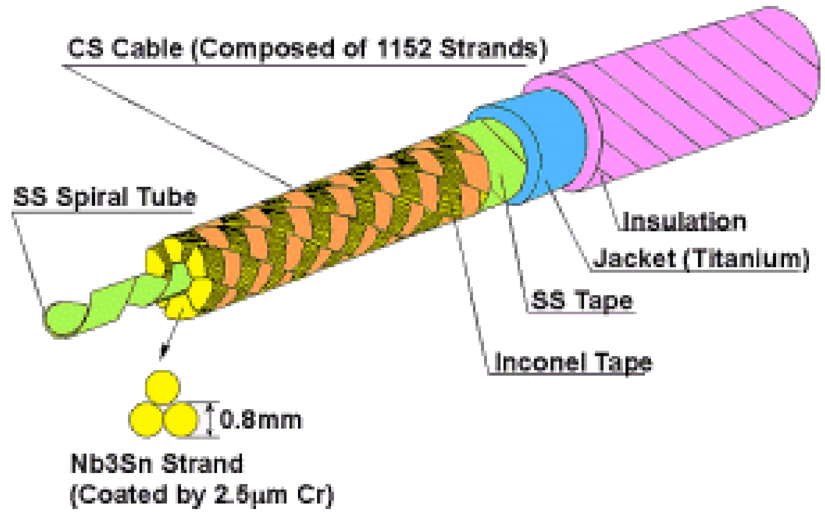
NRE 4610

Basic Tokamak Magnet Systems



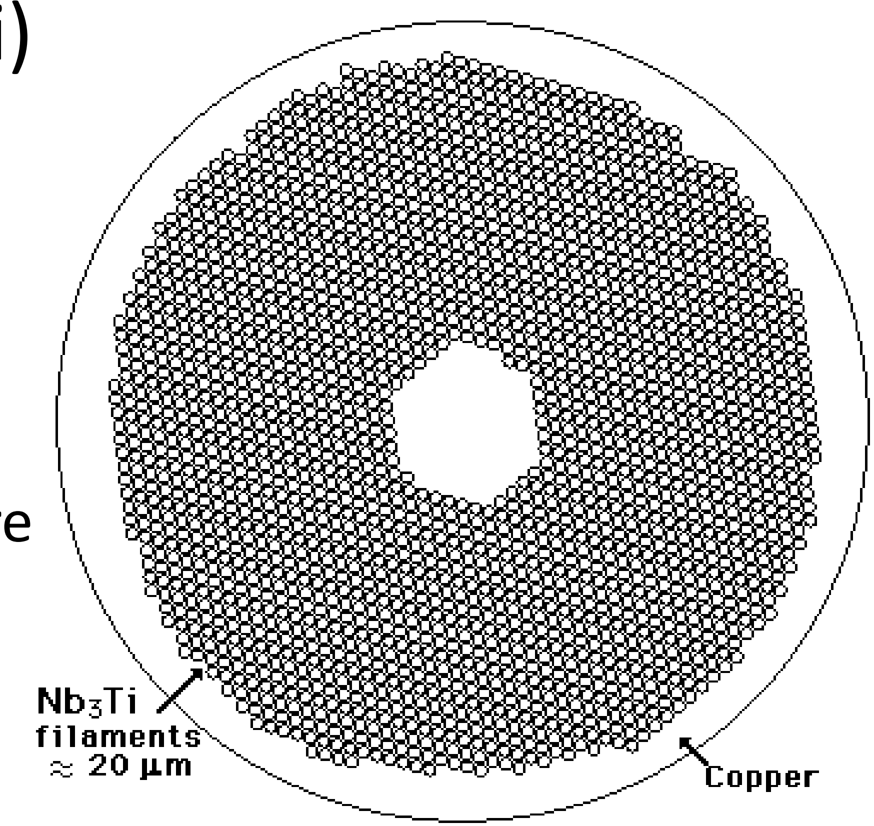
Superconductor Information

- Niobium Tin (Nb_3Sn)
- Characteristics:
  - High performance (better than NbTi)
  - Very brittle and hard to manufacture
  - High costs
  - Used in TFC's and CS



Superconductor Information

- Niobium Titanium (NbTi)
  - Used in PFC and CC
  - Compared to Nb_3Sn [5]
    - Stronger and easier to manufacture
    - Lower critical temperature and current capacity
    - 50-200 €/kg vs 500-1000 €/kg for Nb_3SN



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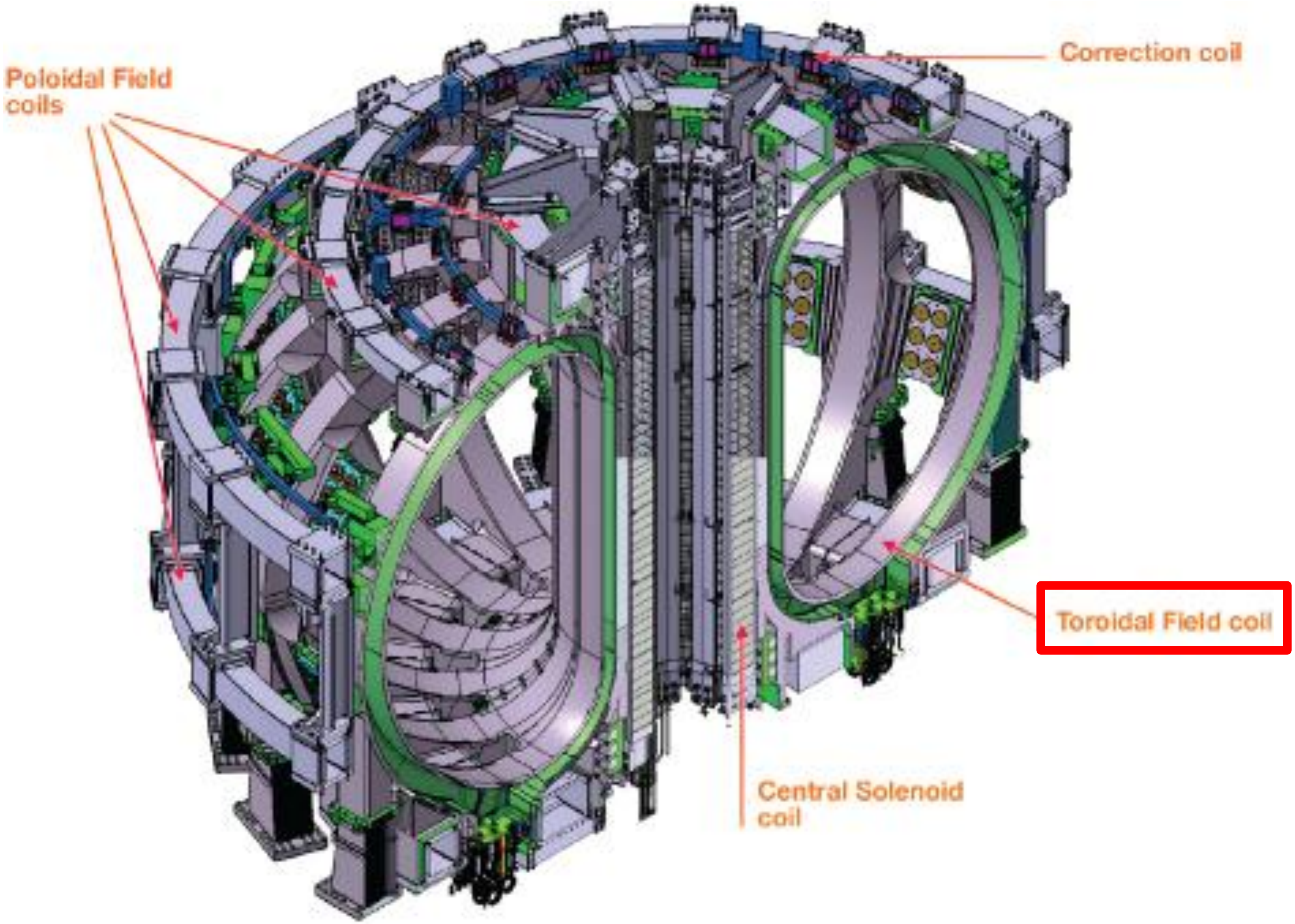


Torodial Field Coils (TFCs)

- The principal function of the toroidal field coils is to provide a toroidal magnetic field that stabilizes the plasma [book]
- Assumptions
  - Made of Nb_3Sn superconductors with I = 68 kA [1]
  - Operating temperature is 4 K
  - $B_{\phi,0}$ is 6 T, leading to high stability

Torodial Field Coils (TFCs)

- $I_{TF} = \frac{B_{\varphi,0} * 2 * \pi * R_0}{N_{TF} * \mu_0}$ = 10.5 MA
- $N_{Cond} = \frac{I_{TF}}{I_{Cond}} = 152$
- $A_{cond,tot} = N_{cond} * A_{cond} = 0.225\ m^2$
- $A_{tot} = A_{case} + A_{cond}$
- Δ_{TF} = 0.75 m, assuming square coils

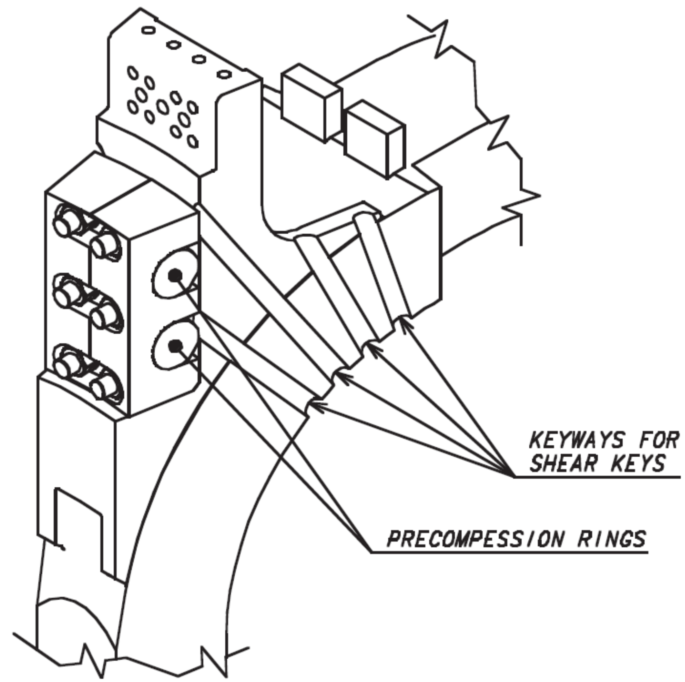
- $B_{\varphi,0}$: $6\ T \rightarrow\ 5.5\ T$
- $N_{TF} = 16$
- $I_{Cond} = 68\ kA$
- $A_{Cond} = 1.48 * 10^{-3}\ m^2$

Torodial Field Coils (TFCs)

- $F_R = 1.53 * \frac{\mu_0 * N_{TF} * {I_{TF}}^2}{2} * \left(1 - \frac{1}{\sqrt{(1-\varepsilon_P)^2}}\right)$ = -484 MN [2]
- $F_T = 1.65 * \frac{\mu_0 * N_{TF} * {I_{TF}}^2}{8 * \pi} * \ln\left(\frac{1+\varepsilon_P}{1-\varepsilon_P}\right) = 195$ MN [2]
- $\sigma_T + \sigma_{bend} \leq 1.5 * S_m$, with S_m = 467 MPa
- σ_{bend} from Iter = *0.224* * σ_T [1]
- $A_{case} = \frac{F_{T,max}}{1.5 * S_m} = 0.34\ m^2$

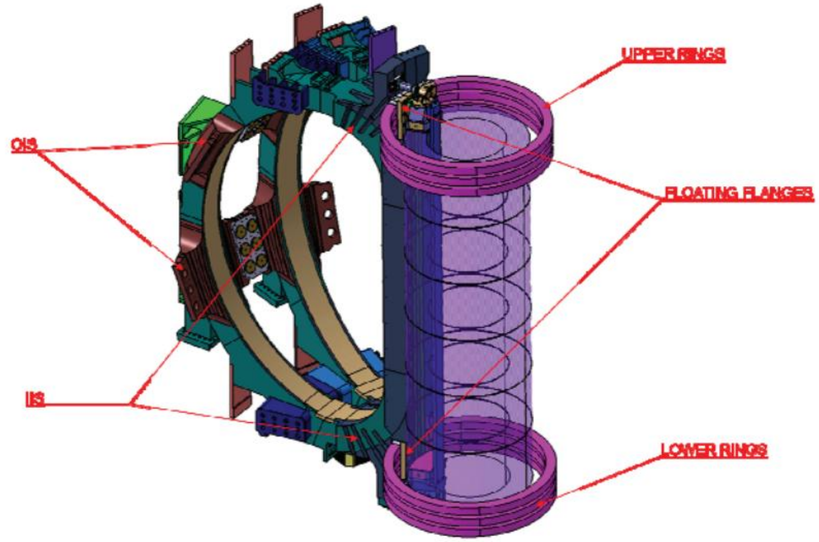
Torodial Field Coils - Forces

- Critical location of the toroidal field coils [1]
  - Highest out-of-plane loads
  - Limited space available
- Measures against centering force:
  - Pre-compression rings
  - Shear keys
  - Wedges



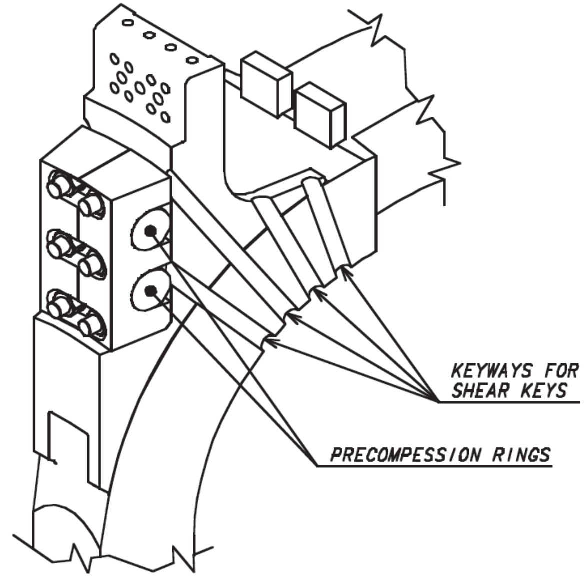
Torodial Field Coils – Pre-compression rings

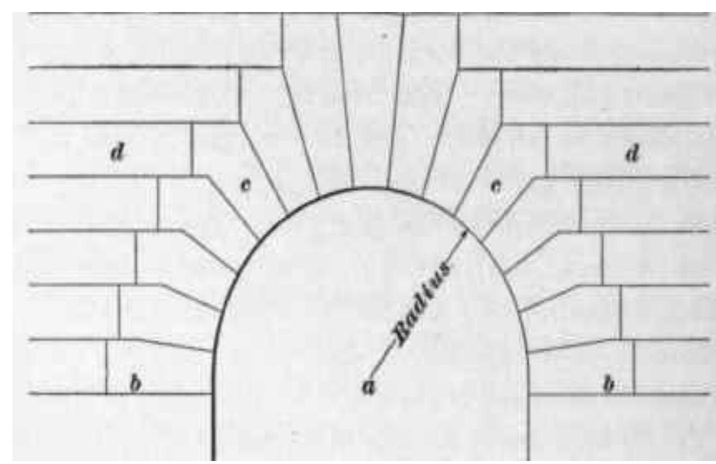
- Composite pre-compression rings [3]
  - Make sure keys do not become loose
  - Put the TF-coils into toroidal compression
- Outer diameter is about 5.5 meters



Torodial Field Coils – Shear keys and wedges

- Shear keys:
  - Prevent development of torsion in the TF cases
- Wedges:
  - Are applied along the full radial thickness
  - Space between coils is about 11.5 cm on the inboard leg



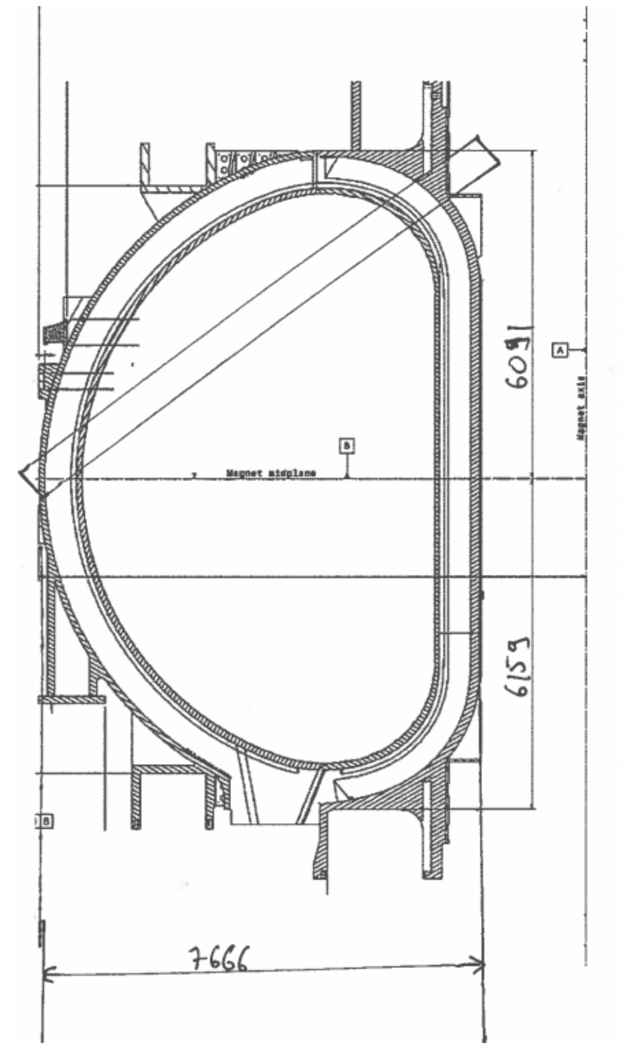


Torodial Field Coils – Conductor Length

- Approximation: Triangular coils with dimensions scaled from ITER [4]
- Estimate the length of a coil:

L_{coil} = 31.9 m

- $L_{conductor} = N_{cond} * L_{coil} * N_{TF} =$ *78 km*

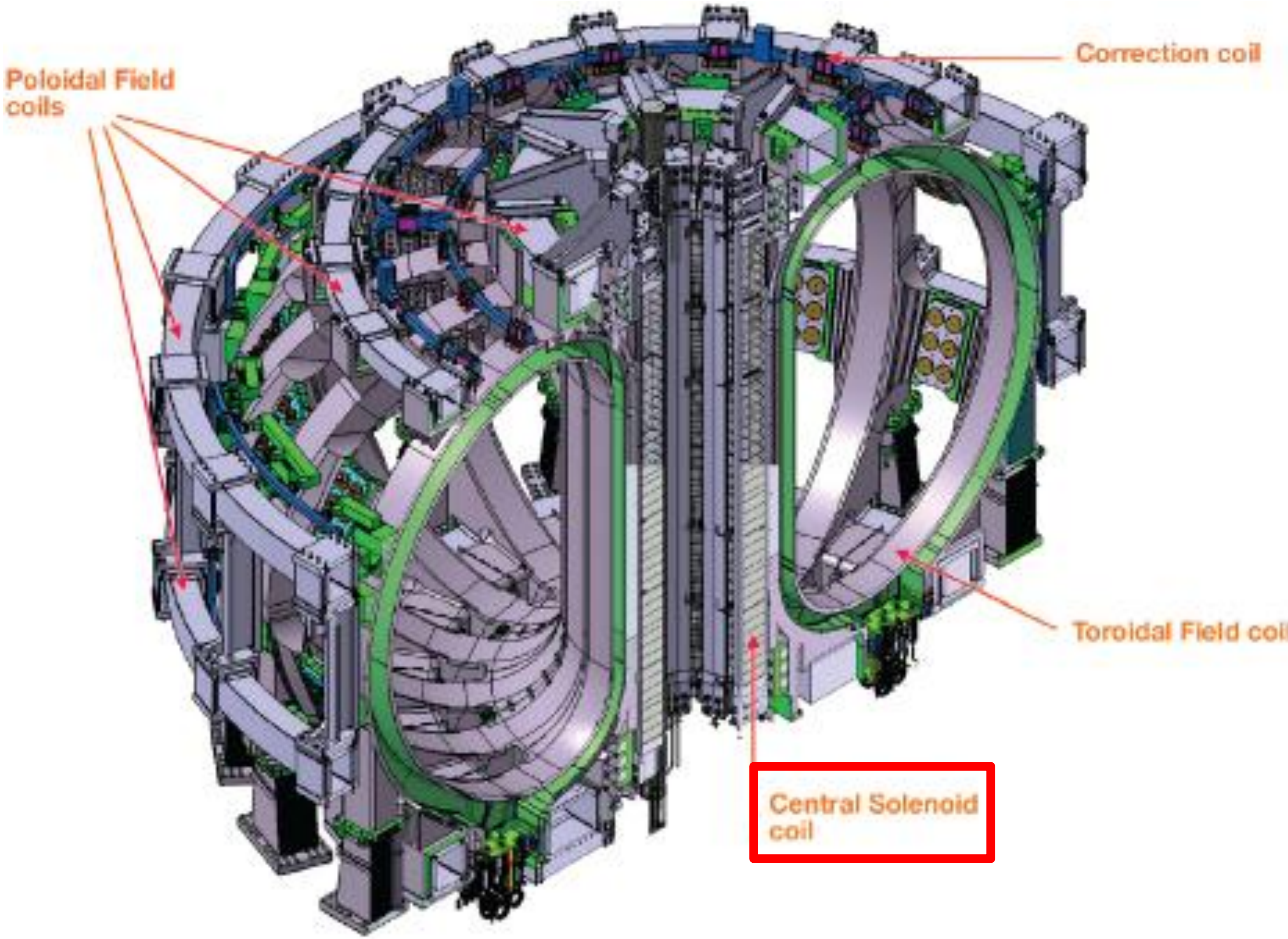


Torodial Field Coils (TFCs) – Weight estimation

- $m_{coil} = L_{coil} * (\rho_{cond} A_{cond} + \rho_{case} A_{case})$ [5]
- Correction factor from ITER scaling: 3.63 [1]
- M_{coil} = 319 tn
- M_{TF} = 5106 tn

- $\rho_{Cu} = 8940\ kg/m^3$ [6]
- $\rho_{Nb3Sn} = 5700\ kg/m^3$ [7]
- $\rho_{SS316} = 8070\ kg/m^3$ [8]

Basic Tokamak Magnet Systems



Central Solenoid (CS)

- The Central Solenoid of a Tokamak is responsible for creating magnetic pulses to get the plasma current high enough to sustain operation.

- Assumptions
  - Made with Nb_3Sn
  - $B_{OH,max} = 13$ T
  - $I_{OH,max} = 46$ kA

Central Solenoid (CS)

- Project Values
  - R_v = 2.00 m
  - ΔOH = 0.18 m
  - Stored Magnetic Energy = 6.4 GJ
  - Conductor Length = 35.6 km

CS - Calculations

- Solenoid Sizing

$$R_v = \mathbf{1.08} * \sqrt{\frac{2 * R_0 * \left(\ln\left(8 * \frac{R_0}{a}\right) - 1.75\right) * I_p}{2 * \pi * B_{OH}}}$$

$$\Delta OH = \mathbf{0.36} * \frac{R_0}{\left(\frac{2 * S_{ss} * \mu_0}{{B_{OH}}^2} - \frac{1}{3}\right)}$$

- Project *vs.* ITER
  - 2.18 m *vs.* 2.20 m

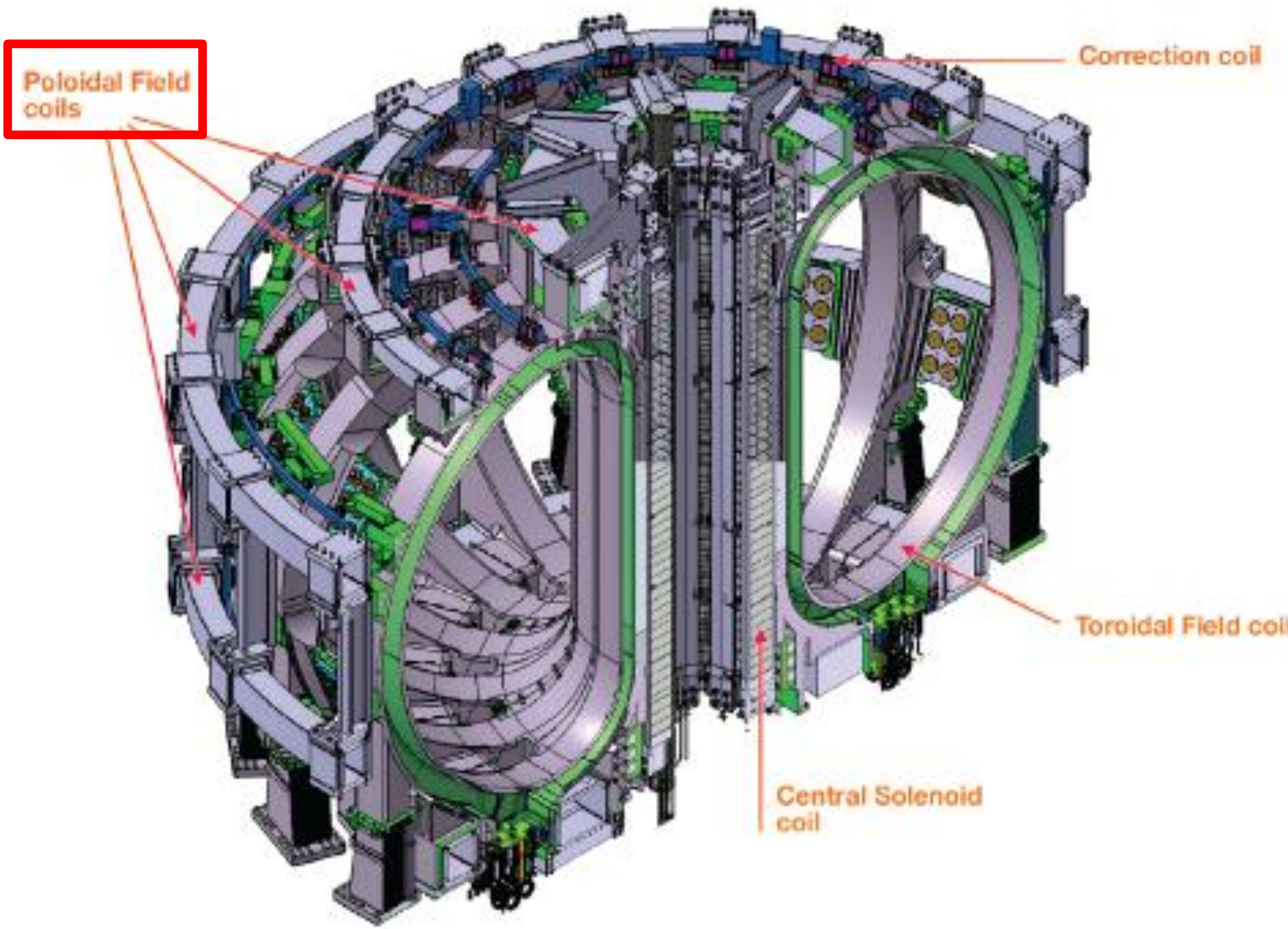
CS – Stress Management

- Buckling Cylinder
  - Steel support cylinder around the solenoid protect it from the centering forces on the TFC.

$$F_R = \mathbf{1.15} * \frac{\mu_0 * N_{TFC} * {I_{TF}}^2}{2} * \left(1 - \frac{1}{\sqrt{1 - {\varepsilon_p}^2}}\right)$$

  - Found to be 461 MN
  - ITER has 403 MN

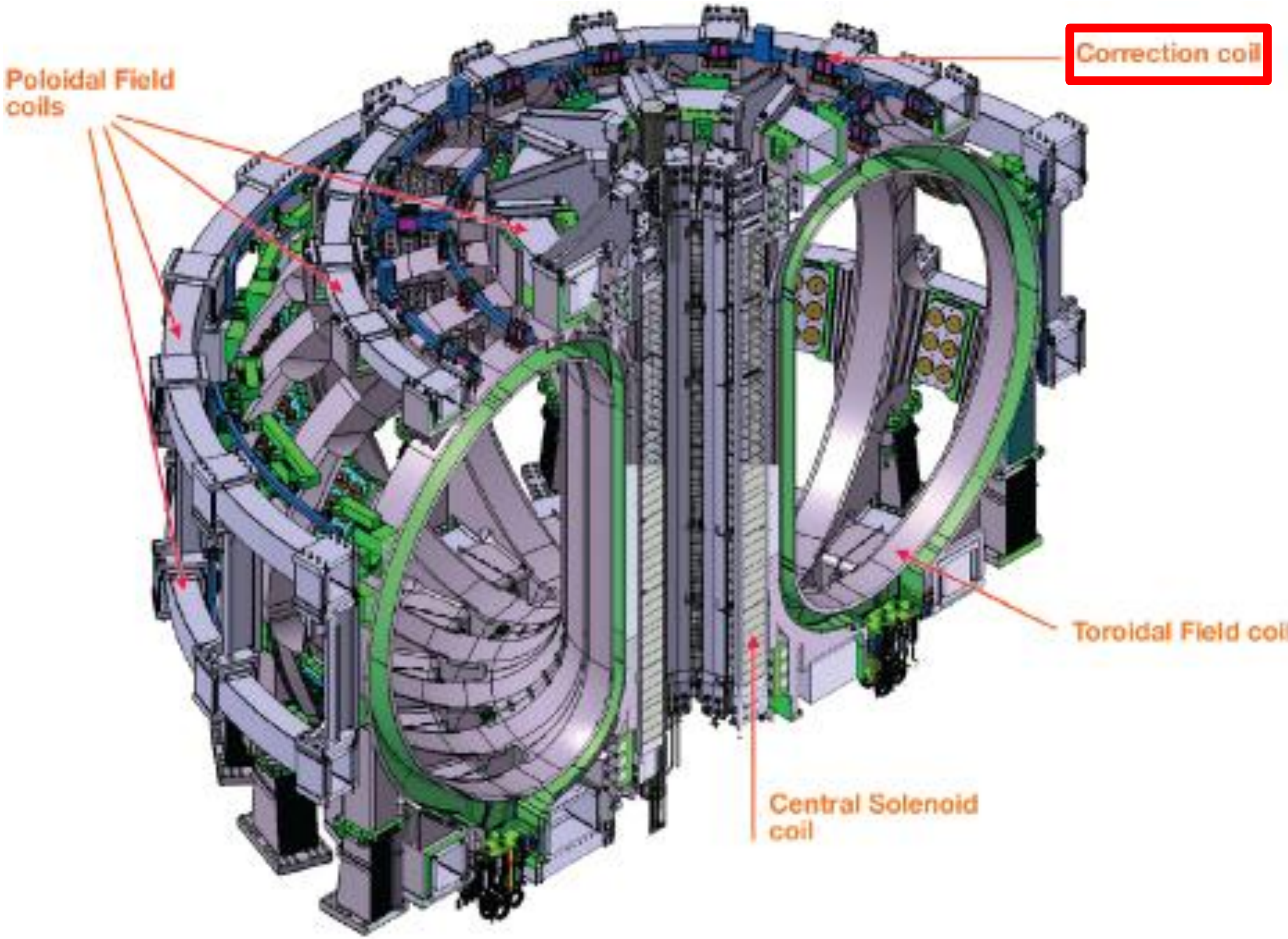
Basic Tokamak Magnet Systems



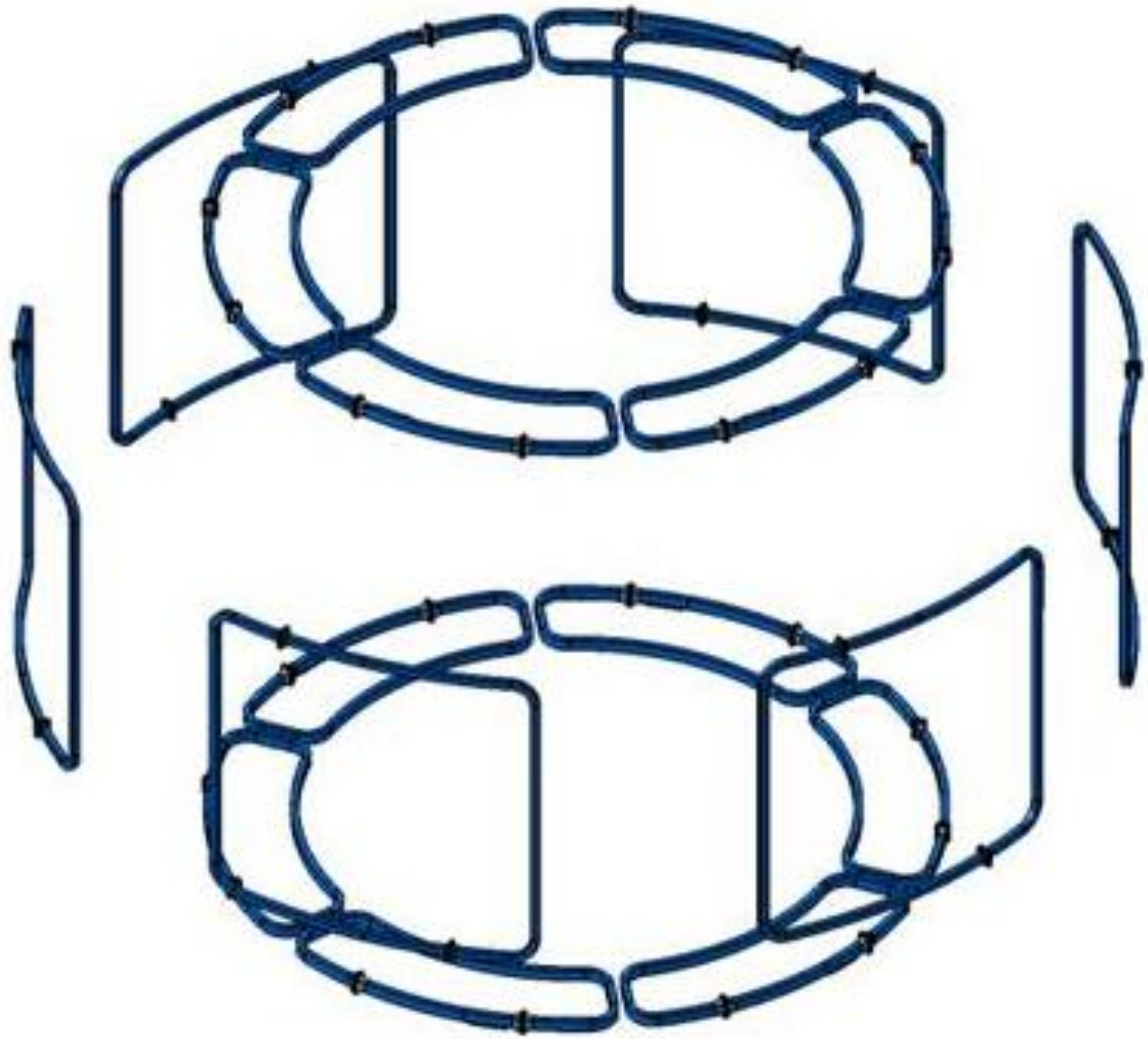
Polodial Field Coils (PFCs)

- The PFCs of a Tokamak are responsible for stabilizing the plasma and keeping it away from the outer first wall.
- Project Values
  - Made out of NbTi
  - $B_{PFC,max}$ = 6 T
  - N_{PFC} = 6
  - $I_{PFC,max}$ = 52 kA
  - Conductor Length: 61.4 km

Basic Tokamak Magnet Systems



Correction Coils (CCs)



Correction Coils (CCs)

- The Correction Coils in a Tokamak are responsible for addressing different instability modes.

- Project Values
  - Made of NbTi
  - Conductor Length = 8.2 km
  - ICC = 7.5 kA

Magnet Cooling Systems

- Liquid Helium is used to cool the superconductors
- Cooling System has dedicated pumps for the CS, TFCs, PFCs, CCs
- Supercritical helium stored in various reservoirs which pumps the helium through a heat exchanger

Magnet Cooling Systems

- Scaling from ITER’s cooling power requirements according to conductor length:
  - CS: 12.3 kW
  - TFC: 27.7 kW
  - PFC: 21.3 kW
  - CC: 2.8 kW

Major Challenges

- Cool-down time
  - Due to superconductor sensitivity, cooling the magnets from 300 K to 4.5 K takes about 2-3 days
- Superconductor Compression
  - Nb_3Sn superconductors are susceptible to crushing into each other which compromises their function

Major Challenges

- Manufacturing
  – Due to the sizes it is necessary to consider location of construction (on site or shipping).

- Assembly and operation
  – Since ITER will be the first project of this scale, a lot needs to be learned from this assembly.

Magnetic System	# Coils	Structural Material	Conductor	Conductor Length
CS	N/A	316 SS	Nb_3Sn	35.6 km
TFC	16	316 SS	Nb_3Sn	78.0 km
PFC	6	316 SS	NbTi	61.4 km
CC	N/A	N/A	NbTi	8.2 km

Magnetic System	Maximum Field	Operating Current	Cooling Power	Stored Energy	System Weight
CS	13 T	46 kA	12.3 kW	6.4 GJ	~1000 tonnes
TFC	11.5 T	68 kA	27.7 kW	41 GJ	~5160 tonnes
PFC	6 T	52 kA	21.3 kW	N/A	~2000 tonnes
CC	N/A	7.5 kA	2.8 kW	N/A	~80 tonnes

References

[1] ITER Design Team, “ITER Technical Basis,” ITER EDA Documentation Series 24, ITER, 2002.

[2] M. Huguet, I. Team and I. Teams, 'Key engineering features of the ITER-FEAT magnet system and implications for the R&D programme', *Nucl. Fusion*, vol. 41, no. 10, pp. 1503-1513, 2001.

[3] H. Rajainmaki, A. Foussat, J. Rodriguez, D. Evans, J. Fanthome, M. Losasso, V. Diaz, “The ITER pre-compression rings A first in cryogenic composite technology ,” in AIP Conference Proceedings, AIP Publishing, 2014.

[4] Mitchell, Neil, Pierre Bauer, Denis Bessette, Arnaud Devred, Remy Gallix, C. Jong, J. Knaster et al. "Status of the ITER magnets." *Fusion Engineering and Design* 84, no. 2 (2009): 113-121.

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[12] M. Holm and L. Pori Oy, 'Industrial Manufacturing of Low Temperature Superconducting (LTS) wires', European Summer School on Superconductivity 2011, 2015.

Division of Work

- Pieter-Bas Bentinck
  - Slides: 3, 5-13, 27
  - Material Responsible for:
    - TFC
    - Stresses
- John Minderman
  - Slides: 4, 14-26
  - Material Responsible for:
    - CS, PFC, CC
    - Cooling