COMPASS-U Poloidal field coils and central solenoid coils v 1.1

Pavel Junek
Institute of Plasma Physics of the Czech Academy of Sciences
Czech Republic

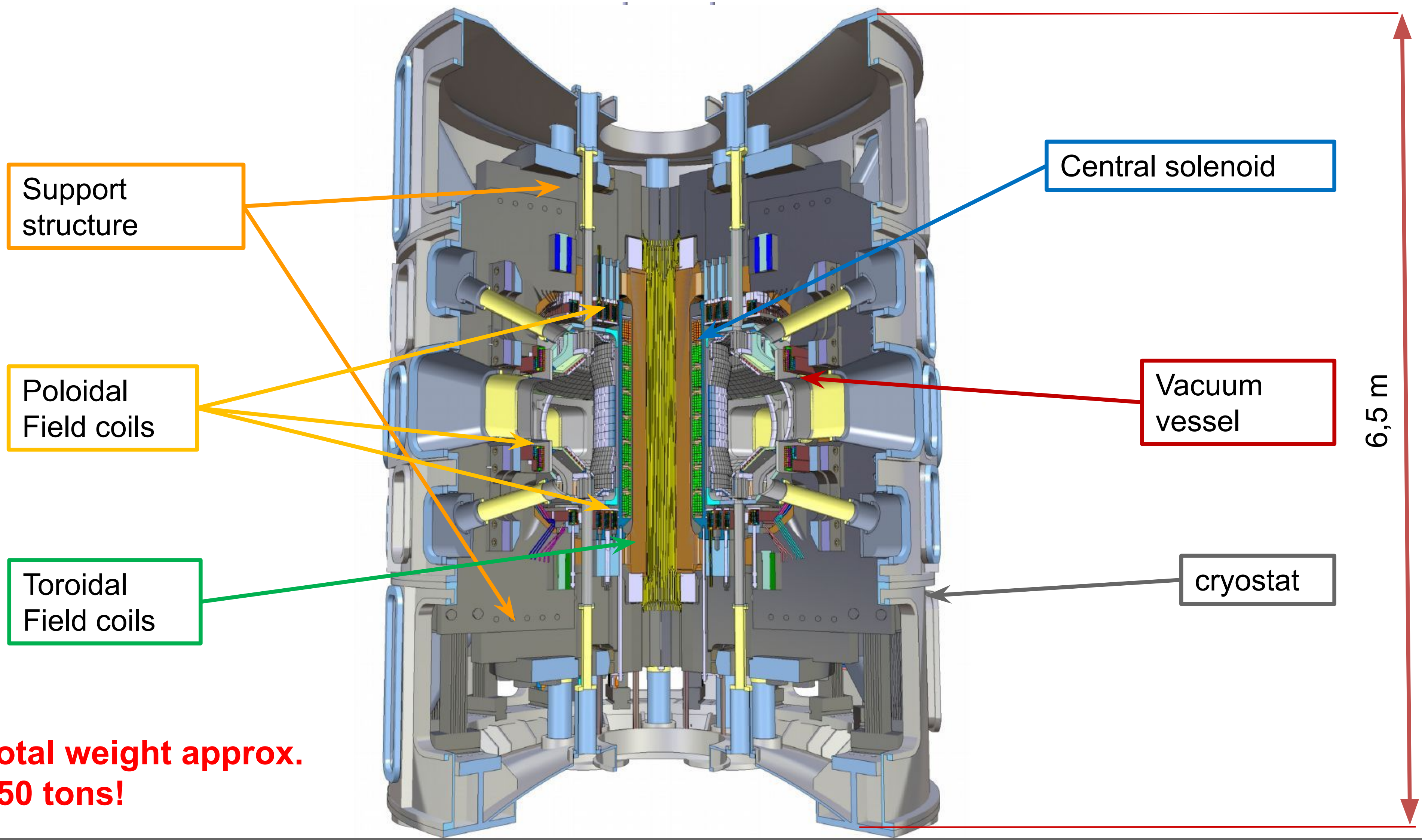
Presentation for Preliminary Market Consultations

Key properties of COMPASS-U:

- High magnetic field to confine plasma (5 T)
- High plasma current (2 mil. Ampers)
- High currents in toroidal coils up to 200 kA
- High currents in poloidal coils up to 50 kA
- Both coils systems from copper alloy materials (discharge durations up to severals seconds)
- tokamak operate at cryogenic temperature
- Operation with high temperature first wall – up to 500°C
- mid-size device

=> unique capabilities to address DEMO challenges

COMPASS-U cross-section



Total weight approx. 250 tons!

Key milestones:

Design of the components	2018 - 2021
launch of tender for PF coils	Q3 2021
launch of tender for TF coils and CS coils	Q4 2021 - Q1 2022
PF and TF Coil manufacturing	2021 - 2023
Assembly and installation	2023

Presumed scope of work

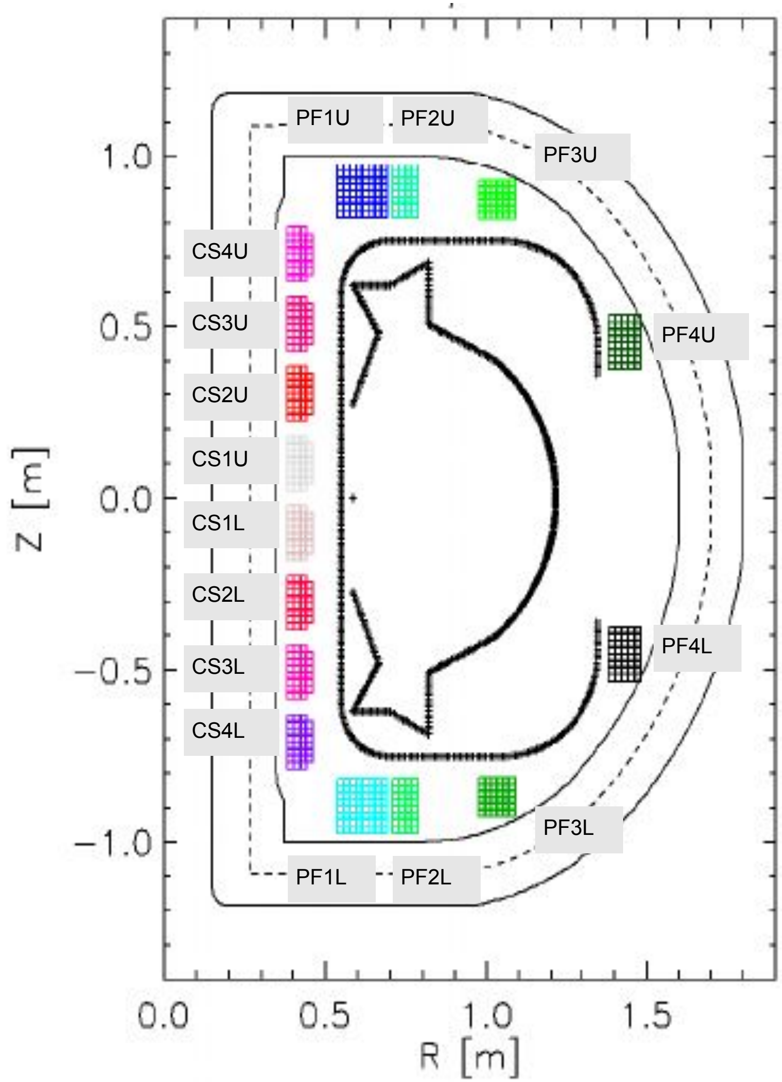
- Prototype coil to confirm design and manufacture procedure
- Manufacture of 10 individual poloidal field coils from hollow conductor from certain alloy of High conductivity oxygen free copper with different radius of coils (0.5 – 1.5 m)
- Manufacture of 8 individual central solenoid coils from hollow conductor from certain alloy of High conductivity oxygen free copper with same radius of coils (0.42 m). Central solenoid coils will be wound on toroidal field coils

Presumed scope of work on the coil

- Manufacture of mechanical support for the coils
- Winding
- Insulation
- Vacuum pressure impregnation
- Electrical and leak testing
- Transport to IPP

Parameters of the coils

coil	Copper turn crossection [mm²]	Coil copper mass [kg]	Positions of coil center dR [m]	Positions of coil center dZ [m]	dR [m]	dZ [m]
CS1U	465.4	374	0.42	0.1015	0.095	0.208
CS2U	465.4	374	0.42	0.3215	0.095	0.208
CS3U	465.4	374	0.42	0.5415	0.095	0.208
CS4U	465.4	374	0.42	0.7615	0.095	0.208
PF1Ua	185.66	197	0.5765	0.895	0.0785	0.15
PF1Ua	185.66	227	0.5765	0.895	0.0785	0.15
PF2U	185.66	257	0.749	0.895	0.075	0.15
PF3U	185.66	387	1.060	0.87	0.120	0.1
PF4U	275.52	889	1.42	0.412	0.121	0.195



Conductor design overview:

coil and quantity	material of the conductor	Height [mm]	width [mm]	dia of hole [mm]	radius of corner [mm]	numb. of turns	medium radius of the coil [m]	length of the conductor [m]
8 x CS	C10700	21	24	8 x 6.2	1	29	0.42	90
2 x PF1a	C10700	15	15	7	1	32	0.576	120
2 x PF1b	C10700	15	15	7	1	32	0.662	137
2 x PF2	C10700	15	15	7	1	32	0.749	155
2x PF3	C10700	15	15	7	1	36	1.06	233
2x PF4	C10700	20	17	9	1	40	1.42	360

Conductor material: (of wounded coils)

- CS coils temper: hard (YS ~ 300 MPa @ 80K)
- PF coils temper: half-hard (YS > 150 MPa @ 80K)

Primer:

- CTD-450 (Manufacturer may suggest other solution)

Epoxy:

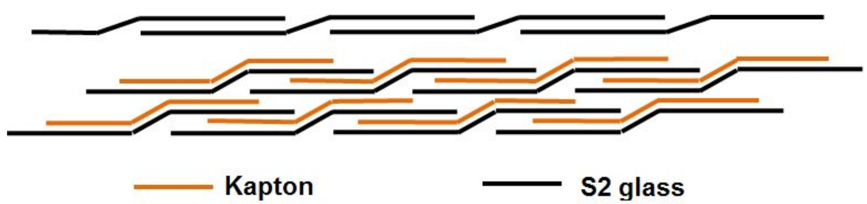
- CTD-101K, GY282, VUPOXY TKM-2K (Manufacturer may suggest other solution)

Insulation overview

PF Conductor insulation total thickness 1mm:

- 2 layers of 0.15 mm half-lapped S2 glass fibre tape interleaved with 25 μm Kapton
- + 1 layer of 0.15 mm half-lapped S2 glass fibre tape (no Kapton)
- Kapton tape width is 80% S2 glass tape
- ground insulation total thickness 3 mm:
  additional 6 layers of 0.25 mm half-lapped S2 glass fibre tape (no Kapton)

NSTX-U like solution



effect of piling up of conductors and tapes (worst case of material tolerance)

accuracy (mm)	CS	PF1a	PF1b	PF2	PF3	PF4
total width	**+2,8**	**+2,8**	**+2,8**	**+2,8**	**+2,8**	**+4,1**
total height	**+5,3**	**+5,3**	**+5,3**	**+5,3**	**+4,1**	**+4,1**

CS Conductor insulation total thickness 1mm (layer same as PF)

- Inter-layer insulation CS total thickness 0.6 mm:
- additional 2 layers of 0.15 mm half-lapped S2 glass fibre tape (no Kapton)
- ground insulation total thickness 3 mm (only in toroidal direction):
- additional 6 layers of 0.25 mm half-lapped S2 glass fibre tape (no Kapton)

maximum working voltage of power supplies for PF system is **1 kV**

circularity tolerance from the coil inner diameter
(may be slightly loosen +(1-2mm))

accuracy (mm)	from 120 to 400	from 400 to 1000	from 1000 to 2000	from 2000 to 4000
	±0.5	**±0.8**	**±1.2**	**±2**

Qualification of insulation system

Paschen testing of CS and PF coils

- testing of insulation strength at Paschen conditions

Leak inspection

- The coil has to be air-flow tested to ensure that the cooling path is free from obstructions
- The coolant medium is gaseous helium
- Hydrostatic pressure test will be performed for 60 minutes

Pressure and leak parameters

circuit	nominal working pressure [Bar]	testing pressure [Bar]	max. leak rate [Pa.m^3/s]
PF	20	30	10e^{-10}
CS	60	90	10e^{-10}

Material properties of Cu alloy:
C10700 Cu-Ag0.1. temper for CS and PF

- YS tests at 300 K and 80 K

chemical composition

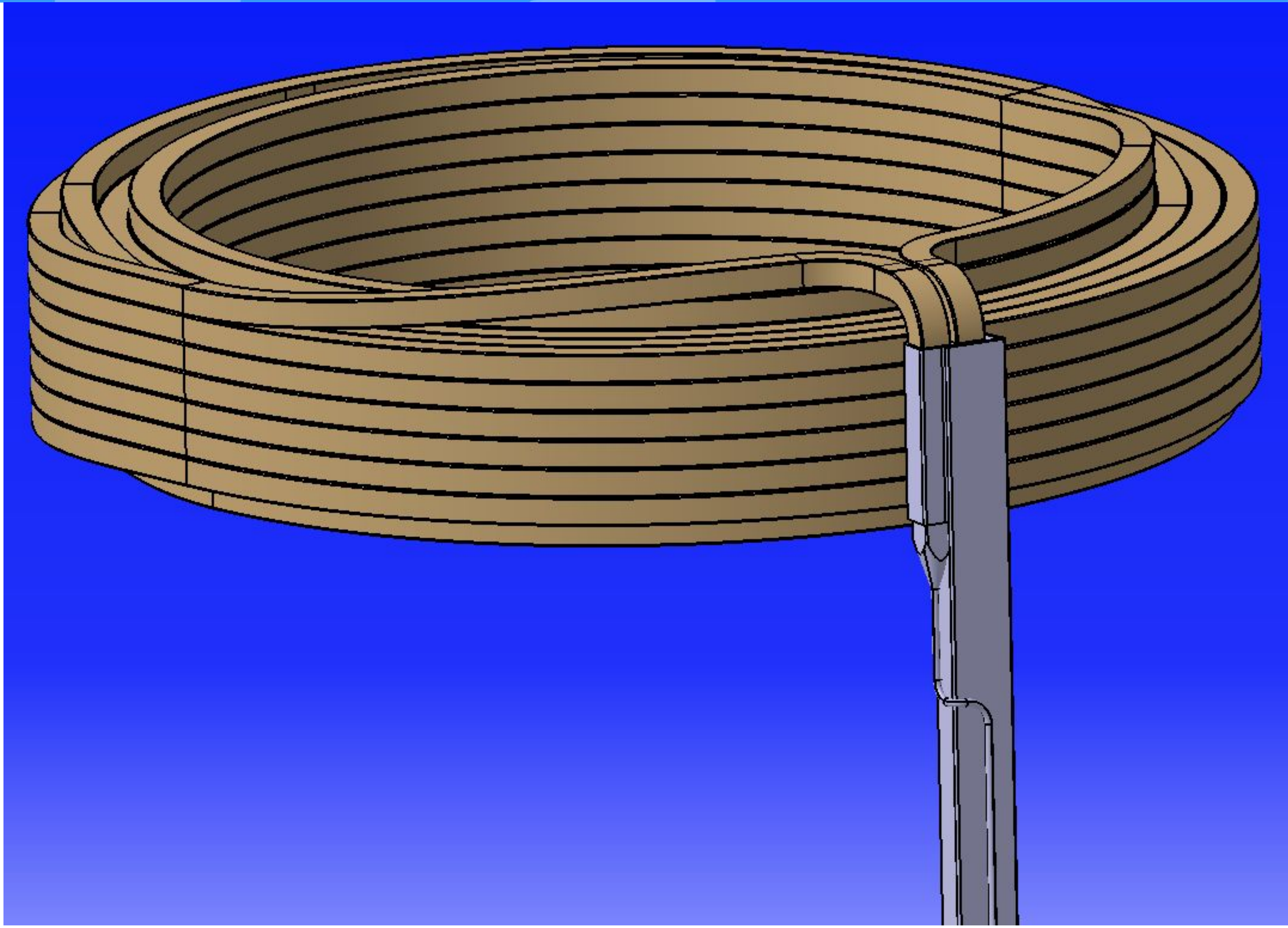
- A chemical analysis shall be carried out on a sample from one extruded/drawn conductor from each cast to confirm that the chemical composition meets the requirements.

Fatigue tests of impregnated samples
Lap shear and tensile test specimen:

- Insulation layout as defined for conductor insulation
- Testing at 300 K and 80K
- Cyclic loads in shear & tension for 50k cycles

CS coil with coaxial conductor

- outer conductor dimension 40 x 30 mm, trapezoid cca 500 mm2, full hard C10700
- inner conductor dimension 24 x 21 mm cooling channel dia 6.2x8 mm (same as coil conductor)
- insulation between conductors (inner conductor insulation) - glass fiber with kapton tape, impregnated with epoxy?
- for OC used only "ground insulation)
- first conductor channel is connected directly to conductor, second is terminated before coaxial cable and coolant is driven separately by copper pipe
- cooling pipe preferably heat insulated from coaxial, but electrically insulated together with outer conductor



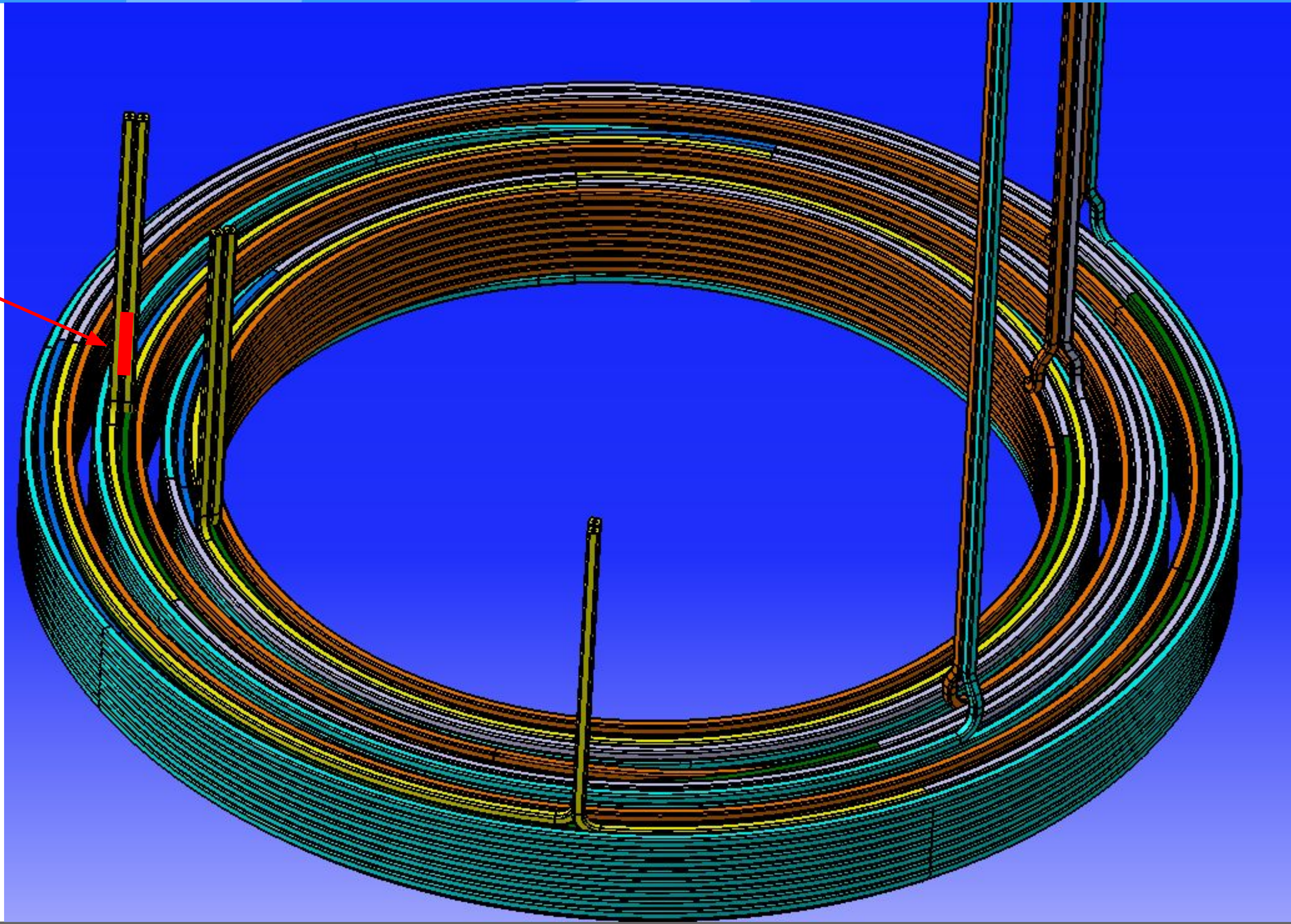
PF1a, PF1b and PF2

coolant inlets brazed point 100 mm long

is 150 - 300 mm above the coil enough space for braze?

coolant inlets are insulated together after they have brazed

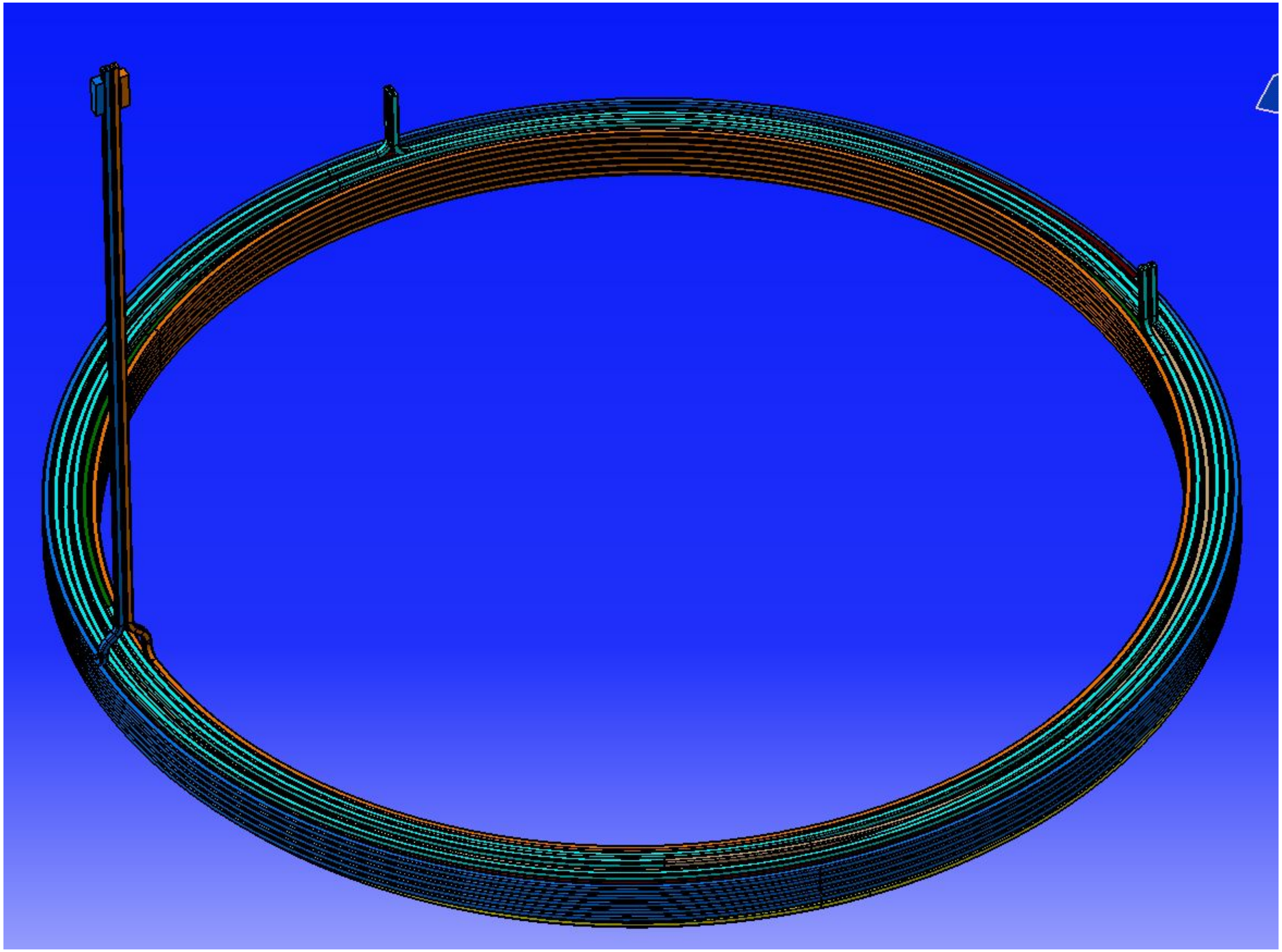
Coils are shown without ground insulation



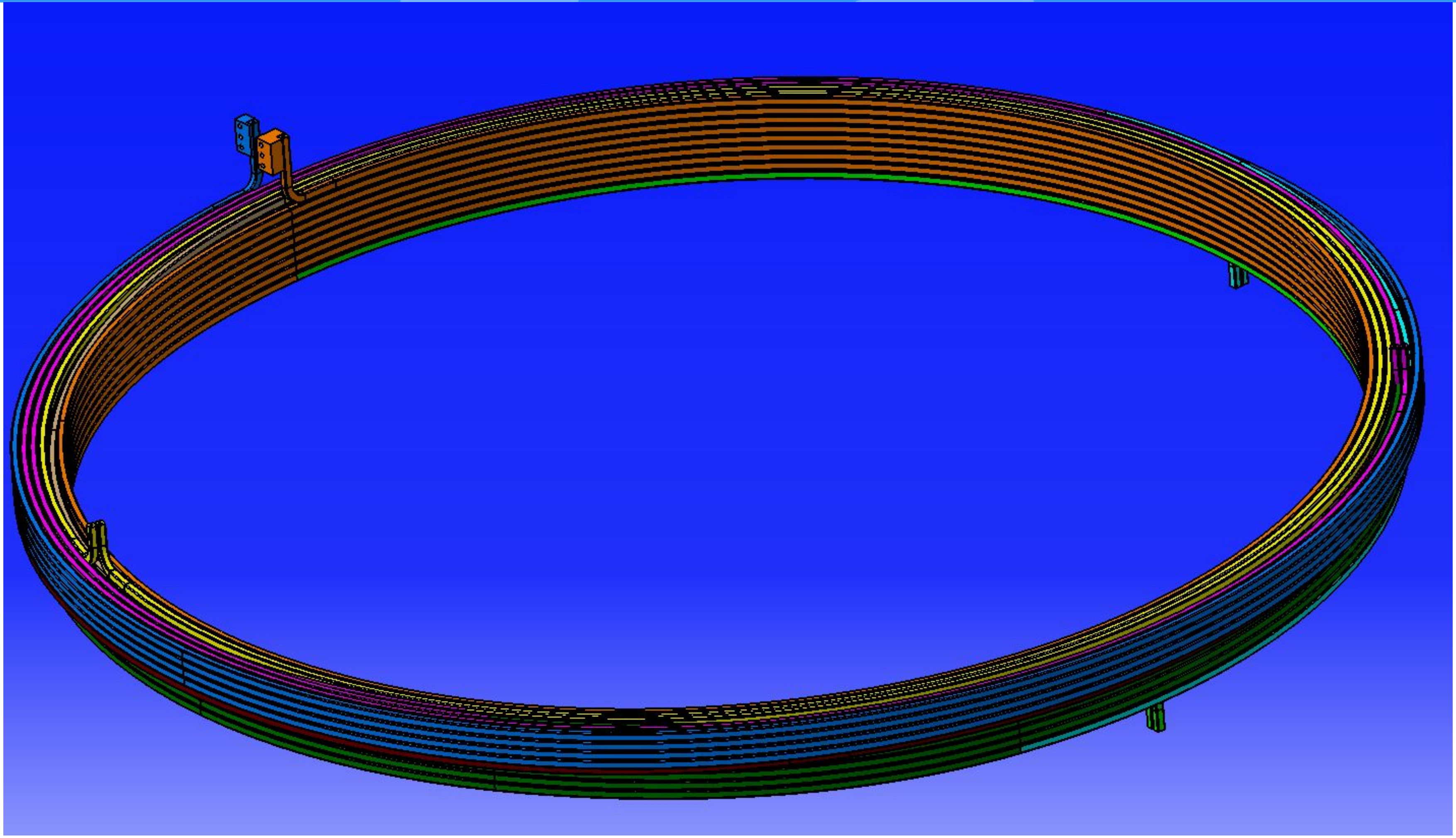
PF3

The cooling pipes have to be insulated as well till the electrical break

Diameter ~ 2 m



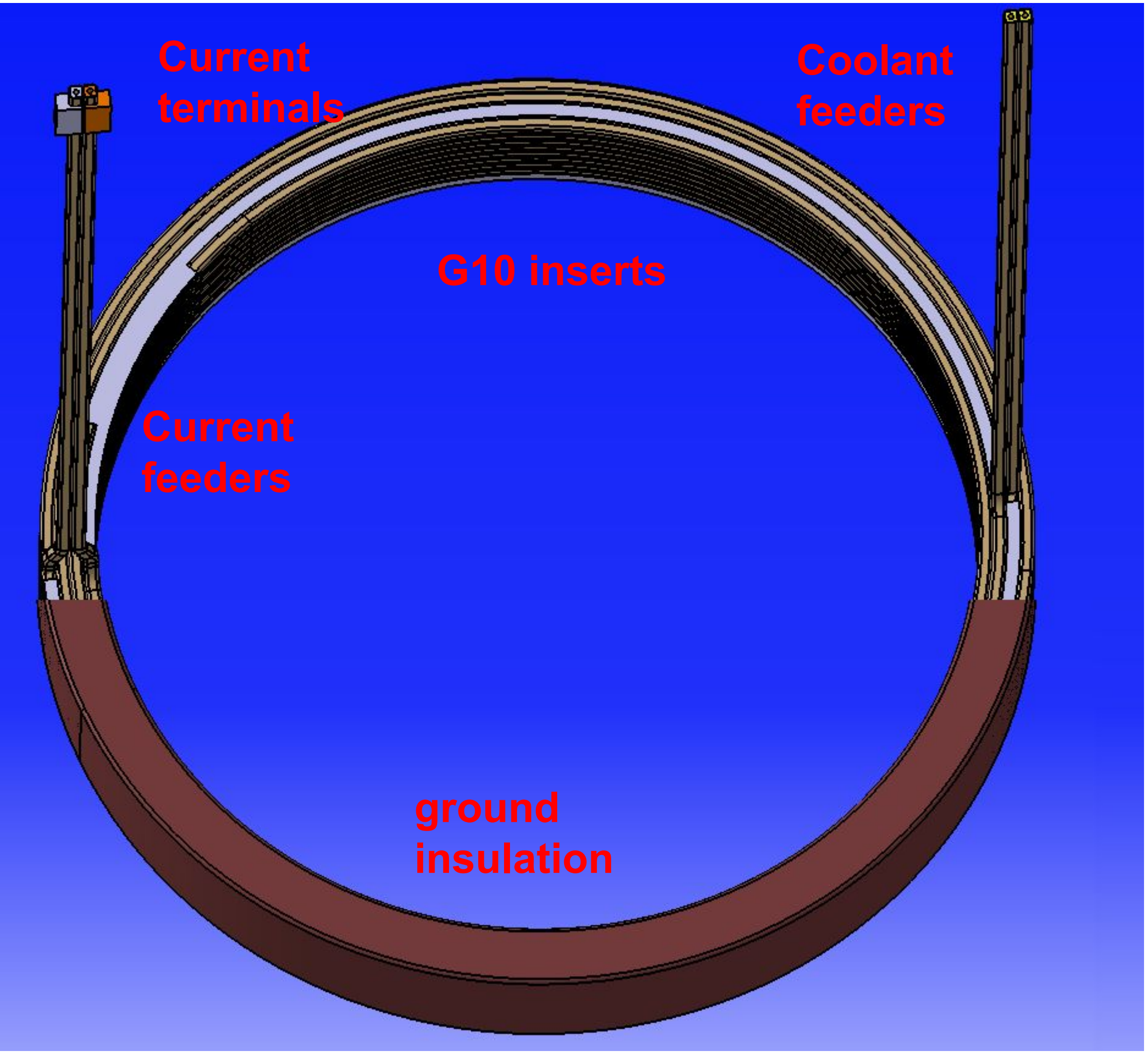
PF4

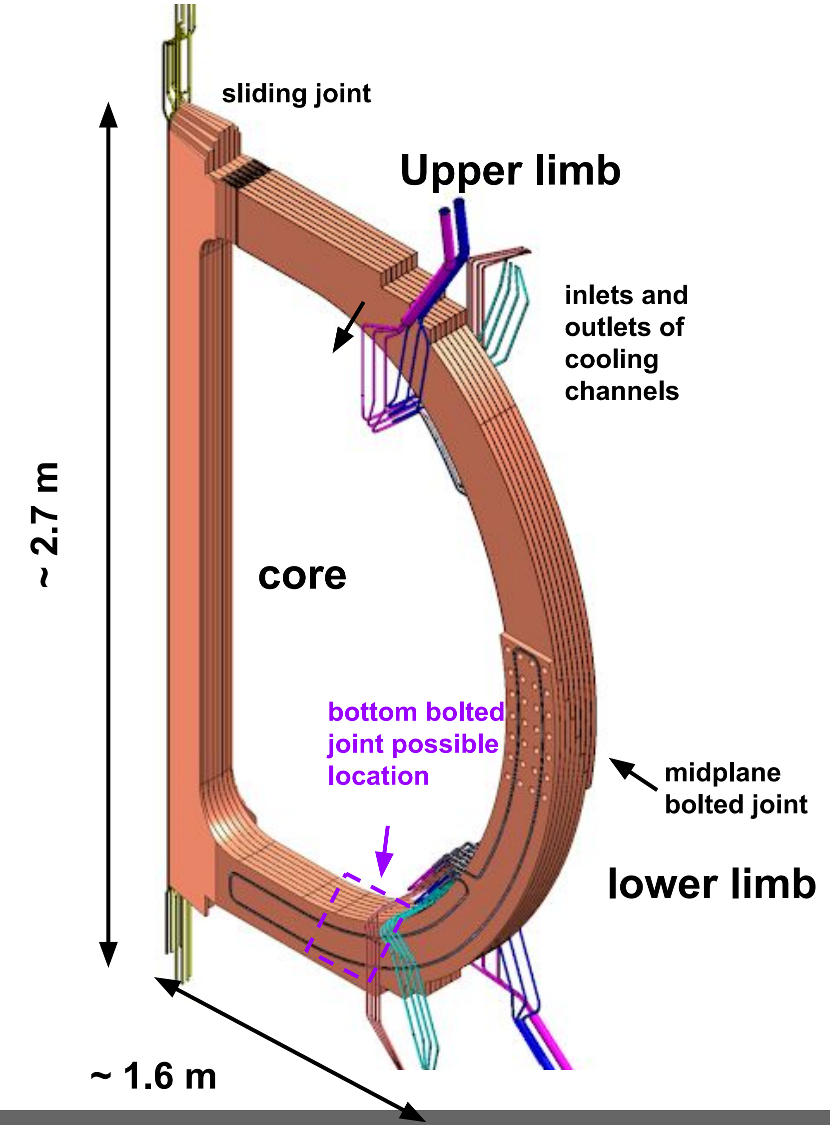


Diameter ~ 3 m, cooling terminals are distributed on the top and bottom of the coil

CS manufacturing process

Terminology PF and TF coil

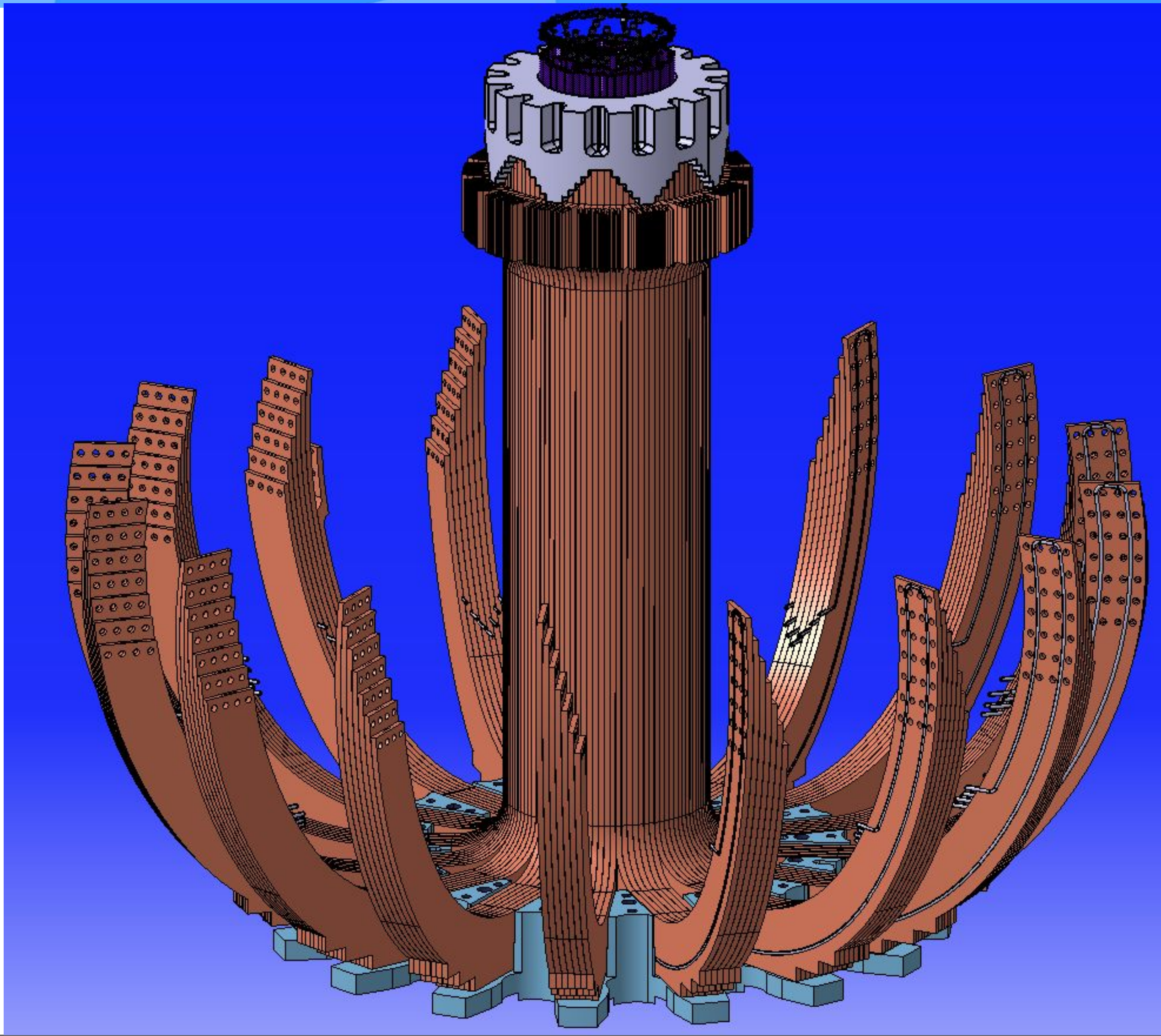




Assembled TF core

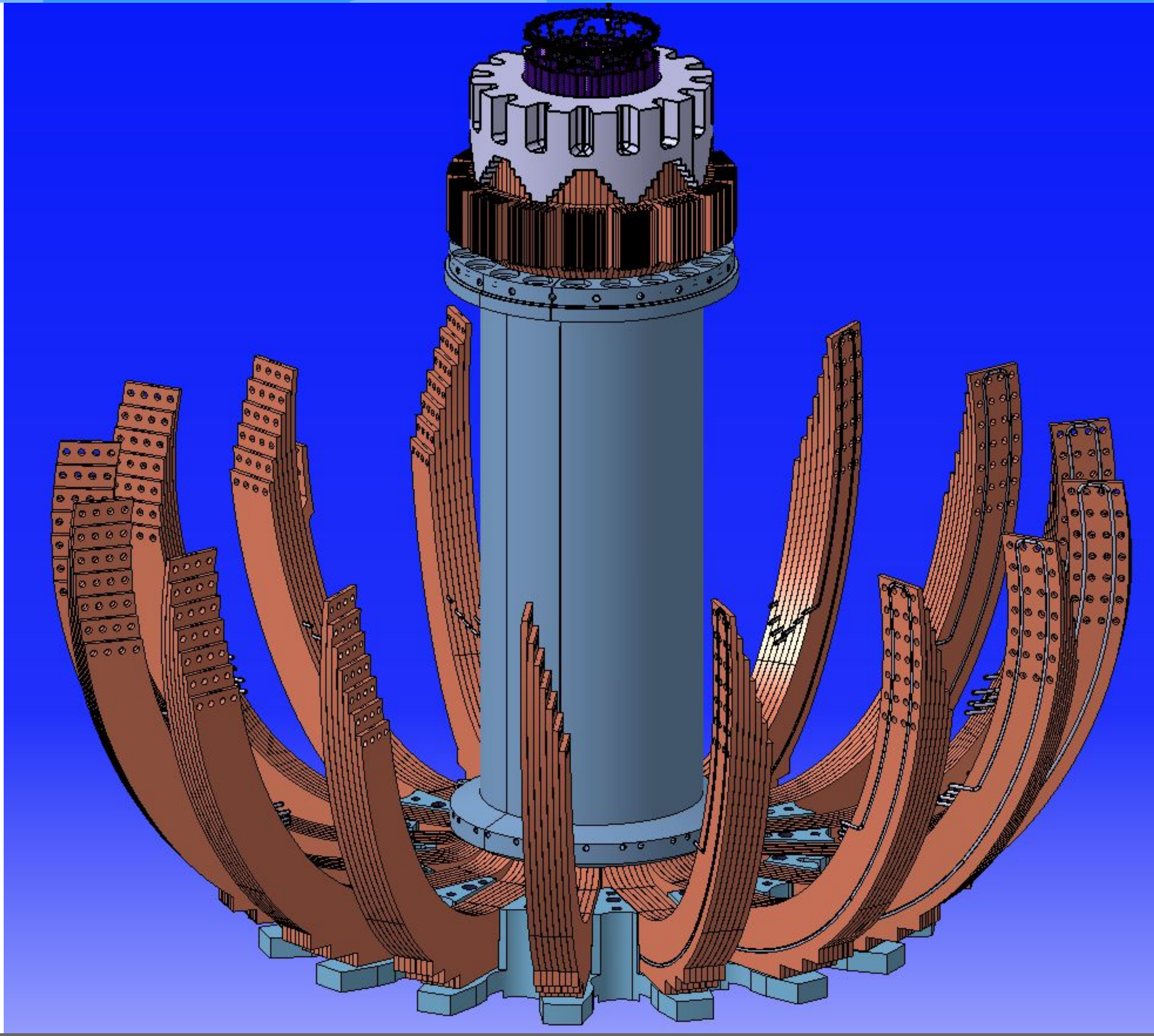
One "piece" of assembled TF core without lower bolted joint

- Outer dimensions of one turn ~ 2.6 x 1.7 m
- TF core ~ 16 tons,
- Turns insulated by fiberglass cloth + VPI - 1 mm thick
- Turn cross section 20 x 200 mm made from hardened(CuAg0.1(OF) or CuZr0.1)
- Cryogenically cooled by gaseous Helium
  down to T > 77 K by cooling channels in each turn

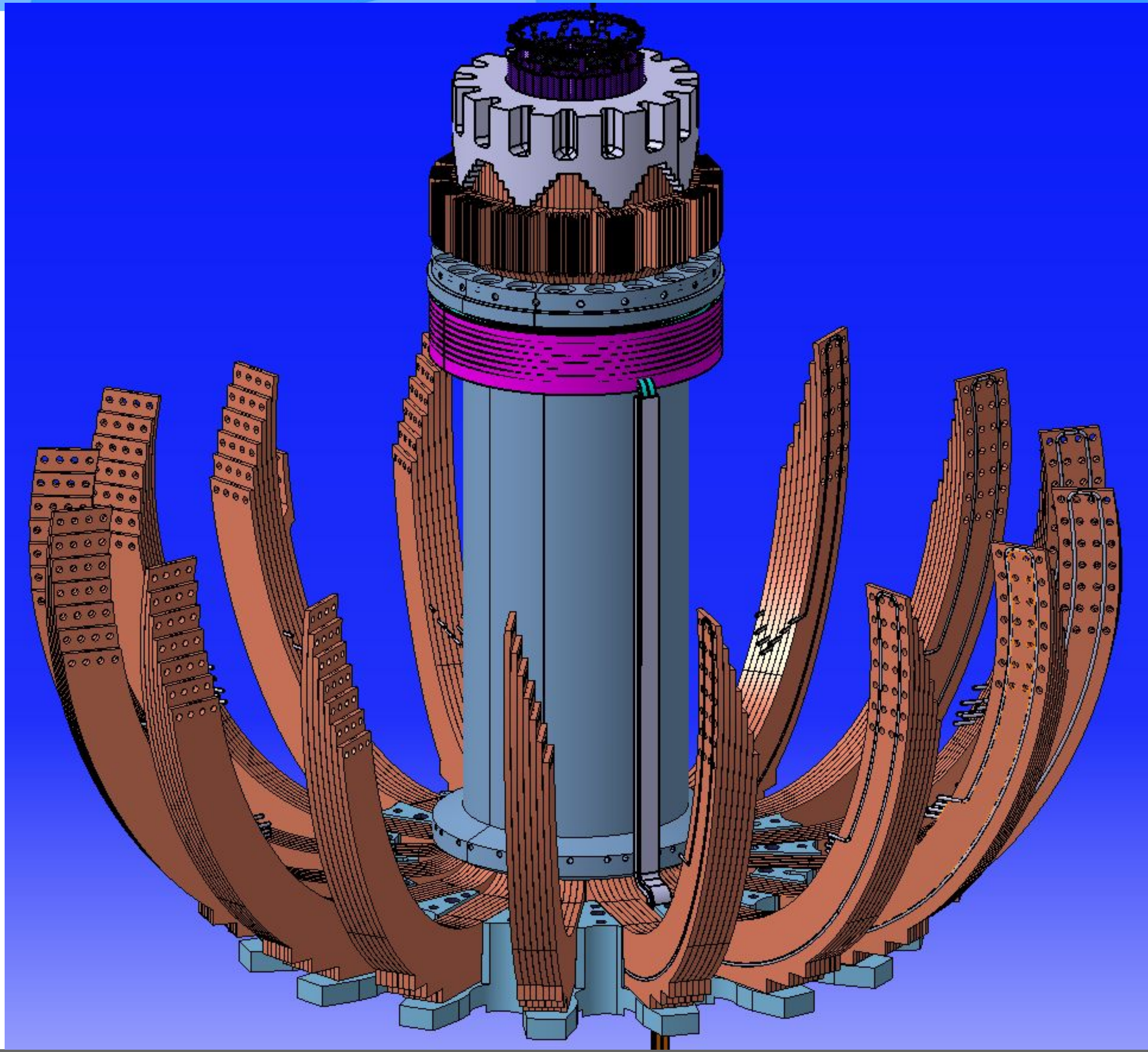


TF core plus inner tie tube

- material of TT - NITRONIC 50 or AISI 316LN
- Gap between TF core and inner tie tube is 3 mm
- Tie tube from 2 pieces

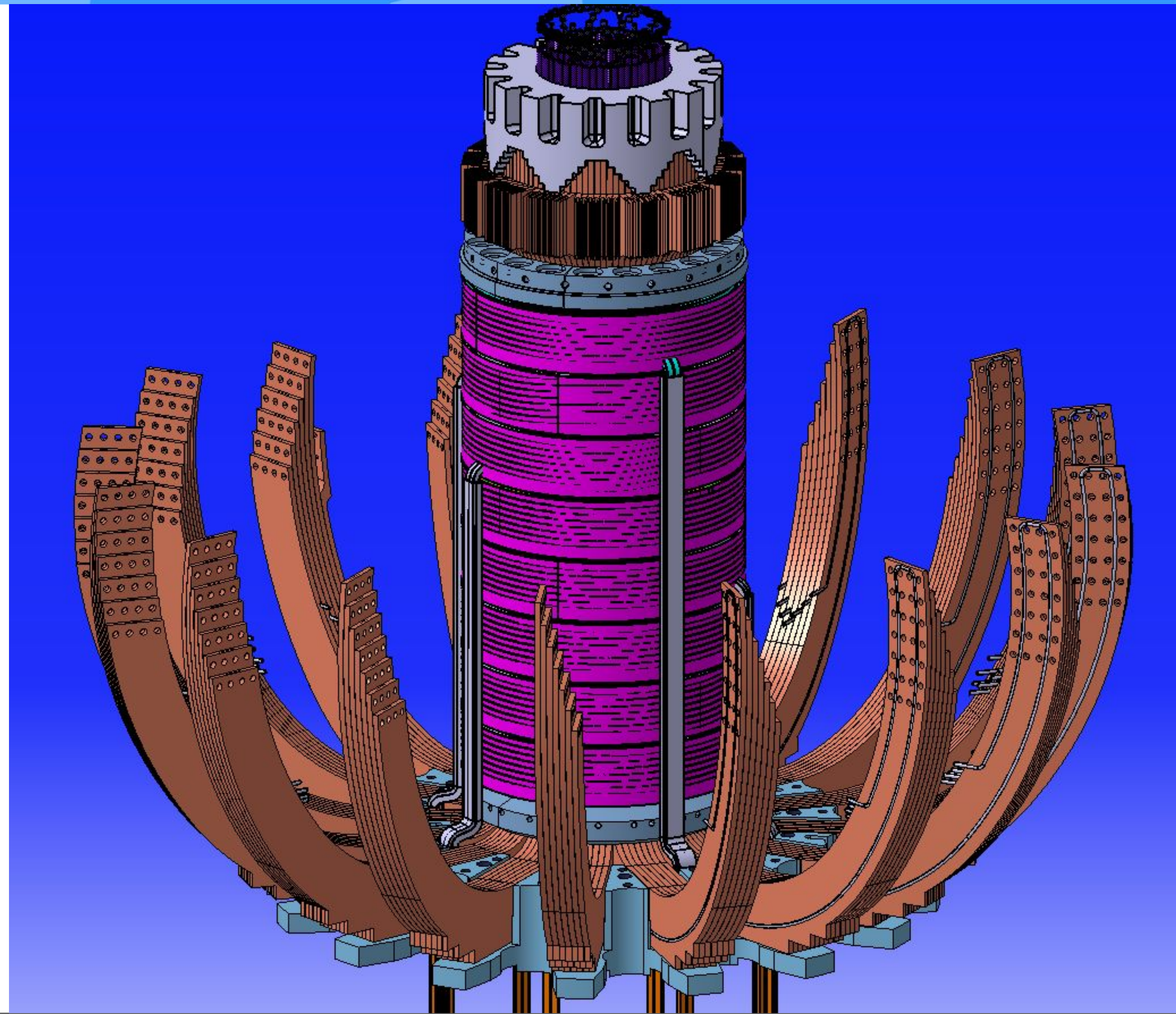


TF core + inner tie tube + first wounded CS coil which will be slided down



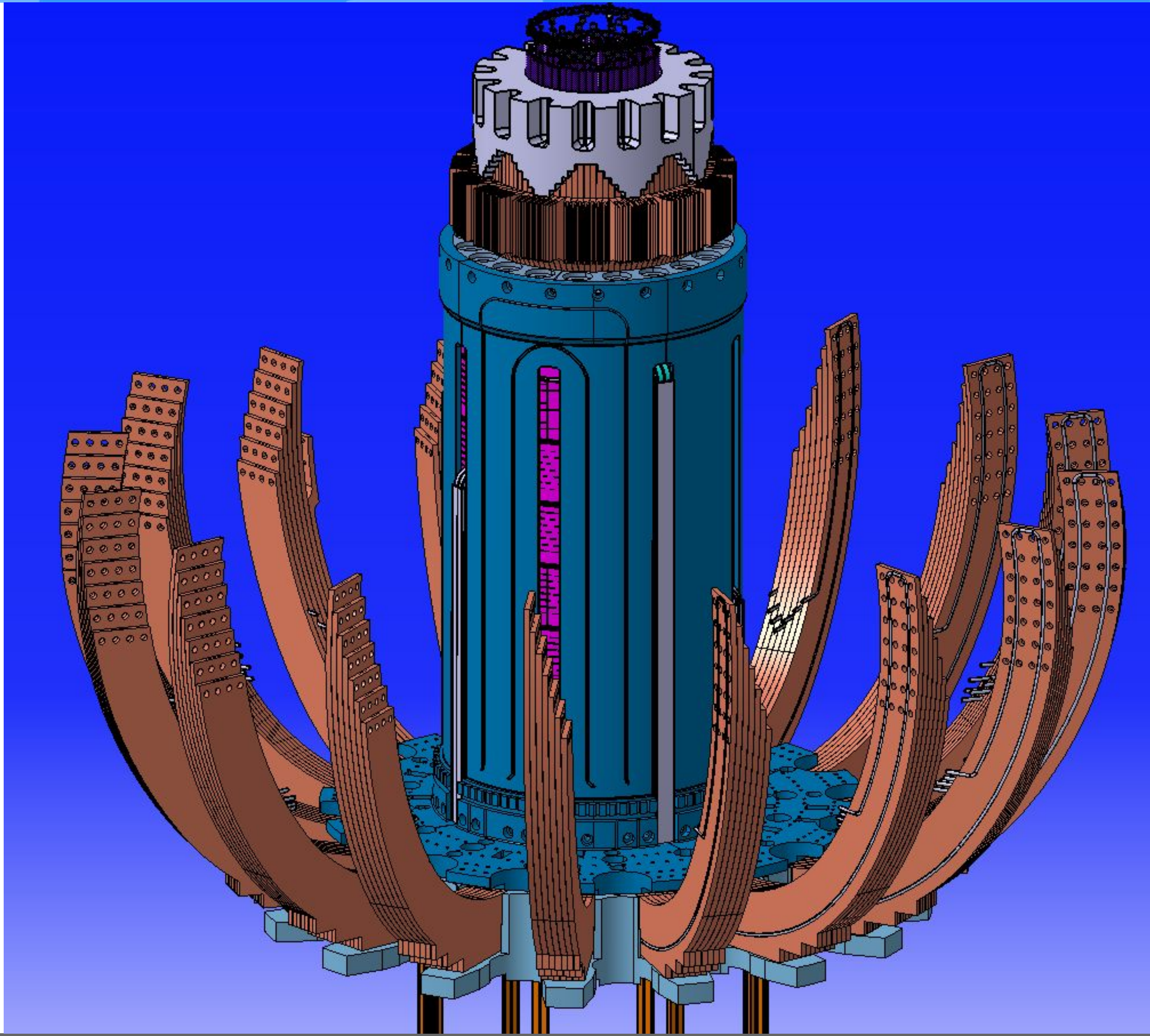
TF core + inner tie tube + 8 CS coils with their feeders

- gap between the top-most coil (with G10 insert) and tie tube is 20 mm
- gap between the bottom-most coil (with G10 insert) and tie tube is 15 mm
- There are two G10 inserts between coils 2 x 6,5 mm, each made from two pieces to be possible to insert.



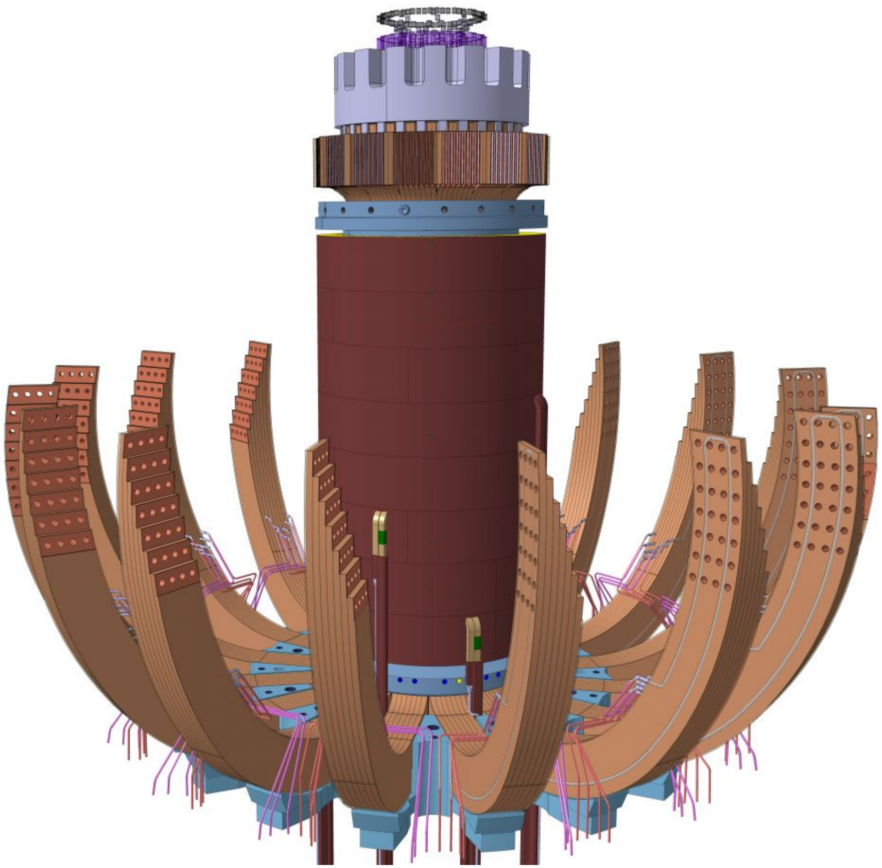
TF core + inner tie tube + 8 CS coils with their feeders + outer tie tube

- Between CS coils and tie tube have to be gap assure that coils can move freely in vertical direction
- Groves for cooling pipes in outer tie tube
- Outer tie tube is made from four parts

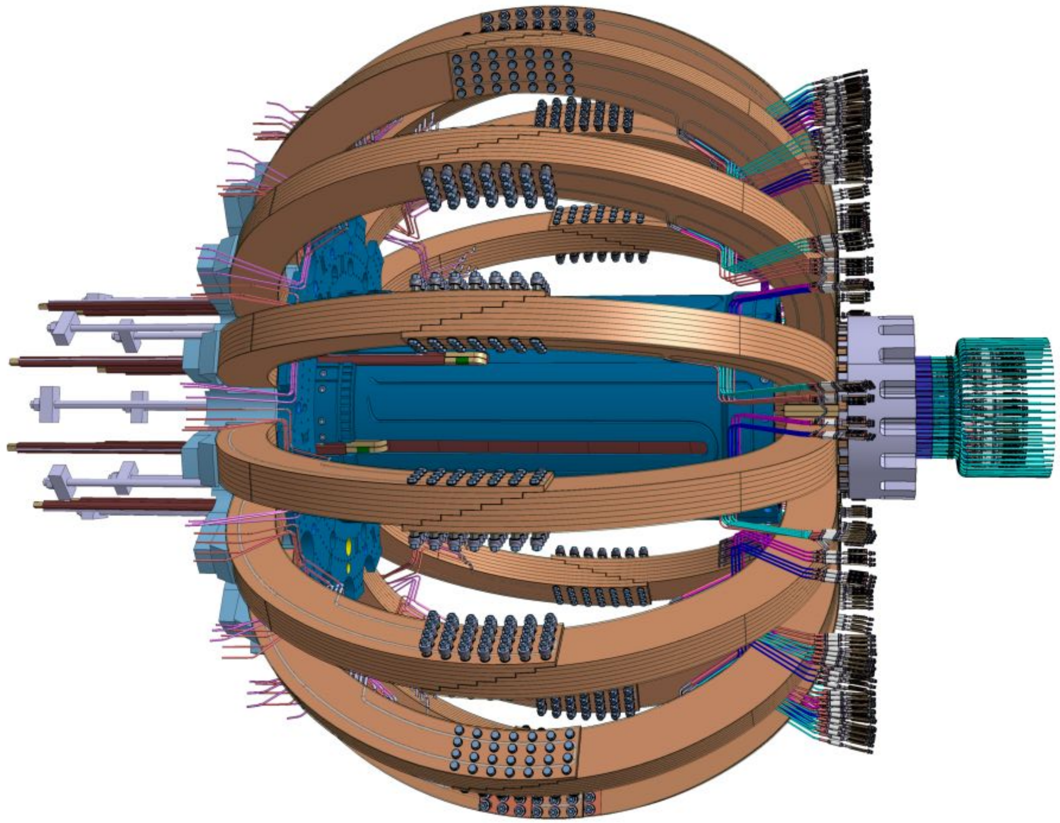


Complete assembly of TF and PF coils

"complex" which will be lifted to SS. Total weight has to be less than 25 tons



TF and CS will be assembled with TF upper limb and prepared for transport in axial direction



Transport dimensions are under 4 meters in height and under 5 meters in length

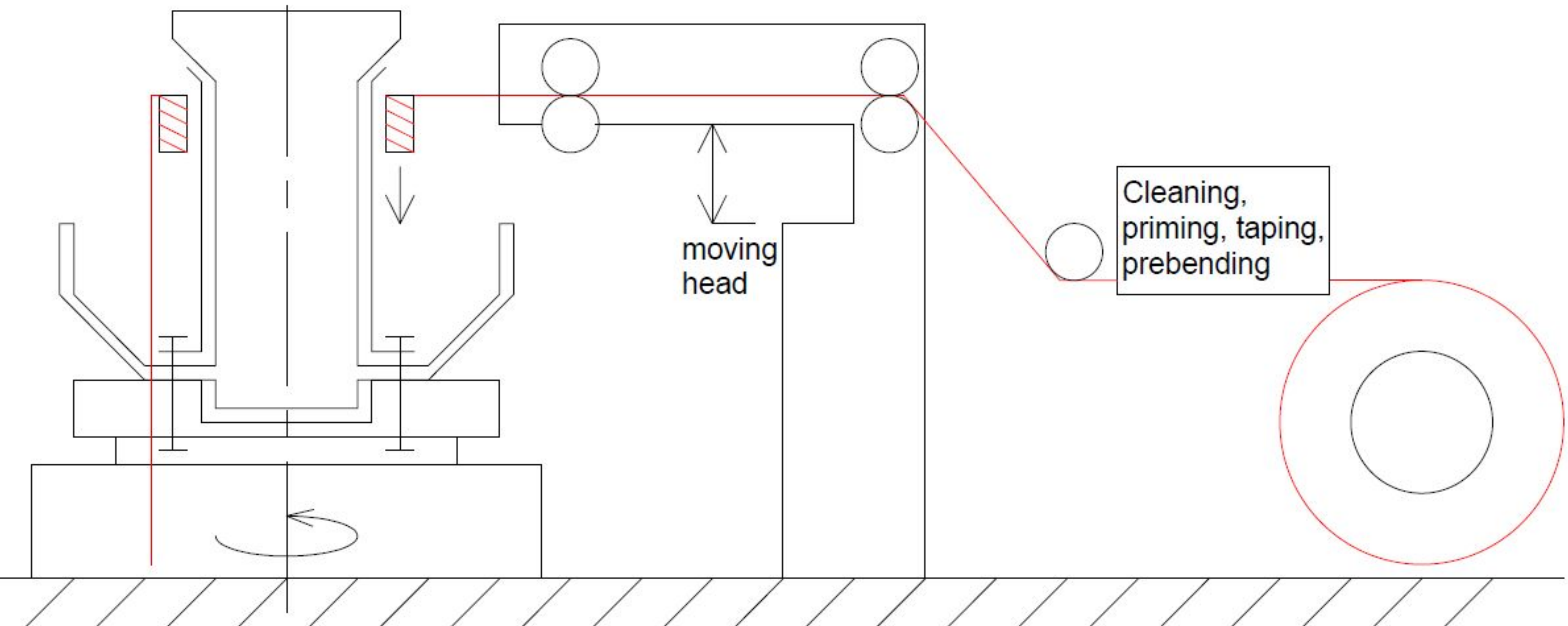
Idea of winding CS coils on TF core:

Coil manufacture procedure:

- Grit blasting, degreasing/cleaning of conductor
- priming
- pre-bending of conductor to requested temper (if necessary)
- Automated taping and winding
- Brazing of coaxial feeders to CS coils?

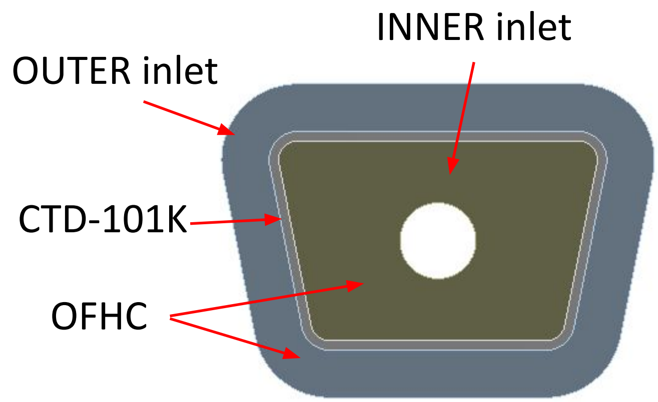
After coils have been wound

- Bakeout/de-gassing of the coil in the VPI mold
- VPI and curing process
- Brazing of coaxial feeders to CS coils?

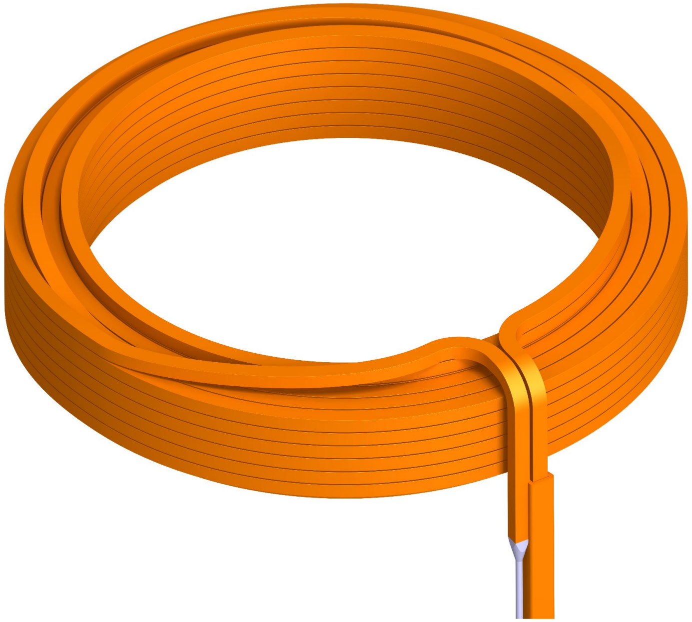


CS Coaxial feeders assembly

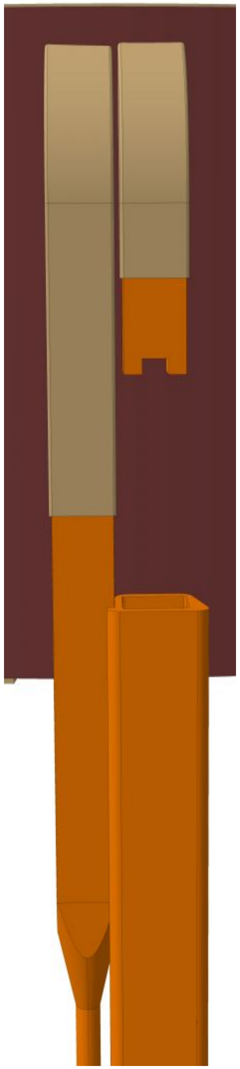
- **Trapezoidal outer conductor** with dimension 40 x 32 mm, cca 535 mm^2, full hard C10700
- Inner conductor dimension 24 x 21 mm, cooling channel dia 6 x 8 mm (same as coil conductor)
- Insulation between conductors 1 mm thick GF interleaved with kapton tape, impregnated with epoxy
- **3 mm ground insulation** of outer conductor
- First conductor channel is connected into the inner conductor. Second conductor is terminated at coaxial joint, coolant is driven separately by copper pipe
- **Cooling pipe** preferably thermally insulated from coaxial conductor to match thermal expansion of inner and outer conductor during discharge, but insulated together with outer conductor by ground insulation



coaxial cable
cross-section
shape



CS Coaxial feeders assembly

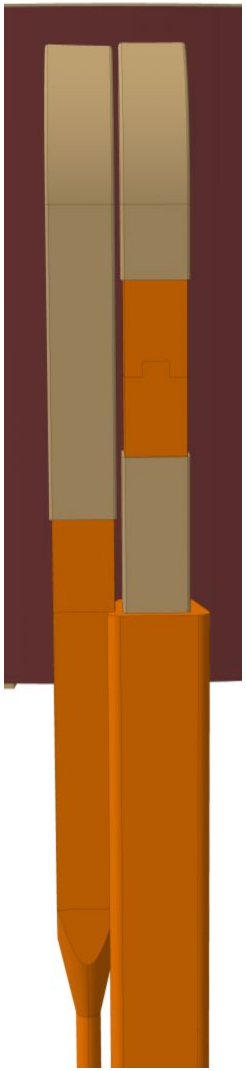


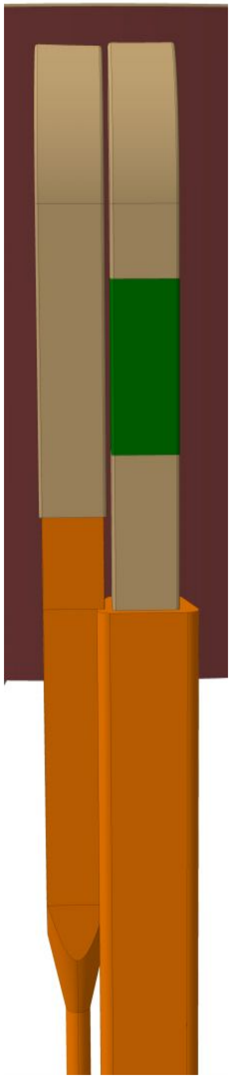
Step 1

The outer conductor is brazed to the longer lead of the coil. The cooling pipe is brazed as well

Step 2

Insulated inner conductor is inserted through outer conductor and brazed to second coil lead



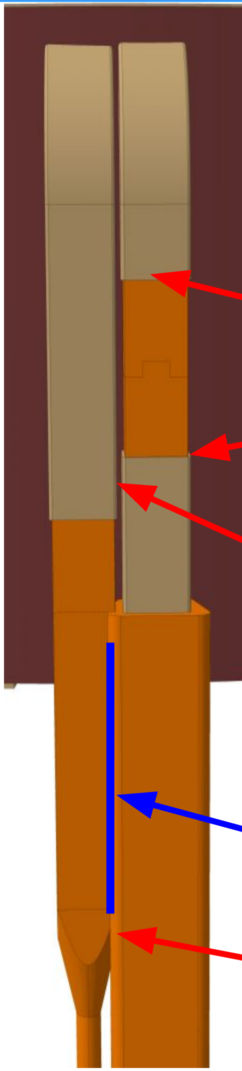


Step 3

Insulate the place where conductors are brazed.
If not possible, insulate gap between conductors

Step 4

Make ground insulation to cover bare conductors



- Cooling pipe will be insulated together with outer conductor

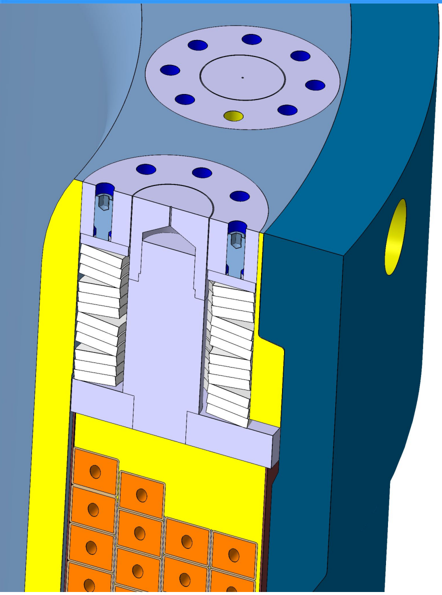
where should insulation of coil stop to perform braze?

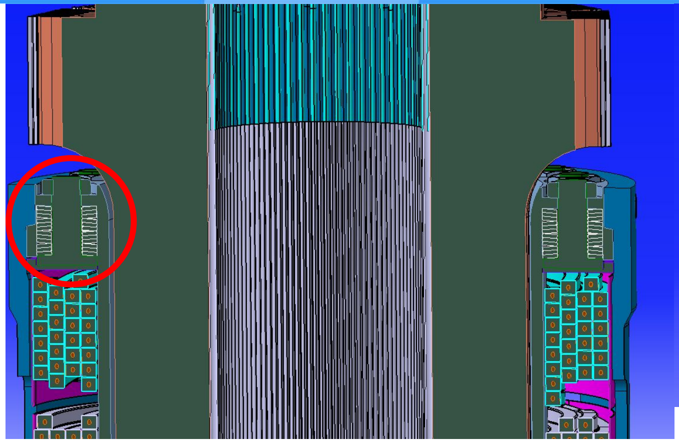
what should be size of the gap between conductors?

braze line of IC

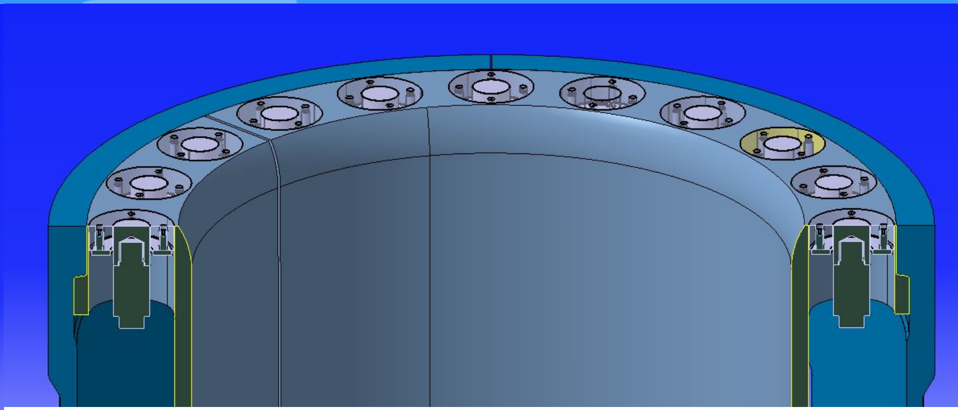
groove inside of OC where coil´s output is brazed

Detail of preload mechanism

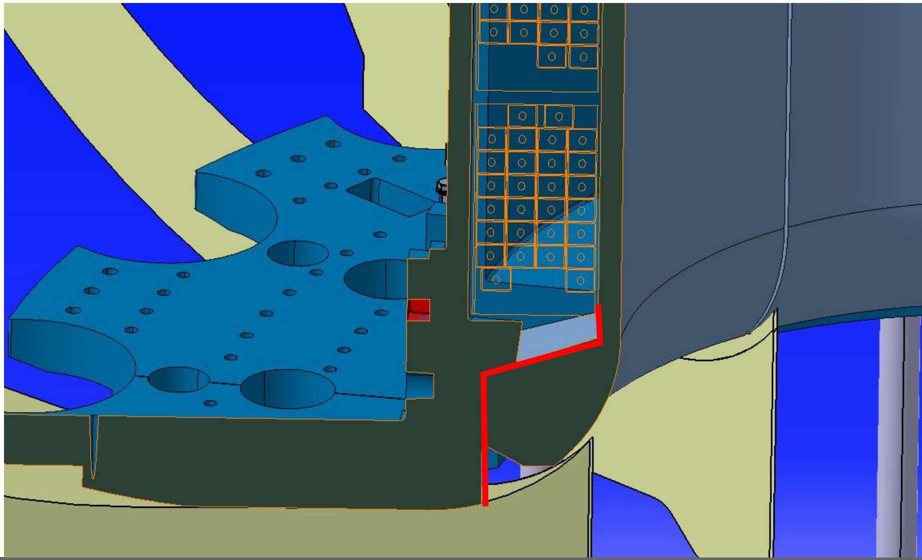




Detail of preload springs



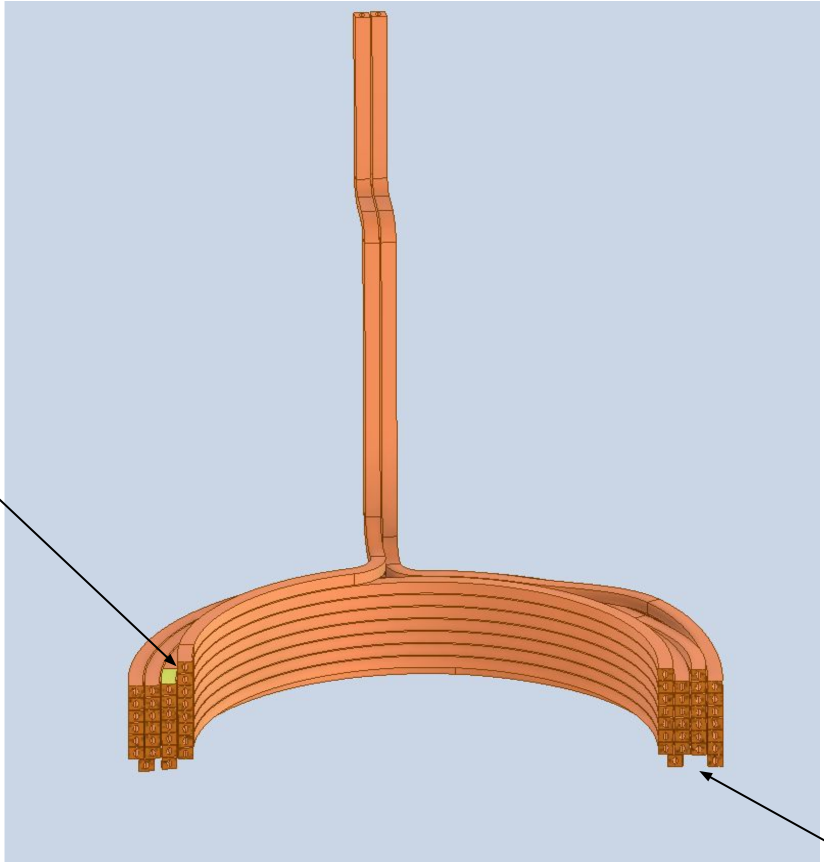
- special Superbolt dia 100 mm with threads in outer head will be used as a cover and to preload springs in cavity



- Preload springs are put in the place after CS is wounded around TF core
- Preload mechanism is possible to adjust or change a springs after is tokamak assembled
- Can inner tie tube be used as vessel for VPI? Place for springs can not be glued by epoxy

Issues in CS production

- Winding CS coils to assembled TF core with lower limb - current design very challenging due to its large dimensions and small tolerances
- Do not damage the TF core insulation during winding process and manipulation
- Make VPI of CS coils at TF core - TF coils are already insulated therefore CS coils have to be VPI-ed on the spot - together or separately with use of inner tie tube as a part of the vacuum vessel and some temporary construction to encapsulate coil(s)
- CS coils and Tie tube can not be glued together - inside of TT put special layer to prevent permanent connection
- Transport to IPP - large load with almost 25 tons and 4 x 4 x 6 meters



PT100 sensors inserted in free space between turns and impregnated together with coil

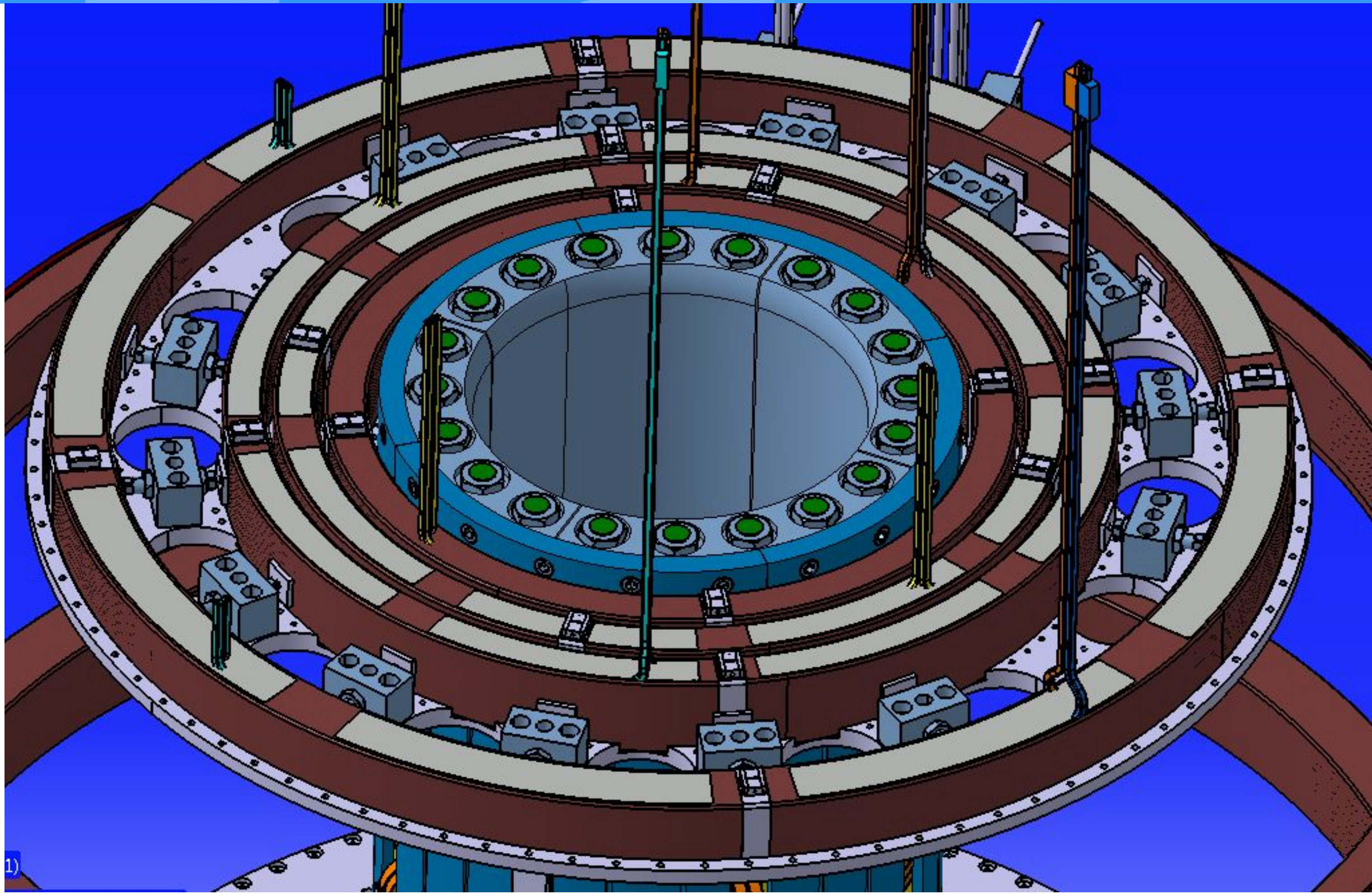
sensor´s cables leads through G10 insert and attached to the closest cable bundle

1 sensor + 1 reserve

PT100 sensor

Our questions:

- To compensate movement of the coils during discharge and thermal expansion will be used sliding pads to allow frictionless sliding
- Could be pads glued to epoxy? (PF coils)



More informations about preliminary market consultaion can be found at:

http://www.ipp.cas.cz/o-ufp/Verejne_zakazky/doc.html

Fabrication procedure for poloidal coils of COMPASS-Upgrade tokamak v1.3 (working version)
http://www.ipp.cas.cz/miranda2/export/sitesavcr/ufp/o-ufp/Verejne_zakazky/Fabrication-procedure-PFC-CU_v1_3.pdf

At web site tenders electronic daily

Notification Number at Tender electronic daily: 2019/S 113-276588

(Číslo oznámení TED: 2019/S 113-276588)

Contact persons :

Ivan Nemec email: nemec@ipp.cas.cz

Pavel Junek email: junek@ipp.cas.cz