COMPASS-U tokamak
Toroidal field coils

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Institute of Plasma Physics of the Czech Academy of Sciences

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Intention of the presentation

Description of toroidal field (TF) coils for companies who shown interest in preliminary market consultations. Document serves for discussion with companies with aim to:

1) Fulfill design requirements.
2) Meet engineering/manufacturing limitations and clarification of manufacturing process.
3) Lower the manufacturing cost.
4) Obtain preliminary price quotation.

Final design will be specified in technical specification for toroidal field coils after discussion with companies.

Presentations consists of:

- Design requirements.
- Purpose of components.
- Questions for companies.
- Not fixed parameters (depending on answers from companies)

Further information (drawings) which are regularly updated can be found in http://www.ipp.cas.cz/o-ufp/Verejne_zakazky/doc.html under section “Coils of toroidal field”.

COMPASS-U project

Toroidal field coil is one of the subsystems of COMPASS-U tokamak.

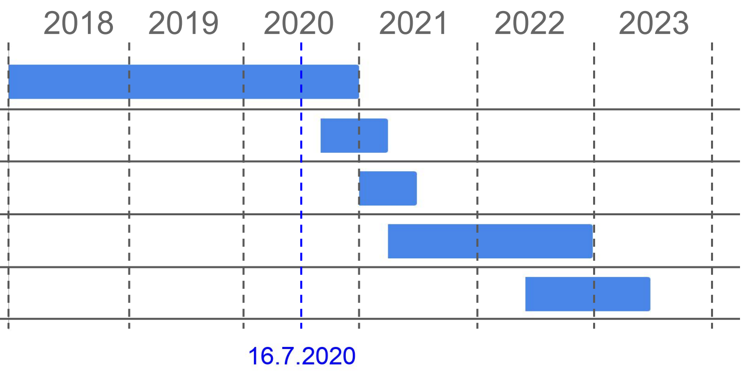
Key properties of COMPASS-U:

- High magnetic field to confine plasma (5 T) and high plasma current (2 mil. Amperes)
- Discharge durations up to several seconds, advanced plasma configurations, high heat fluxes
- Operation with high temperature first wall – up to 500°C
- Mid-size device with flexibility for scalings towards ITER and DEMO

⇒ **<u>unique capabilities to address DEMO challenges</u>**

Indicative timetable of the project:

Design of the components	2018 - 2020
Final design review (FDR)	end of 2020
Launch of tender for TF coils	beginning of 2021
TF Coil manufacturing	2021 - 2022
Assembly and installation	2022 - 2023



Scope of work

Presumed scope of work:

- Manufacture of 16 toroidal field coils

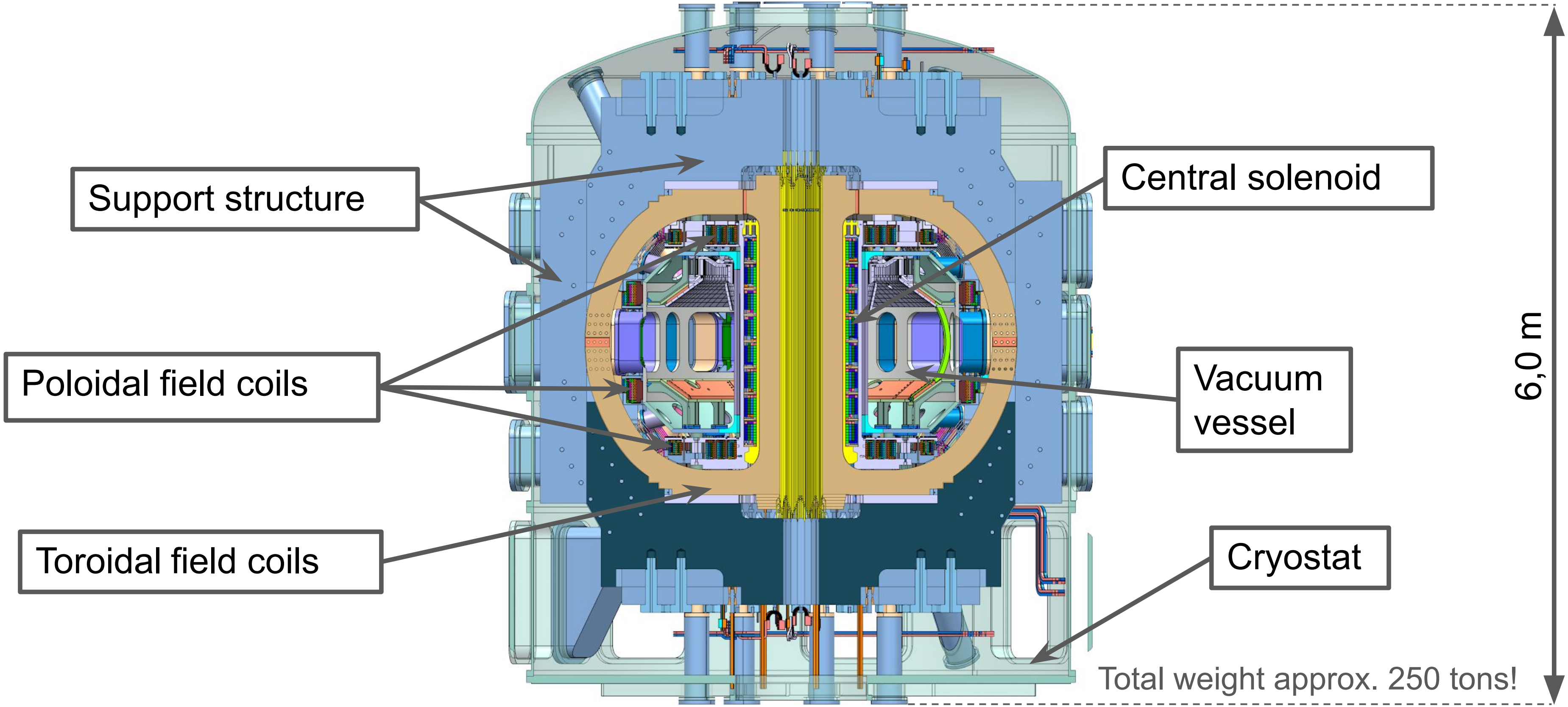
Presumed scope of work on the coil (what to expect):

- Machining of copper plates and connection (welding/brazing/soldering) of separately machined parts e.g. sliding/bolted joints if not possible to machine in one piece
- Insulation with fiberglass cloth
- (Vacuum pressure) epoxy impregnation
- Electrical testing
- Test assembly
- Transport to IPP

Notes:

- Coil of central solenoid (not part of the delivery) has to be wound on assembled TF core.
- Feltmetal (described later) is not part of delivery.
- Coil models and coil parameters in this presentation are preliminary and could change during preliminary market consultations.

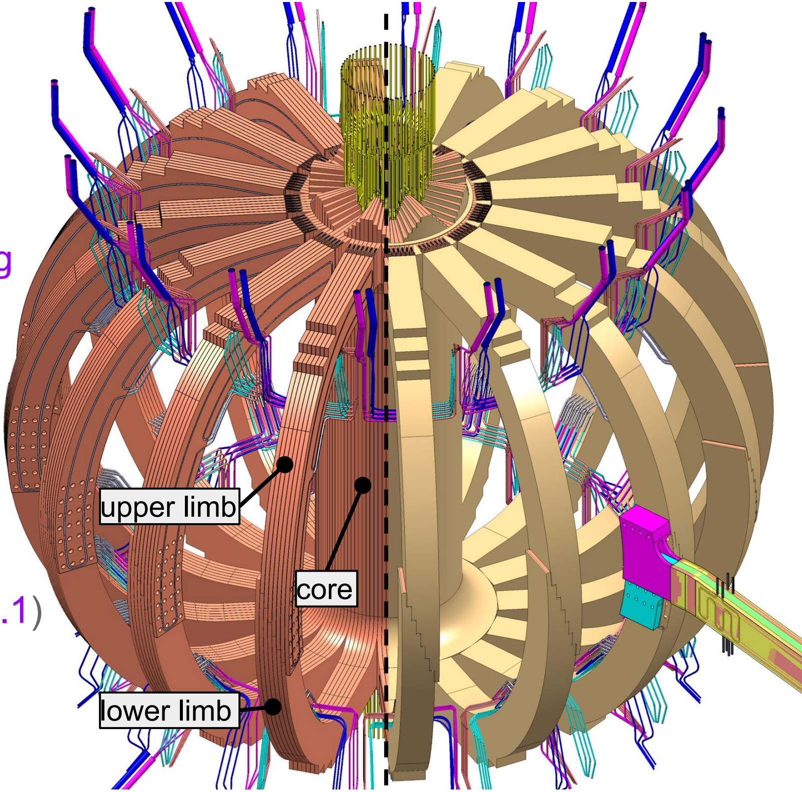
TF coils in COMPASS-U



TF coils - overview

Preliminary parameters:

- 112 D-shaped turns grouped to 16 bundles with 7 turns
- Each turn composed of (2 or 3) parts with joints (upper and midplane joint - allow vertical assembly of parts inside of TF coils, lower joint - if required for winding of central solenoid or because of impregnation reasons)
- Outer dimensions of one turn ~ 2.6 x 1.7 m
- Total mass ~ 24 tons (TF core ~ (9 or 16) tons, Outer limbs ~ (15 or 8) tons)
- Turns insulated by fiberglass cloth + VPI
- Current 200 kA providing 5T @ R = 0.896 m for ~ 5 s
- Turn cross section 20 x 200 mm made from hardened OFHC copper or similar material (CuAg0.1(OF) or CuZr0.1)
- Cryogenically cooled by gaseous Helium down to T > 50 K by cooling channels in each turn
- TF coils are held in place by support structure (TF coils itself cannot withstand forces during operation) - not part of the delivery

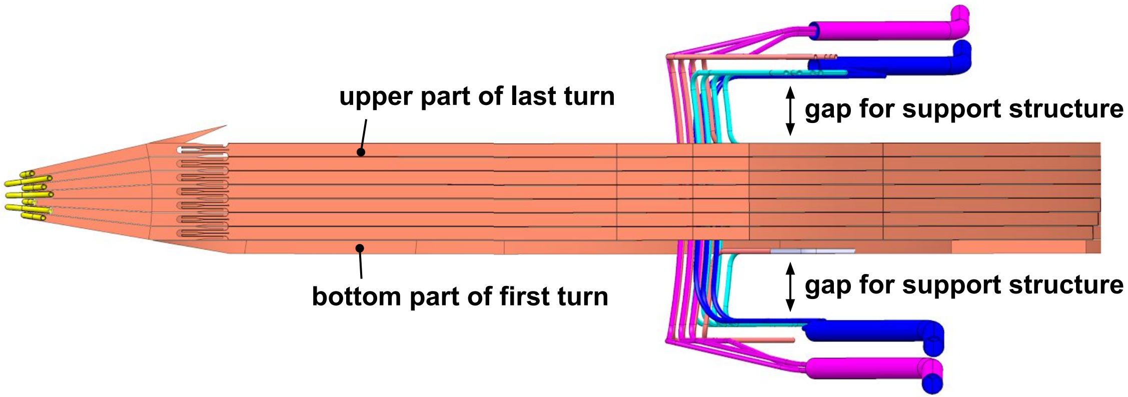


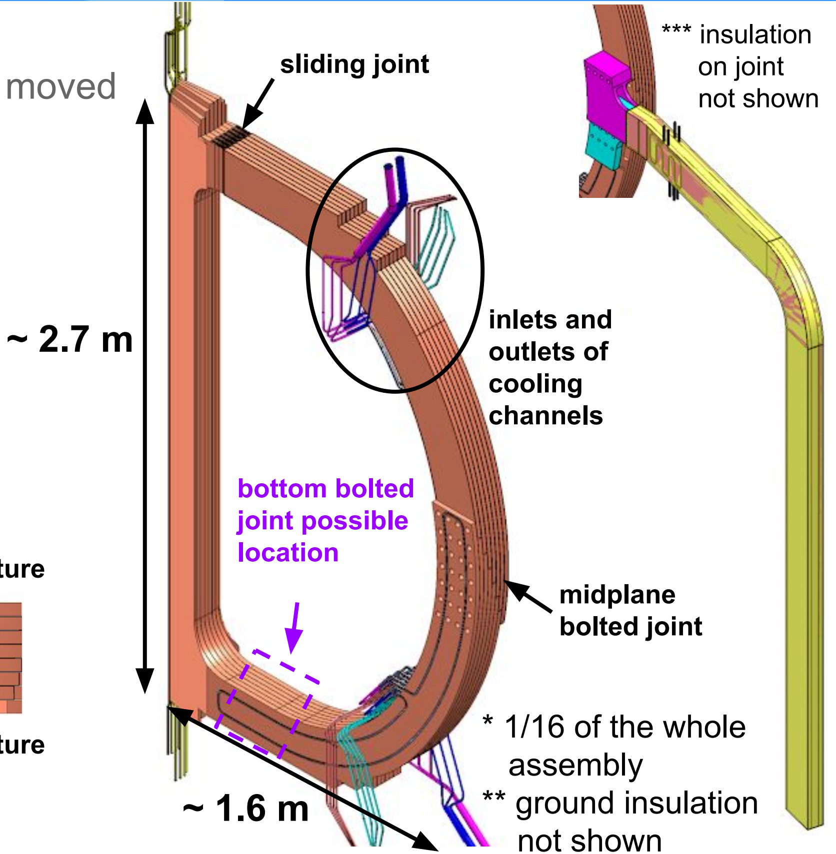
*ground insulation removed for better illustration

TF coils - detailed view

Detailed view (preliminary design)

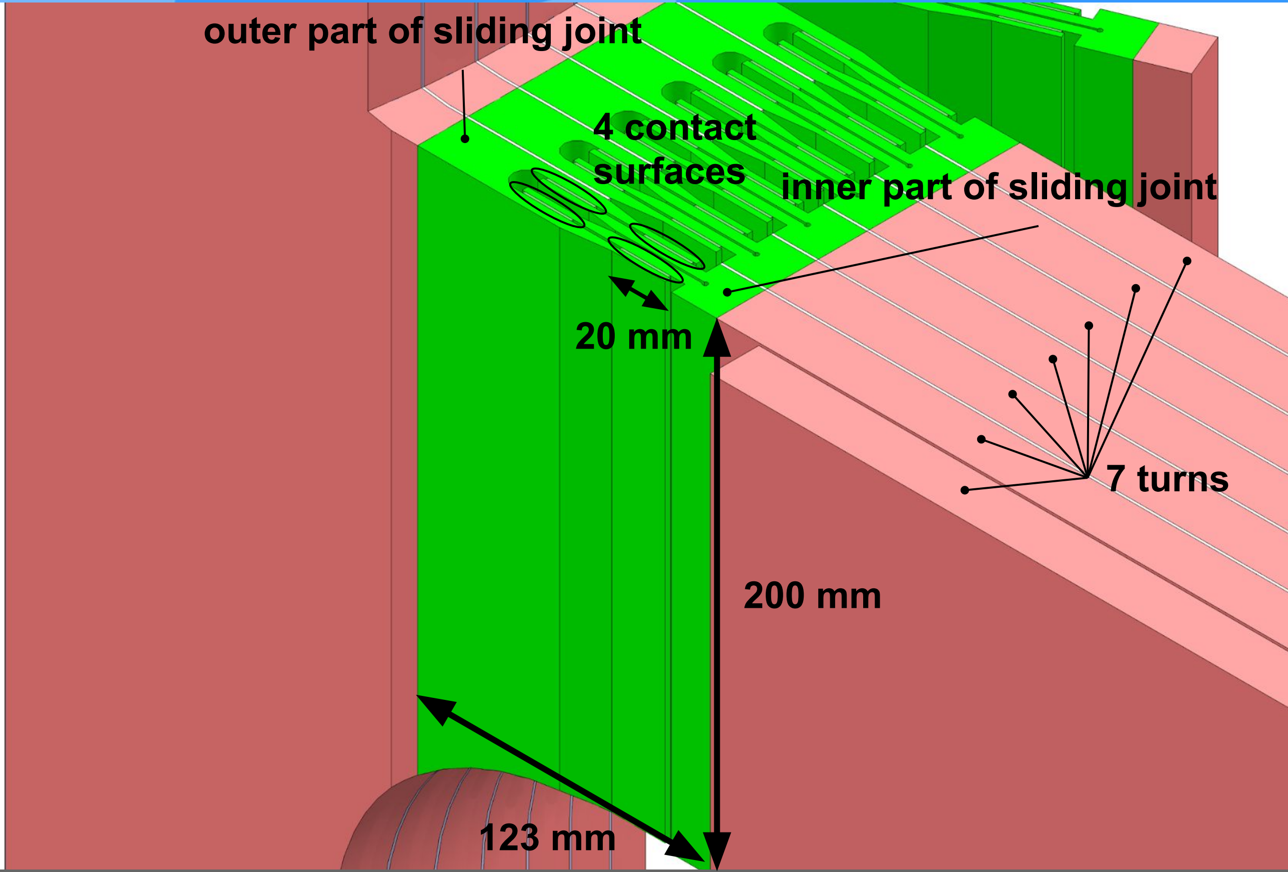
- position of cooling inlets and outlets in limbs can be slightly moved
- presence of bottom bolted joint is subject of discussion
- upper and lower half of the coil are shifted by one turn to allow turn-to-turn transition by overlapped bolted joint
- first turn of first bundle is connected to electrical feeds



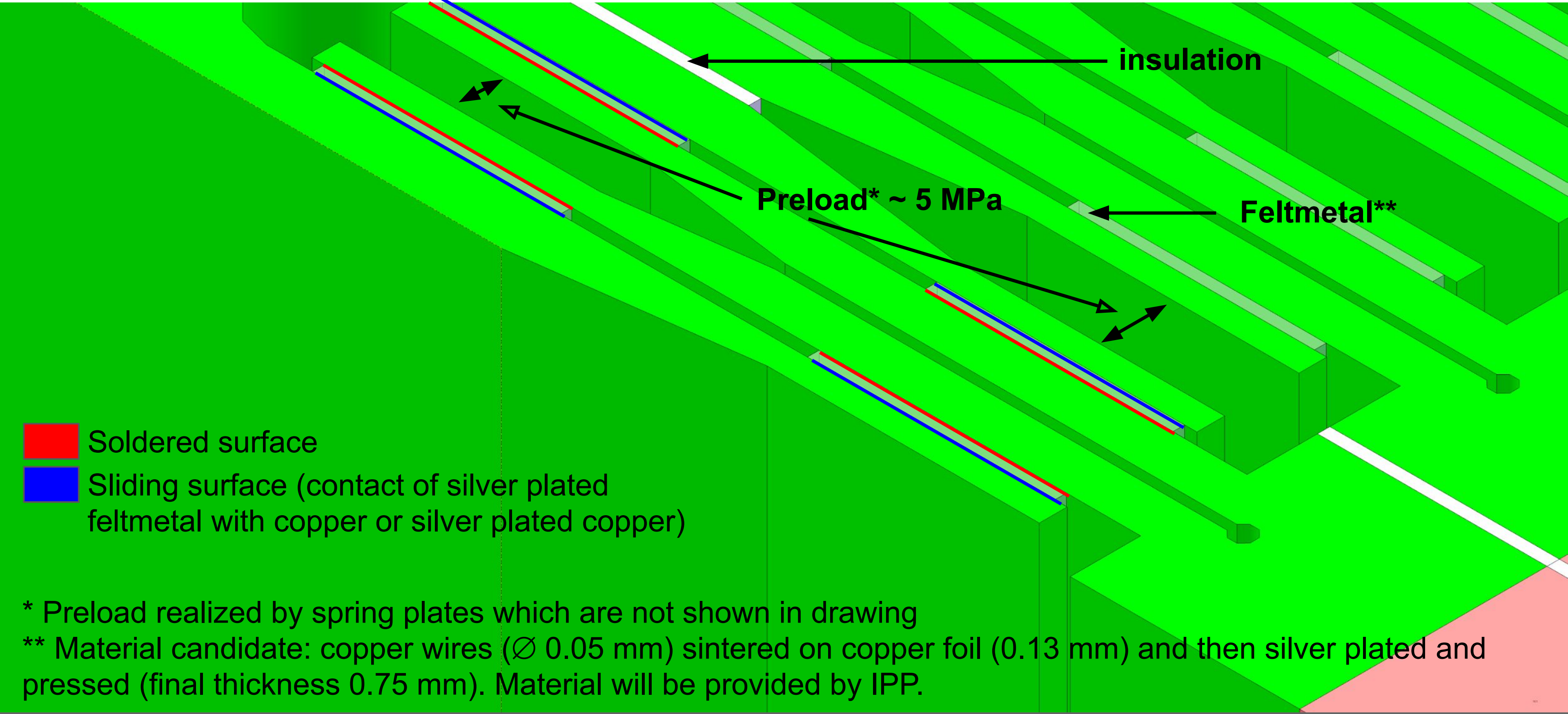


TF coil - sliding joint

- coil current: 200 kA
- 7 turns per coil bundle
- 1 sliding joint per turn
- 4 contact surfaces per joint
- each surface has 20x200 mm
- average current density:
  1.25 kA/cm^2
- peak current density:
  ~ 5 kA/cm^2



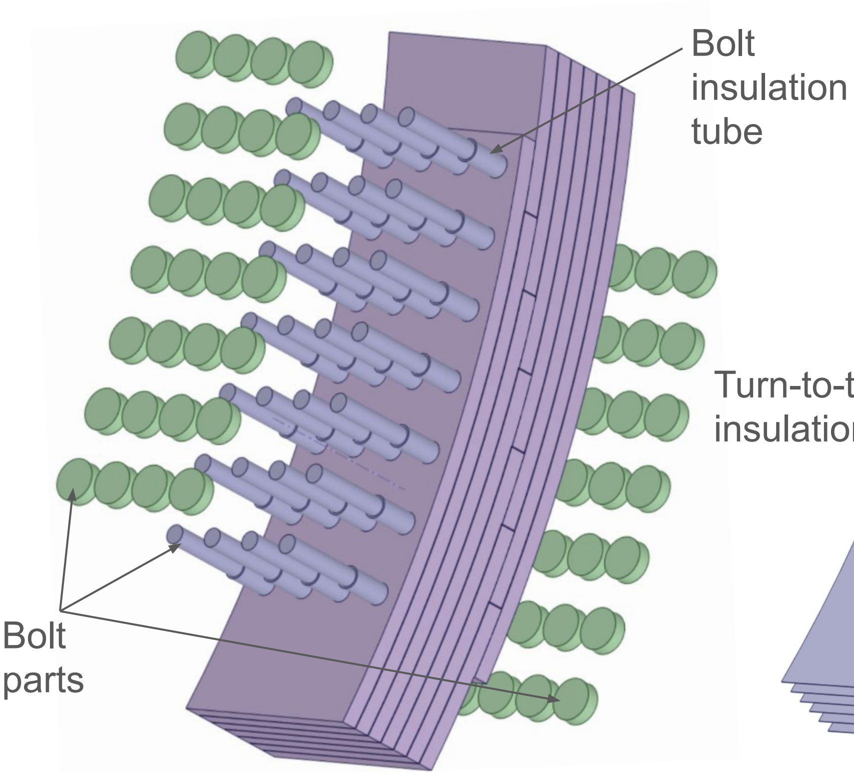
TF coil - sliding joint (detail)

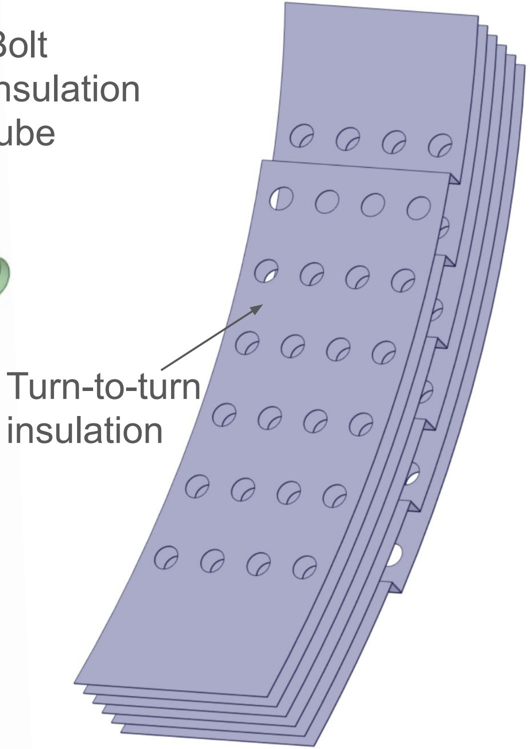


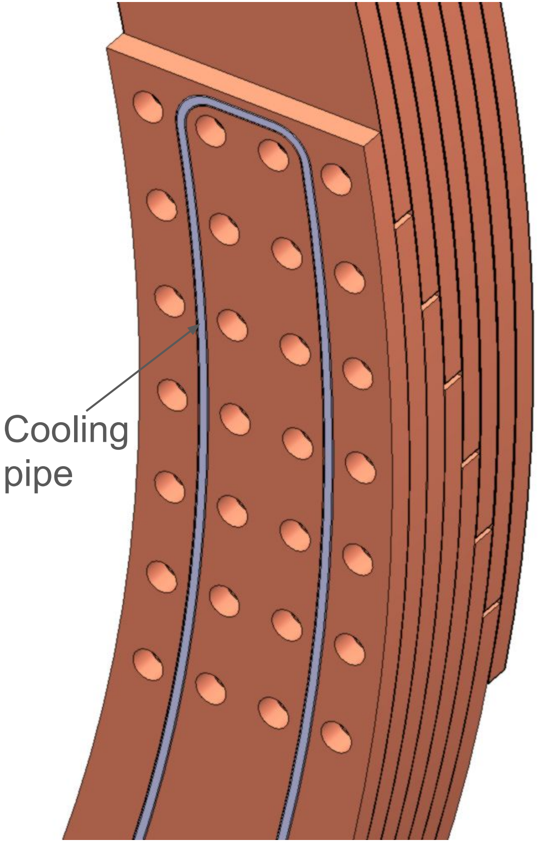
* Preload realized by spring plates which are not shown in drawing
** Material candidate: copper wires (∅ 0.05 mm) sintered on copper foil (0.13 mm) and then silver plated and pressed (final thickness 0.75 mm). Material will be provided by IPP.

TF coils - midplane bolted joint

- 28x M20 bolt with insulation tube

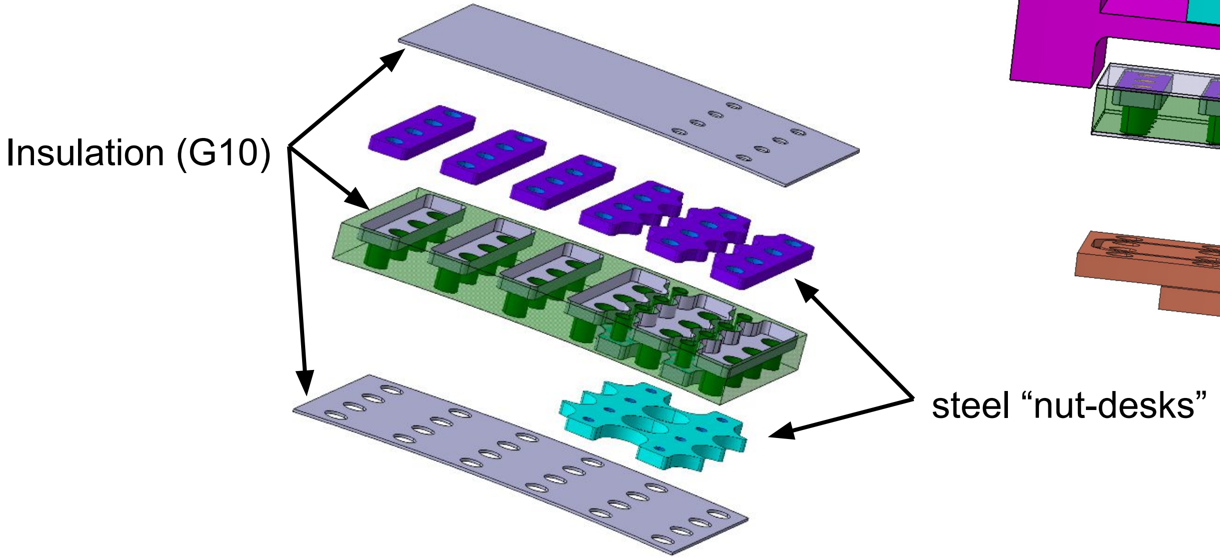


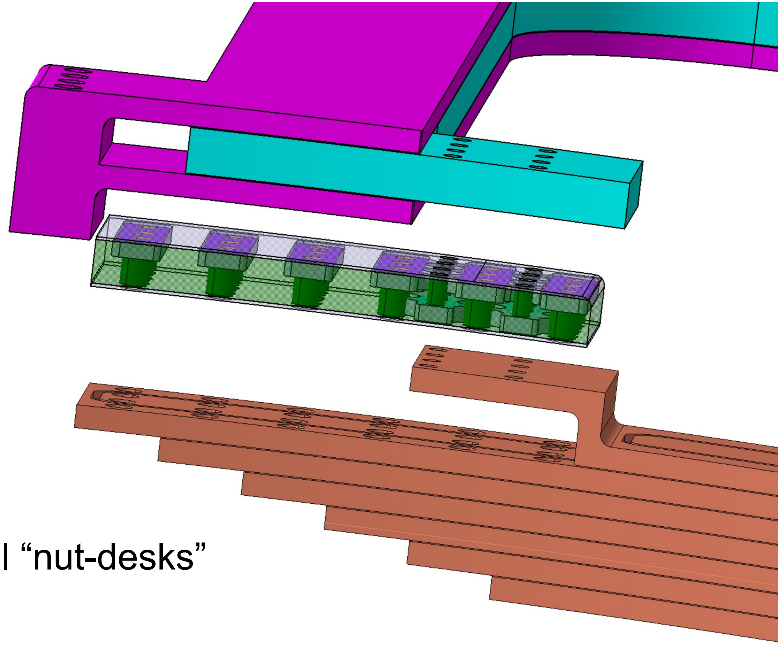




TF coils - midplane bolted joint

- one modified bolted joint for connection of TF feeds
  - last turn modified + different size of bolts
- 1000 V between first and last turn
  - extra piece of insulation added to separate screws of 1000 V turn



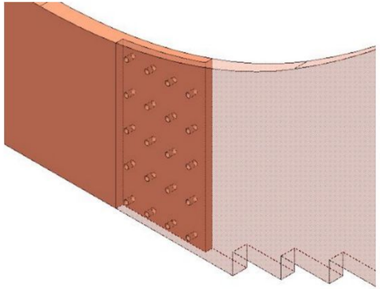


TF coils - bottom bolted joint

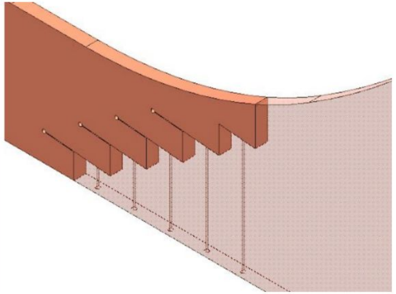
Joint is required in case that:
1) TF core and lower limb cannot be impregnated as a whole.
2) Central solenoid cannot be wound on the TF core with the lower limbs attached (question related to manufacturer of central solenoid)
3) Transport of TF core + lower limb with central solenoid is not possible (total mass of 25 tons)

Several concepts:

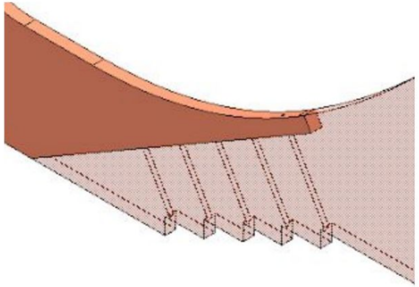
A)



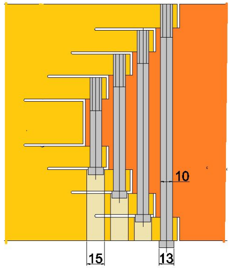
B)



C)



D)



TF coils - insulation

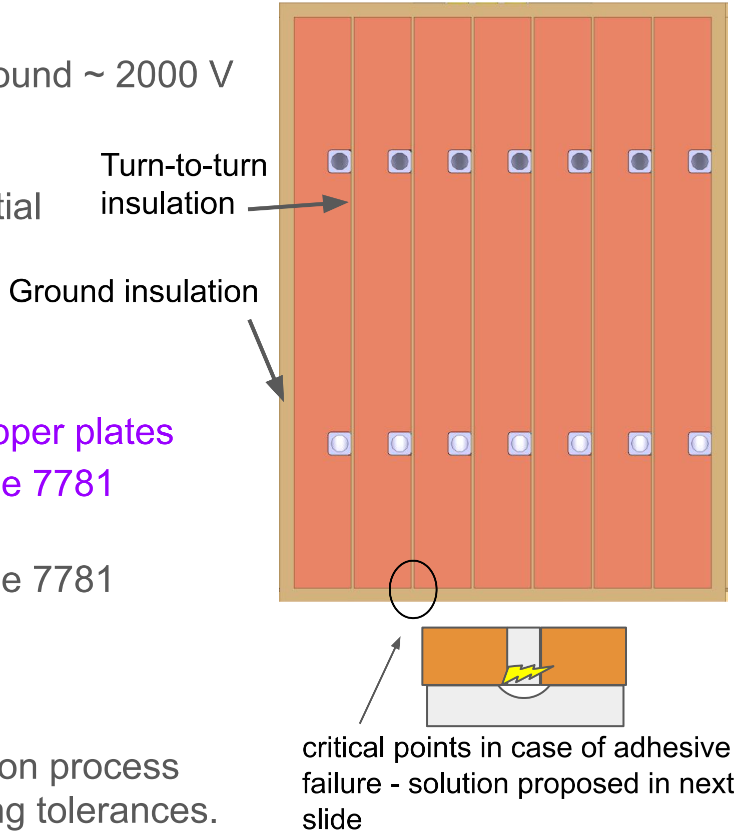
Operation parameters:
Voltages: turn-to-turn ~ 10 V, first-to-last turn ~ 1000 V, turn-to-ground ~ 2000 V
High mechanical stresses: through thickness tension ~ 20 MPa,
shear stresses ~ 50 MPa
Requirement: no direct visibility of parts at different electric potential in case of intra-laminar or adhesive failure of insulation

Insulation design:
Turn-to-turn insulation ~ 0.8-1 mm thick (2 options):
- G10 plates bonded with epoxy resin or prepreg sheet to copper plates
- (Vacuum pressure) epoxy impregnation of E glass cloth style 7781

Ground insulation ~ 5 mm thick:
- (Vacuum pressure) epoxy impregnation of E glass cloth style 7781 around TF core and each bundle

Joint insulation + joint for TF feeds:
- extra pieces of G10 around joints

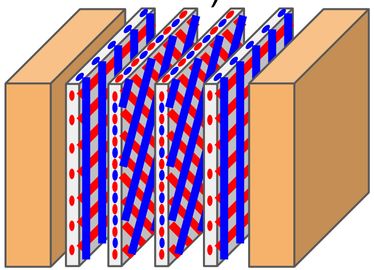
Note: Contractor is encouraged to propose an alternative insulation process with equivalent or superior properties meeting the machining tolerances.



Turn-to-turn insulation

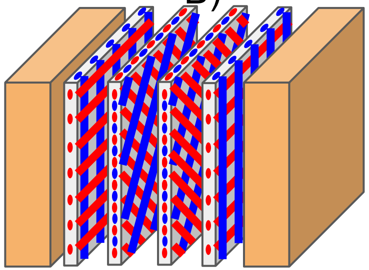
- 4 layers of fiberglass fabric style 7781 (8H satin weave, E-glass)
  - covers curved surfaces more easily (not necessary for TF coils)
  - higher strength than plain weave
  - high glass to resin ratio
  - thickness 0.22 mm, filament 6 um
  - **which finish to use?** just finish compatible with epoxy resin or does some finish causing superior mechanical properties exist? (proposed epoxy resin system is CTD-101K or VUPOXY E-1K)
  - asymmetric sides (warp and weft dominant) ⇒ anisotropic properties
- total insulation thickness after 10% compression 0.8 mm
- Several layups possible. Layup **B)** is proposed for insulation

A)



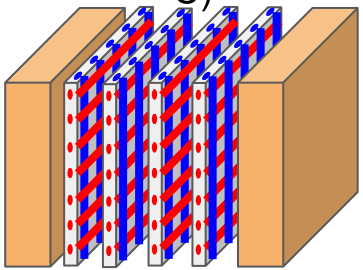
- same strength in warp & weft direction
- asymmetric connection to copper
- quasi isotropic layup (0/90° & -45/45°)

B)

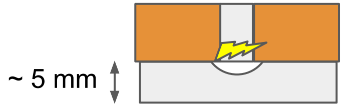


- stronger in warp direction?
- symmetric connection to copper
- quasi isotropic layup (0/90° & -45/45°)

C)

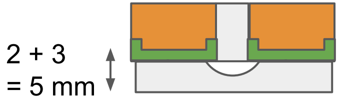


- stronger in warp direction?
- symmetric connection to copper
- not quasi isotropic layup (0/90° & -45/45°)



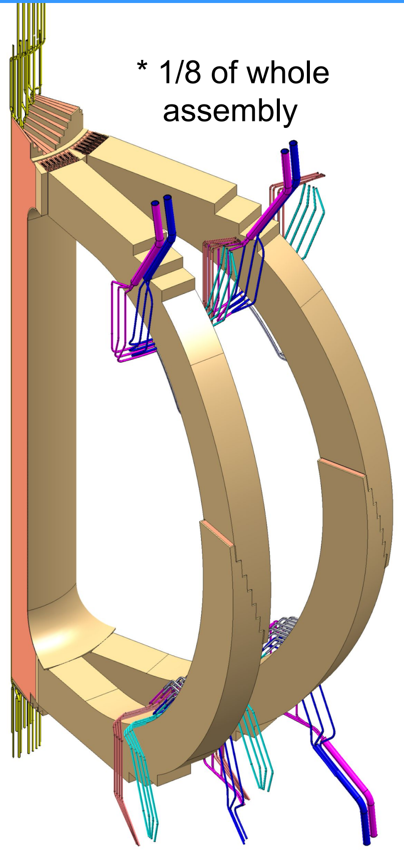
critical points in case of adhesive failure

Proposed modification: G10 or prepreg caps along the turn edge (caps can have round edges)



Ground insulation

- fiberglass fabric style 7781 (8H satin weave, E-glass)
- Is it possible to insulate wholly assembled TF core + lower limb?
- What would be proper insulation process?
  1) Impregnation of whole assembly together with impregnation of turn-to-turn insulation
  2) First the impregnation of bundles and then assembly of TF core (with lower limbs) and impregnation of whole assembly. How would be bundles connect to each other in TF core region?



* 1/8 of whole assembly

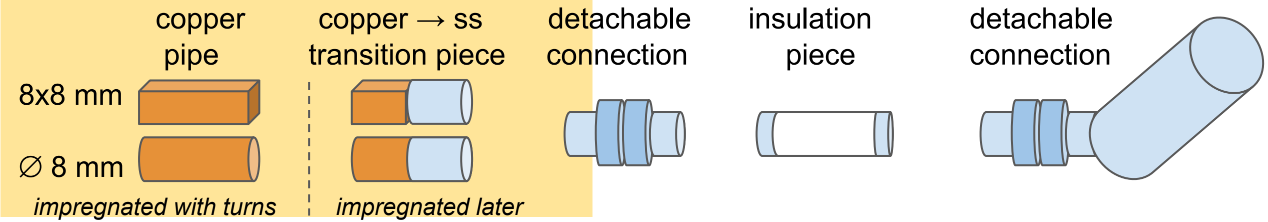
TF coils - cooling

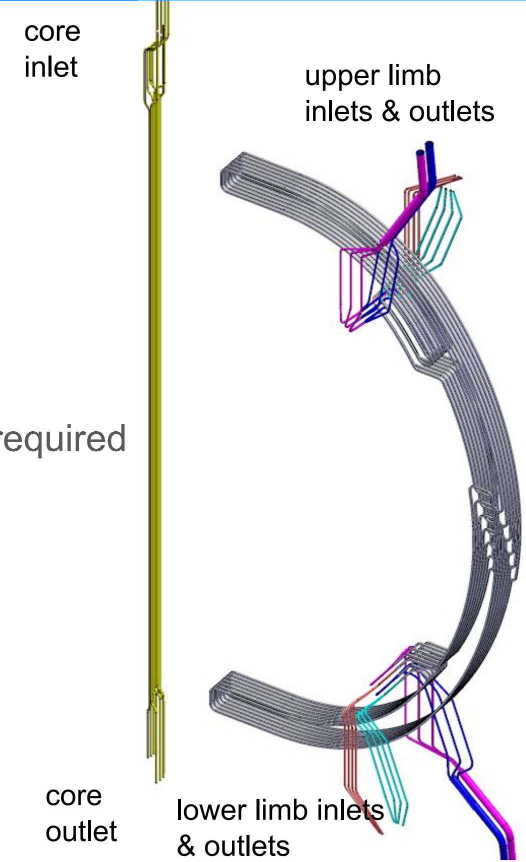
Operational parameters:

- Initial temperature 80 K, ΔT ~60 K in ~10 s, cooldown time ~ 30 minutes

Cooling:

- Each part of the turn has its own cooling pipe
- Grove and pipe concept
- Material of pipes: copper (to match CTE + high conductivity)
- Connection of pipes: soldering (process should not anneal TF base material from full hard copper)
- Coolant: gaseous helium, pressure ~20 bar ⇒ helium tight connections required
- Distribution of helium outside TF coils by stainless steel pipes ⇒ copper to stainless steel transition required (covered under insulation)
- Pipes electrically connected to turns ⇒ insulation piece required
- Production and connection of transition piece not yet decided

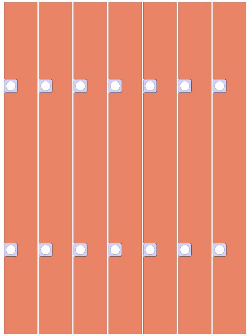


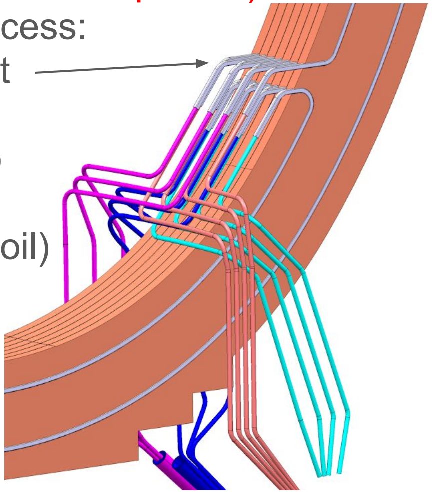


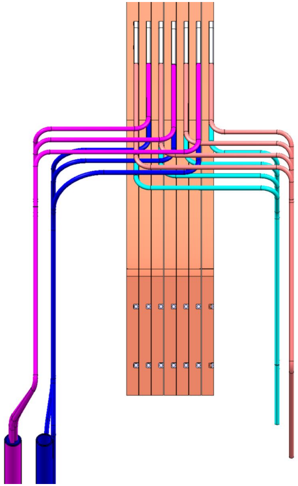
Cooling - Outer limbs

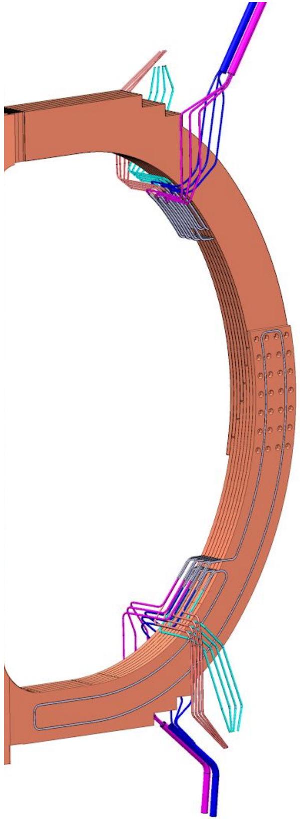
Cooling pipes:

- copper pipes dimension two options
  1) outer ∅ 8 mm, inner ∅ 6 mm
  2) outer 8x8 mm, inner ∅ 6 mm
  Preferable choice is 2) ⇒ pros: less amount of solder, rectangular groove; cons: connection of rectangular pipe to stainless steel circular pipe
  Is it easier/cheaper to manufacture option 2)?
- Proposed manufacturing process:
  VPI of coil only with grey part
  (no bend outside of coil)
  → color part (stainless steel) will be connected/welded
  → the grey part (outside of coil) will be bended





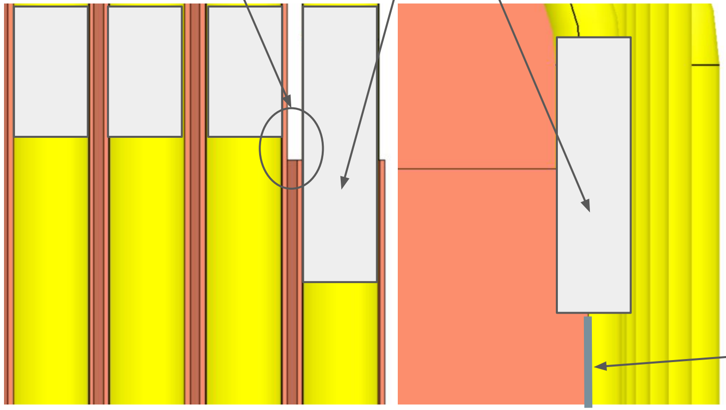


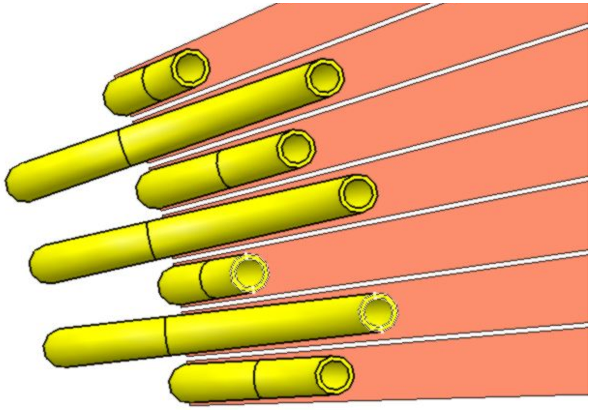


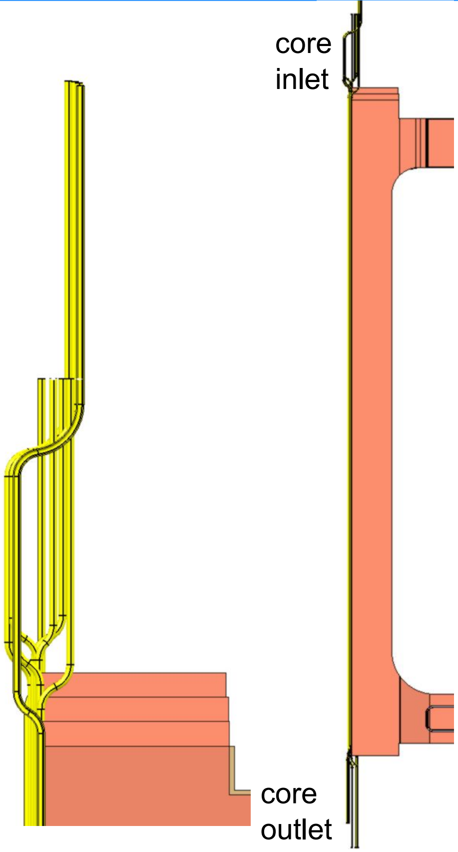
Cooling - TF core

Cooling pipes:

- copper pipes (outer ∅ 8 mm, inner ∅ 6 mm)
- soldered to groove
- insulation should begin before end of core to avoid direct visibility of neighbouring pipes







TF coils - machining tolerances & tests

Machining tolerances:

- General tolerances will be set by DIN ISO 2768 mK.
- Tolerances for preliminary design of TF core are shown in attachment *HFCU-04-00-v7-3_B.pdf* (Sheets 1-4)
- TF core is a critical component in the sense that it is composed of 112 turns (parts) and the small variations on one turn can after assembly of 112 turns lead to significant variation. Second challenge is that the TF core part has to fit into upper limb in the location of sliding joint which is very detailed structure. Therefore, the tolerances on TF core parts are very tight.
  There is a space for discussion how to meet requirements using different manufacturing process. Is there any preferable manufacturing process how to meet TF core tolerances (including VPI)?

Electrical Tests:

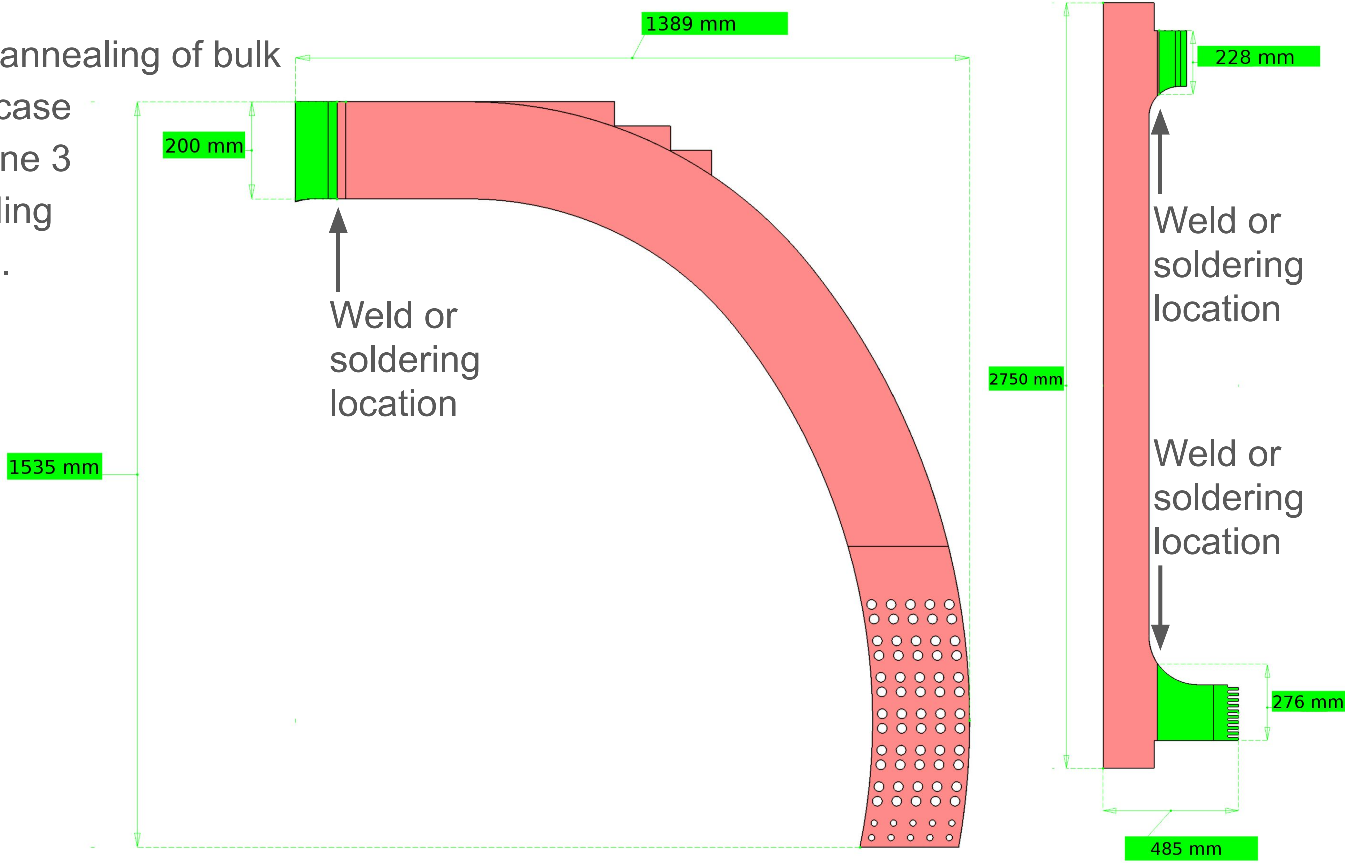
- Turn to turn voltage 700 V
- First turn to last turn voltage 3500 V
- Coil to ground voltage 7000 V

TF coils - comments on machining

Soldering or welding (without annealing of bulk material) may be done in the case that it is not possible to machine 3 parts of turn precisely or bending of TF core turn is not possible. Bending angle is 11.25°.

Length of connections:
- 200 mm, 228 mm, 276 mm

Material candidates:
- Silver-bearing oxygen-free copper (UNS C10700)
- Copper Zirconium alloy (UNS C15100)



Not fixed parameters and questions

1. Number of turn parts (2 or 3) and existence of bottom bolted joint - depends on:
   a. Is it possible to insulate whole assembly TF core + lower limb?
   b. Is it possible to transport TF core + lower limb as one piece? (Outer diameter will be ~ 4 m. TF core cooling pipes height is now 3.7 m but it can be shortened a little bit)
2. Insulation process (fiberglass cloth + VPI or G10 composite or prepreg sheets) - depends on:
   a. Which process can fulfill our requirement on “no direct visibility in case of intra-laminar or adhesive failure of insulation” and can be used for manufacturing.
3. Connection of cooling pipes to coils
   a. Is it possible to solder pipes to grooves without annealing of TF base material? If not is there any other option e.g. electron beam welding?
4. Is there any preferable manufacturing process how to meet TF core tolerances (including VPI)?
5. Copper pipe dimension in limbs 1) outer ∅ 8 mm, inner ∅ 6 mm or 2) outer 8x8 mm, inner ∅ 6 mm
   a. Is it easier/cheaper to manufacture option 2)? (do not forget the transition piece Cu→ SS)
6. Turn-to-turn insulation ~ 1 mm thick (2 options): 1) G10 plates bonded with epoxy resin or prepreg sheet to copper plates or 2) (Vacuum) epoxy impregnation of E glass cloth style 7781
   a. Option 2) is prefered. Would option 1) help with meeting manufacturing tolerances on TF core?
7. Which finish is recommended for E glass fiber? (proposed epoxy system is CTD-101K or VUPOXY E-1K)
8. Fiberglass cloth layup
   a. Do you have experience with fiberglass cloth (style 7781) layup? Which layup would you propose to maximise shear strength of insulation.

Not fixed parameters and questions

10. What process do you recommend for the ground insulation of the TF core (+ lower limb)?
11. Production and connection of Cu→ Stainless steel transition piece for cooling pipes not yet decided.
    a. Is there any recommend manufacturing process for production/connection of such a piece (friction welding...)?
12. Is it possible to machine each of the 2 (3) parts of one TF turn out of one copper plate (including the precise machining of the sliding/bolted joint area) or would you recommend to machine the sliding/bolted joint area separately and connect it (EBW, soldering) to the rest of the given TF part? (see slide 20)
13. There are two bends in TF core with 11.25° angle. 6 of 7 turns are bended in same direction. One turn has top and bottom bend in opposite direction. It was assumed that bending will be done with thicker plates and then precise machining will be done. Is it possible to meet prescribed tolerances using this approach?
14. How would you transport finished piece to IPP?
15. What is an approximate cost for manufacturing of the TF coils?

In case of any questions do not hesitate to contact us via email (next slide) or videoconference.

Contacts

Further information (drawings) which are regularly updated can be found in http://www.ipp.cas.cz/o-ufp/Verejne_zakazky/doc.html under section "Coils of toroidal field". (there is a language switch in upper right corner)

At website tenders electronic daily

Notification Number at Tender electronic daily: 2019/S 113-276584
(Číslo oznámení TED: 2019/S 113-276584)

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Jaroslav Krbec email: krbec@ipp.cas.cz (also put nemec@ipp.cas.cz in the copy)

Attachment description

Attachment:

- *CU_CUPG-04-00-V08-B.zip*
  - Model of TF coils:
    - *CU_CUPG-04-00-V08-B.stp*
  - Drawings and machining tolerances of TF coils
    - *CU_CUPG-04-00-V01-A.pdf*