COMPASS-U tokamak
Toroidal field coils

v4.0
10.5.2021

Institute of Plasma Physics of the Czech Academy of Sciences

Content

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.

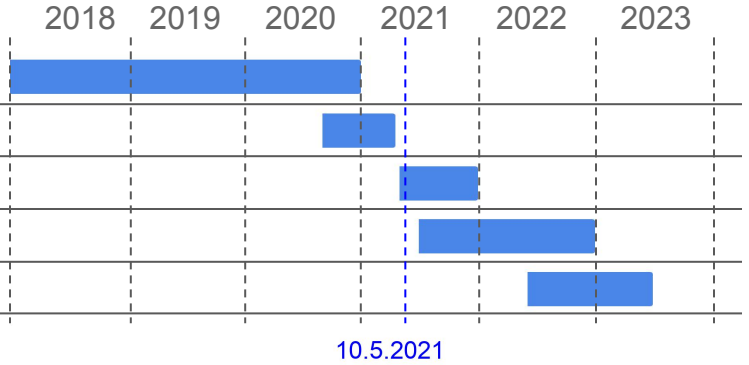
Key properties of COMPASS-U:

- 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

⇒ **unique capabilities to address DEMO challenges**

Indicative timetable of the project:

Design of the components	2018 - 2020
Final design review (FDR)	April 2021
Launch of tender for TF coils	middle 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

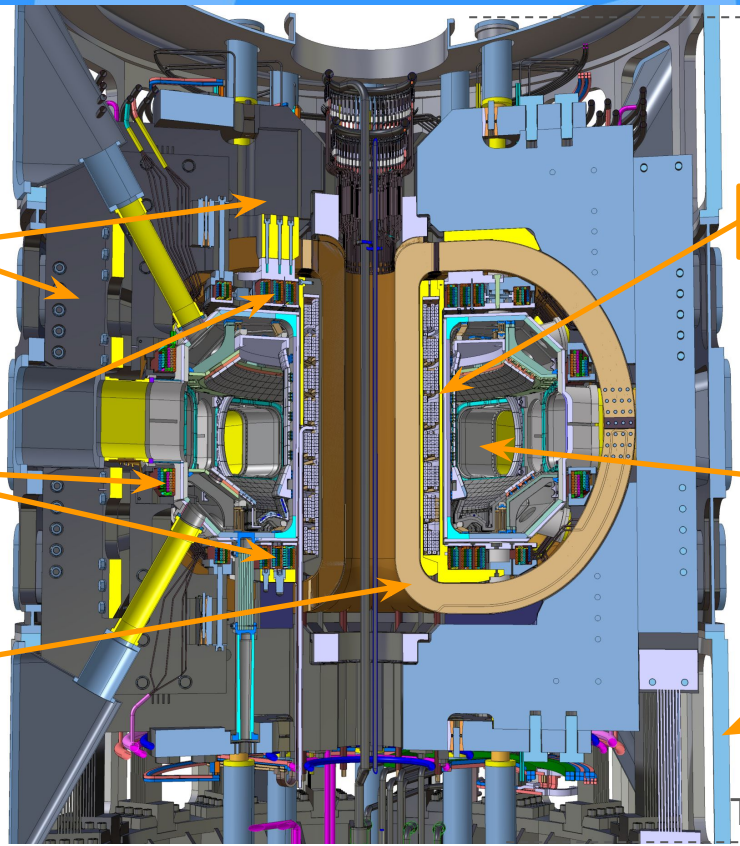
Presumed scope of work on the coil (what to expect):

- 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 and VPI and prepreg
- 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



Support structure

Poloidal field coils

Toroidal field coils

Central solenoid

Vacuum vessel

Cryostat

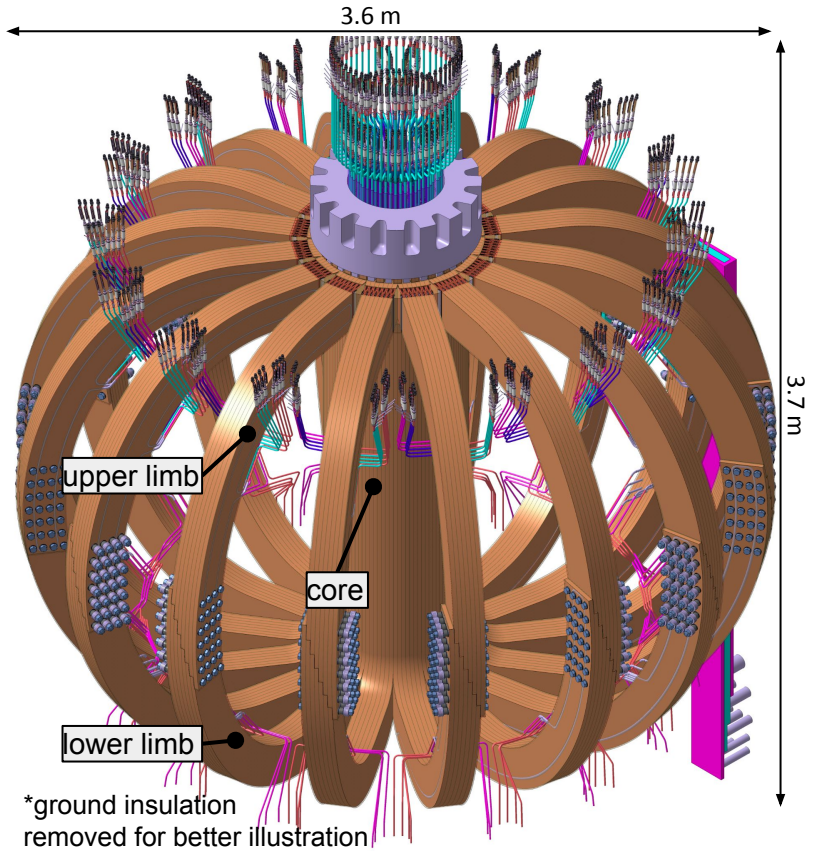
6,0 m

Total weight approx. 250 tons!

TF coils - overview

Preliminary parameters:

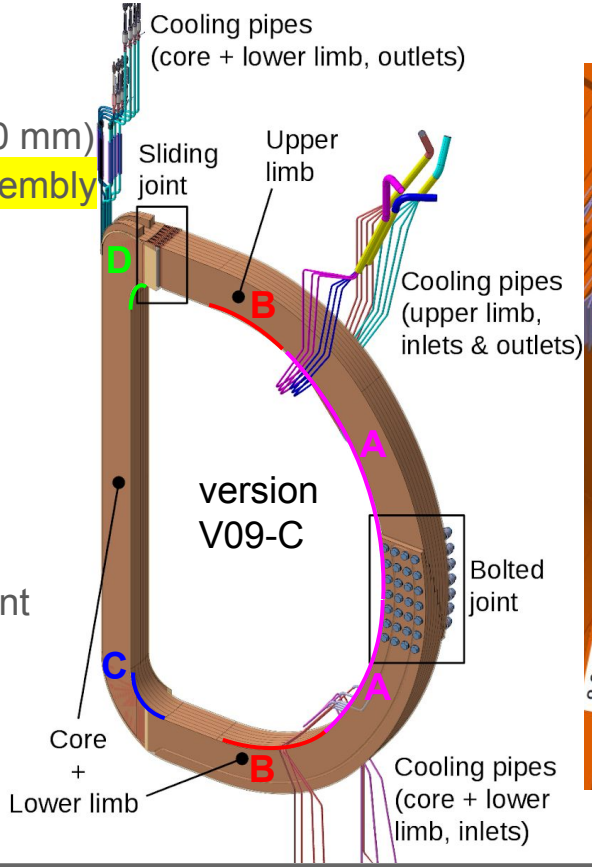
- 112 D-shaped turns grouped to 16 bundles with 7 turns
- Each turn composed of 2 parts with joints (upper and midplane joint - allow vertical assembly of parts inside of TF coils)
- Outer dimensions of one turn ~ 2.6 x 1.7 m
- Total mass 22.7 tons (core+lower limbs: 14.8 tons, 16 upper limbs: 7.9 tons)
- Turns insulated by fiberglass cloth + VPI + prepreg
- 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))
- Cryogenically cooled by gaseous Helium down to T > 50 K by cooling channels in each turn

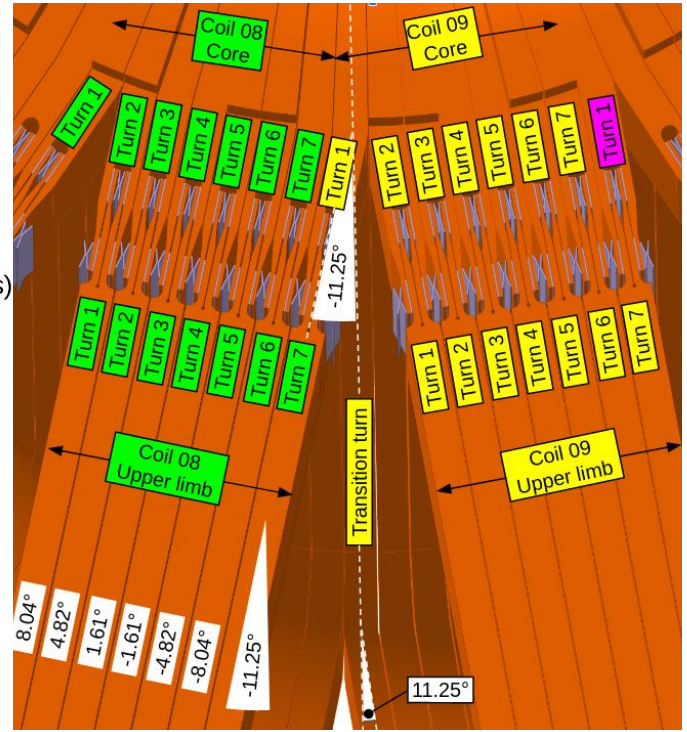


Design description

Preliminary design:

- D-shape vertically asymmetric:
  4 radii (r_{inner} = 1300, 700, 175, 100 mm)
- VV & PF inside ⇒ vertical disassembly
  ⇒ two joints
- Upper joint in high stressed area
  ⇒ sliding joint
- Structural parts:
  - upper limb (planar geometry)
  - core (cylindrical)+
    lower limb (planar) ⇒ bend)
- Feeder connection and
  turn-to-turn transition in bolted joint
- Coil-to-coil transition in core





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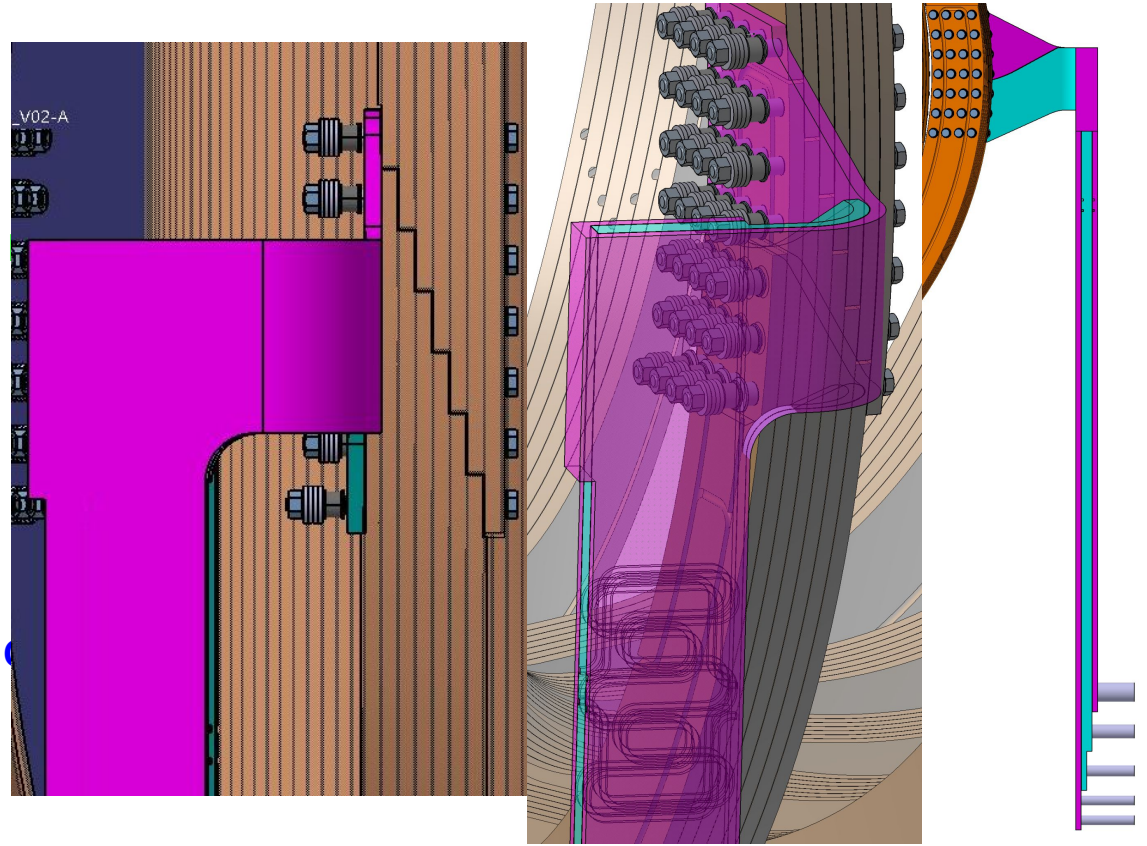
- Feeder connection and
  turn-to-turn transition in bolted joint
- Coil-to-coil transition in core
- Feeder: ΔT ~ 200 K ⇒
  ⇒ cross-section doubled
  ⇒ dipole → quadrupole
  ⇒ thermal anchor



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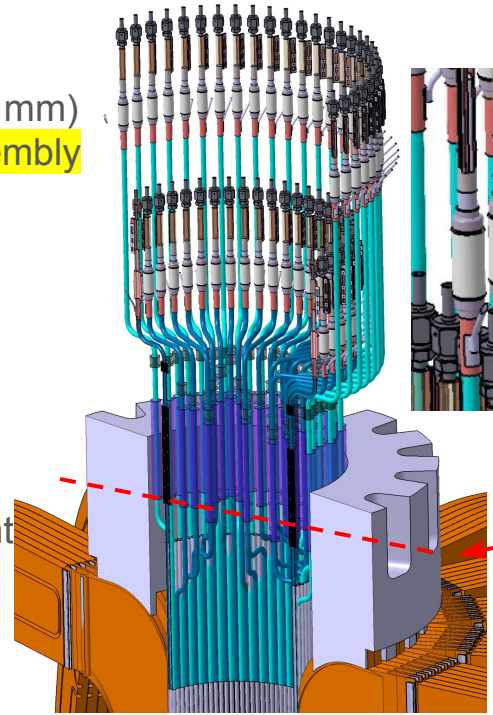
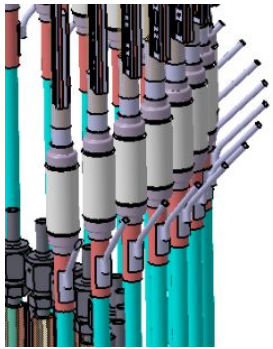
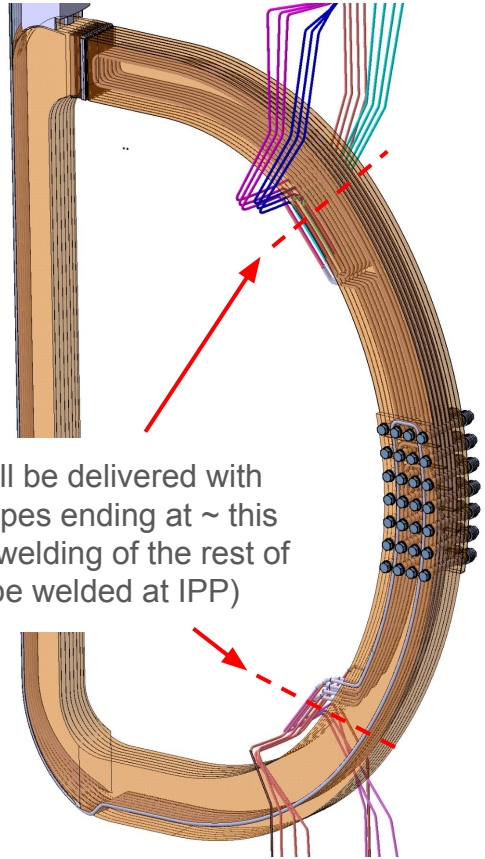






TF coil will be delivered with cooling pipes ending at ~ this location (welding of the rest of pipe will be welded at IPP)

- Cooling:
  - grove and pipe concept (soldered), gaseous helium @ 20 bar
  - upper limb inner ∅ 6 mm, core + lower limb elliptical inner dimension 6x10 mm
  - helium tightness ⇒ copper→ stainless steel transition @ DC break (brazed)

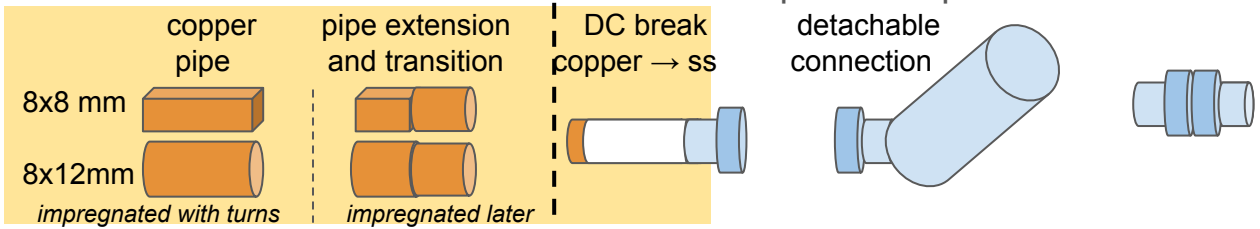
Cooling

Operational parameters:

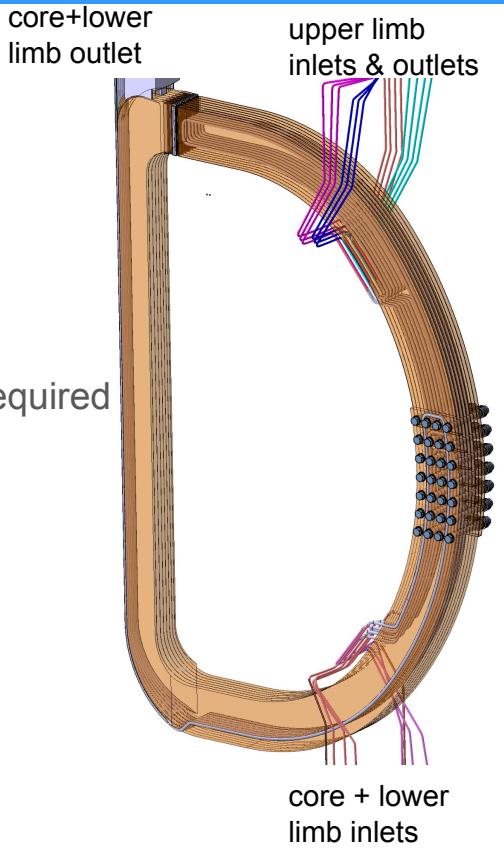
- Initial temperature 80 K, ΔT ~60 K in ~10 s, cooldown time ~ 30 minutes

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 part of TF coils delivery



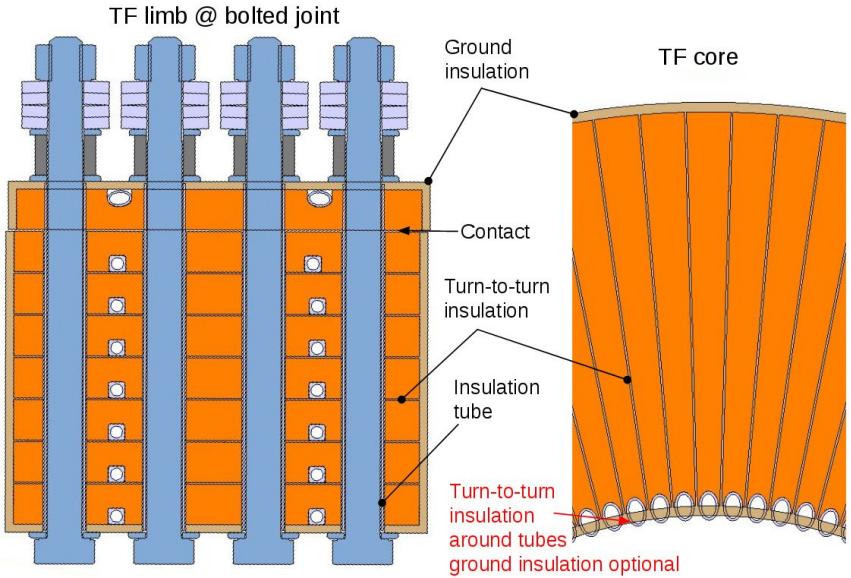
part of TF delivery | not part of TF delivery

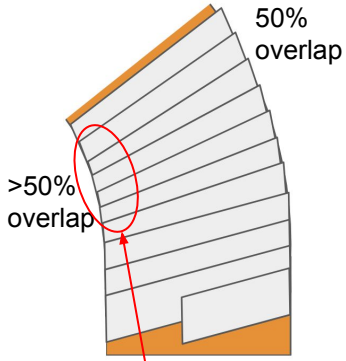


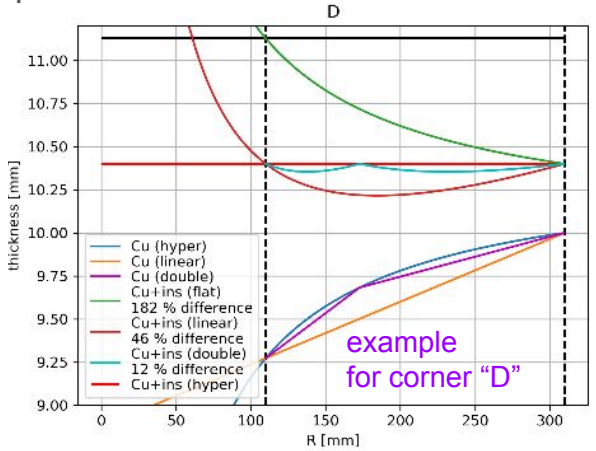
Insulation

Design: (one of proposed solutions)

- Voltage: turn-to-turn 10 V, first-to-last turn 1 kV, turn-to-ground 2 kV. Stresses: tension 20 MPa, shear 50 MPa
- turn-to-turn 1 mm (fiberglass tape 50 % overlap + VPI) ⇒ different overlap in radius ⇒ different thickness
- ground (including turn-to-turn) 4 mm (prepreg sheet) ⇒ ground 3.5 mm
- insulation of cooling pipes and voltage taps up to DC break



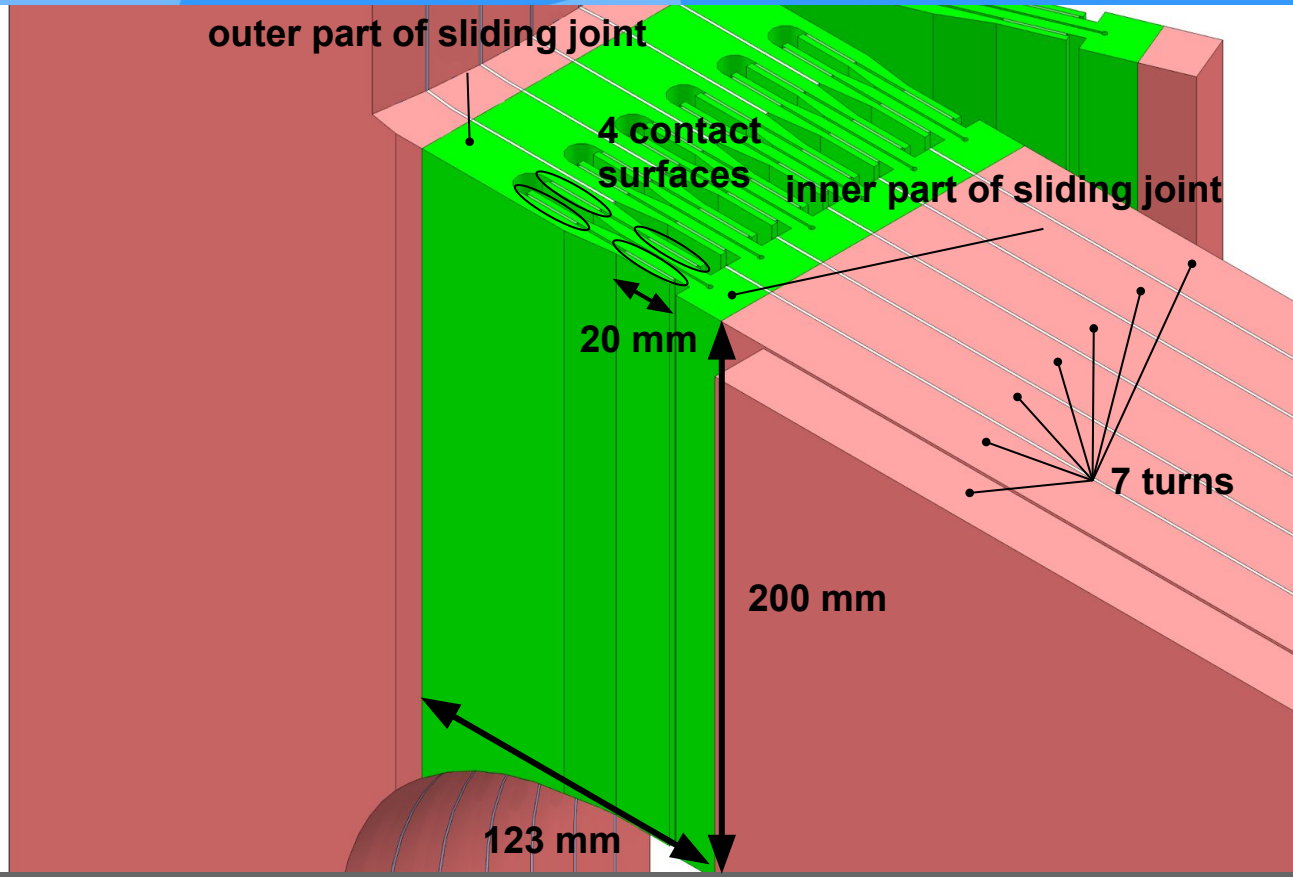




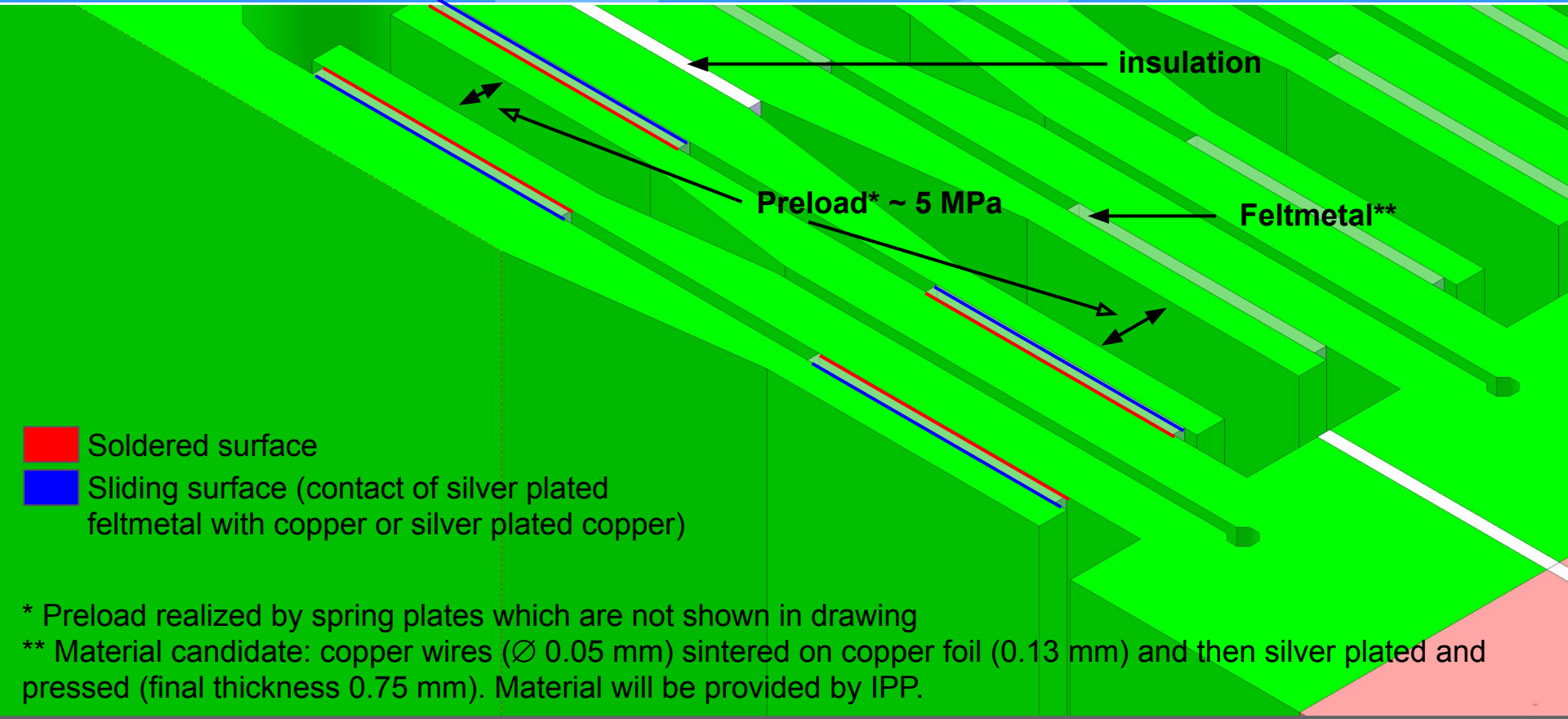
Different plate thickness at inner and outer radius ⇒ 3D machining required. Is is possible to? (fiberglass tape allows compression ⇒ double roof shape sufficient)

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



Sliding joint (detail)



Soldered surface

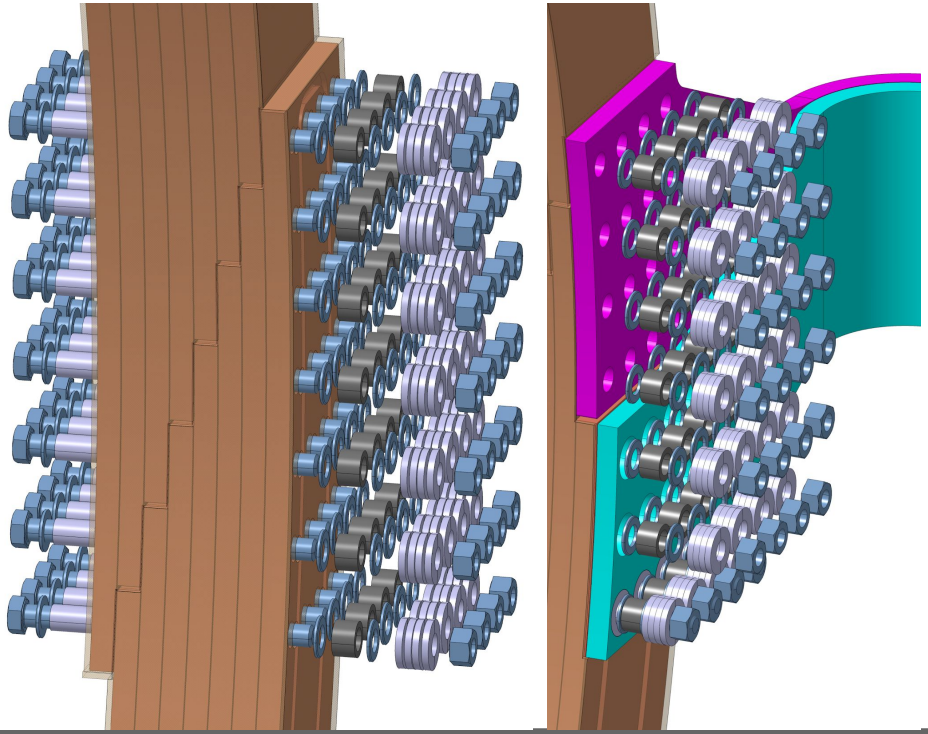
Sliding surface (contact of silver plated feltmetal with copper or silver plated copper)

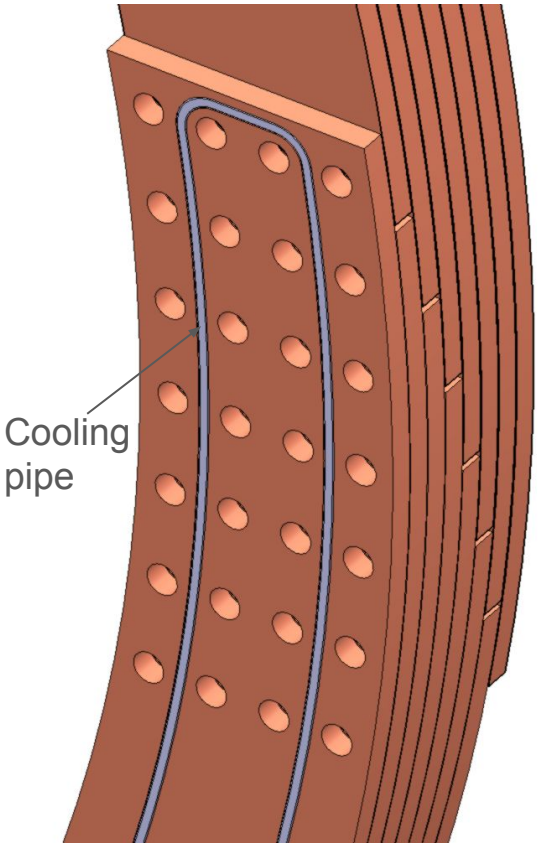
* Preload realized by spring plates which are not shown in drawing

** 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.

Bolted joint

- 28x M20 bolt with insulation tube





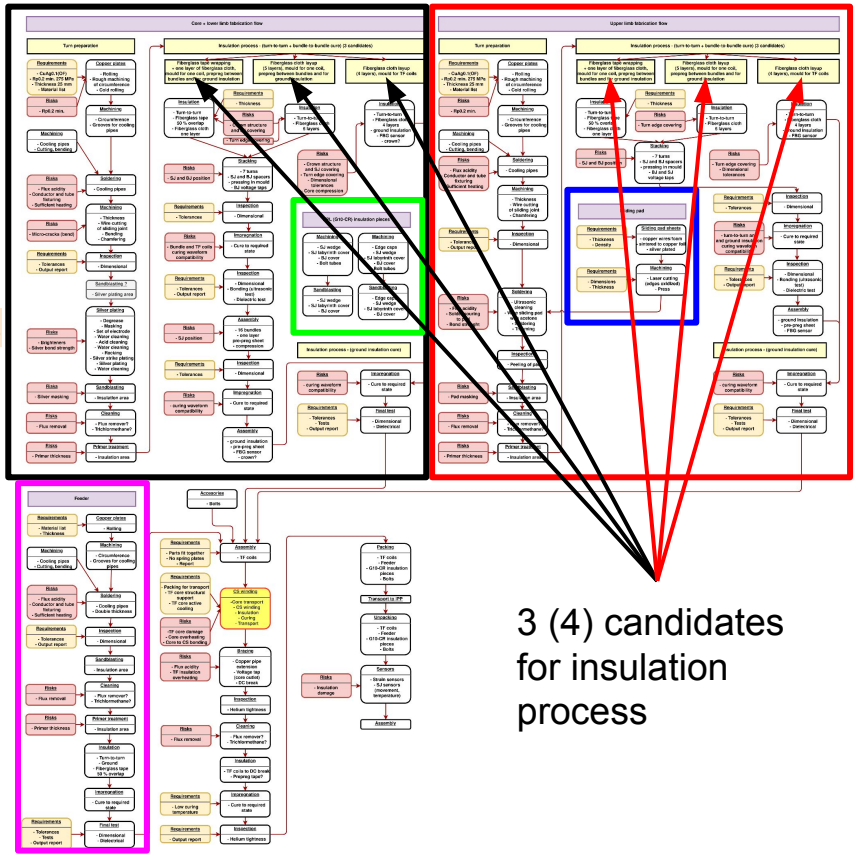
Materials, Manufacturing

Materials:

- Turns: CuAg0.1(OF) ⇒ higher strength w/o negative effect on conductivity, RRR > 30, $Rp_{0.2}$ > 275 MPa
- Composite:
  - VPI (reinforcement): E-glass tape or cloth 7781 style, VPI (matrix): epoxy resin CTD-101K or GY282
  - Ground insulation and bundle-to-bundle connection: prepreg sheet ← compatible curing waveforms
  - G10-CR for insulation pieces machined from HPL
- Solder:
  - Sliding pad: Sn96Ag4
  - Cooling pipes: not yet decided
- Sliding pad material: Feltmetal™ or Copper foam
- Grease: Aremco 641-EV or CHO-LUBE 2440

Main parts:

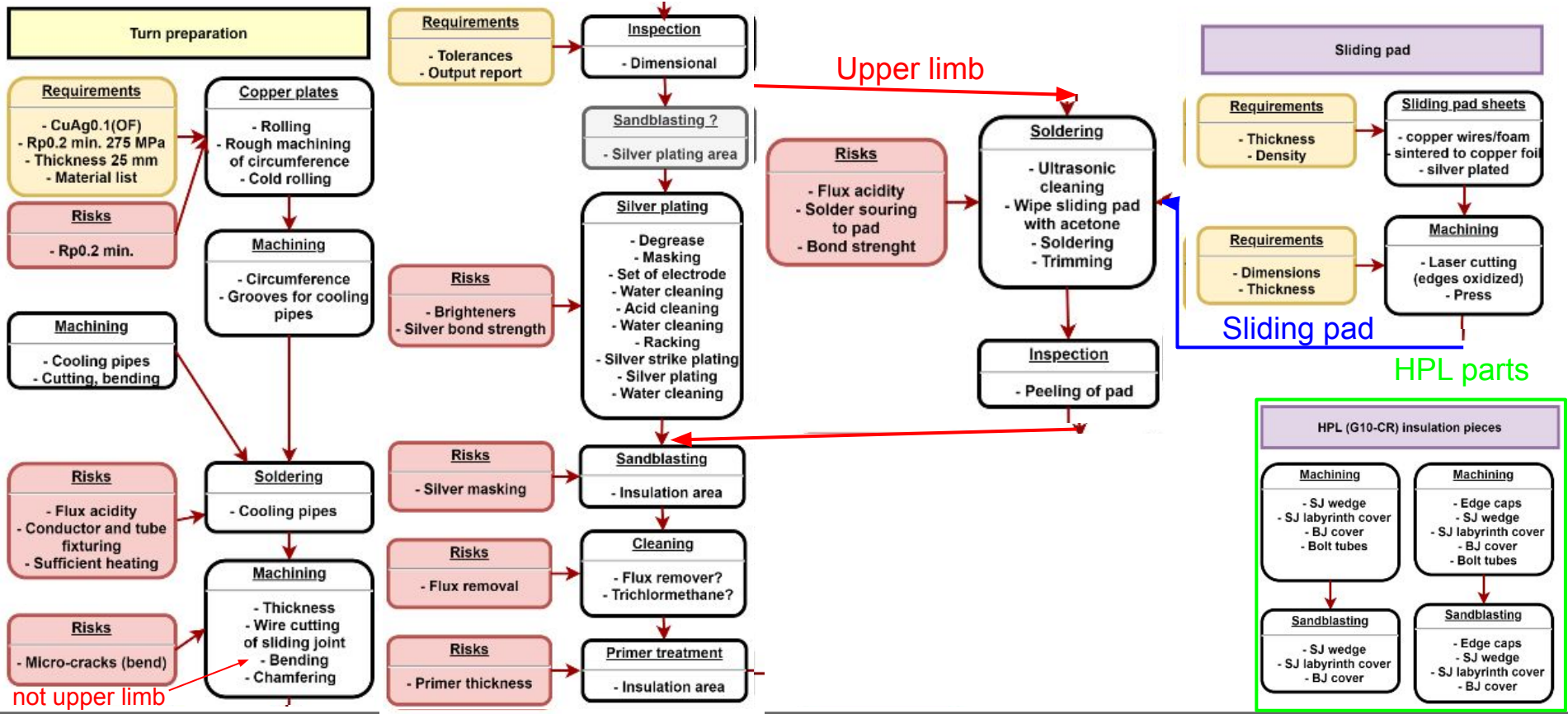
- Core + lower limb including HPL parts
- Upper limb including Sliding pads
- Feeder and CS winding



3 (4) candidates for insulation process

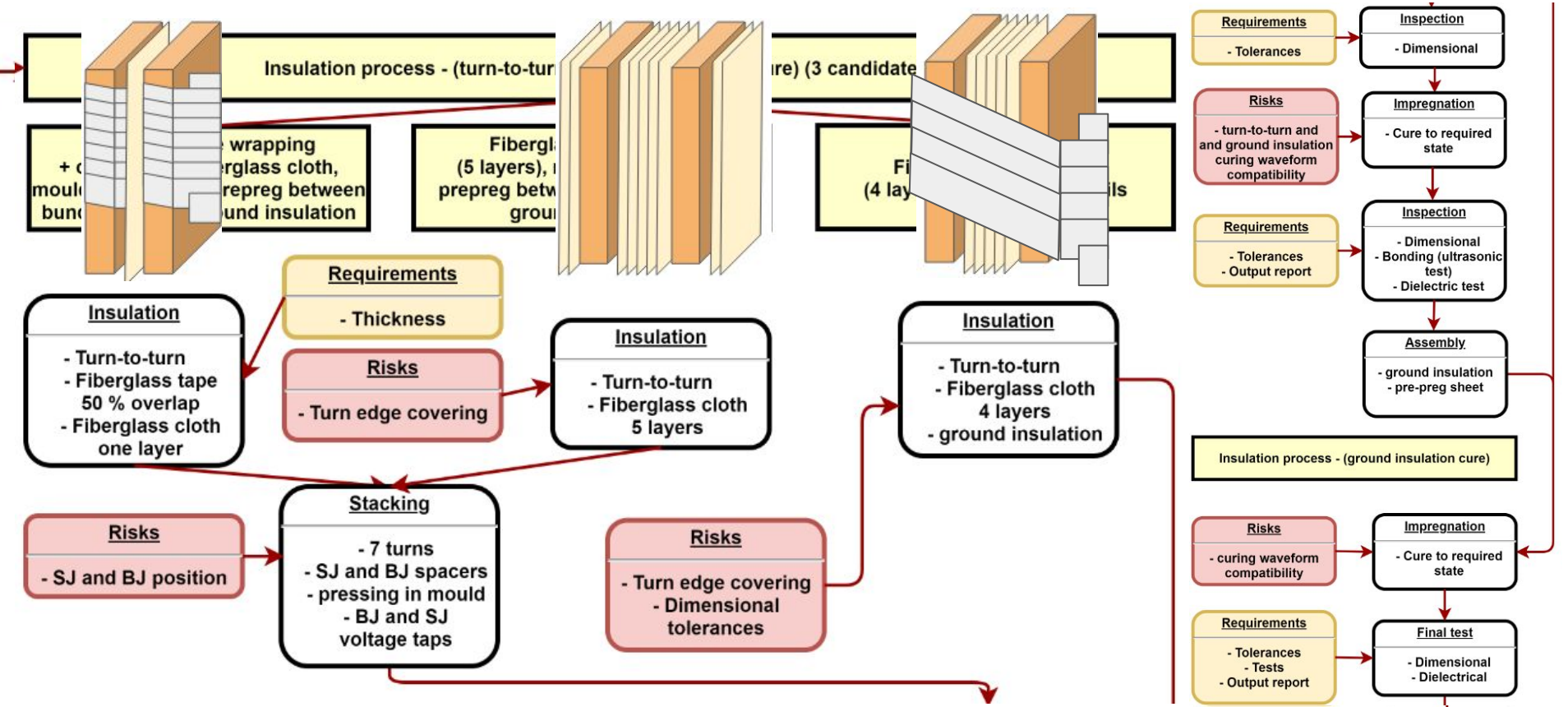
Materials, Manufacturing

Turn preparation: Core + lower limb | upper limb

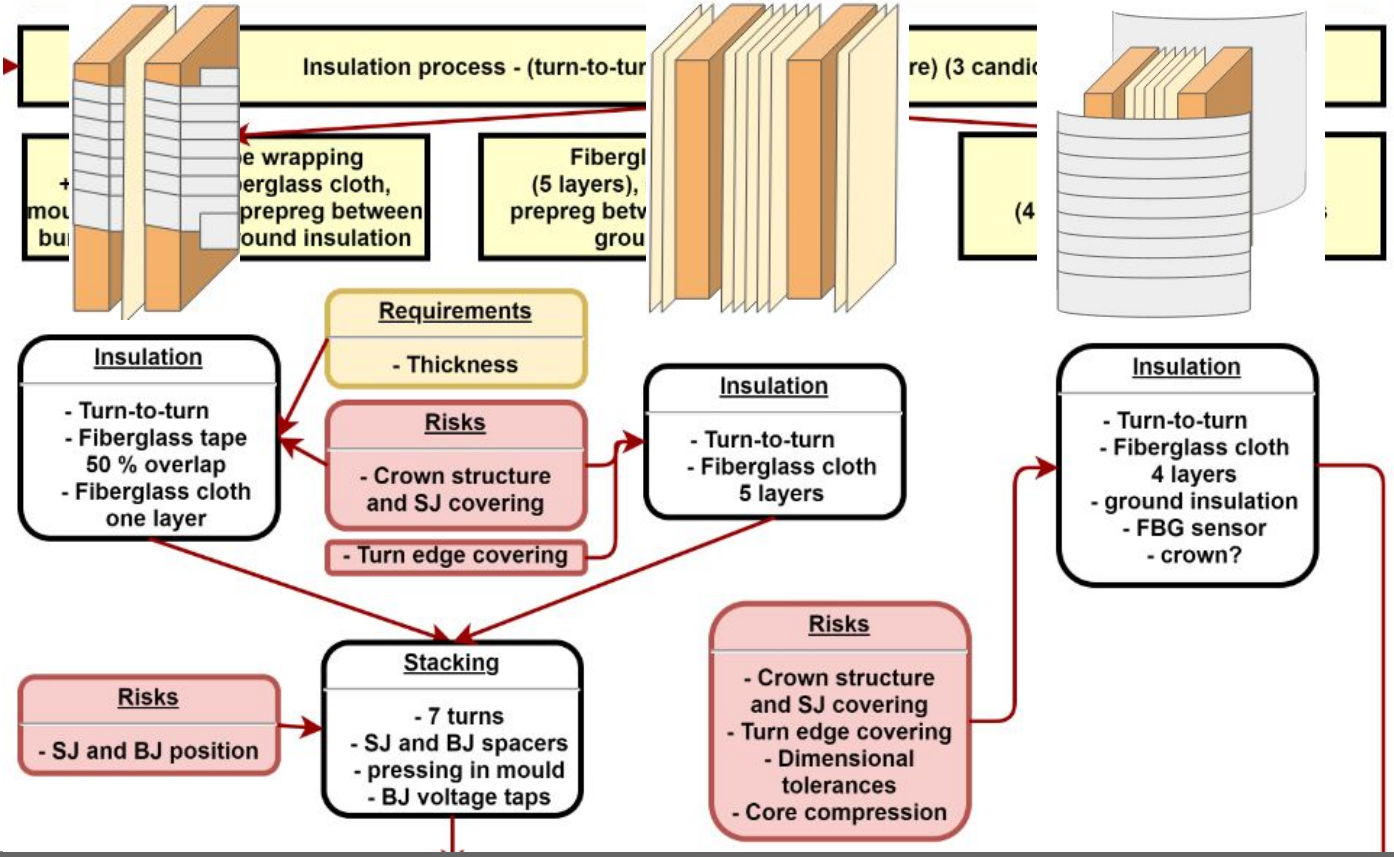


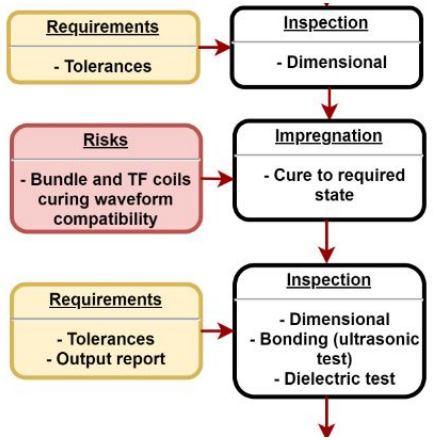
Materials, Manufacturing

Insulation: upper limb



Materials, Manufacturing
Insulation: core + lower limb





turn-to-turn insulation process

Materials, Manufacturing

Insulation: core + lower limb

bundle-to-bundle

Assembly
- 16 bundles
- one layer pre-preg sheet
- compression

Risks
- SJ position

Requirements
- Tolerances

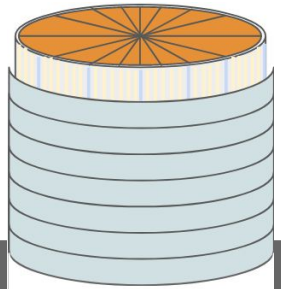
Inspection
- Dimensional

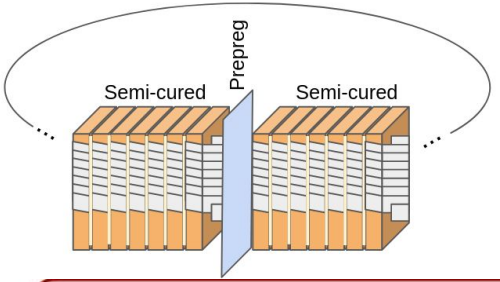
Risks
- curing waveform compatibility

Impregnation
- Cure to required state

ground

Assembly
- ground insulation
- pre-preg sheet
- FBG sensor
- crown?





ulation cure)

Risks
- curing waveform compatibility

Impregnation
- Cure to required state

Requirements
- Tolerances
- Tests
- Output report

Final test
- Dimensional
- Dielectrical

Requirements
- Tolerances

Inspection
- Dimensional

Risks
- Bundle and TF coils curing waveform compatibility

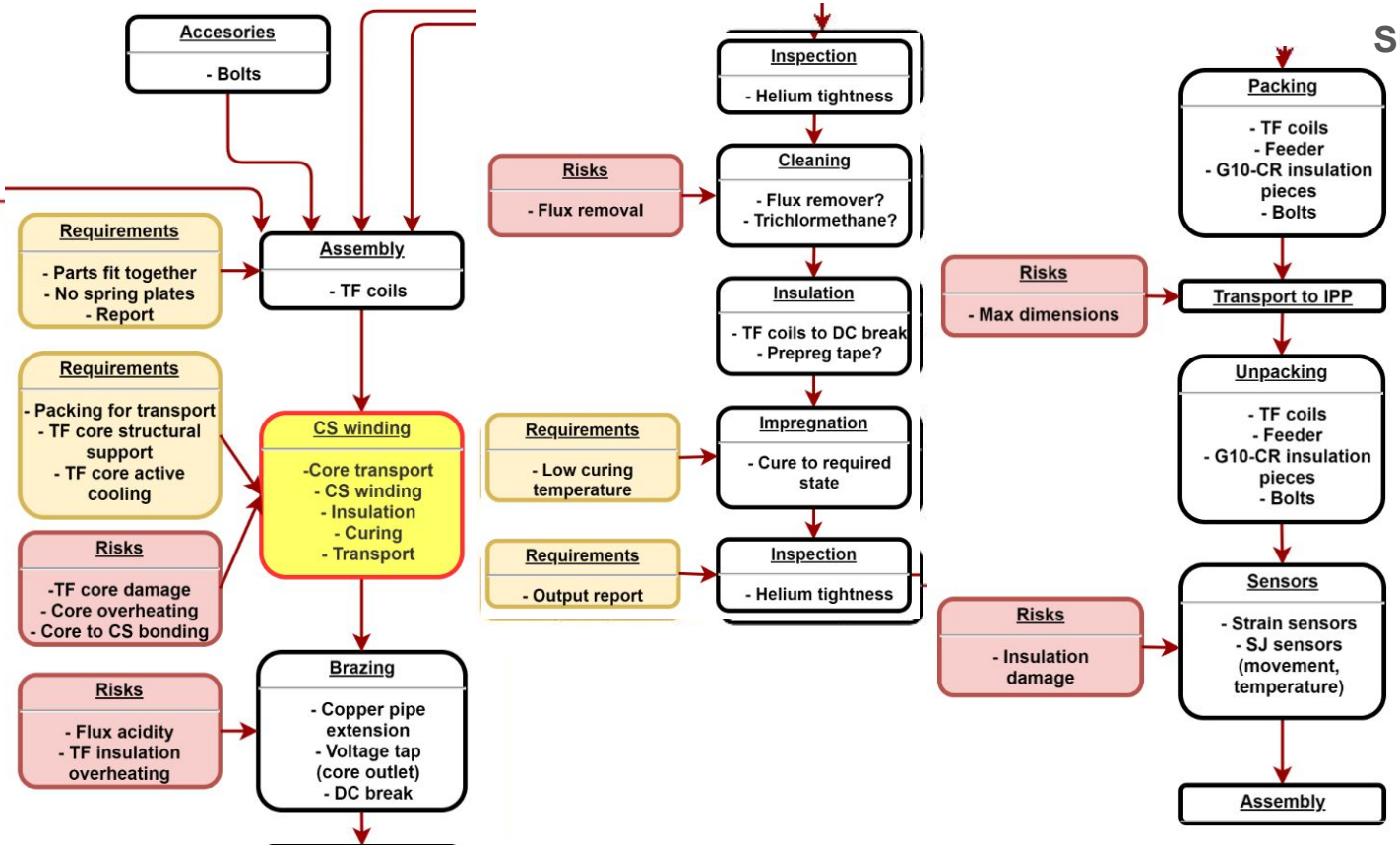
Impregnation
- Cure to required state

Requirements
- Tolerances
- Output report

Inspection
- Dimensional
- Bonding (ultrasonic test)
- Dielectric test

turn-to-turn insulation process

Materials, Manufacturing
Feeder, CS, DC breaks, Sensors



Summary

- Reliable insulation by VPI
- Combination with prepreg sheet ⇒
  ⇒ to meet manufacturing tolerances
  ⇒ lower the costs
- Variable overlap ⇒
  ⇒ higher thickness in corners
- Critical operation: CS winding on the TF core

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 1 kV
- First turn to last turn voltage 3 kV
- Coil to ground voltage 3 kV

Not fixed parameters and questions

1. Insulation process (fiberglass cloth + VPI or G10 composite or prepreg sheets) - depends on:
   a. Which process can fulfill requirements on electrical and mechanical insulation properties and which can meet manufacturing tolerances
2. 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?
3. Different plate thickness at inner and outer radius ⇒ 3D machining required. Is is possible to? (fiberglass tape allows compression ⇒ double roof shape sufficient)
4. 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)

Contact persons:

Ivan Němec email: nemec@ipp.cas.cz
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*