Analysis of cooling process of central solenoid coil

1. Scope

a. The aim of the analysis:

To simulate a cooling process of central solenoid coil (see Fig.1) from initial temperature (120K, 160K) after a tokamak discharge down to operating temperature 80K. The coil will be actively cooled through cooling channels inside the OFHC copper conductor by gaseous coolant (helium, hydrogen). The analysis should provide time evolution of the temperature in the body of the coil and coolant, and stresses in the coil conductor and insulation during the cooling process. The calculation is requested for 3 different cooling scenarios (defined below).

b. Details of the central solenoid (CS) coils:

Central Solenoid (CS) coils are high power tokamak coils wound around the tokamak core in toroidal direction, creating mostly vertical magnetic field inside the vacuum vessel. The main purpose of CS coils is to induce large toroidal current in the plasma by electromagnetic induction. CS coils carry large electric currents in the range of -50 to +50kA and they are placed in the region of very strong magnetic fields, resulting in significant material stresses. The whole CS coils stack is precompressed by a system of springs. The coils will be actively cooled through internal conductor cooling channels by gaseous helium to liquid nitrogen temperature (80K) in order to reduce their el. resistivity. Machine protection system will be designed to allow maximum temperature increase of the coils by 80K (i.e. up to 160K) during a discharge. Both the heating of CS coils during a discharge and their subsequent cool-down in-between the discharges will induce significant thermal stresses in the conductor and insulation. Spring preload also adds an additional stress to the coil.

c. Description of the cooling model:

After the end of a discharge, the temperature of both the cooling medium and the copper conductor will be set to a certain value (120K or 160K, according to defined scenarios lower). The insulation of the coil is expected not to heat during the short tokamak discharge and therefore its initial temperature for simulation is 80 K.

As a preparation of the model, the coil will be placed between two ideal infinitely stiff surfaces (see Fig.4) and as the first step (Load step 1), the upper surface will push on the coil by 4 MN force to pre-compress it. As the second step (Load step 2), the whole coil (conductor, fiberglass reinforced epoxy insulation and G10 filler parts) will be cooled from the room temperature of 300 K (no stress reference) down to 77 K. In a third step (Load step 3), only the copper conductor and the cooling medium in the cooling channels should be heated (to 120/160K) - this will be the initial condition for subsequent transient thermo-mechanical analysis.

Coil is actively cooled via an internal cooling channel. The channel has an elliptical shape (6x8mm) elongated in the vertical direction. Coolant is a gaseous pressurized helium or hydrogen (no phase transitions). Mass flow (mFlow) is prescribed as an input of the simulation. Coolant inlet temperature will be set dynamically as the coolant outlet temperature minus dT, until the target outlet temperature is reached. Both outlet and inlet coolant temperatures should be logged during the whole simulation.

Since the length of the cooling channel is many times larger than its diameter, the flow of helium should be addressed by 1D fluid model to keep the computational demands sufficiently low. For that purpose, ANSYS APDL has FLUID116 element type with the ability to conduct heat and transmit fluid between its nodes. This element may solve for two different types of degrees of freedom, temperature and/or pressure. Solution for temperature degree of freedom only is requested in the demanded analysis of the CS coil cooling. Convection may be accounted for by surface elements SURF151 or SURF152. The cooling model should be then built in the following way: 1. Use FLUID116 elements for meshing of the 1D line object in the middle of the cooling channel and assign helium material properties to it, 2. Link the 1D helium model with inner walls of the cooling channel by “Convection” boundary condition with specified heat transfer coefficient (HTC), 3. Set up the thermal model: specify initial temperature of coil turns and insulation, specify coolant mass flow and inlet temperature (given by outlet temperature minus dT). This kind of setting can be done directly in Workbench, we provide an example of such a model in the attachment (*Example_fluid116.wbpz*, *Example_fluid116.pdf*).

2. Input documentation to start and realize activity

- **a. Type of analysis:**
    - i. Coupled thermal-structural transient analysis
    - ii. 1D geometry of cooling helium coupled with 3D geometry of the coil
- **b. Geometry**
    - i. Geometry file (.stp) will be provided.
    - ii. 3D model of CS1U coil composed of copper turns with internal cooling channels, fiberglass reinforced epoxy insulation in between the turns and filler G10 parts (to fill voids and create rectangular coil shape). 1D model of the coolant (elliptical cross section 6x8 mm should be assigned to this line body).
- **c. Material properties**
    - i. Cooling medium = helium/hydrogen (as specified in the scenarios). Temperature dependent coolant parameters (density, thermal conductivity, heat capacity) are provided in the attached text files for coolant pressure of 60 bar (see the requested cooling scenarios below).
    - ii. OFHC copper 10700 as the conductor of CS coil, fiberglass reinforced epoxy insulation (CTD101-K) and G10 glass-fiber laminate as void fillers.
    - iii. OFHC copper: Values of density, Young modulus, Poisson ratio and Yield strength are provided for an average temperature of 120K (the temperature dependence for these quantities is considered either small or not important for the calculation). Necessary temperature dependent quantities of thermal conductivity, specific heat and coeff. of thermal expansion are provided in a separate data file.
    - iv. CTD101-K (fiberglass reinforced epoxy insulation): Values of density, Young modulus, Poisson ratio and flexural modulus are provided for an average temperature of 120K (the temperature dependence for these quantities is considered either small or not important for the calculation). Necessary temperature dependent quantities of thermal conductivity, specific heat and coeff. of thermal expansion are provided in a separate data file. Note that CTD101-K will use orthotropic thermal properties. Description of the insulation layers direction can be found on Fig.2. below.
    - v. G-10: Again, quantities with small temperature dependence are provided as a constant for temperature of 80K (significant heat-up of the G10 parts is not anticipated). Necessary temperature dependent quantities are provided in a

separate data file. For the purpose of this model, G-10 is assumed to be isotropic material.

Table 1: Material properties

Material	Material property	Value
OFHC copper	ρ [kg/m³]	9009
	λ [W/(m•K)]	data file[2]
	c_p [J/(kg•K)]	data file[2]
	CTE [K^{-1}]	data file[2]
	E [GPa]	122
	YS [MPa]	304[1]
	E_T [GPa]	0
	ν [-]	0.31
G10	ρ [kg/m³]	1850
	λ [W/(m•K)]	data file[3]
	c_p [J/(kg•K)]	data file[3]
	CTE [K^{-1}]	data file[3]
	E [GPa]	20.6
	ν [-]	0.35
	G [GPa]	8.6
CTD101-K	ρ [kg/m³]	1850
	λ [W/(m•K)]	data file[4]
	c_p [J/(kg•K)]	data file[4]
	CTE [K^{-1}]	data file[4]
	E [GPa]	16.7
	ν [-]	0.3
	G [GPa]	27.9

d. Boundary conditions

i. Thermal calculations

- Coolant inlet is at the outer coil radius, outlet at the inner radius.
    - target outlet temperature = 80K (but due to minimum coolant temperature of 80K, this cannot be achieved in reasonable time, therefore the analysis will be limited to certain time)
    - coolant inlet temperature = coolant outlet temperature – dT
    - coolant mass flow = mFlow
- Convection BC between helium and inner wall of the cooling channel with temperature dependent heat transfer coefficient (HTC).

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[1] Bi-linear model is required
[2] See attached data file *Cu_material_data.csv*
[3] See attached data file *G10_material_data.csv*
[4] See attached data file *CTD101K_material_data.csv*

ii. Structural calculations

Contacts

- All contacts within the coil (Cu - insulation - G10) are bonded
- Coil is sitting between two ideal infinitely stiff surfaces, which exert a vertical compressing force of 4 MN on the coil. (one of the surfaces is fixed, the second one is pushing on the coil).
- Frictional contact between the coil and the idealized surfaces with frictional coefficient 0.4

e. Cooling scenarios

i. Scenario A

- Copper conductor heat-up to 120K, insulation and G10 stays on 80K
- Cooling medium is gaseous helium, pressurized to 60bar, mass flow 12g/s
- Inlet coolant temperature = max(outlet coolant temp - 40K;80K). This means the inlet coolant temperature will dynamically change according to outlet coolant temperature with dT=40K, but will be limited to lowest value of 80K.
- Run analysis for 60 minutes of cooldown
- HTC [W/m2/K] provided in data file *htc_scenario_a.txt*

ii. Scenario B

- Copper conductor heat-up to 160K, insulation and G10 stays on 80K
- Cooling medium is gaseous helium, pressurized to 60bar, mass flow 12g/s
- Inlet coolant temperature = max(outlet coolant temp - 40K;80K). This means the inlet coolant temperature will dynamically change according to outlet coolant temperature with dT=40K, but will be limited to lowest value of 80K.
- Run analysis for 120 minutes of cooldown
- HTC [W/m2/K] provided in data file *htc_scenario_b.txt*

iii. Scenario C

- Copper conductor heat-up to 160K, insulation and G10 stays on 80K
- Cooling medium is gaseous hydrogen, pressurized to 60bar, mass flow 9.5g/s
- Inlet coolant temperature = max(outlet coolant temp - 40K;80K). This means the inlet coolant temperature will dynamically change according to outlet coolant temperature with dT=40K, but will be limited to lowest value of 80K.
- Run analysis for 60 minutes of cooldown
- HTC [W/m2/K] provided in data file *htc_scenario_c.txt*

3. Deliverables

a. **Intermediate report:**
provide intermediate report (in form of presentation) after calculation of the first scenario A is performed:
   i. Presentation in English
   ii. Analysis results
      - scenario A
      - time evolution of the temperature in the body of the coil and coolant
      - von Mises stress and deformation in the coil conductor
      - First principal stress, shear stress and deformation of the insulation and G10 parts
   iii. Provide all files (.doc, .xls, .ppt, ...) constituting the report

b. Final report
   i. Presentation in English
   ii. Analysis results
      - all scenarios
      - time evolution of the temperature in the body of the coil and coolant
      - von Mises stress and deformation in the coil conductor
      - First principal stress, shear stress and deformation of the insulation and G10 parts
   iii. Provide all files (.doc, .xls, .ppt, ...) constituting the report
   iv. Provide all files (ANSYS, ...) constituting the modelling and results

Attachment: figures

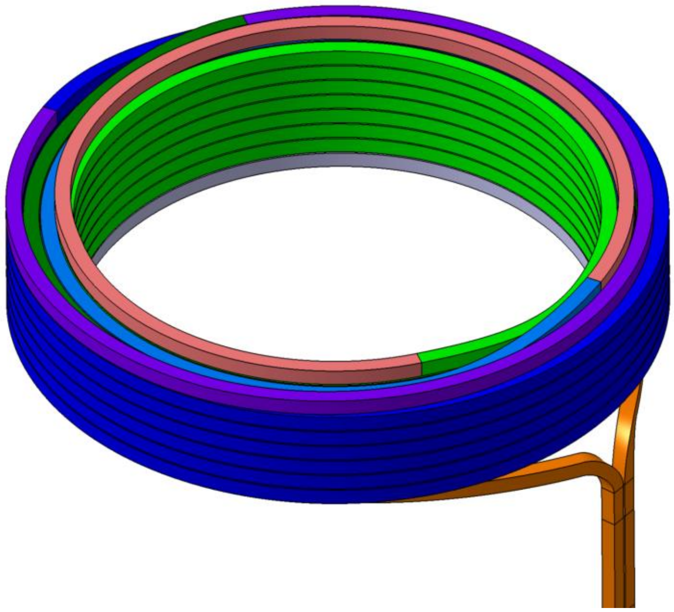

Fig.1: A model of central solenoid coil with parallel leads

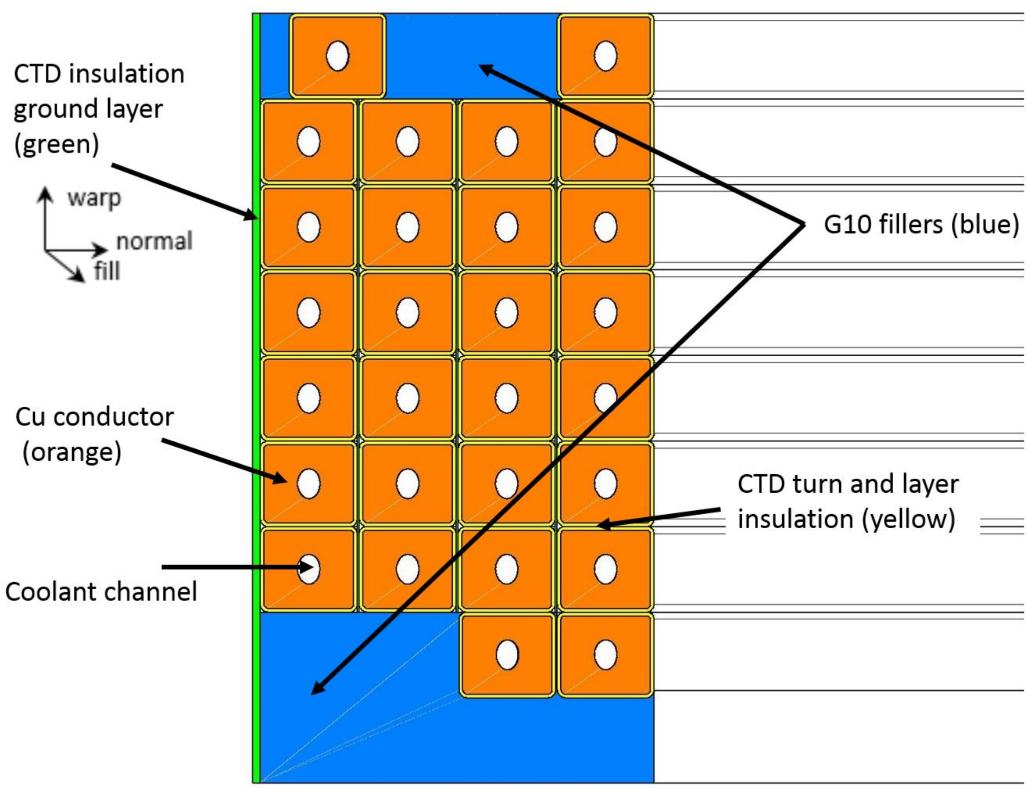

Fig. 2: Schematic cross-section of CS coil with described materials
and orthotropic insulation wrap directions

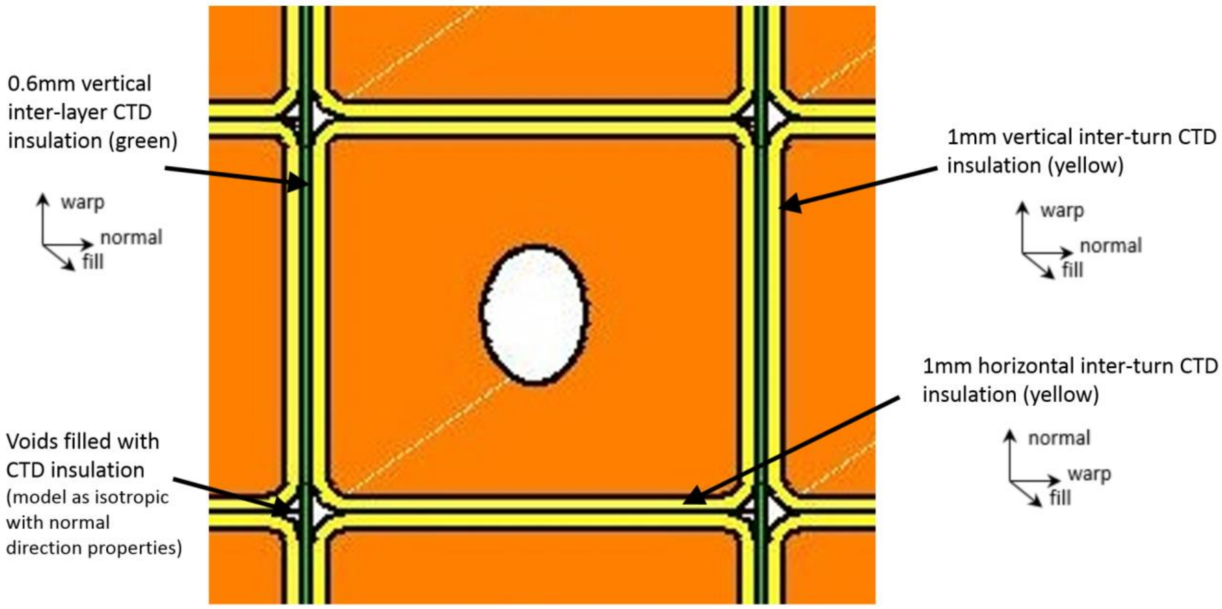

Fig. 3: Detail of inter-turn and inter-layer insulation with insulation wrap directions

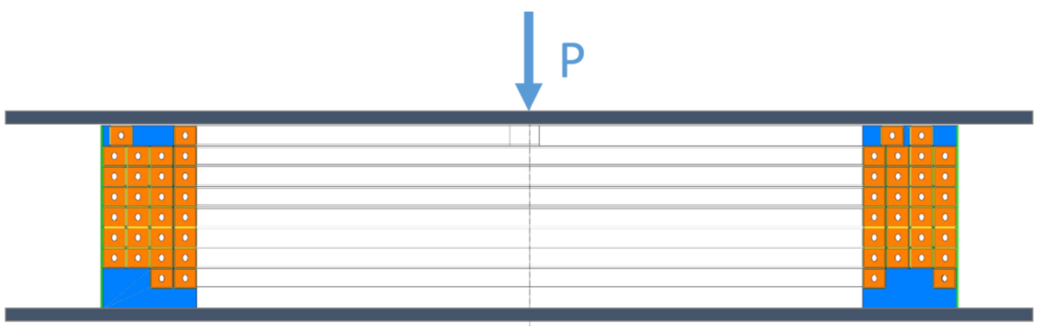

Fig. 4: Idea of the coil compression - coil placed between 2 infinitely stiff surfaces. Lower surface is fixed; upper surface is pushing on the coil with force P = 4 MN.