EM + thermal analysis of PF4U coil

1. Scope

a. The aim of the analysis:

The aim is to simulate the combined effect of worst-case electromagnetic and thermal loading of PF4U coil. Full 3D geometry of the coil will be modelled. Electromagnetic forces for 3 worst case plasma scenarios (baseline, 6500, 7500) will be used, together with thermal load of the coils. The analysis should provide deformation and stresses in the coil conductor and insulation. The calculation is requested for 3 different electromagnetic loading scenarios.

b. Details of PF2 coil:

PF4U coil (see Fig.1) is a high power tokamak coil wound in toroidal direction, creating a poloidal magnetic field inside the vacuum vessel to shape the plasma. It carries large electric currents in the range of -30 to +30 kA and is placed in the region of strong magnetic fields, resulting in significant material stresses. It is made of OFHC alloy silver bearing copper conductor insulated by fiberglass-reinforced epoxy resin composite CTD101K (schematic cross-section of the coil, describing the layout of insulation is shown in Fig.2. and Fig.3.). The coil will be actively cooled through an internal conductor cooling channel by gaseous helium to liquid nitrogen temperature (80 K) in order to reduce its el. resistivity. Machine protection system will be designed to allow a maximum temperature increase of the coils by 80 K (i.e. up to 160 K) during a discharge. Both the electromagnetic forces (created by the coil itself as well as other coils and plasma) and coil heat-up during a discharge will induce significant stresses in the conductor and insulation. PF4U coil comprises 37 turns in 5 radial layers (5 x 8 turns layout with voids due to turn-to-turn transitions). It has a central diameter of 1.43 m and total length of the conductor is approx. 330 m. The coil is supported from top and bottom by 16 toroidally distributed holders (see Fig.4). The coil is sitting on special metallic pads with a low friction surface, allowing the coil to expand freely in radial direction.

c. Description of the model

Geometry file of the coil and insulation and holders (.step) will be provided by IPP.
The supplier will prepare the electromagnetic forces for 3 requested scenarios from given block geometry of all surrounding magnetic coils and plasma and their respective electric currents (see Fig.5).
The coil holders will be modelled as infinitely stiff material, serving to pre-compress and secure the coils in vertical and toroidal direction, while allowing radial coil expansion.

<u>The loading steps will be applied as follows:</u>

1. Each of 16 holders: the upper holder surface will push on the coil by 100 kN force to pre-compress it, while the lower holder surfaces will be fixed.
2. Cool down the whole structure (coil conductor + insulation) from the room temperature of 300 K (no stress reference) down to 77 K.

3. Apply EM forces acting on the coil conductor
4. Heat-up the coil conductor only (not insulation) to 160 K

2. Input documentation to start and realize activity

a. Type of analysis:

i. Coupled electromagnetic-thermal-structural static analysis

b. Geometry

i. Geometry file of the coil and insulation (.step) will be provided.

ii. 3D model of PF4U 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). 3D model of 16 toroidally distributed coil holders (modelled as infinitely stiff material).

c. Material properties

i. OFHC copper 10700 as the conductor of CS coil, fiberglass reinforced epoxy insulation (CTD101-K) and G10 glass-fiber laminate as void filler.

ii. OFHC copper: values of density, Young modulus, Poisson ratio, Yield strength and coeff. of thermal expansion (CTE) provided.

iii. CTD101-K (fiberglass reinforced epoxy insulation): values of density, Young modulus, Poisson ratio, Flexural modulus and coeff. of thermal expansion (CTE) are provided. CTD101-K is orthotropic material, with significantly different thermal expansion in the fiberglass plane and in the normal direction - therefore CTE values will be provided as orthotropic. Description of the insulation layers direction can be found on Fig.2. below.

iv. G-10 void fillers: values of density, Young modulus, Poisson ratio, Flexural modulus and coeff. of thermal expansion (CTE) are provided. For the purpose of this model, G-10 is assumed to be isotropic material.

Table 1: Material properties

Material	Material property	Value
OFHC copper half-hard	ρ [kg/m^3]	9009
	CTE [K^{-1}]	data file[1]
	E [GPa]	122
	E_T [GPa]	0
	YS [MPa]	304[2]
	v [-]	0.306
G-10	ρ [kg/m^3]	1850
	CTE [K^{-1}]	data file[3]
	E [GPa]	20.6
	v [-]	0.35
	G [GPa]	8.6
CTD101-K	ρ [kg/m^3]	1850

[1] See attached data file *Cu_CTE.csv*

[2] Bi-linear model is required

[3] See attached data file *G10_CTE.csv*

	CTE [K^{-1}]	data file[4]
	E [GPa]	16.7
	v [-]	0.3
	G [GPa]	27.9

d. **Boundary conditions: Contacts**
   i. All contacts within the coil (Cu - insulation - G10) are bonded
   ii. Coil is sitting between 16 toroidally distributed holder structures. Each holder is to be taken as infinitely stiff. Each upper holder surface exerts a vertical compressing force of 100 kN on the coil, the lower surface on which the coil is sitting is fixed. This way, vertical coil movement is restricted.
   iii. Toroidal coil movement (rotation) should be forbidden in the model.
   iv. Frictional contact between the coil and the upper and lower holder surfaces with frictional coefficient 0.05

Deliverables

Intermediate report

provide intermediate report (in form of presentation) after calculation of the first electromagnetic loading scenario is performed:

- Presentation in English
- Analysis results (first scenario)
- von Mises stress and deformation in the coil conductor
- Through thickness (normal) stress, shear stress and deformation of the insulation and G10 parts
- Provide all files (.doc, .xls, .ppt, ...) constituting the report

Final report

- Presentation in English
- Analysis results (all 3 scenarios)
- von Mises stress and deformation in the coil conductor
- Through thickness (normal) stress, shear stress and deformation of the insulation and G10 parts
- Provide all files (.doc, .xls, .ppt, ...) constituting the report
- Provide all files (ANSYS, ...) constituting the modelling and results

[4] See attached data file *CTD101K_CTE.csv*

Attachment: figures

Fig.1: Realistic model of poloidal field coil PF4U.

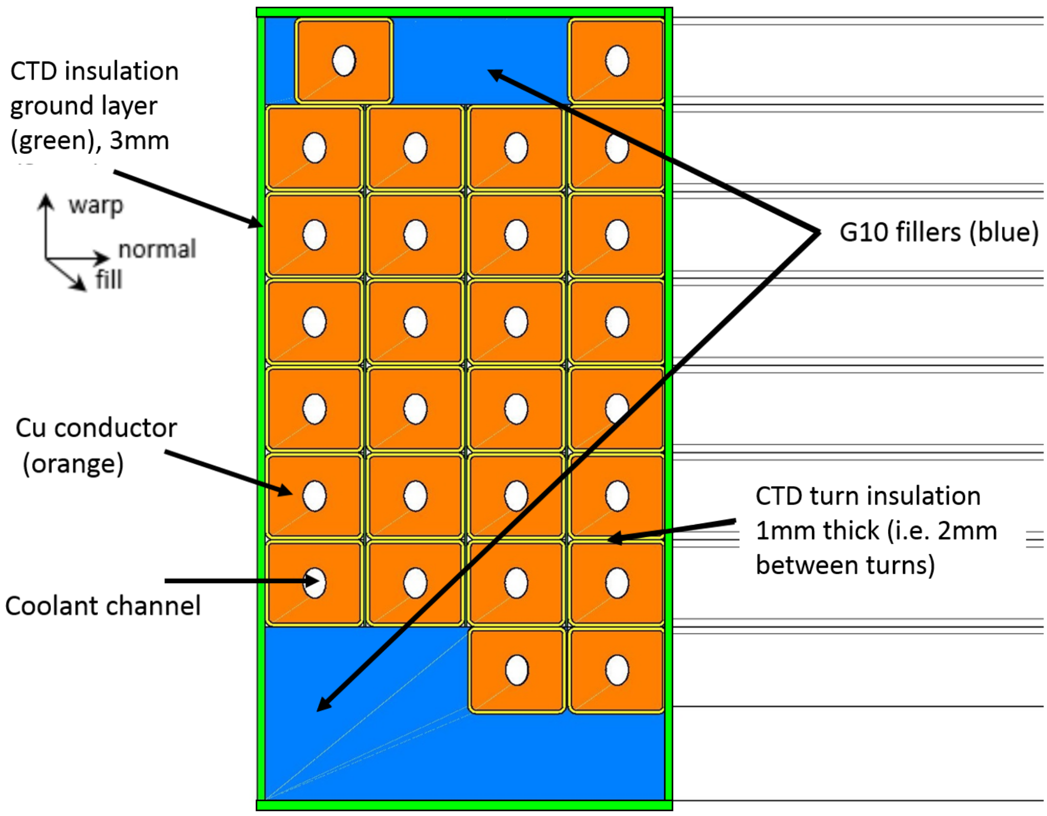

Fig. 2: (left) Schematic cross section of the PF4U coil. Scheme of the insulation layers: (1) inter-turn, (2) ground.

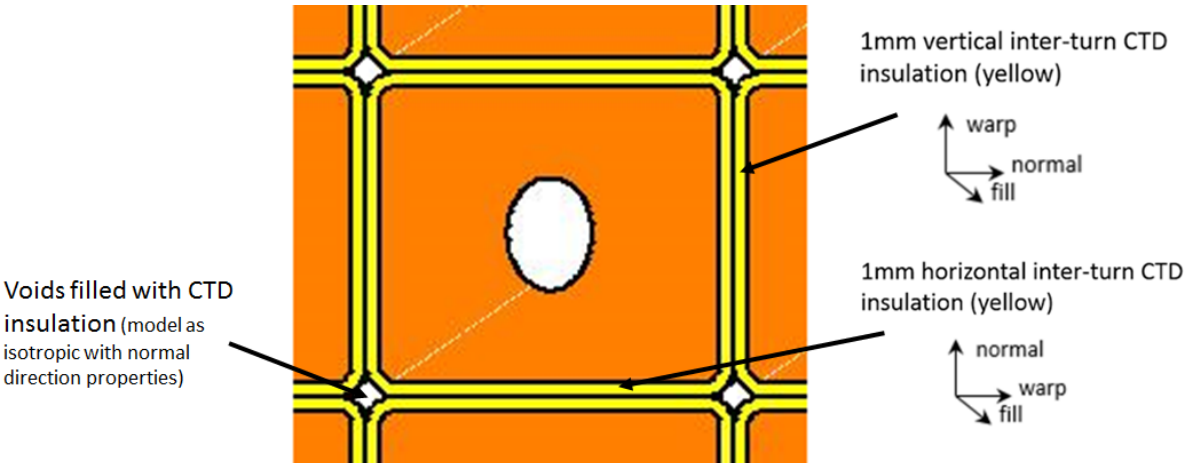

Fig. 3: Detail of inter-turn insulation with insulation wrap directions

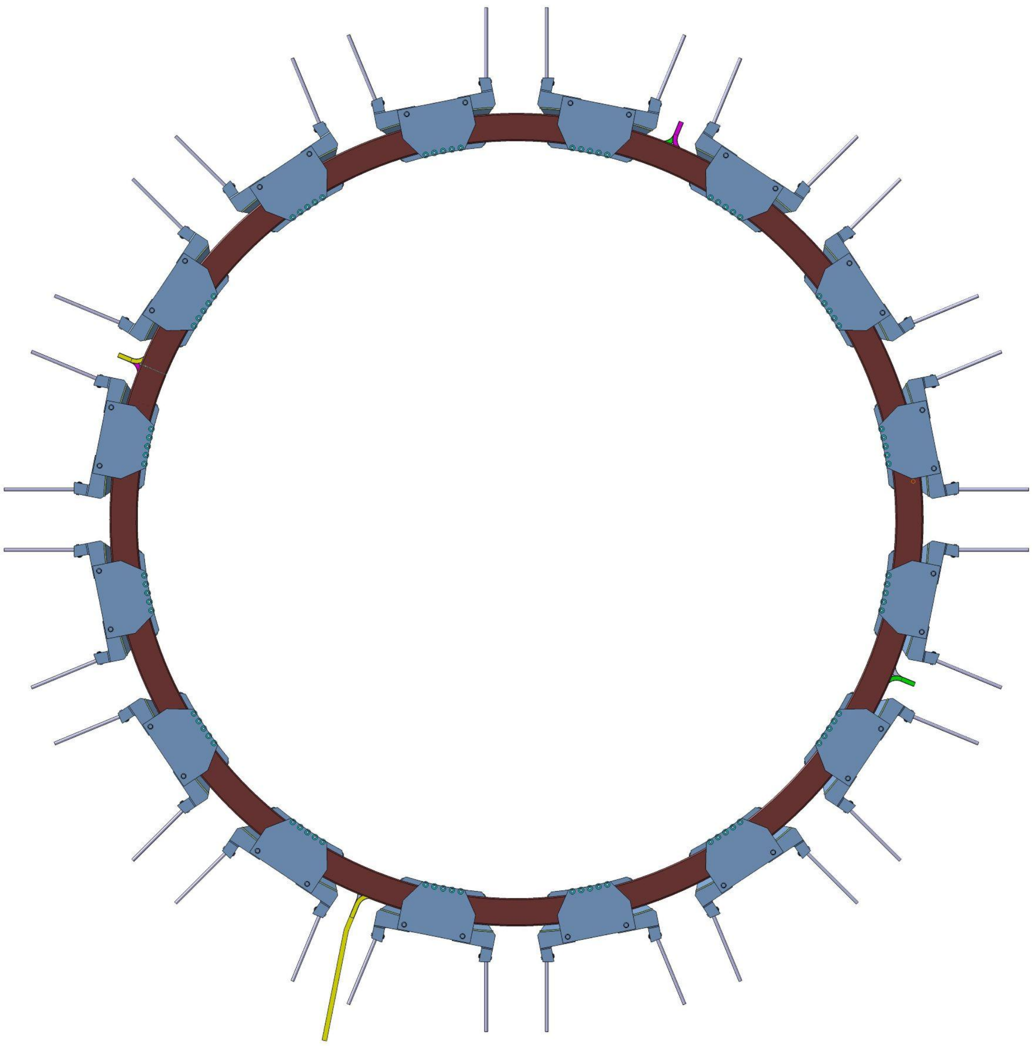

Fig. 4: Top view of the realistic model of PF4U coil with its 16 holders
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Fig. 5: Poloidal cross section showing positions of Central Solenoid (CS) coils, Poloidal Field (PF) coils, one toroidal field (TF) coil and plasma (can be considered as a single-turn coil).