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Finite Element Analysis of CICC Joints in SST-1

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Abstract. We have analysed the newly designed CICC joints in SST-1 using finite element method for their in-situ performance in SST-1 operation. Cool-down characteristics, thermo-structural stresses due to cool-down and electromagnetic forces, electrical resistance characteristics have been investigated. These results will be discussed in this paper.

1. Introduction
One of the most critical components of SST-1 Magnet System is the joint between Cable-in-Conduit-Conductor (CICC) terminations. There are 115 such joints in SST-1 magnet. Successful operation of the Magnet System is thus highly dependent on reliable joints design and fabrication. In order to assess the possible failures and to increase the reliability of the design, detailed structural, thermal, electrical and electromagnetic analyses have been done in this report using the commercial software Ansys [1] based on finite element method.

2. Design details of CICC joint
Two lugs of made of OFHC copper (RRR=100) with dimensions 320X28X18 mm are used to make the lap-type joint. Each of these lugs has long square bore to insert the superconducting wires (after removing the SS conduit of CICC) and solder them. At a distance of about 40 mm a SHe inlet stub is provided as shown in the below figure-1.

![Figure 1. Conduction cooled lap-type joint](image)
3. Electrical analysis

In the above shown lap type joint OFHC copper blocks are overlapped by a length of 300 mm, soldered on 28X300 mm surface contact area. In order to calculate the exact electrical resistance of this type of joint, a detail finite element analysis has been done. In this analysis at temperature the following material properties are used.

| Material            | Resistivity At 4.5 K | Resistivity At 300 K |
|---------------------|----------------------|----------------------|
| OFHC Copper         | 1.65x10^{-10} Ω-m    | 1.65x10^{-8} Ω-m     |
| Solder              | 1x10^{-9} Ω-m        | 2.5x10^{-9} Ω-m      |
| NbTi Superconductor | 1x10^{-17} Ω-m       | 1.65x10^{-8} Ω-m     |

The Element SOLID69 is used for the 3-D modelling of solid structure with elements as shown in the figure 2. SOLID69 has a 3-D thermal and electrical conduction capability. The element has eight nodes with two degrees of freedom, temperature and voltage, at each node. The thermal-electric solid element is applicable to a 3-D, steady state or transient thermal analysis.

The current density profile is shown in the figure-3 and 4. Most of the current is driven through the superconducting path as expected. For the elements at the outlet, these normal current density values are multiplied with cross section area to calculate the total current for an applied voltage of 1 Volt across the joint. From the Ohm’s law, the total resistance of the joints is calculated to be 0.384 nΩ at 4.5 K and 7.745 µΩ at 300 K.
4. Transient thermal analysis

The lap type joint proposed here is conduction cooled type i.e. SHe will not flow through the joint but reaches up to both ends and diverted through a separate path. It is very essential to see whether the design parameters will ensure the conduction cooling i.e. whether conduction cooling is sufficient to cool the whole length of joint up to the operation temperature. A detailed 3D transient thermal analysis has been carried out to validate this.

SOLID70 element is used to model the problem as shown in the figure-5. This element has a 3-D thermal conduction capability. It has eight nodes with a single degree of freedom, temperature, at each node. The element is suitable for 3-D, steady state or transient thermal analysis. In order to simulate the radiation load on the joint, SURF152 elements are used with emissivity e=0.25 and form-factor ‘1’ (worst case condition) with surrounding temperature 80 K. SURF152 allows for radiation between the surface and an extra node. Material properties of copper (RRR=100) are taken from NIST program.
4.1. Case-I
In the first analysis, in order to see the feasibility of purely conduction cooling from room temperature to operating temperature of 4.5 K, the model is analyzed with both boundaries at 4.5 K and rest of the volume at 300 K as the initial condition. Only radiation from 80 K surrounding is applied as the external load. The final saturation temperature after 400 sec. on the joint is as shown in the below figure-6.

It is clear from the above figure that the entire joint can be cooled down to ~ 4.5 K with very small gradients of order of 0.05 K. The cool-down curve for a mid node is plotted in the figure-4. In 240 sec, the temperature reaches to ~ 4.5 K. This analysis establishes the validity of the conduction-cooled design of the lap-type joint without current.
4.2. Case-II
In the second case, after reaching the operation temperature of ~ 4.5 K, we have added the joule heating effect also in the analysis. In the most pessimistic case if the joint resistance is 5 nΩ, the joule heating will be 0.5 W. This heat load is added as an extra internal uniform heat generation load (which corresponds to 1993.62 W/m³) in the entire copper lugs. The temperature profile on the joint after 350 sec. is shown figure-8. The temperature at mid-point of the joint oscillates around a T~ 4.65 K and finally saturates at T~ 4.655 K as shown in the figure-9.

The above transient thermal analysis shows that the newly proposed conduction cooled lap-type joint is a well valid design, which can sustain the operating conditions.
Temperature fluctuations around T=4.655 K at mid-point on the joint

5. Thermo-structural analysis

The joint termination on the SST-1 coils are as shown in the figure-9. It is subjected to thermo-structural stresses during the cool-down. To assess the possible structural & thermal stresses that may arise, a detail finite element analysis has been done.

There are stresses due to thermal contraction and attractive electromagnetic forces between adjacent cables. The weakest point in this jumper type structure is the brazing between the copper block and CICC cable.

The following material properties are used in this analysis.
Table 2. Material properties used in the analysis

| Material   | Property          | Value       |
|------------|-------------------|-------------|
| CICC       | Young’s Modulus $E_x$ | 19.48 GPa   |
| CICC       | $E_y$             | 19.48 GPa   |
| CICC       | $E_z$             | 101.43 GPa  |
| CICC       | Poisson’s Ratio $\nu_{xy}$ | 0.418     |
| CICC       | $\nu_{yz}$       | 0.2913      |
| CICC       | $\nu_{zx}$       | 0.0559      |
| CICC       | Coeff. of Thermal Expansion $\alpha_x$ | $1.136 \times 10^{-5}$ |
| CICC       | $\alpha_y$       | $1.136 \times 10^{-5}$ |
| CICC       | $\alpha_z$       | $1.066 \times 10^{-5}$ |
| OFHC copper| Young’s Modulus   | 139 GPa     |
| OFHC copper| Poisson’s Ratio   | 0.337       |

The Element SOLID226 is used for the 3-D modelling of solid structure with 3200 elements. This element has twenty nodes with up to five degrees of freedom per node. In addition to Structural-Thermal capabilities, it can also handle Piezo-resistive, Electro-elastic, Piezoelectric, Thermal-Electric, Structural-Thermoelectric and Thermal-Piezoelectric. However these additional properties are switched off in the analysis. The structural capabilities are elastic only and include large deflection and stress stiffening.

The total length of each cable in the model is 1.4 m and the distance between two adjacent parallel cables is 6 cm. For a maximum current of 10 kA, the total electromagnetic force is 466.66 N. This force is uniformly applied along the total length. The model is fully restricted at both ends and at the copper block in the middle.

![Finite element model of the joint termination on the TF coil](image)

Figure 10. Finite element model of the joint termination on the TF coil

In addition to electromagnetic attraction force as a structural load, thermal loads also applied with initial temperature of 293 K and final temperature as 4.5 K. Due to contraction, thermal stresses also generated in the model.
A maximum deflection of 4.9 mm is observed in the bottom part of the CICC as shown in the figure-11. A maximum stress of 574 MPa is observed at the junction of CICC-Copper block, which may be higher than the tolerable limit. A detail stress profile (von-Mises) is shown in the figure-12.

When we remove only the bottom restriction (which may be possible by providing spring type cushion at the bottom of coppers block of the joints), there is a maximum deformation of 5.77 mm in the downward direction due to thermal contraction as shown in the figure-16. For this it very clear that, if we allow it to contract freely in the downward direction, thermal stresses may reduce on the CICC-Copper block junction.

References
[1] ANSYS, Version 11, Ansys Inc.