CERN Summer Student Programme 2019

Summer Student Report

THERMO-MECHANICAL DESIGN ANALYSIS OF SUPERCONDUCTING RADIO-FREQUENCY (RF) CAVITY COMPONENTS AND CORRESPONDING CRYOMODULE.

Idd Mohamed Yunusu
Supervisors:
Eduardo Cano Pleite
Ofelia Capatina
ABSTRACT
Engineering Unit of the Mechanical Design Office is ongoing with the design of radio frequency (RF) cavity components and corresponding cryomodule for High Luminosity- LHC project. This report presents the Studying and running simulations for numerical analysis of RFD Support System based on the thermo-mechanical analysis. Studying and performing simulation for thermal analysis of RFD tuning system. Studying and performing simulation for thermal analysis of the cryomodule Cold-Warm Transitions (CWT).
# TABLE OF CONTENT

ABSTRACT .............................................................................................................................................. i
TABLE OF CONTENT ............................................................................................................................. ii
TABLE OF FIGURES ............................................................................................................................. iii
TABLES ................................................................................................................................................... iii

1. INTRODUCTION............................................................................................................................... 1
   1.1 THE CRYOMODULE AND CRAB CAVITIES .............................................................................. 1
   1.2 SCOPE OF ANALYSIS .............................................................................................................. 2

2. ANALYSIS MODELS AND METHODS ......................................................................................... 3
   2.1 MODELS ..................................................................................................................................... 3
   2.2 MESH ......................................................................................................................................... 5
   2.3 BOUNDARIES CONDITIONS ..................................................................................................... 5
   2.4 MATERIALS .............................................................................................................................. 6

3. RESULTS AND DISCUSSION ......................................................................................................... 8
   3.1 RESULTS .................................................................................................................................. 8
      3.1.1 TEMPERATURE DISTRIBUTION ...................................................................................... 8
      3.1.2 HEAT LOSS ......................................................................................................................... 9
      3.1.3 CONTRACTION .................................................................................................................. 9
   3.2 DISCUSSION ........................................................................................................................... 10

REFERENCES ......................................................................................................................................... 11
TABLE OF FIGURES
Figure 1: RFD Cryomodule................................................................................................... 1
Figure 2: Bunches colliding with (a) a crossing angle without crab crossing, (b) with the crab crossing................................................................................................................................. 2
Figure 3: RFD Support System.......................................................................................... 3
Figure 4: RFD cavity and the numerical model for the tuning frame............................... 4
Figure 5: Cryomodule parts and CWT simplified model.................................................. 4
Figure 6: Models mesh..................................................................................................... 5
Figure 7: Static structure of the RFD support system....................................................... 5
Figure 8: Boundaries condition....................................................................................... 6
Figure 9: Isotropic Thermal Conductivity of 316L(INOX) ........................................... 7
Figure 10: Isotropic Thermal Conductivity of Titanium.................................................. 7
Figure 11: Isotropic Thermal Conductivity of Niobium................................................... 8
Figure 12: Isotropic Thermal Conductivity of Ni-Ti....................................................... 8
Figure 13: Temperature distribution on the models......................................................... 9
Figure 14: Total deformation......................................................................................... 10

TABLES
Table 1: Heat loss in the models.................................................................................... 9
Table 2: Heat loss on the blades................................................................................... 9
Table 3: Heat loss on the blades................................................................................... 9
Table 4: Directional deformation of RFD Support System......................................... 10
1. INTRODUCTION
1.1 THE CRYOMODULE AND CRAB CAVITIES

Superconducting crab cavities are one of the key devices of the HL-LHC upgrade, a project that aims at achieving instantaneous luminosity a factor of five larger than the nominal LHC luminosity. The crab cavities provide a deflecting kick on the proton beam, maximizing the overlap at the collision points. The cavities are placed in a cryomodule and are cooled down to 2K with superfluid helium. A second circuit with helium gas at a temperature of 50 to 70 K is used to cool down the cryomodule. To limit the heat loss to 2K bath, and thus the consumption of superfluid helium, several of the main components are connected to the thermal shield, which is directly cooled with the secondary circuitry via copper braids that act as heat interceptors.

Below are some of cryomodule and its parts:

![Figure 1: RFD Cryomodule](image)

There are two different crab cavity concepts which have been developed: the Double Quarter Wave (DQW) and RF Dipole (RFD). Currently, two DQW crab cavity prototypes have been successfully fabricated and tested with the beam in the super Proton Synchrotron (SPS) at CERN in May 2018, whereas the prototyping stage of the RFD cavities is currently ongoing.

The LHC uses a 60 m common focusing channel plus 21 m common drift space and 20 m common dipole channel on each side of the interaction region, where the two counter – rotating beams have to be separated transversely to avoid parasitic collisions. The time – dependent transverse kick from an RF deflecting cavity is used to perform a bunch rotation, in the x –z plane or y –z plane depending on the crossing angle orientation, about the barycentre of bunch. Since luminosity
1.2 SCOPE OF ANALYSIS

This report presents the study and simulations for numerical analysis of RFD Support System based on the thermo-mechanical analysis. Also it presents the study and simulations for thermal analysis of RFD tuning system and Cold-Warm Transition (CWT). The results obtained from the numerical analysis of thermo-mechanical analysis, update of a detailed model of a radio-frequency coaxial line extracting RF power from a cavity cooled by superfluid helium at 2K to ambient temperature. Also it explains the assessment of the temperature distributions in the systems.
2. ANALYSIS MODELS AND METHODS

2.1 MODELS

Three parts in the cryomodule were analysed which are RFD support system, RFD tuner and the Cold-Warm Transition cavity.

RFD SUPPORT SYSTEM

The simplified model consist of two blades and FPC system which support the cavity as indicated in the model below. All these three supporting systems directly connect the cold mass to the cryomodule walls at room temperature to about 300 K. To reduce the heat loss by conduction, these components are thermally intercepted by helium gas circuit at about 80 K. The following is the RFD support system and the simplified model for analysis.

![Figure 3: RFD Support System](image)

RFD TUNER

This part provides the ability to tune and maintain crab cavity resonance through quasi-symetric elastic deformation to the cavity capacitive plates. It also provide the ability to detune and providing compensation for Lorentz Force detuning. Below is the simplified model for the RFD tuner used in analysis.
COLD-WARM TRANSITION (CWT)
CWT connects directly the cavity with the warm beam line by a stainless steel tube and a system of thermally intercepted bellows and fingers. The static heat loads at CWT comprise heat load by thermal radiation from room to cryogenic temperature through the vacuum chamber aperture and thermal conduction through the chamber walls.

Thermal and thermo-mechanical study on the components was done using Ansys Workbench 2.0 Framework version 17 and MathCad. Thermo-mechanical study on the RFD support system using Ansys, thermal analysis on the Cold-Warm-Transitions and analytical analysis without RF fingers section in the Mathcad. Thermal analysis of RFD tuner using Ansys.
2.2 MESH
The reference model used in the analysis were meshed with
- 867651 nodes for the CWT with an element size of 6.0mm,
- 1592027 nodes for the Support cavity with an element size of 5.0 and 8.0mm,
- 260910 nodes for RF tuner with an element size of 5.0mm

This mesh is considered good enough to correctly evaluate both the thermal and the thermo mechanical problems.

2.3 BOUNDARIES CONDITIONS
Figure 6 shows the boundary conditions and loads used for structural assessment of the cavity using FE analysis:
- Standard Earth Gravity
- Fixed support in the upper part between the cavity and the
- Point mass of about 250Kg attached to the bottom part due to the weight of the cavity carried within the box

Figure 6: Models mesh

Figure 7: Static structure of the RFD support system
The other boundary conditions of temperature on the models are presented on figure 7. The models are subjected to three different temperature involving room temperature, thermalization temperature and 2 K bath on different positions. The room temperature used is 300 K and thermalization temperature considered in this case is 80 K.

Figure 8: Boundaries condition

2.4 MATERIALS
There are a variety of materials used by the components. Table 1 includes the list of the materials and the relevant material properties used in the analysis presented in this report. The properties are extracted from CERN thermal calculation materials.

Table 1: Relevant material properties for numerical analysis

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [kg/m$^3$]</th>
<th>Young Modulus [GPa]</th>
<th>Poisson’s ratio [-]</th>
<th>$R_{p0.2}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Niobium RRR300</td>
<td>8600</td>
<td>106</td>
<td>0.38</td>
<td>60</td>
</tr>
<tr>
<td>Stainless steel 1.4429 (316LN)</td>
<td>7950</td>
<td>196</td>
<td>0.27</td>
<td>280</td>
</tr>
<tr>
<td>55Ti-45Nb</td>
<td>6360</td>
<td>73</td>
<td>0.38</td>
<td>410</td>
</tr>
<tr>
<td>Titanium, Gr. 2</td>
<td>4510</td>
<td>102</td>
<td>0.34</td>
<td>280</td>
</tr>
<tr>
<td>CuBe 17410</td>
<td>8250</td>
<td>125-130</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>8950</td>
<td>117</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following materials are expressed with their thermal conductivity.

a) Stainless steel (316L, INOX)
Most of the parts in the models are made of stainless steel from the parts exposed to room temperature to the parts joining the 2K bath region except for the parts at 2K bath region. The parts are FPC system, blades, bellows and SS tubes.
Figures 9 and 10: Isotropic Thermal Conductivity of 316L(INOX) and Titanium

b) **Titanium**
The parts at 2K bath region are made of titanium, it involves the helium vessel and the cold magnet shield parts.

c) **Niobium**
Niobium has been used in the RFD support system in the FPC parts system
d) 55Ti-45Nb

3. RESULTS AND DISCUSSION
Due to the difference in thermal conductivity of the materials dependent on temperature in the parts, each part contracts and expands differently from each other. The analysis based on thermal and thermo-mechanical calculations to evaluate heat loss and contraction of the supports, predicting the potential tilting of the He vessel during cool-down resulted in the following results.

3.1 RESULTS
3.1.1 TEMPERATURE DISTRIBUTION
The temperature distribution in the models at steady state conditions are as shown in Figure 13.
3.1.2 HEAT LOSS

Table 2: Heat loss in the models

<table>
<thead>
<tr>
<th>Part</th>
<th>Heat loss (W) to 2K</th>
<th>Heat loss (W) to 80K</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFD support system</td>
<td>0.64</td>
<td>11.92</td>
</tr>
<tr>
<td>RFD tuner</td>
<td>0.47</td>
<td>3.61</td>
</tr>
<tr>
<td>CWT</td>
<td>6.89</td>
<td>24.18</td>
</tr>
</tbody>
</table>

Heat loss in the RFD support system with different boundary conditions

i. FPC at thermalization temperature of 80K and 10K

Table 3: Heat loss on the blades

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Heat loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.72</td>
</tr>
<tr>
<td>80</td>
<td>7.62</td>
</tr>
</tbody>
</table>

ii. FPC at thermalization temperature of 80K and 4K

Table 4: Heat loss on the blades

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Heat loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.72</td>
</tr>
<tr>
<td>80</td>
<td>7.62</td>
</tr>
</tbody>
</table>

3.1.3 CONTRACTION

Table 5 shows the directional deformation of the RFD support system in three different axis.
Table 5: Directional deformation of RFD Support System

<table>
<thead>
<tr>
<th>Directional deformation</th>
<th>Value mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X axis</td>
<td>0.58</td>
</tr>
<tr>
<td>Y axis</td>
<td>0.96</td>
</tr>
<tr>
<td>Z axis</td>
<td>1.37</td>
</tr>
</tbody>
</table>

The Figure 14 shows the total deformation of the RFD support system

![Figure 14: Total deformation](image)

3.2 DISCUSSION

i. The analysis of the CWT cavity was done using the single line in the cavity since the design of the other line is ongoing.

ii. The indicated results for the CWT is based on two symmetrical cavity in the cryomodule.

iii. The indicated heat loss for the RFD Support System was based on the 80K thermalization and 2 K of the blades only in the system.

iv. Although three different analysis condition of thermalization temperature was done on the FPC System of the RFD Support System, there was no influence of heat loss change in the blades.

v. The indicated results for the RFD Tuner is for the single RFD tuner.

vi. The heat loss at 2 K bath in the CWT is very large compared to the heat budget expected from the last expectations. It may has been contributed by the increase in thickness of bellows from 0.15 mm to 0.25 mm, the presence of RF fingers and use of Cu which is a good conductor.
REFERENCES

- C. Zanoni, Pressure assessment of the Helium Biphase Line for the Crab Cavities Cryomodule, EDMS n.1727787.
- J. Apeland, DQWCC instrumentation thermal loads, EDMS n. 1760706
- T. Capelli, RFD cryomodule design for SPS tests, International Review of the Crab Cavity for HL – LHC – 20/06/2019