Cool-Down Analysis of SSR1 Cryomodule

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Abstract

The superconducting cavities and, especially, the magnets in high intensity proton linac need to be aligned to the beam with typical transverse tolerance of $\pm$ 0.25 mm at the temperature of 2K. This is necessary to limit the emittance growth and minimize beam losses. The goal of the analysis is evaluating the displacement of target points through a finite elements analysis (FEA) model. Results will be used during alignment at room temperature in order to have all the bodies properly positioned at cold temperature.

Contents

I. Cryomodule and Main Component

The SSR1 Cryomodule is a section of PIP-II project This project consists in upgrading the existing linear accelerator (LINAC) at Fermiab to higher energies.

The SSR1 cryomodule (Figure 1) contains eight single spoke resonators operating at 325 MHz and four superconducting solenoids in sequence C-S-CC-S-CC-S-CC-S-C. It consists of an outer vacuum vessel, thermal shield, magnetic shield, support posts, helium chambers etc.

Strongback All of the cavities and solenoids will be mounted on individual support posts which are in turn mounted to a full-lenght strongback located between the vacuum vessel and the thermal shield. The strongback will be maintained at room temperature in order to minimize axial movement of the cold elements during cooldown reducing displacement of couplers, current lead and many internal piping components.

Support Post The support post are made of glass and epoxy composite tube and stainless steel rings. They are assembled using a shrink-fit technique in which the composite tube is sandwiched between an outer metal ring and inner metal disk. All the cavities and solenoids are mounted to the support posts using adjustable positioning mechanism.

Cavity and Tuners The single-spoken resonator accelerate protons in condition of continuos wave current and 2K temperature. Essentially composed by niobium cavity and helium vessel, each cavity has its own tuner. The tuner is used to keep the cavity in specified resonant frequency of 325 MHz.

Solenoid The four magnet packages in the cryomodule each containing focusing solenoids and two diapole correctors all opeating in a helium bath at 2K. A Beam Positioning Monitor (BPM) is incorporated into the solenoid magnet package. A bellow at each end of the beam tube will allow independent adjustment of each magnet.
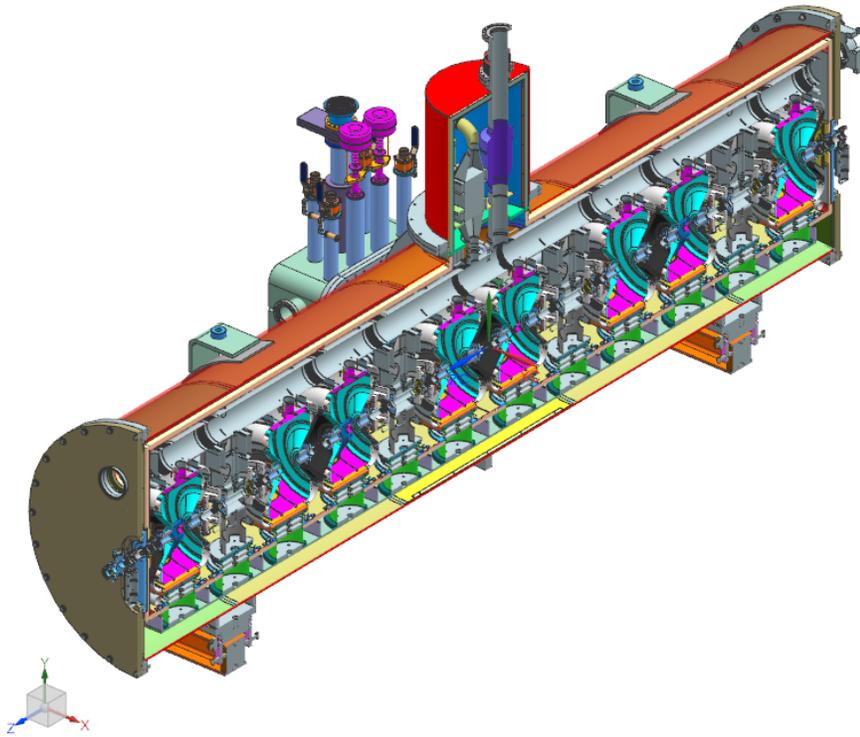
Figure 1: *A section view of the SSR1 cryomodule.*

Couplers   RF input couplers for accelerating cavities are passive impedance matching networks designed to efficiently transfer power from an RF power source to a beam-loaded cavity operating under ultra-high vacuum conditions and as transmission lines, coaxial or waveguide, are usually filled with gas, couplers have to have RF- transparent vacuum barriers (RF windows).

Current Lead   Each solenoid package contains three magnet coils, the main solenoid, operating nominally at 100A and two steering correctors each operating nominally at 50 A. Thermal intercepts at 45-80K and 5K reduce the heat load to 2 K, nonetheless, these current leads represent a significant source of heat at the low temperature end. on lead assembly for each magnetic element.

Pipelines   Cavities and magnets need to be cooled at 2K and 5K temperature and a helium distribution system is required. Pipelines are positioned around the coldmass into the vacuum vessel corresponding and include also bayonet, heat exchanger and many type of valves.
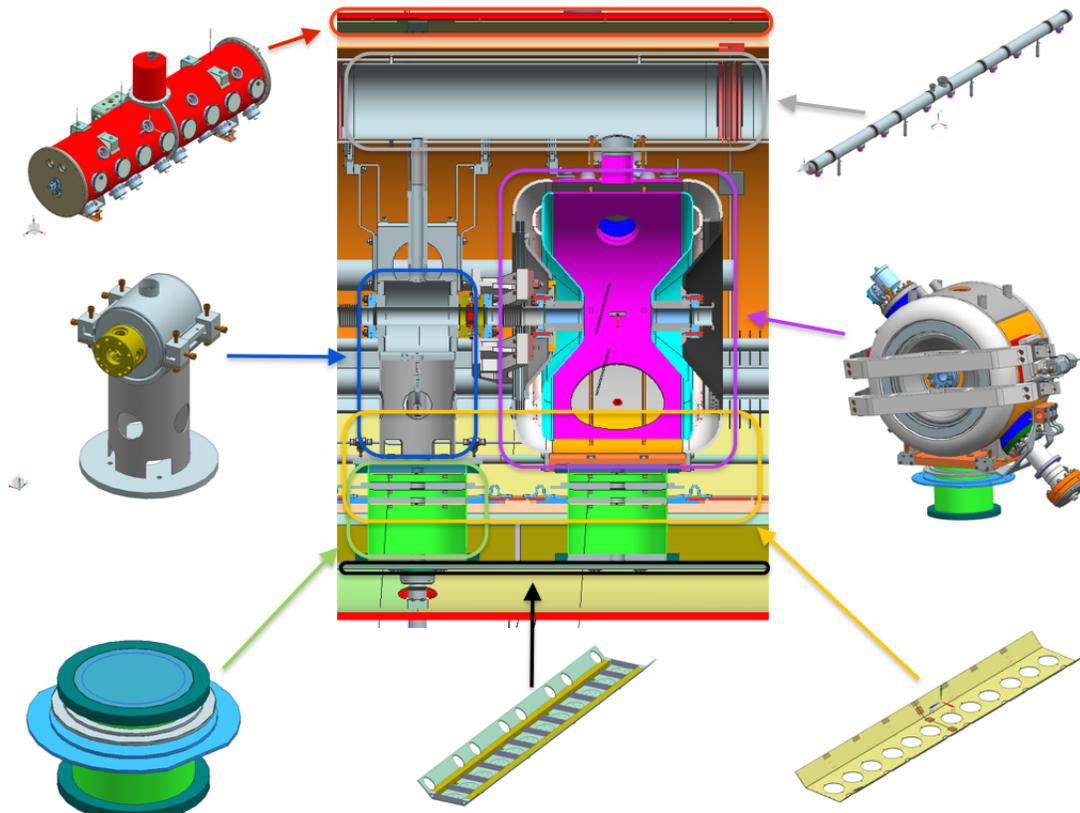
Figure 2: *Main Components of SSR1 Cryomodule.*

Thermal Shield   Cryomodule has a single thermal shield cooled with helium gas, nominally at 45÷80 K. It is an alumium alloy frame with cooling channels on both sides with two 15-layer blankets of MLI (Multi Layer Insulation), between the vacuum vessel and the thermal shield reduces the radiation heat load from the room temperature strongback.

Vacuum Vessel   The vacuum vessel serves to house all the cryomodule components in their as-installed positions, to provide a secure anchor to the tunnel floor, to insulate all the cryogenic components in order to minimize heat load to 80 K, 4.5 K and 2K, as well as maintain the insulating vacuum.

II.   ANALYSIS

In the evaluation of the shifts, only the thermal contraction of bodies is taken into account. Future analysis will consider gravity effects, vacuum force acting, deformation of the helium jacked due to cavity vacuum and liquid helium pressure that could affect the position of the target points.

I.   Project Scheme

The Finite Elements Analysis is performed using ANSYS® Workbench 16.1. The project scheme is composed by the data blocks (geometry and engineering data) and one steady-state thermal analysis linked to a static structural analysis (Figure 3).
The temperature map evaluated as a result of the first block is imported to the static structural analysis as setup. Thermal loads are applied step by step and the large deflection command in activated in order to simulated the cavity's bellow deformation. The results are the directional deformation of the target points evaluated in a Coordinate System fixed on the strongback with axes direction as in Figure 1 .
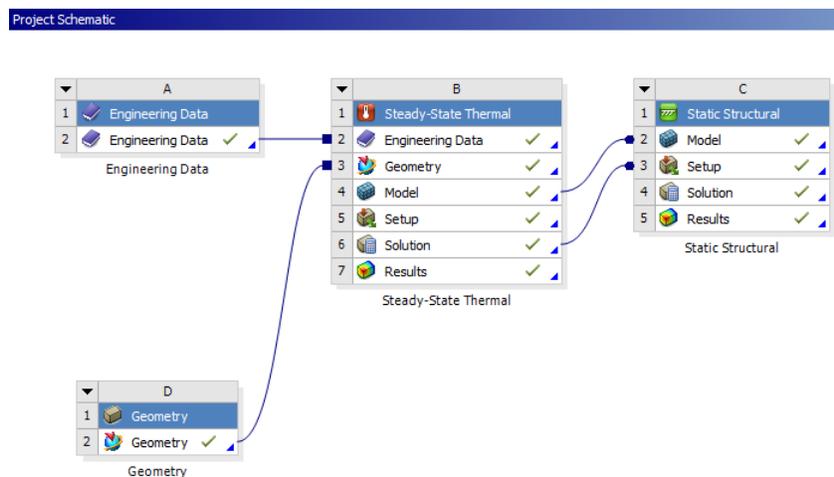In order to validate the results a mesh convergence analysis is done.

Figure 3: *Project scheme used in the analysis.*

II.   Simplified Cryomodule

The complete assembly was reduced to the main components: strongback, support post and cavities(Figure 4).

The selection is based on the stiffness of single component and how they are linked together. Vacuum vessel is not considered due to its no influence on the thermal-static analysis. The vacuum beam and helium pipelines have bellows (Figure 5(a)) so they do not affect the total stiffness of the structure. For the same reason the thermal shield is not included in the simplified model (Figure
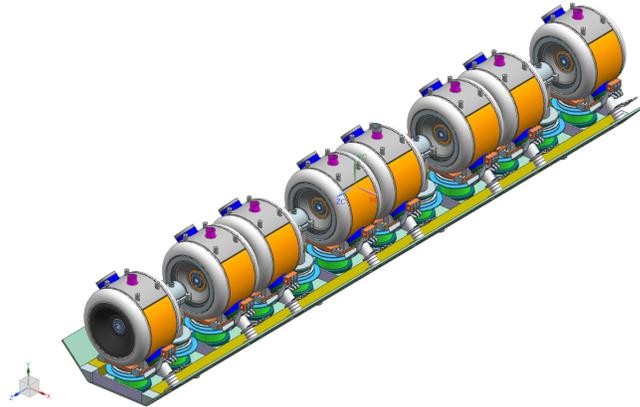
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Figure 4: *The simplified SSR1 cryomodule.*

5(b)). All the structural component that do not signitifically influence results are removed (i.e. magnetic shield, input coupler, BPM, current leads).
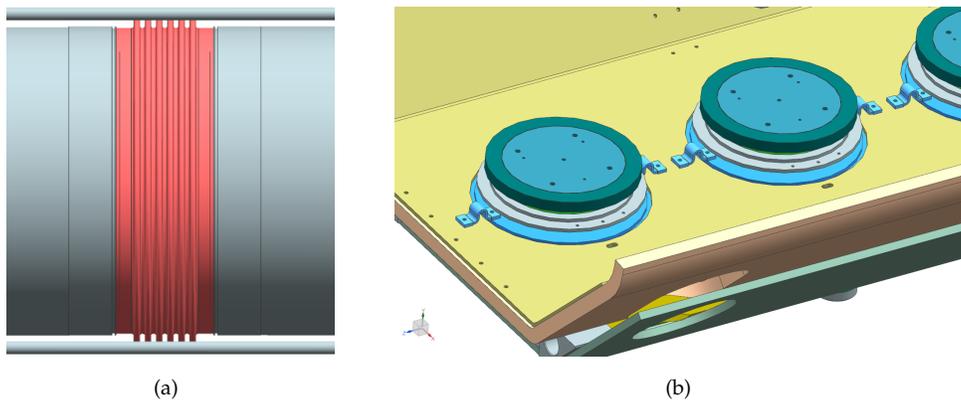

(a)   (b)

Figure 5: *Two example of low stiffness point.*

III.   Model

The geometry used in the simulation is one-half of the simplied cryomodule. A symmetrical boundary condition is applied to the cut surfaces of the strongback (plane x-y) and the lower surfaces of the supporting pins are constrained as fixed supports.

IV.   Temperature Map

In the steady-state thermal analysis, the temperatures are imposed as in Figure 6. The inner surfaces of the helium space and the solenoid chamber are cooled down at 2 K by helium, the
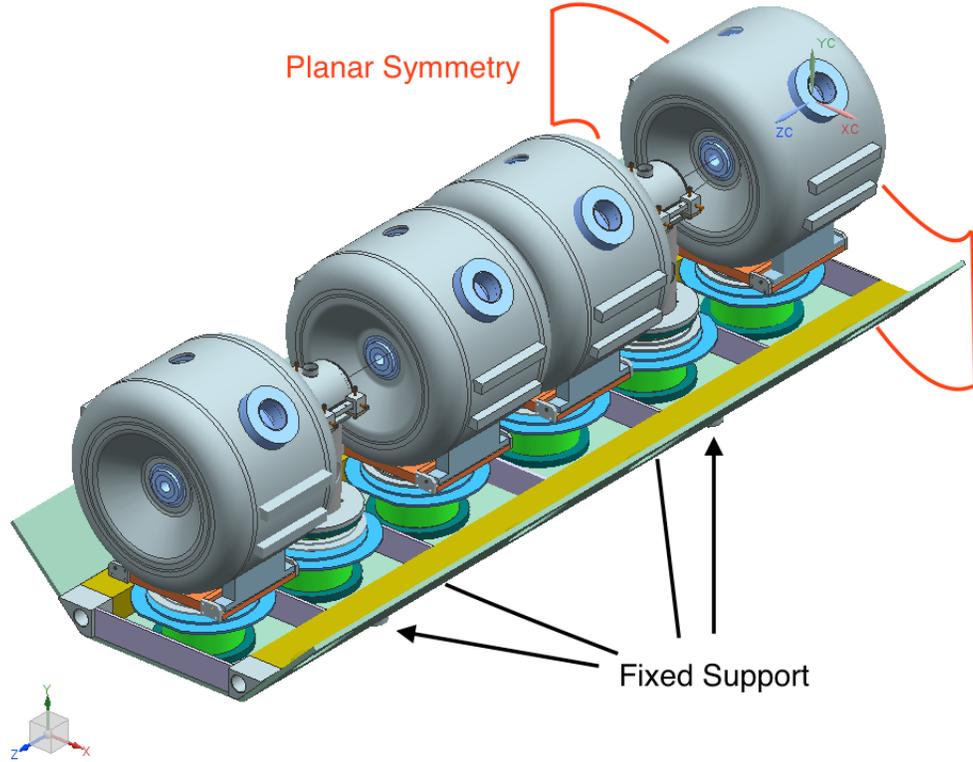
supporting post are at room temperature (293 K) and the thermal intercepts of the support post are at 5 K and 80 K.

V.   Materials Characterization

In order to numerically simulate the behavior of the bodies, the mechanical characteristic of the four materials in which cryomodule is made are presented in this section: Poisson ratio (Table 7) and Young's modulus (Figure 8) as Elastic properties, thermal expansion (Figure 9) and thermal conductivity (Figure 10) as thermal properties. Due to low temperature working environment of materials a cryogenic characterization of these is required. For each material is present the value or curve in a plot. Other consulted resources for comparison and validation are [1, 2, 3, 4].

Thermal contraction deserves a little explanation. When cooling down a material shrinks, when increasing the temperature it expands. It is worth to notice that most of the literature calls *thermal expansion* the change in length that the material undergoes when the temperature is reduced and provides a positive value. The thermal expansion data we present are defined as

$$\frac{L_{293} - L}{L_{293}} \tag{1}$$

Looking at the definition above it is clear that we will have a positive value when the temperature
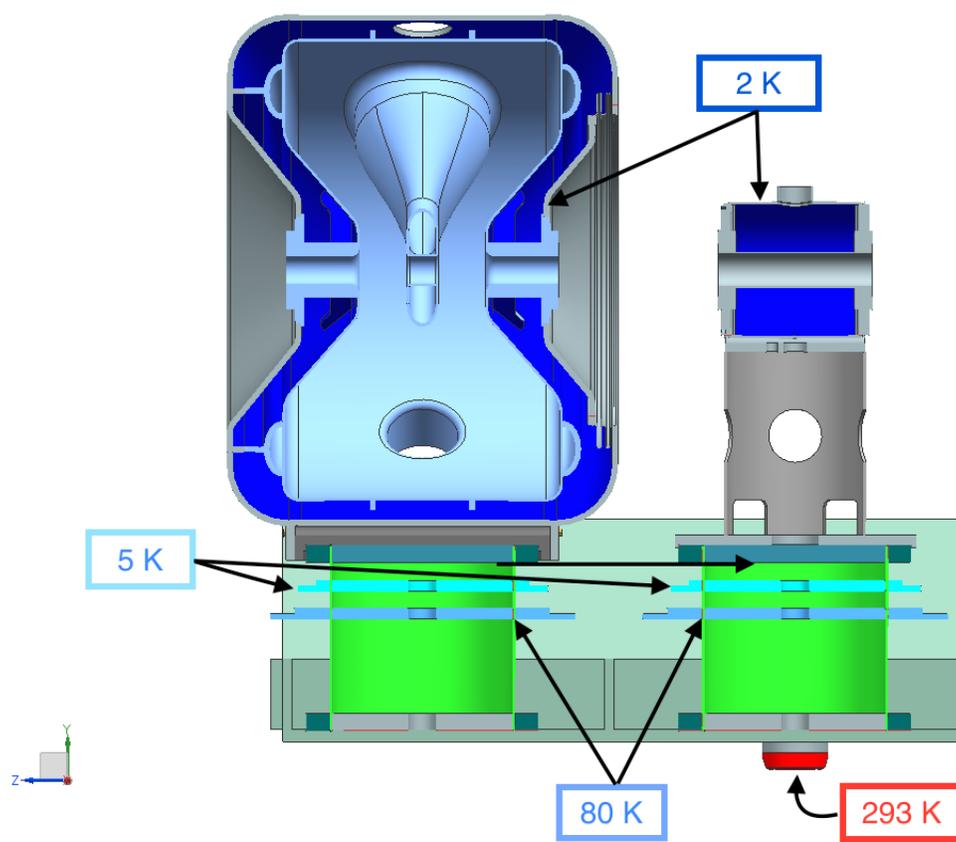
Figure 6: *The imposed temperature in the analysis*

is reduced, giving the misleading idea that there has been an increase in length of the specimen. For consistency the thermal expansion value for cryogenic applications should have a negative sign. We decided to follow the literature sources consulted: the change in length occurring at low temperature will be called thermal expansion and it will have a positive sign. However one should keep in mind that the material is actually shrinking.

VI.   Results

The target points of interest are twelve and are located on the center-point of the end flanges of cavities and solenoids (Figure 13). Points' name are assigned starting from the end resonator in progressive sequence as P_i with i = 1..12. In the following graphs point will be classified on their position: in cavities B are the bellows side points and A the no-bellow side points, magnets follows the sequence A-B-A-B-A-...

Material	Poisson's Ratio
Al 6061	0.30
Stainless Steel	0.31
G-10	0.30
Niobium	0.38

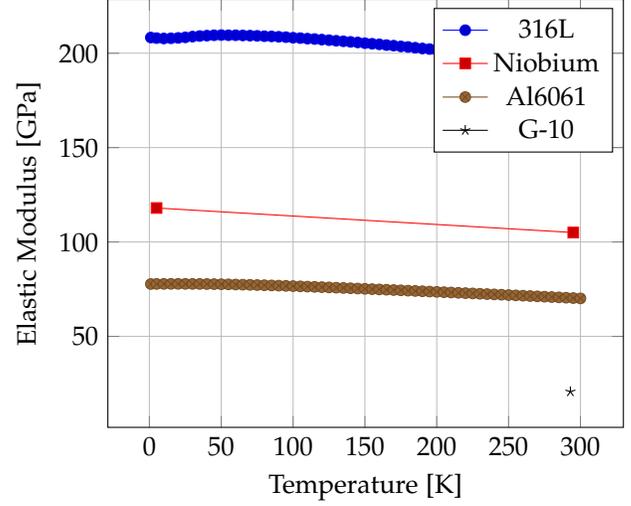**Figure 7:** *Poisson's Ratio values. The values are temperature independent.*

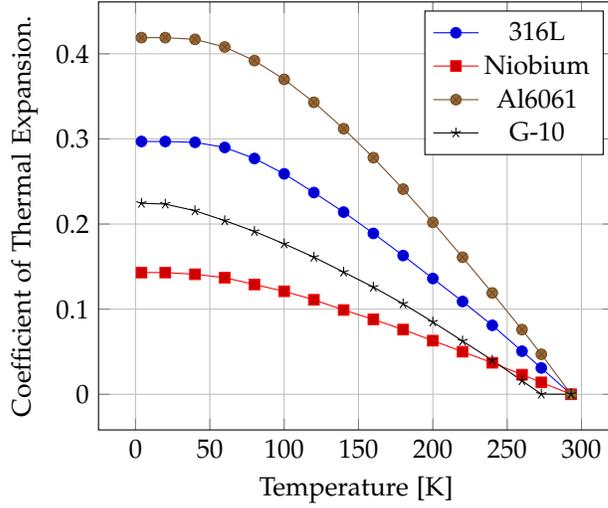**Figure 8:** *Relationship between temperature and Elastic Modulus.*

Figure 9: *Relationship between Coefficient of Thermal Expansion and Temperature.*
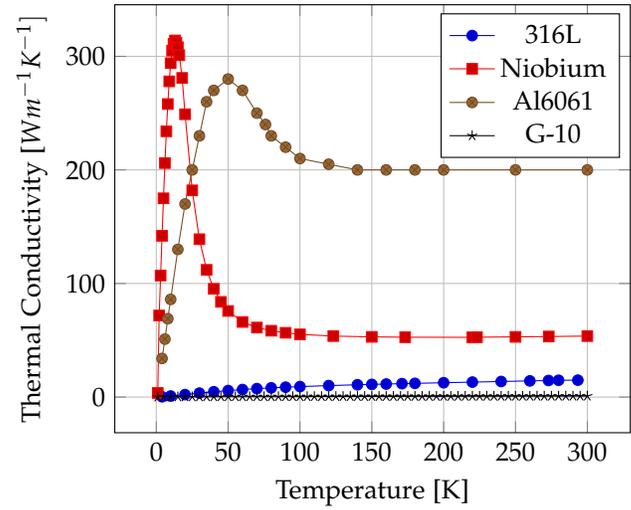
Figure 10: *Relationship between Thermal Conductivity and Temperature.*

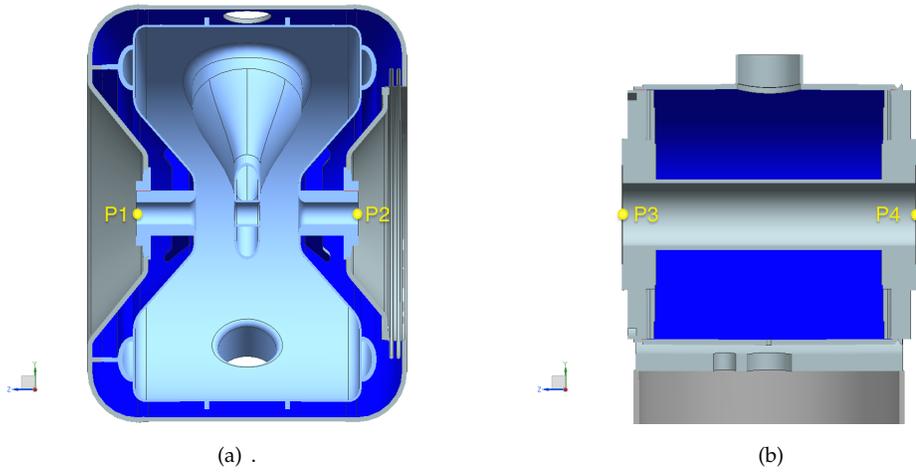**Figure 11:** *Material Properties of components of SSR1 Cryomdule.*

(a) .

(b)

Figure 12: .

Figure 13: *Target Points of cavities and solenoids.*

i	P_i		
	δ_x	δ_y	δ_z
1	3.45×10^{-2}	-1.12	-0.777
2	5.97×10^{-2}	-1.14	2.63×10^{-2}
3	0.110	-1.15	-0.346
4	0.127	-1.17	0.148
5	0.253	-1.21	-0.698
6	0.263	-1.21	0.105
7	0.143	-1.21	-0.693
8	0.142	-1.21	0.111
9	-7.03×10^{-3}	-1.22	-0.275
10	-1.89×10^{-3}	-1.23	0.218
11	6.80×10^{-2}	-1.24	-0.654
12	7.19×10^{-2}	-1.23	0.149

Table 1: *Directional displacement of the target points.*

As Shown in Figure 15 the shifts of points of the same category are quite similar. The differences between displacement along vertical direction (Figure 16) are small. Future analysis will focus on finding if strongback temperature influences them or they depends on the mesh elements size. Displacement along the beam direction (Figure 17) behave similar to *x-direction* shifts.

B: Steady-State Thermal
Temperature
Type: Temperature
Unit: K
Time: 1
9/23/2015 1:08 PM

293.01 Max
291
260
200
150
100
80
50
20
1.9824 Min
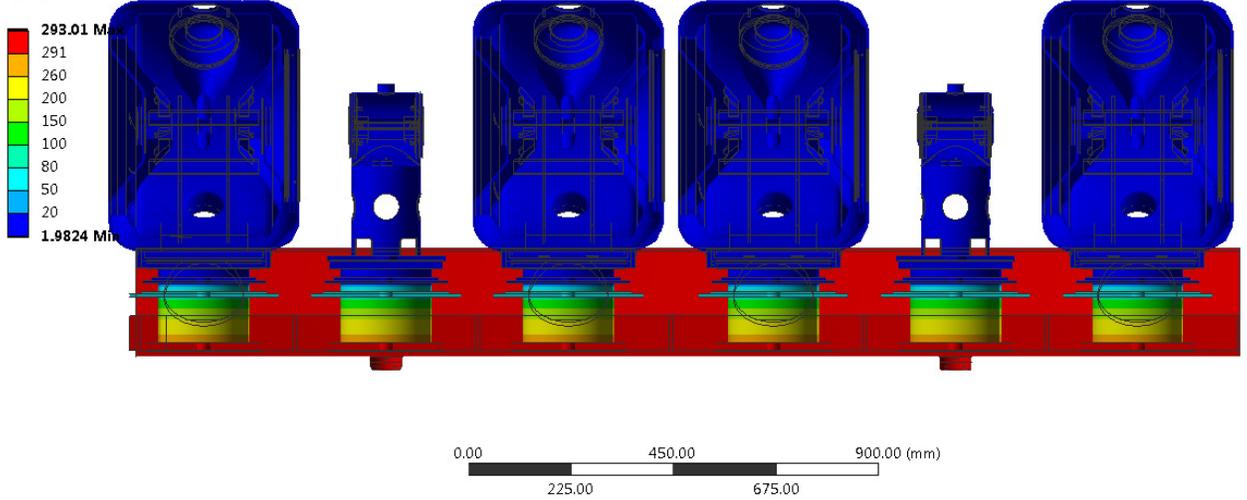
C: Static Structural
Directional Deformation
Type: Directional Deformation(Y Axis)
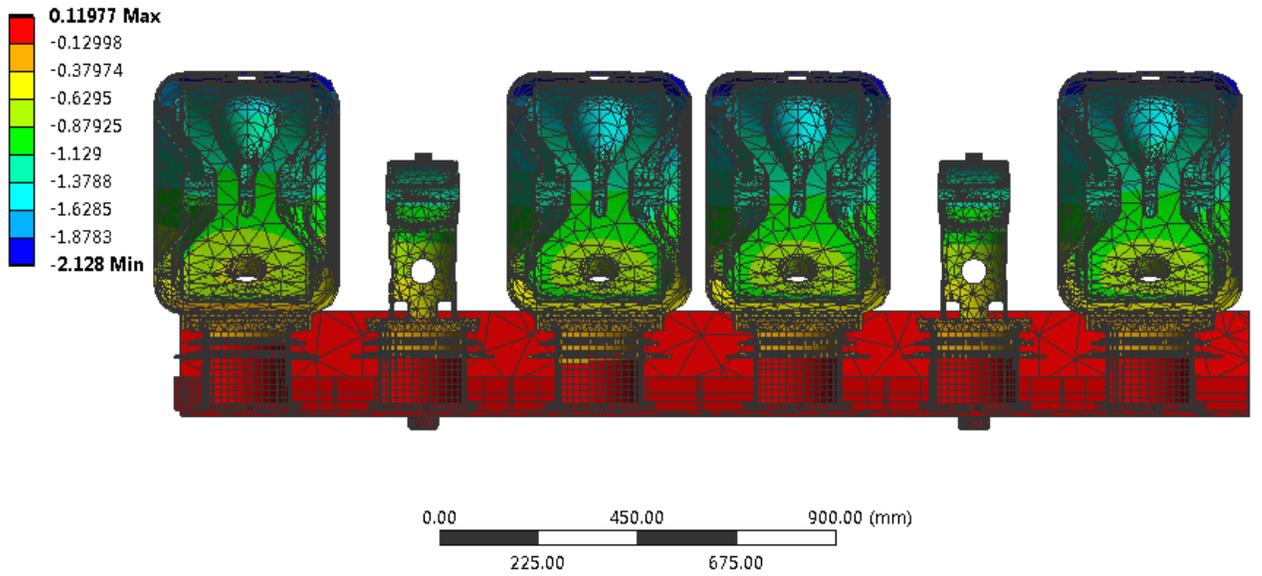Unit: mm
Global Coordinate System
Time: 1
9/23/2015 2:17 PM

0.11977 Max
-0.12998
-0.37974
-0.6295
-0.87925
-1.129
-1.3788
-1.6285
-1.8783
-2.128 Min

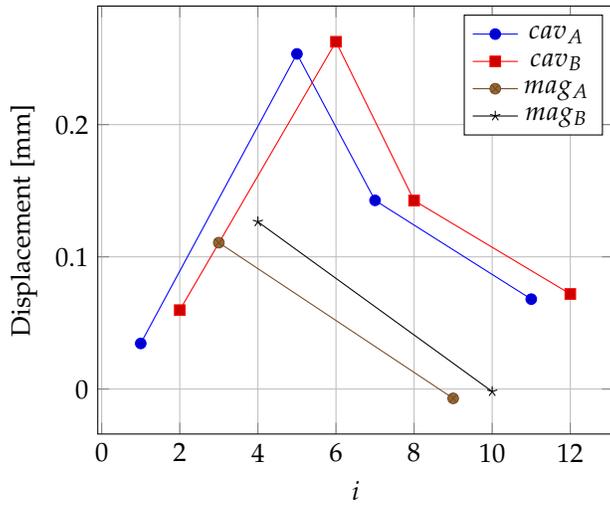**Figure 14:** *Map temperature and overall deformation along x axis.*

Figure 15: *Displacement along transverse direction.*

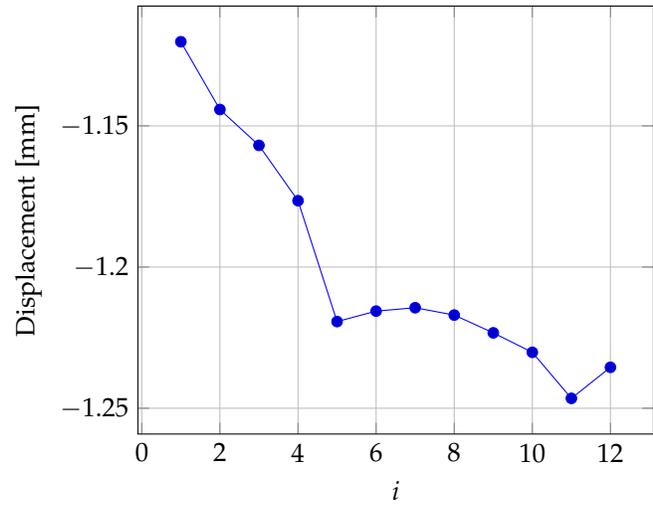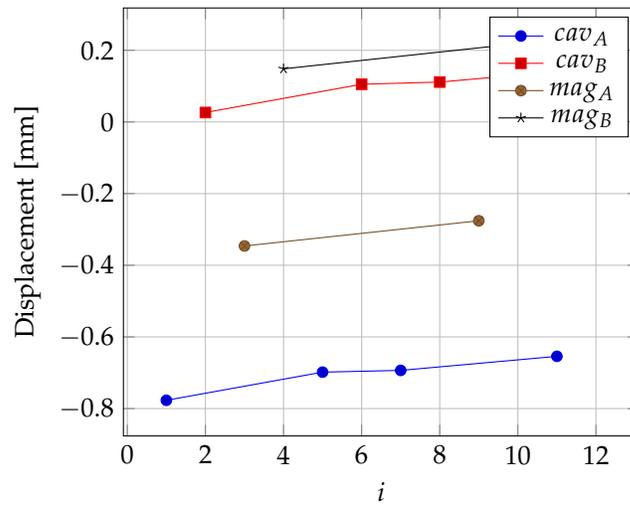**Figure 16:** *Displacement along vertical direction.*

Figure 17: *Displacement along axial direction.*

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