DESIGN OF THE HIGH BETA 650 MHz CRYOMODULE - PIP II *

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Abstract

In this paper the design of the high beta 650 MHz cryomodule will be presented. This cryomodule is composed of six 5-cell 650 MHz elliptical cavities, designed for β=0.92. These cryomodules are the last elements of the Super Conducting (SC) linac architecture which is the main component of the Proton Improvement Plan-II (PIP-II) at Fermilab.

This paper summarizes the design choices which have been done. Mechanical, thermal and cryogenic analyses have been performed to ensure the proper operation. First the concept of having a strong-back at room temperature has been validated. Then the heat loads have been estimated and all the components have been integrated inside the cryomodule by designing the supports, the beam line, the thermal shield and the cryogenic lines. All these elements and the calculations leading to the design of this cryomodule will be described in this paper.

INTRODUCTION

The high beta 650 MHz cryomodule is based on the design of the SSR1 325 MHz cryomodule with a strong-back at room temperature supporting the cavities [1]. These two cryomodules are parts of the SC linac architecture of PIP II in order to accelerate a beam current in the energy range 11 MeV - 800 MeV. The high beta 650 MHz cryomodule is composed of six superconducting 5-cell 650 MHz elliptical cavities. One particularity of these cavities is that the chimney makes an angle with the vertical axis. This requirement comes from the test station for which without this angle the cavity would not fit.

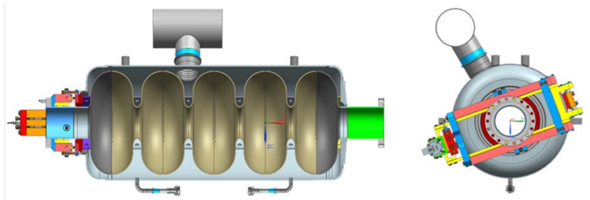

Figure 1: Cross section of the high beta 650 MHz dressed cavity with its tuner.

These cavities will be operated at 2K. Cryogenics lines have been designed in order to meet the requirements according to heat-loads and flux trapping during the cool-down.

This cryomodule is 9.8 m long with a diameter of 1.2 m. Thus insertion tooling of the cold mass inside the vacuum vessel has been designed and particular attention has been taken considering the shrinkage of the material during the cool down.

MECHANICAL DESIGN

This cryomodule shares several elements of design with the SSR1 cryomodule in order to minimize the design cost and to use similar tooling and procedures during the assembly and operation.

Description of the Cryomodule

Figure 2 presents the cryomodule with its main components. One of the main issues during the design stage was to integrate the two phase helium pipe with the chimney. For this a custom elbow with a belled connection has been used in order to be able to weld the chimney once the cold mass is inside the vacuum vessel.

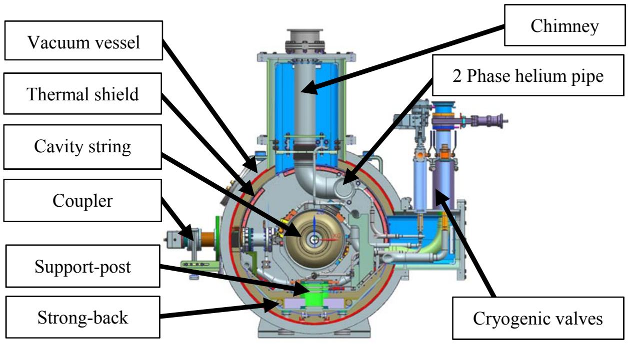

Figure 2: Cross-section of the high beta 650 MHz cryomodule.

Vacuum Vessel Design

Two big openings are located in the middle of the vessel. The first one is dedicated to the cryogenic valves and the other one to the chimney and the heat exchanger in order to reach 2K. Other ports are dedicated to the coupler, tuner, instrumentation, and relief valve.

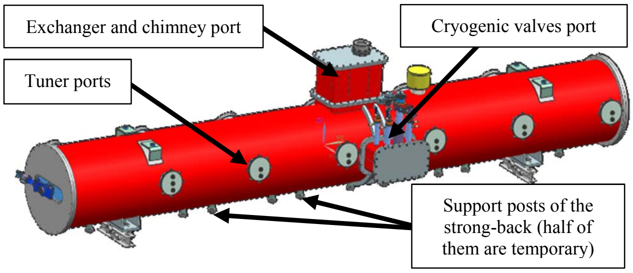

Figure 3: Vacuum vessel.

The alignment of the cavities will be done on the strong-back outside the vacuum vessel. To keep the alignment the strong-back needs to be supported in the exact same way when it will be inside the vessel. For this laser trackers will

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* Work supported by Fermi Research Alliance, LLC under Contract No. DE AC02 07 CH11359 with the United States Department of Energy

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be used, to record the location of the support posts of the strong-back inside the vessel. To insert the cold mass, two rails on the vessel and wheels below the strong-back have been designed. Finally the strong-back will be moved down on its support posts by moving the temporary support posts down. Note that during this process the final support posts will not be moved in order to keep the cavities aligned.

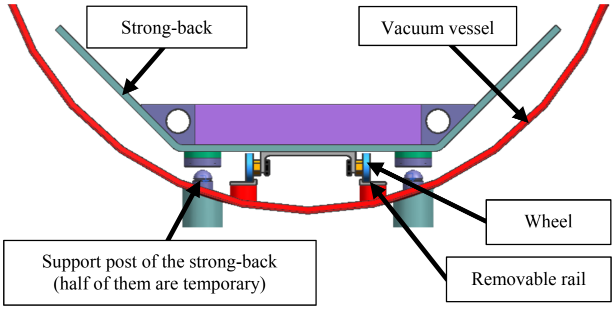

Figure 4: Tooling to insert the cold mass inside the vessel.

Strong-Back Design

The goal of the strong-back is to support the weight of the cold mass from the bottom. The strong-back is fixed to the vacuum vessel. Compared to a LCLS-II cryomodule design [2] where the cavities are supported from the top, the assembly process will be much easier because all the components will be added one above the others. Finite element analysis has been performed to warrant that the strong-back was properly design. A maximum displacement around 0.22 mm have been calculated on the support posts location. Once the cavities will be set on the strong-back, the alignment will be done using the same fixtures used for LCLS II cryomodule [2]. These fixtures can align the cavities on a range of +/- 2.5 mm. Details about cavity's design can be found in [3].

The Cavity String

The cavity string is composed of 6 dressed cavities with a bellow between all of them. During the cool down this bellow will see an elongation of 2.4 mm.

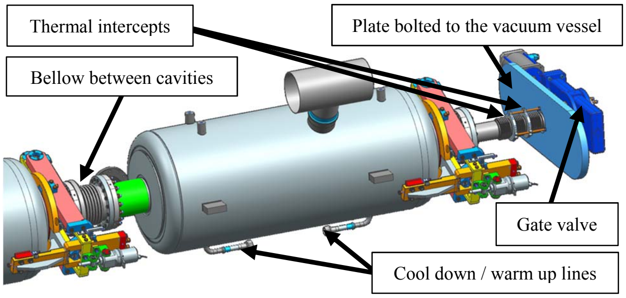

Figure 5: Cavity string.

Each end of the cavity string is composed of 3 bellows to allow thermal contraction between the vacuum vessel, thermal intercepts at 70K and 5K, and the dressed cavity.

CRYOGENIC DESIGN

This cryomodule is composed mainly of four cryogenic lines as we can see in the following schematic.

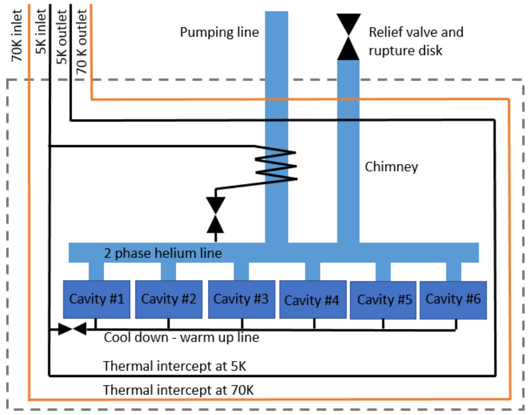

Figure 6: Schematic of the cryogenic lines.

The 70K line is used to cool down the thermal shield all around the cold mass. Besides this line and the 5K line will be used to intercept the heat on the support posts of each cavity, on the cryogenic valves and on the cold to warm end transitions of the cryomodule. The cool down - warm up line has been designed to minimize the flux trapping inside the cavities during the superconducting transition. The 2K helium line provides superconducting helium to all cavities thanks to an exchanger and a Joule Thomson valve. All the lines have been designed for a pressure of 20 bar except the two phase helium line and the cavities with a pressure of 2.05 bar warm and 4.1 bar cold.

Heat-Loads

The heat loads by conduction and radiation have been estimated analytically.

Table 1: Heat Loads

	70K stage	**5K stage**	**2K stage**
Static	98.4 W	26.3 W	5.1 W
Static and dynamic	102.5 W	28.6 W	149.6 W

2 Phase Helium Pipe

This pipe is composed a six branch connections with the dressed cavities. Between them a bellows was needed to take in consideration the shrinkage during the cool down. A displacement of 4.5 mm is expected. Moreover invar rods have been set up on the pipe in a way that in case of the loss of insulating vacuum or an over pressure inside the pipe no force will be seen by the cavities. Therefore the cavities will be kept aligned in all scenarios.

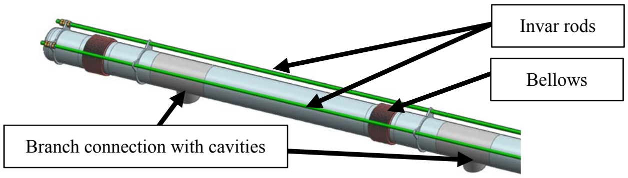

Figure 7: Part of the two phase helium pipe.

The Cavity String

Calculations have been performed on the 3 bellows of the cavity string in order to be sure about the motion during the cool down. For this all scenarios have been considered, whichever line is cooled first. A displacement of 4.6 mm is expected on the beam axis but also around -1.3 mm on the vertical axis which brings a bending of the first bellow as we can see in the Figure 8. The stress value on the bellow is similar to the value calculated with the ASME code (545 MPa compared to 530 MPa). Therefore the fatigue evaluation calculated with ASME code is also well estimated.

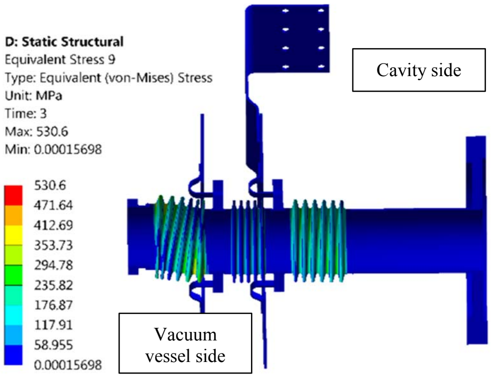

Figure 8: Von Mises stress at the end of the cool down.

Strong-Back Temperature

The alignment of the cavities being done at room temperature, we need to be sure that the temperature of the strong-back won't change significantly during the cool down. In the Figure 9, the evolution of each heat load and their sum have been plotted versus the strong-back temperature. According to the first law of thermodynamics, it means that the equilibrium temperature of the strong-back can be read when this curve intersects the X axis. Thus, the equilibrium temperature of the strong-back will be around 287K during operation considering a vacuum vessel at 293K.

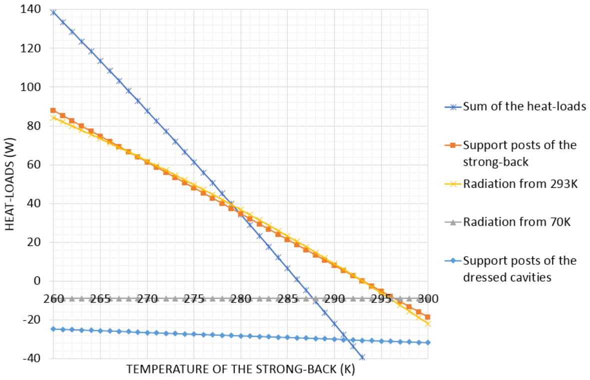

Figure 9: Heat-loads applied on the strong-back.

Considering a coefficient of thermal expansion of 23.10^{-6} m/(m.K) and a thickness of 12.7 mm, the maximum vertical displacement of the strong-back due to the temperature will be around 1.8 µm. Therefore this variation of temperature is not an issue for the alignment of the cavities.

Thermal Shield

The design of this thermal shield is based on the Tesla Test Facility cryomodule for which the thermal shield was connected to the helium lines with finger welds [4].

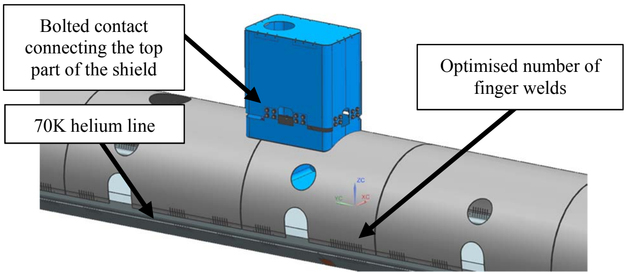

Figure 10: Finger welds on the thermal shield.

A thermo-mechanical analysis have been performed in order to know what will be the temperature distribution and the stress state due to the variation of temperature. In order to cool down the top part of thermal shield where the thermal intercept with the chimney is, thermal contacts have been improved and additional finger welds have been added. Thus a maximum temperature around 115K is expected.

CONCLUSION

The preliminary design of the high beta 650 MHz cryomodule has been completed. This design based on a strong-back at room temperature supporting the cavities from the bottom is promising and will be able to keep a good alignment of the cavities after the cool down. Instrumentation will be set up during the assembly in order to evaluate the efficiency of this design.

The next steps of the project will be to define the assembly process. Then the piping engineering note will be written in order to check the code compliance and define the pressure tests and radiographic examinations to be done. The design review is foreseen for January 2017.

ACKNOWLEDGMENT

The authors would like to thank the Technical Division Design and Drafting department and especially Glenn Nelson for his support during the design stage.

REFERENCES

[1] T. H Nicol, *et al.* "High intensity neutrino source superconducting spoke resonator and test cryostat design and status", *IEEE Trans. Appl. Supercond.* 19(3), 1432-1435, Fermilab-Conf -08-260-TD, 2009.

[2] T. Peterson, "LCLS-II 1.3 GHz Cryomodule design – modified tesla-style cryomodule for CW operation", in *Proc. SRF2015*, Whistler, Canada, Sept 2015.

[3] V. Jain, *et al.*, "650 MHz Elliptical Superconducting RF Cavities for PIP-II Project", presented at NAPAC 2016, Chicago, USA, Oct 2016.

[4] C. Pagani, *et al.*, "Design of the thermal shields for the new improved version of the tesla test facility (TTF) cryostat", *Advances in Cryogenic Engineering,* vol 43, pp 307-314, 1998.