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DESIGN OF THE 650 MHz HIGH BETA PROTOTYPE CRYOMODULE FOR PIP-II AT FERMILAB*

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Abstract

The Proton Improvement Plan II (PIP-II) is the first U.S. accelerator project that will have significant contributions from international partners. The prototype High Beta 650 MHz cryomodule (pHB650 CM) is designed by an integrated design team, consisting of Fermilab (USA), CEA (France), STFC UKRI (UK), and RRCAT (India). The manufacturing & assembly of this prototype cryomodule will be done at Fermilab, whereas the production cryomodules will be manufactured and/or assembled by STFC UKRI, RRCAT, or Fermilab. Similar to the prototype Single Spoke Resonator 1 cryomodule (pSSR1 CM), this cryomodule is based on a strong-back at room temperature supporting the coldmass. The pSSR1 CM led to significant lessons being learnt on the design, procurement, and assembly processes. These lessons were incorporated into the design and processes for the pHB650 CM. Amongst many challenges faced, the main challenges of the pHB650 CM design were to make the cryomodule compatible to overseas transportation and to design components that can be procured in USA, Europe, and India.

INTRODUCTION

The design of the Single Spoke Resonator (SSR) and the 650 MHz PIP-II CMs share the same design concept: a room temperature strong-back and the cryogenic layout is identical (Figure 2) even if the cavities and solenoids configurations are different for each cryomodule type [1].

The design, assembly, and successful test of the pSSR1 CM [2] were a great source of lessons learned to design the pHB650 CM. Improvements have been made to increase the performance, ease the assembly process, and reduce the heat loads. Moreover, the experience from the transportation of the LCLS-II cryomodules from Fermilab to SLAC [3] had significant impact on the pHB650 CM design and led to transportation requirements for this new prototype. Thorough analysis on individual parts and on the full cryomodule assembly were performed to meet these requirements.

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LESSONS LEARNED FROM SSR1 CM

Many lessons learned have been gathered during the design, assembly, and test of the pSSR1 CM. The main lessons learned applied to the design are listed below:

- The warm global magnetic shield of the pSSR1 CM was placed on the inner lower surface of the vacuum vessel without being connected to anything. Due to the weight of the shield it was difficult to maintain the shield in the proper position during the assembly.
- During the cold test, the temperature of the strong-back was lower than expected: 260 K instead of 280 K.
- The heat loads measurements were matching the calculations, but several optimisations could be done to lower the heat loads on the 2 K components.

All these lessons learned have been taken into consideration to design this new prototype cryomodule.

DESCRIPTION OF THE CRYOMODULE

The cryomodule is illustrated in Figure 1, which includes the following main components listed from bottom to top: the vacuum vessel, strong-back, G11 supporting post, thermal shield, cavity support, C-shape brackets, cavity, two phase pipe, heat exchanger, pressure transducer lines, and relief line.

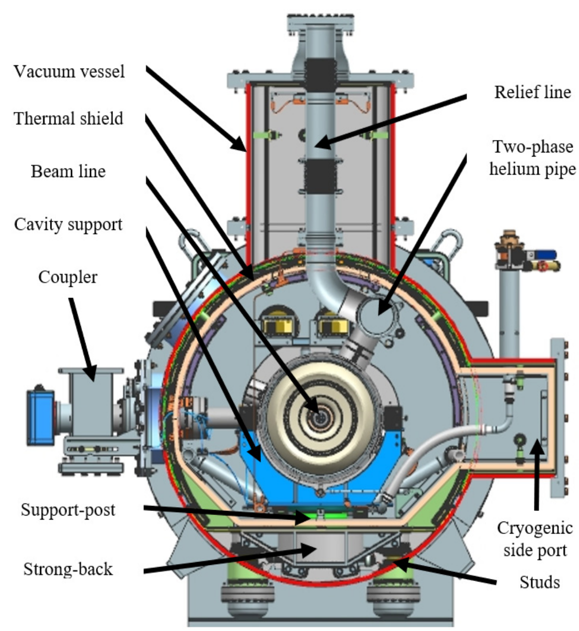

Figure 1: Cross-section of the pHB650 CM.

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The High Temperature Thermal Shield (HTTS) is used to reduce the heat loads on the Low Temperature Thermal Source (LTTS) and on the 2 K components. As shown in Figure 2, the LTTS is used as thermal intercepts and it allows cool down of the cavities until 5 K through the cool down line. The cool down line has been designed to allow fast cool down capability to minimize magnetic flux trapping in the cavities during the superconducting transition. The 2 K helium line provides superconducting helium to all cavities thanks to an exchanger and a Joule Thomson valve. All lines have been designed for a pressure of 20 bar except the two-phase helium line and the cavities which use a dual design pressure of 2.05 bar warm / 4.1 bar cold.

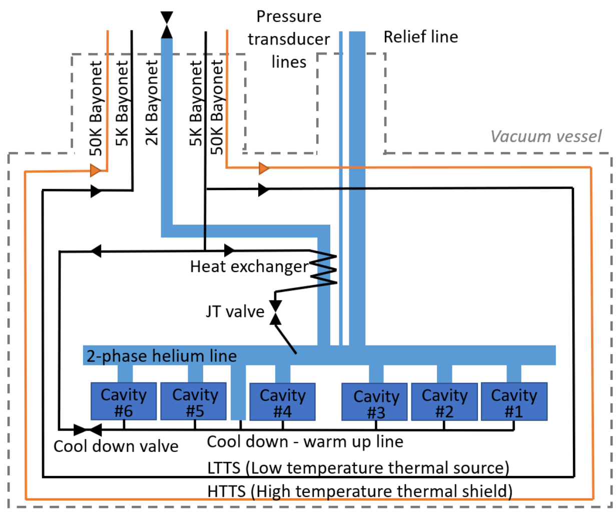

Figure 2: Schematic of the cryogenic lines.

One of the main differences between SSR and 650 MHz CMs [4, 5] comes from how the cavities are supported and aligned: from the bottom for the SSR cavities and from the side lugs for the 650 cavities. Similar C shape brackets as used for LCLS-II CMs [6] have been designed (Figure 3) to align the 650 cavities and to constrain the cavities during transportation.

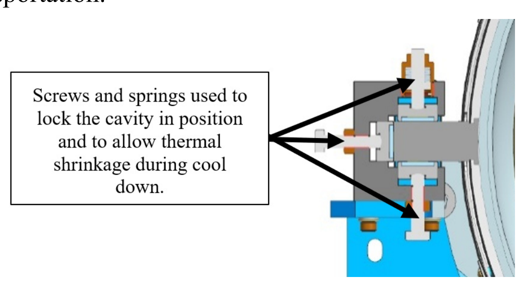

Figure 3: Cross-section of the C-shape bracket.

Moreover, contrary to the SSR CMs, the 650 CMs will be transported overseas from UK for the HB650 CMs and from France for the LB650 CMs. The transportation requirements led to two different ways to connect the strong-back to the vacuum vessel and to insert the coldmass into the vacuum vessel. SSR CMs use a strong-back with two rails that mate with bushings mounted inside the vacuum vessel. The 650 CMs use a strong-back on wheels to slide inside the vacuum vessel and afterwards 14 spherical studs are used to lift the coldmass to its nominal position and rigidly connect the vacuum vessel to the strong-back (Figure 4).

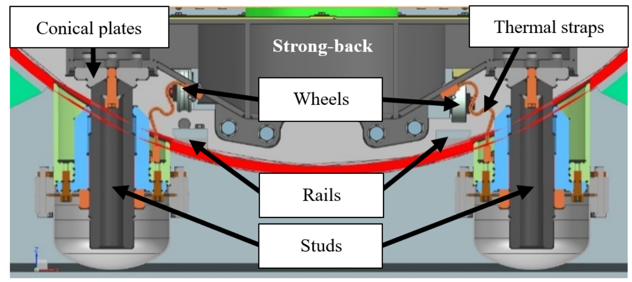

Figure 4: Cross-section of the interface between the vacuum vessel and the strong-back.

ASSEMBLY PROCESS AND ALIGNMENT

The assembly process to assemble the pHB650 CM is like that of the pSSR1 CM [7]. The six phases of the assembly process are illustrated below, from Figure 5 to Figure 12.

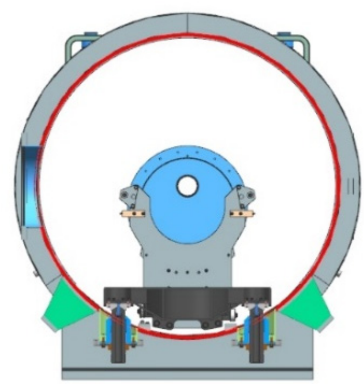

Figure 5: Phase 1, vacuum vessel and strong-back fitment.

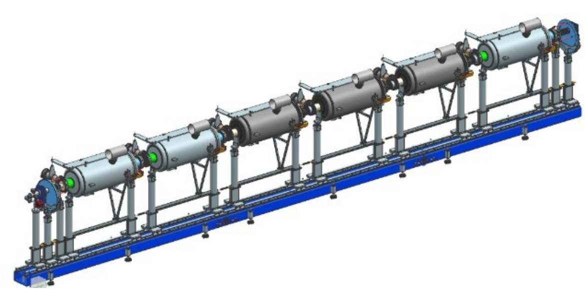

Figure 6: Phase 2a, beam line assembly.

Figure 7: Phase 2b, strong-back assembly.

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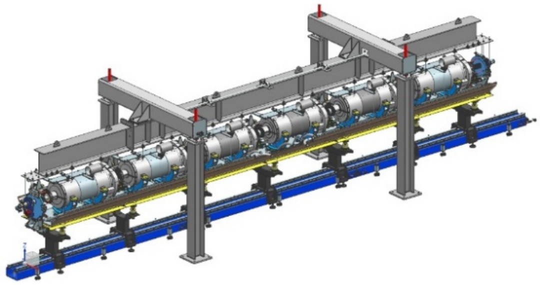

Figure 8: Phase 2c, beam line and strong-back assembly.

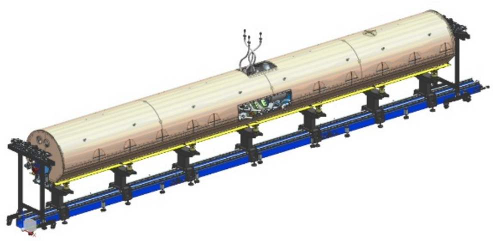

Figure 9: Phase 3, coldmass assembly.

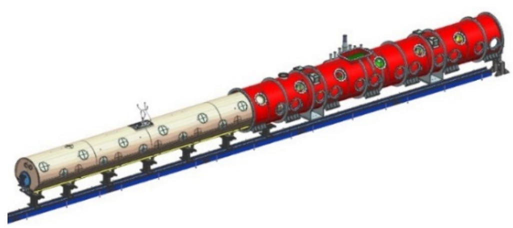

Figure 10: Phase 4, insertion of the coldmass into the vacuum vessel.

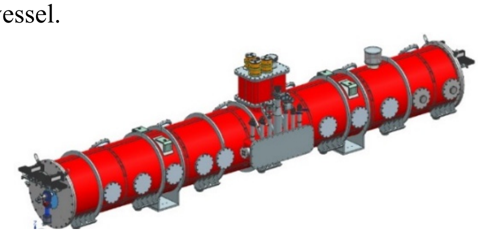

Figure 11: Phase 5, final cryomodule assembly.

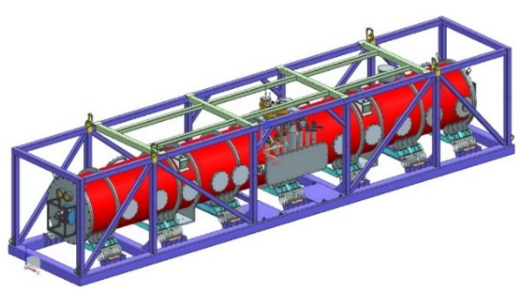

Figure 12: Phase 6, cryomodule assembly on the transport frame ready for overseas transportation.

The assembly process and alignment strategy consist of assembling the coldmass outside the vacuum vessel, performing the final alignment, inserting the coldmass into the vacuum vessel, and raising the coldmass to its nominal position using the studs. Phase 1 is essential to ensure that the beam line remains aligned after the last step. During phase 1, the studs are connected to the vacuum vessel and install in their nominal position. A laser tracker is used to measure the bottom face of the studs. Then, the studs are removed and the strong-back without the conical plates (Figure 4) is inserted into the vacuum vessel. Finally, the studs with the conical plates are connected to the vacuum vessel, the strong-back is moved up to its nominal position and the conical plates are screwed to the strong-back. To make sure of the longitudinal position of the beam line during phase 2c, the dummy beam pipe end assembly will be installed and a laser tracker will be used to set them in their nominal position.

With the final alignment of the cavities being done outside the vacuum vessel, it was important to calculate the deformation of the vessel under the weight of the coldmass at each stud location. As shown in Figure 13, when vacuum is created inside the vacuum vessel, stud #11 moves up around 0.20 mm compared to the other studs. To avoid misalignment of the cavities, this stud will be moved down to compensate for this 0.20 mm movement after the connection with the strong-back is completed at the end of phase 4. Note that by taking the alignment reference with the "strong-back only" phase 1, the maximum vertical misalignment will be around 50 µm.

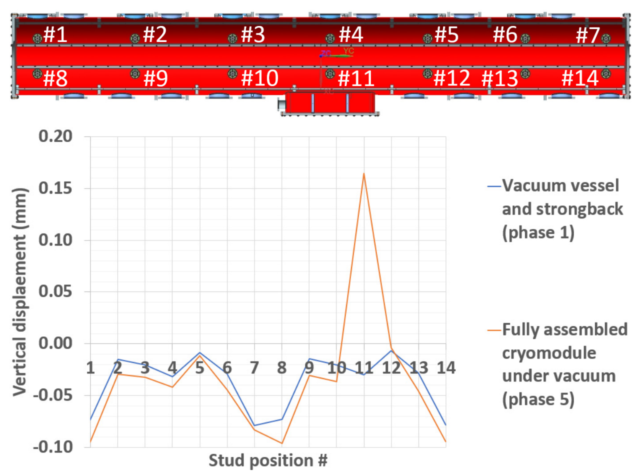

Figure 13::Deformation of the vacuum vessel at the stud location.

MECHANICAL DESIGN

Beam Line

The cavity string is composed of six dressed cavities, five interconnection bellows assemblies, and two beam pipe end assemblies. While the production cryomodule will use only Beta 0.92 650 MHz cavities, the prototype cryomodule uses Beta 0.92 and 0.90 650 MHz cavities. These two cavities have different geometry (length, flange size, lugs, and chimney position) and therefore several types of interconnection bellows were designed.

To avoid having unsupported masses, the beam pipe end assembly has only one bellows and one thermal intercept (Figure 14) compared to three bellows and two thermal intercepts for the pSSR1 CM. In the new configuration the bellows is longer and the effect on the heat loads at 2K is below 0.1W.

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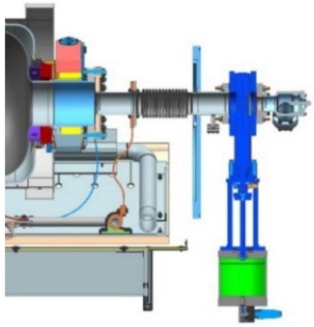

Figure 14: Beam pipe end assembly.

A new rail system with tooling supporting all the parts of the beam line (Figure 6) has been designed, similar to that of the LCLS-II project with 1.3 GHz cavities [8].

Vacuum Vessel Design

The vacuum vessel is 9.65 m long with an outside diameter of 1.22 m. As shown in the Figure 11, two large openings are located in the middle of the vessel. One is dedicated to the cryogenic valves and bayonets, and the other is dedicated to the relief line, heat exchanger, and pressure transducer lines. Other ports are dedicated to the coupler, tuner, instrumentation, relief valve, and 10 transportation access ports which are used to lock the movement of the cavity lugs prior to transportation.

Based on lessons from the pSSR1 CM, a skeleton containing threaded holes, as shown in Figure 15, is welded to the inside of the vacuum vessel in order to bolt on the room temperature global magnetic shield.

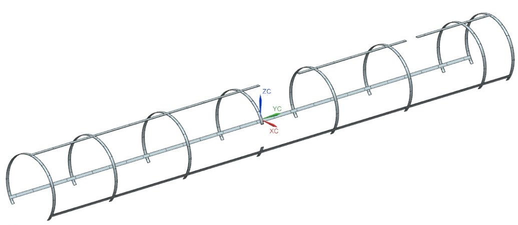

Figure 15: Skeleton on the inside of the vacuum vessel.

To insert the coldmass, two adjustable rails (one flat, one circular) are attached to the inner surface of the vessel. These rails mate to wheels below the strong-back (Figure 4).

Strong-Back Design

The strong-back is a key component of the cryomodule. It plays an important role in transportation since it supports the weight of the entire coldmass and provides stable alignment of the string. To optimize manufacturing, the strong-back was divided into six modules as shown in Figure 16 and Figure 17.

Figure 16: Strong-back.

The location of the studs and wheels has a significant impact on the movements seen by the beam line bellows during coldmass insertion and transportation. Calculations showed that the best performance was achieved by matching the wheel and stud locations with the bellows locations in the longitudinal direction. Moreover, to increase stiffness and have the eigen frequencies above 30 Hz, the strong-back is made from 8 mm thickness plate in stainless steel.

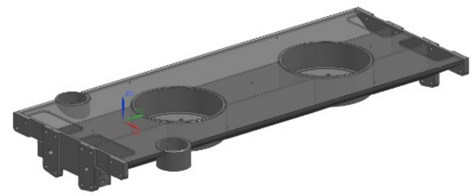

Figure 17: Details of the geometry of one module.

Since the strong-back is connected to a warm source (the vacuum vessel through studs) and cold sources (the support posts of the cavities and the thermal shield), maintaining it at room temperature may be a challenge. To increase the heat exchange by radiation between the vacuum vessel and the strong-back, the lower surface of the strong-back is sand-blasted and the inner surface of the vacuum vessel is covered by epoxy. Therefore, both surfaces are expected to have an emissivity around 0.7. In addition, 14 thermal straps connect the strong-back to the vacuum vessel as shown in Figure 4. To evaluate the strong-back temperature, a thermal analysis has been performed considering that only 20% of the total gross contact area transmits heat. Considering the vacuum vessel at 293 K, the expected temperature of the strong-back is 290 K.

Support Post and Cavity Support

Contrary to the LCLS-II project, there is no invar rod connecting all the cavities together to make sure that they remain aligned after cool-down. For the pHB650 CM, this role is performed by the cavity support. Calculations have shown that since the cavity support is made of titanium, the support and the cavity will shrink approximately the same amount, keeping the cavity aligned.

Due to the V-shape of this support, it was necessary to add a solid piece of titanium located in the middle to meet the transportation requirements (Figure 18).

Figure 18: Support post and cavity support.

The G10 support post located below the cavity support is a shrink fit assembly designed to support the coldmass and to isolate the strong-back from the coldmass.

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HTTS

The design of the thermal shield has been improved to allow cool down at a rate of 20 K/hour compared to 5 K/hour for pSSR1 CM. This was achieved by using vertical welds between the cryogenic lines and the thermal shield as shown in Figure 19 instead of using horizontal welds like pSSR1 CM and the Tesla Test Facility cryomodule [9].

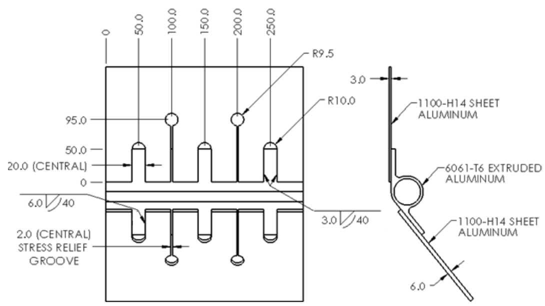

Figure 19: Finger welds on the thermal shield.

In this configuration, the forces on the welds are in compression instead of shear. The stresses on the welds are therefore lower during the cool down.

Cryogenic Lines

This cryomodule has been designed using metric and ISO pipes in order to ease sourcing of the LB650 and HB650 cryomodules in Europe and India. For more flexibility, ISO pipes matching imperial pipes have been preferred. Despite this, procurement of these components in the USA was more complicated, requiring several negotiations with vendors.

HEAT-LOADS

The heat loads by conduction and radiation have been estimated analytically and listed in Table 1.

Table 1: Heat Loads

	HTTS	LTTS	2K
Static	107.3 W	13.7 W	10.0 W
Static and dynamic	152.3 W	26.9 W	128.5 W

TRANSPORTATION ANALYSIS

To validate the design for transport, the pHB650 CM will be shipped from FNAL to the U.K. and back. As part of the design, the CM was evaluated for transportation loading scenarios. Per FNAL's Transport Specification, components of the CM must withstand the following accelerations (to be considered separately) without plastic deformation: 5G longitudinal, 3G vertical, and 1.5G transverse. Additionally, critical components must have resonant frequencies above 20 Hz in their final 'as installed' configuration to mitigate fatigue failure.

Using FEA (Figure 20), all major components of the CM were evaluated with modal and static structural analyses. First, individual sub-assemblies were checked, which allowed a finer level of detail. The geometry was then simplified to limit computational expenses, and the models were combined to form successively larger assemblies. Ultimately, the entire CM was modelled with 178,000 elements.

Results from the analysis were used to improve the design of several components. Changes included making the cavity supports stiffer to prevent misalignment, the thermal shield was given more contact points to the vacuum vessel during transportation, the heat exchanger was to be given support for any onsite transport, and more invar rod guides were added to the two-phase pipe to limit bellows movement. For further details, a complete write up of the HB650 transportation analysis is available [10].

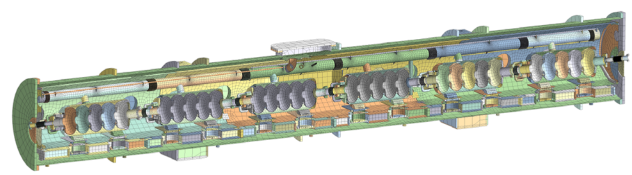

Figure 20: Cryomodule assembly mesh.

CONCLUSION

The design of the prototype High Beta 650 MHz cryomodule has been completed by an integrated design team and the procurement phase has started. The assembly process from the beam line assembly to the transport frame have been detailed. This work will be used by STFC UKRI for the assembly of the production High Beta 650 MHz cryomodules, and by CEA for the design and assembly of the pre-production and production Low Beta 650 MHz cryomodules.

The next steps of the pHB650 CM is to perform quality control after receiving the parts, assemble, test, validate the design, and implement any new lessons learned into the design optimization phase before going into production.

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