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DESIGN STRATEGY OF THE PIP-II CRYOMODULES*

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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. Research institutions in India, Italy, UK and France will build major components of the particle accelerator. The High Beta 650 MHz (HB650) prototype cryomodule is being designed jointly between Fermilab (USA), CEA (France), STFC (UK) and RRCAT (India). The assembly of this prototype cryomodule will be done at Fermilab whereas the production cryomodules will be assembled in UK. Concerning the Low Beta 650 MHz (LB650) cryomodules, they will be designed and assembled at CEA. To reduce the cost of the project and to increase the quality it is essential to define a design strategy for each cryomodule which includes a degree of standardization. In this way, the lessons learned on each prototype cryomodule will positively impact on all the other cryomodules types. An international joint design also brings additional challenges to the project: which unit system should be used? Should a common project lifecycle management system be used for all partners? How to transport the cryomodules overseas?

INTRODUCTION

The superconducting linac architecture of PIP-II comprises 5 types of cryomodules with many contributions from international partners (see Fig. 1).

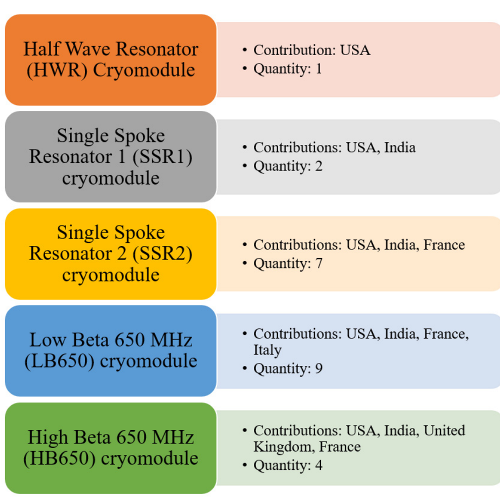

Figure 1: Layout of the PIP-II superconducting linac.

The half wave resonator (HWR) cryomodule has been designed and manufactured at Argonne and is nearing completion. This cryomodule is based on a "top loaded box cryomodule" design [1]. This choice has been made due to past experiences of Argonne with assembling this type of cryomodule. The next cryomodules will all have significant contributions from international partners, for this reason it is important to define a design strategy and a working model to allow the sharing the experience.

DESIGN STRATEGY

The design of SSR1, SSR2, LB650 and HB650 cryomodules are based on a strong-back at room temperature supporting the coldmass from the bottom [2, 3]. This choice was originally done to make easier the assembly of the coldmass by putting the elements one above the others.

The configuration of cavities (C) and solenoids (S) will be different for each cryomodule type (see Table 1), nevertheless the cryogenic layout will be very similar for all of them [2].

Table 1: Cryomodule's Layout

SSR1 cryomodule	C-S-C-C-S-C-C-S-C-C-S-C
SSR2 cryomodule	S-C-C-S-C-C-S-C
LB650 cryomodule	C-C-C-C
HB650 cryomodule	C-C-C-C-C-C

The shape of the single spoke cavities is very different from the elliptical cavities, making it was necessary to support and align cavities in a different way. The spoke cavities and solenoids are supported by one G11 support post (see Fig. 2) and aligned by a set of screws [4]; whereas the elliptical cavities are supported by two G11 support posts (see Fig. 3) and aligned thanks to four lugs welded on the dressed cavities [3].

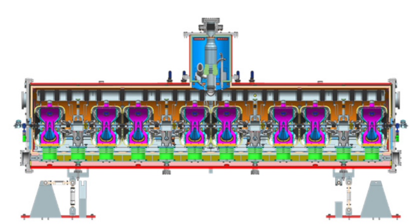

Figure 2: SSR1 cryomodule configuration.

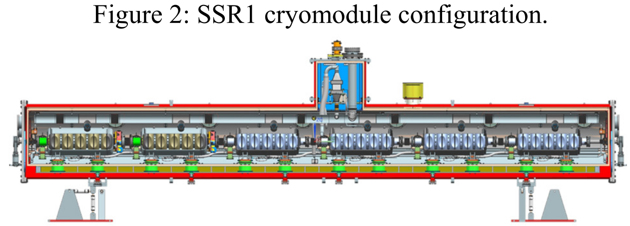

Figure 3: HB650 cryomodule configuration.

To validate the current design strategy and to mitigate the technical risks, one prototype for each cryomodule type will be manufactured. The first prototype will have a major impact on the project because it will validate the assembly sequence common to all cryomodules (see Fig. 4) [5].

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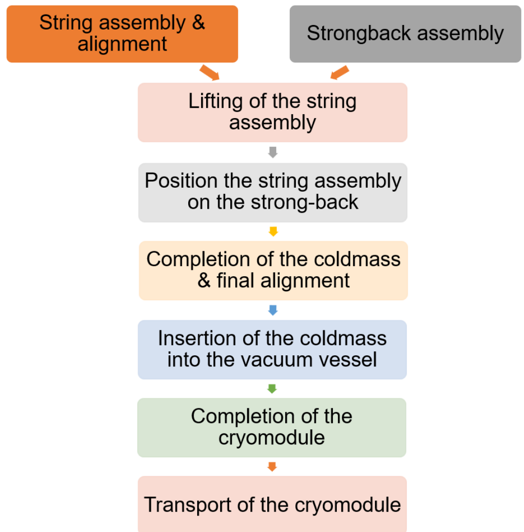

Figure 4: Assembly sequence of SSR1, SSR2, LB650 and HB650 cryomodules.

Fermilab is using Teamcenter® as a product lifecycle management (PLM) system and NX® as a CAD model software. Both are fully integrated in one platform enabling design teams in different locations to work together. Thus, all PIP-II partners have access anytime to the most up-to-date design. However, being Teamcenter limited to integrate only the NX® CAD software, it limits the interaction with partners and the effectiveness of the working group if they are using a different CAD software. For this reason, the technical requirements system (TRS) and functional requirements system (FRS) have been written and shared with the partners. Of course, regular meetings are also organised to share design status, ideas and experiences.

SSR1 PROTOTYPE CRYOMODULE

The SSR1 prototype cryomodule will be the first prototype to be completed. Its achievement will be a major milestone for the project because it will validate:

- The "strong-back" design strategy.
- The string lifting tooling.
- The insertion of the coldmass inside the vacuum vessel.
- The alignment strategy included the use of HIE-ISOLDE Brandeis CCD Angle Monitor to control the alignment during transportation and cool-down [6].
- The transport frame tooling.
- The cryomodule lifting tooling.

The string assembly was completed in January 2019 [4]. Since then, our focus has been to order all the components and tooling of the cryomodules and to start the coldmass assembly process. In May 2019, the strong-back assembly has been completed (see Fig. 5) and the lifting tooling has been set up (see Fig. 6). The lifting tooling has been designed to be common to all SSR and 650 cryomodules. This step is critical because no forces must be applied on the beam line during this process. Once the string is lifted, the eight cavities and the four solenoids need to match with their support post when moving down the string assembly.

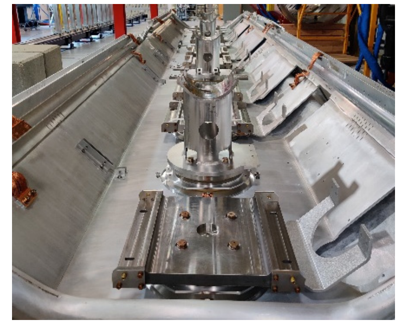

Figure 5: SSR1 Strong-back assembly.

Figure 6: String assembly under the lifting tooling.

In the meantime, the insertion tooling used to insert the coldmass into the vacuum has been validated by performing dry-runs. Then, the magnetic shield has been assembled into the vacuum vessel (see Fig. 7).

Figure 7: Magnetic shield inside the vacuum vessel.

The current leads are right now under manufacturing at Fermilab. The prototype is currently being inspected and tested to validate its performance [7] and to proceed with the fabrication of the production ones.

In addition to the design, this first cryomodule gave us the possibility to define a procurement and quality control process. Tools have been set up to follow up each procurement and to know the status of each part, making sure quality control is performed or if addition work is needed. From this experience we learned that it would be beneficial if for the production phase we try to minimize the number of orders combining more parts/sub-assemblies in the same order, like LCLS II project at Fermilab did [8]. Also the incoming inspection would be simplified if receive pre-assembles units.

During the assembly, we benefited from the experience of LCLS II cryomodules. Travellers have been set up and

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a document described the assembly process of each connection: the torque value, the use of indium and Loctite®, Belleville washers and other hardware.

The SSR1 prototype cryomodule is expected to be completed in October 2019. Then, based on this experience, the design of the HB650 prototype cryomodule will be updated to get the preliminary design review by the end of CY2019.

HB650 AND LB650 CRYOMODULES

The HB650 and LB650 cryomodules will have both important contributions from international partners:

- The HB650 cryomodule will be jointly designed by Fermilab, STFC, CEA and RRCAT with Fermilab leading the design. The prototype cryomodule will be assembled at Fermilab and the production will be done at STFC in UK.
- The LB650 cryomodules will be designed and assembled by CEA based on HB650 cryomodule design. The LB650 cavity is being designed by INFN in Italy.

To reduce the cost of the project, efforts have been made to standardise the design of these two similar cryomodules. Nevertheless, the most important challenge of this international joint design will be the transportation of these cryomodules overseas. The transportation will have a very important impact on the design, every part needs to be designed in a way to reduce vibration and mitigate the risk of failure.

Design of the HB650 Prototype Cryomodule

Work packages have been defined among the partners to define the scope of the work and the interfaces:

- CEA is in charge of the design of the strong-back which includes the study of the insertion of the cold-mass into the vacuum vessel.
- STFC is in charge of the design of the transportation frame.
- RRCAT is in charge of designing the thermal shield.

Based on the experience of the SSR1 prototype cryomodule, improvements have been done in order to make easier the assembling and the procurement. We are planning to procure an assembly composed of the vacuum vessel, the strong-back, the G11 support posts, the cavity supports, the thermal shield and the 5K line. The Fig. 8 presents the strong-back assembly.

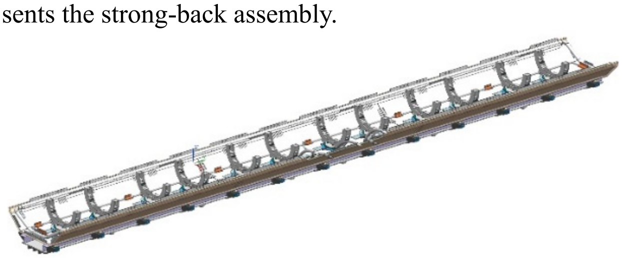

Figure 8: HB650 Strong-back assembly.

All the components of the cryomodules are being designed in metric units, that includes especially all the hardware, the bellows, the flexible tubes and the cryogenic lines with the exception of the two-phase helium pipe for which a 6” outside diameter is needed for the interface with the cavities. All the cryogenic lines have been preliminary designed. The main difference with SSR1 prototype cryomodule is the interface with the heat-exchanger and the relief line (see Fig. 9):

- The location of the relief line and heat exchanger have been chosen to limit the displacement during the cool down in the Y direction.
- The heat-exchanger is fixed to the vacuum vessel to reduced displacement during transportation and a bellows has been designed between the heat-exchanger and the two-phase helium pipe to compensate the thermal contraction along z.

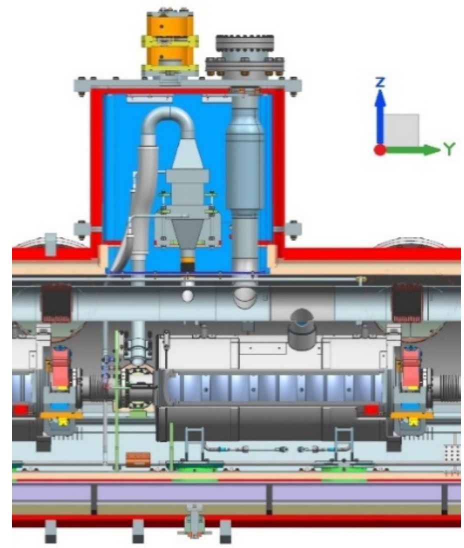

Figure 9: Interface with the relief line and heat-exchanger.

The first transportation analysis including static structural and modal analysis was performed to validate the design concept and to highlight parts that need to be improved. One of the improvements suggested by this analysis was the use of one bellows instead of three for the beam pipe end assembly (see Fig. 10).

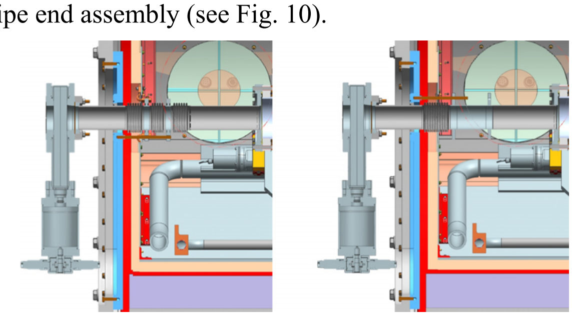

Figure 10: Beam pipe end assembly. On the left: the previous design. On the right: the new design.

The natural frequency of this new beam pipe end assembly is higher than the previous design because there is no more unsupported mass. Thus, this will reduce the risk of problem during transportation. The use of one bellows does not increase significantly the heat loads at 5 K and 2 K (see Table 2) since the heat loads by radiation is the driving parameter.

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Table 2: Heat Loads on the Beam Pipe End Assembly

	Three bellows configuration	**One bellows configuration**
Heat loads at 50 K [W]	1.35	0.85
Heat loads at 5 K [W]	0.5	0.75
Heat loads at 2 K [W]	0.25	0.26

After the completion of the SSR1 cryomodule, the HB650 prototype cryomodule will validate the transportation and the alignment strategy. Works are still ongoing to define the best way to align the cavities, to secure them during the transport and to make sure that they remain aligned after transportation and during operation at cold temperature.

Design of the LB650 Prototype Cryomodule

Overall the design of the LB650 cryomodule should be very similar to the HB650 cryomodule. With four cavities slightly smaller than the HB650 cavity, this LB650 cryomodule should be also easier to design compared to the HB650 cryomodule:

- This cryomodule being shorter, the longitudinal thermal contraction will be smaller.
- The size of the cryogenic lines used for the HB650 cryomodule will match with the requirements of the LB650 cryomodule because the heat loads will be smaller.
- Several parts and tooling will be identical or similar. For example, the beam tube having the same diameter, the string assembly and its tooling will be similar.
- The temperature gradient on the thermal shield will be smaller and the maximum cool down rate will be higher.
- The string lifting tooling, the cryomodule lifting tooling, and the vacuum vessel endcap tooling are expected to be compatible for both cryomodule.

The design stage of this cryomodule should start in 2020 at CEA after the final design review of the HB650 prototype cryomodule.

CONCLUSION

The completion of the SSR1 prototype cryomodule is an important step to learn and collect possible design improvements for common assemblies to all PIP-II cryomodules. Also, its validation through cryomodule testing will be an important milestone for the PIP-II cryomodule design strategy. The 650 program has additional challenges: first from the technical point of view especially considering the transport of cryomodules overseas, but also from the management point of view by setting up an international joint design.

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