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FINAL DESGIN OF THE LB650 CRYOMODULE FOR THE PIP-II LINEAR ACCELERATOR

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Abstract

The Proton Improvement Plan II (PIP-II) that will be installed at Fermilab is the first U.S. accelerator project that will have significant contributions from international partners. CEA joined the international collaboration in 2018, and its scope covers the supply of the 650 MHz low-beta cryomodule section, with the design of the cryostat (i.e the cryomodule without the cavities, the power couplers and the frequency tuning systems) and the manufacturing of its components, the assembly and tests of the pre-production cryomodule and 9 production modules. An important milestone was reached in April 2023 with the Final Design Review. This paper presents the design of the 650 MHz low-beta cryomodules.

INTRODUCTION

The PIP-II project is an upgrade of the accelerator complex of Fermilab to enable the world's most intense neutrino beam for the Long Baseline Neutrino Facility (LBNF) and the Deep-Underground Neutrino Experiment (DUNE) located in South Dakota, 1200 km from the neutrino production in Illinois.

PIP-II will deliver 1.2 MW of proton beam power from the injector, upgradeable to multi-MW capability. The central element of PIP-II is an 800 MeV linear accelerator, which comprises a room temperature front end followed by a superconducting section. The superconducting section consists of five different types of cavities and cryomodules, including Half Wave Resonators (HWR), Single Spoke and elliptical resonators operating at state-of-the-art parameters.

PIP-II is the first U.S. accelerator project that will be constructed with significant contributions from international partners, including India, Italy, France, United Kingdom and Poland [1]. As described in [2], the CEA contribution focuses on the 650 MHz superconducting accelerating section, with the design, fabrication, assembly and test of 1 pre-production and 9 production low-beta 650 MHz cryomodules (Figure 1 - called "LB650" hereafter) according to the PIP-II project specified requirements.

DESIGN OF THE LB650 CRYOMODULE

The LB650 cryomodule, that houses four 5-cell β=0.61 cavities (developed by Fermilab, INFN, and VECC for the pre-production cryomodule and series cryomodules), is similar to the HB650 cryomodule that that was assembled and cold RF tested at Fermilab [3]. The frequency tuning systems and the power couplers for the low beta and high beta cavities are identical and are procured by Fermilab.

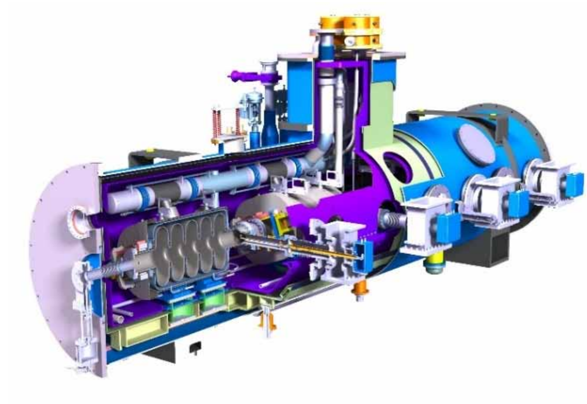

Figure 1: The LB650 cryomodule.

In order to benefit from the HB650 cryomodule design and to apply the same design concepts to the LB650 cryomodule, CEA was part of the integrated design team with Fermilab, UKRI-STFC and DAE. CEA was in charge of the mechanical and thermal design of the strongback and performed similar computations as the ones described in [4]. Moreover, the design strategy for the LB650 cryomodule was to reuse components designed for the HB650 cryomodule as much as possible and to do modifications whenever necessary.

Thanks to a close collaboration between CEA and Fermilab design teams, lessons learnt from the HB650 prototype cryomodule have been implemented in the design of the LB650 cryomodule. These lessons learnt were gathered either during visits of CEA personnel during the assembly phase and then the testing phase, or during several workshops organized by Fermilab to share experiences and solve problems.

The LB650 cryomodule is shown in Fig. 2. It is 5.52-meter long, 2.34-mm tall (distance between the feet and the helium guards at the top). The diameter of the main tube of the vacuum vessel is 1.22 m. The total weight is 7.5 tons.

Each cavity is connected to a supporting system that stays at room temperature, the strongback, using two support posts made of low thermal conductivity material to limit the thermal load between the room temperature strongback and the helium temperature devices. The posts have two thermal intercepts, one connected to the thermal shield (cooled around 40 K with pressurized helium gas) and the 5 K line where liquid helium flows inside.

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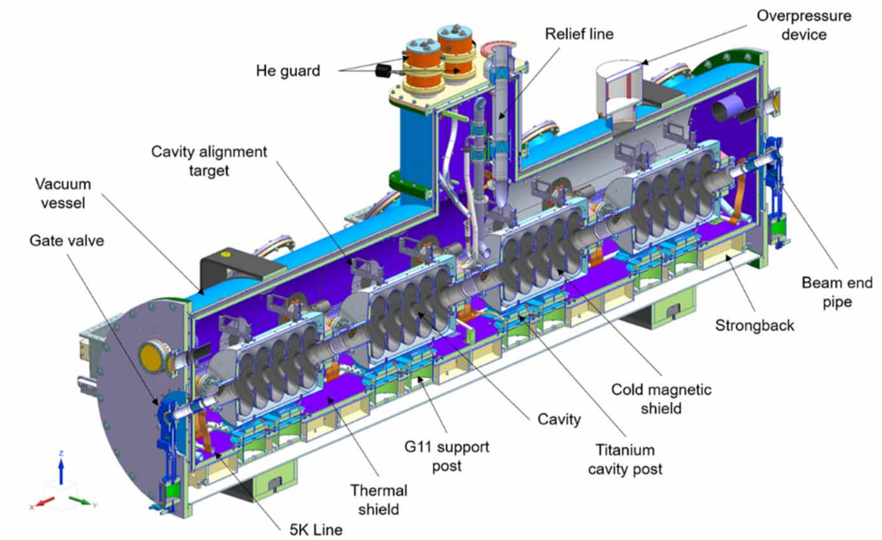

Figure 2: Layout of the LB650 cryomodule.

The thermal shield is used to limit the thermal radiation of the warm parts on the cold mass, and to heat sink the components whose one end is at room temperature and the other at cold (like the power couplers, the support posts, the cables …). The shield is made of aluminium and cooled using pressurized helium gas (19 bar – 40 K).

In order to protect the superconducting cavities against ambient magnetic field and in order to reach the PIP-II requirements, there are two layers of magnetic shielding: a global magnetic shield that is between the vacuum vessel and the thermal shield. This one is made of mu-metal and stays at room temperature. There are four local shields, one of each installed on a cavity. These shields are made of cold service special mu-metal.

Assembly studies and design of the associated tooling have been conducted in parallel with the design of the cryomodule to allow for potential minor design changes to facilitate assembly steps or to allow for the addition of interfaces [5].

The design of the LB650 cryomodule was independently reviewed in April 2023. The Final Design Review is an important milestone for CEA activities as it closes the design phase and starts the construction phase of the LB650 preproduction cryomodule.

DESIGN OF THE COMPONENTS

Vacuum Vessel

The vacuum vessel is a 1.22-meter diameter and 5.5-m long tube made of carbon steel. It has two large openings in the middle, one is called the side port, the other the top port. The first one is dedicated to the cryogenic valves and bayonets. The second one is dedicated to the relief line, the heat exchanger, and the pressure transducer and instrumentation cables lines. There are also many ports for the power couplers, the instrumentation flanges and the interfaces with the strongback. Access ports are also included to install blocking parts before the shipment of the cryomodule from France to the USA and to replace a motor or piezo of the tuning system if necessary. Note that the flanges of these ports are made of stainless steel 304L.

The vacuum vessel was designed according to the European norm 13445-3, with an additional requirements on the displacement of the connection points for the strongback and on the deformation of the coupler port. Pressure simulations in nominal operation or in accidental case have been performed. Displacement and stress, after stress linearization, are acceptable. Moreover, nonlinear buckling with the four main shapes from the eigenvalue buckling simulations and using perfect elastoplastic materials have been performed. The simulations with the four shapes from the eigenvalue buckling simulations show a safety margin of the loads over 3. Figure 3 presents the maximal stress and plastic strain for an increasing external pressure up to 3.5 bars and a release to atmospheric pressure.

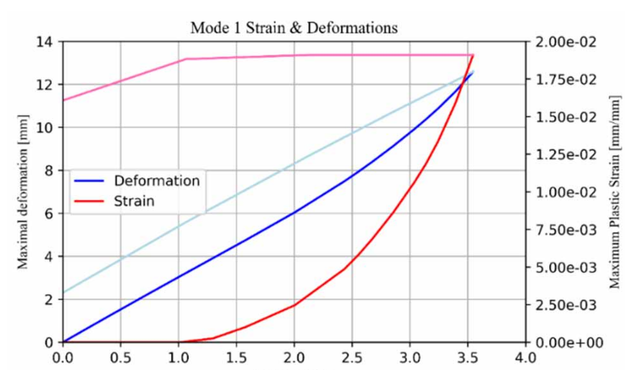

Figure 3: Maximum plastic strain and deformations for nonlinear buckling with the first shape from the eigenvalue buckling simulation.

The interfaces for lifting the cryomodule have been designed according to the European norm 10001-3-1. And the maximum principal and shear stress are acceptable with 1.5 time the nominal load.

To insert the cold mass inside the vacuum vessel, two interfaces for rails are welded on the inner bottom surface.

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These rails mate to the wheels attached at the bottom of the strongback.

As thermal simulations showed that it is mandatory to have high emissivity of the inner surface of the vacuum vessel in order to increase the radiative heat loads on the strongback and to keep it at room temperature [4], this one will be painted with white epoxy paint.

Strongback

The strongback is a key component for the alignment of the cavity string. Indeed, the cavities are aligned before the insertion of the cold mass in the vacuum vessel. After the insertion, there is no way to adjust the individual alignment of each cavity. The strongback also plays an important role during the transportation of the cryomodule since it supports the weight of the entire cold mass.

Because of these mechanical and thermal requirements, two sets of studies have been performed: mechanical computations to check the deformations of the strongback (and thus the cavity string) during the assembly and transport of the cryomodule, and thermal computations to assess the temperature of the strongback in nominal operation, but also in case of degradation of the insulation vacuum.

For the temperature of the strongback in nominal operations, the thermal computations have been presented in [4]. The temperatures measured on the strongback of the HB650 prototype cryomodule during the cold RF are consistent with the ones given by computations, thus validated the model and the boundary conditions.

For the temperature of the strongback in case of a degradation of the insulation vacuum, in addition to the boundary conditions used in the previous case, convection between the thermal shield and the strongback and between this last one and the vacuum vessel was added using the Kennard's law:

$$Q = A_1 \cdot \alpha(T) \cdot \Omega \cdot P \cdot (T_1 - T_2), \qquad (1)$$

where $\alpha(T)$ and Ω are coefficient depending on gas species (helium in this case) and its temperature, P is the pressure in the insulation vacuum, T1 is the temperature of the strongback and T2 the temperature of the thermal shield.

As it is difficult to assess the temperature of the gas in the vacuum vessel, computations have been performed using different gas temperature in the 50 – 150 K. Results show that the temperature of the strongback stays above 283 K when the pressure in the insulation vacuum is 10^{-3} mbar, whatever the temperature of the gas.

If the pressure is 10^{-2} mbar, the temperature of the strongback is not acceptable whatever the temperature of the gas. Indeed, the thermal gradient in the strongback creates too much thermal stress and deformations that could lead to a misalignment of the cavity string.

For the mechanical study, computations in nominal operation but also in accidental cases have been performed, as example during the insertion of the cold mass inside the vacuum vessel. Figure 4 presents the deformation of the strongback in such an event where there is no contact between the rails and the wheels on both ends.

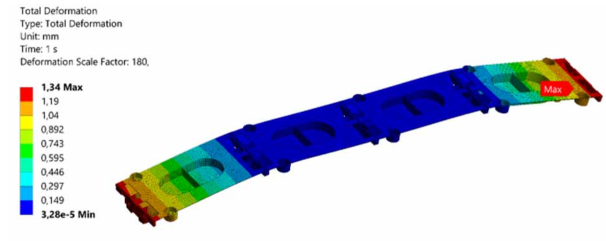

Figure 4: Deformation of the strongback in case of no contact between the rails and the wheels on both ends.

Cavity Support

Each cavity are supported by two cavity supports. These supports are connected to the strongback and consist of three main elements: the G11 post, the titanium post and two C-shaped elements as shown in Fig. 5.

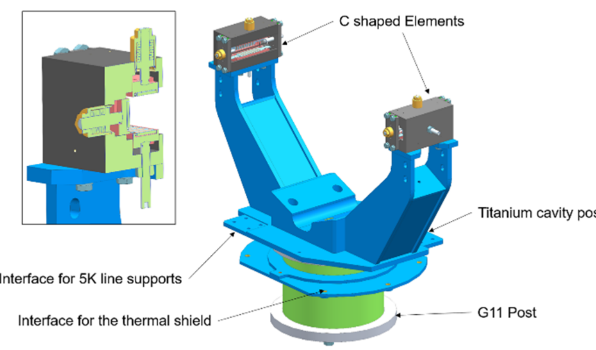

Figure 5: The cavity post.

The G11 post is designed to limit the thermal conduction from the strongback, close to the room temperature, to the cold mass that is at 2 K. The G11 post also supports the weight of the cavity string and thermal shield.

For this purpose, the posts are made of a G11 epoxy tube, with three interfaces. Each interface consists of a ring and a disc, which are shrink-fitted to the G11 epoxy tube. The lower interface is directly connected to the strongback, an interface at the 2/3 of the height of the G11 posts supports the thermal shield and the upper interface is attached to the titanium post. The upper and lower interface discs and rings are made of stainless steel 316L for magnetic hygiene issues, and the central disc and ring are made of aluminum 6061-T6 in order to avoid thermal shrinkage differences with the thermal shield that is connected to it.

The titanium post is a post made of titanium grade 2 with two interfaces for the C-shaped elements. Titanium has been chosen for magnetic hygiene and to prevent lateral misalignment of the cavity. Furthermore, the post has been designed to withstand accelerations and to avoid low frequency modes during the transport of the cryomodule.

The C-shaped elements are mainly made of titanium grade 2. Each C-shaped element has three pads with ceramic needles to allow the cavity to move longitudinally during the cooling down. These pads are connected to the main block by using screws or Belleville washers. The screws allow to proceed with the cavity alignment, while the Belleville washers are used to prevent a contact loosening due to thermal shrinkage. The ceramic needles, pads

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and screws are held in place by titanium clips, allowing the C-shaped elements to be fully assembled on a workbench, before being installed between the cavity and the titanium post.

Thermal Shield

The thermal shield aims at to reduce radiative heat loads from the room temperature parts of the cryomodule to the cold mass. Parts that have one end at room temperature and the other at liquid helium temperature are also heat sunk on the thermal shield using thermal intercepts.

The thermal shield is made of aluminum and is actively cooled with 19 bar helium gas at a temperature of 40 K flowing in the cooling channel welded to the bottom part. All the external surfaces of the thermal shield are covered with multi-layer insulation.

The design of the thermal shield of the LB650 cryomodule slightly differs from the HB650 cryomodule. The assembly of the upper parts of the thermal shield is bolted rather than welded to ease the assembly of the cold mass or its disassembly if necessary. Moreover, the top port is segmented into three parts, always in the way to ease the assembly process.

Thermal simulations have been performed in steady-state and time dependent configurations with cooling down rate of 10 $K.h^{-1}$ and of 20 $K.h^{-1}$. The helium mass flow is deducted from the mixture of warm gas at 300 K with a 1.5 $g.s^{-1}$ flow of cold gas at 40 K.

The thermal intercept heat loads and the radiative heat flux are temperature dependent. The convection coefficient between the helium and the cooling channel of the thermal shield is calculated by using Johannes's correlation:

$$Nu = 0.0259 \cdot Re^{4/5} Pr^{2/5} \left(\frac{T_s}{T_f}\right)^{-0.716}. \qquad (2)$$

The fluid temperature along the circuitry is also taken into account. For instance, Fig. 6 presents the temperature distribution of the helium gas along the cooling channel in case of steady-state simulations.

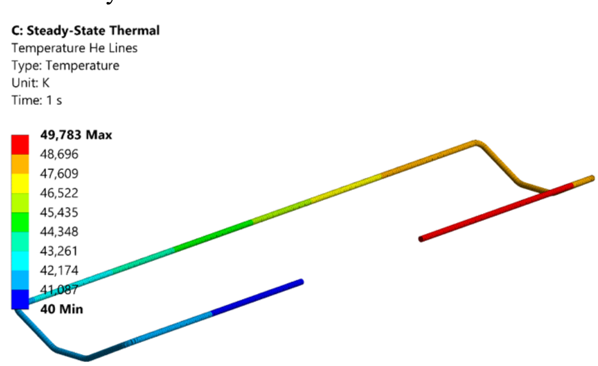

Figure 6: Helium temperature in the cooling channel, steady state simulations.

The welded beads are represented on the model in order to verify the stress during cool down of the thermal shield. Frictionless contacts with no thermal conduction is set between components that are in contact and a poor thermal contact conductance of 200 $W.m^{-2}.K^{-1}$ is used at the bolted interfaces. Figure 7 presents the temperature distribution of the thermal shield 13.5 h after the start of the cool down, with a cooling down rate of 20 $K.h^{-1}$.

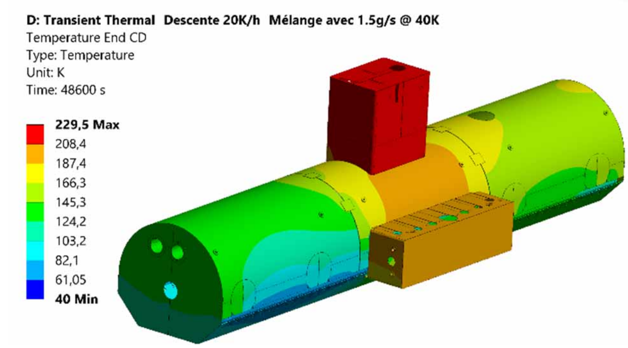

Figure 7: Temperature distribution of the thermal shield 13.5 h after the start of the cool down, with a cooling down rate of 20 $K.h^{-1}$.

Then, a thermo-mechanical simulation of the thermal shield when the thermal shrinkage is maximal at the bolted interfaces is performed to assess the stress in the screws. Figure 8 presents the stress of the thermal shield during the cooling down with a cooling down rate of 20 $K.h^{-1}$.

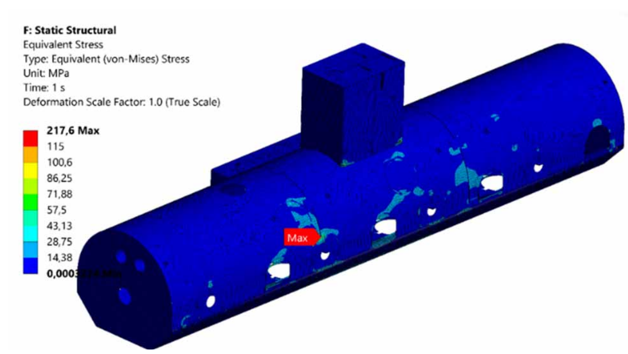

Figure 8: Stress of the thermal shield during the cooling down with a cooling down rate of 20 $K.h^{-1}$.

Cryogenic circuitry

The design of the cryogenic circuitry of the LB650 cryomodule is similar to the HB650 cryomodule. Figure 9 presents the principle of the cryogenic circuitry. In addition to the thermal shield, there is a Low Temperature Thermal Source (LTTS) that is used as thermal intercept for the components of the cold mass that have links with higher temperature. The line is also connected to the 5 K line through the cool down valve to allow the cool down of the cavities to 5 K. The cool down line has been designed to allow fast cool down capability to minimize magnetic flux trap-ping 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.

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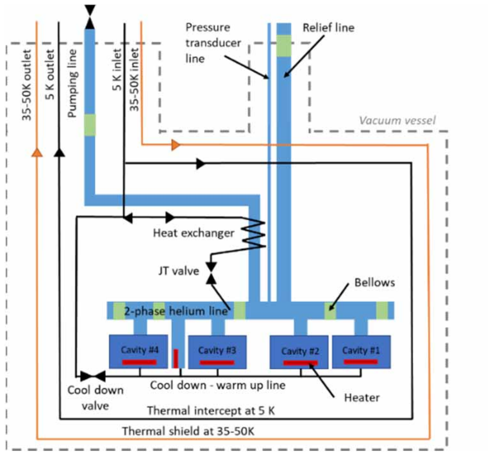

Figure 9: Principle of the cryogenic circuits of the LB650 cryomodule.

Figure 10 presents the cool down line, the pumping line and the two phase pipe. Note the copper blocks brazed on the 5 K line: these ones are used to connect the thermal intercepts. For each two-phase pipe segments, two bellows are used to facilitate the welding on the cavity. Titanium rods are used in order laterally maintain the two-phase pipe segments and to balance the pressure effect that occur at each extremity. In the same way, the relief line presents two bellows in order to avoid stress during the cooling down and to ease its assembly.

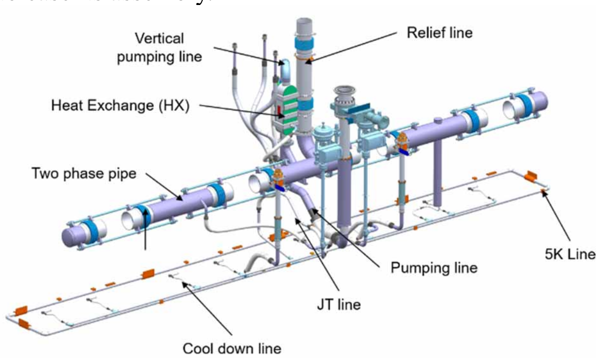

Figure 10: Overview of the cryogenic circuitry of the LB650 cryomodule.

As the cold RF tests of the HB650 cryomodules will be performed at CEA and as each cryomodule needs to be reconfigured for transportation between France and the USA, the circuitry in the top port (vertical pumping line, heat exchanger and relief line) must be removed. CEA has designed a specific flange that is used to allow bolted interfaces with a gasket for the cold RF test configuration and a welded interface for the final configuration of the cryomodule at Fermilab. Figure 11 shows the specific flange in the two configurations for the connection between the heat exchanger and the two-phase pipe. Such flanges are installed at different locations in the circuitry in the top port.

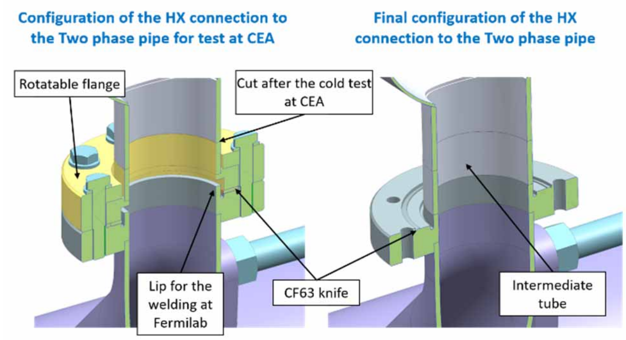

Figure 11: Specific flange for bolted connection – cold test configuration at CEA, right - and welded assembly – final configuration at Fermilab.

ALIGNMENT SIMULATIONS

In addition to the simulations performed on each individual component, simulations have been performed on the entire cryomodule to estimate the transverse displacement of the cavity due to strongback and vacuum vessel deformations under external pressure. Figure 12 shows the deformations of the cryomodule in nominal operation.

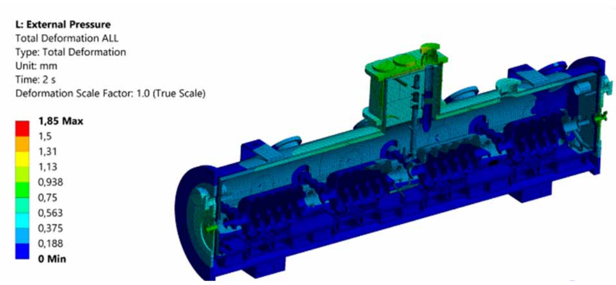

Figure 12: Deformations of the cryomodule with pressure in the insulation vacuum.

The impact on the cavities alignment can be assessed by monitoring the lateral displacement of the cavity extremities. It shows that the cavity axis remains in a 0.2 mm diameter circle, and that a vertical offset of -0.10 mm and a lateral one of 0.12 mm have to be taken into account during the assembly and the alignment process. As well as the thermal shrinkage of the cavity post: 0.81 mm has to be added to the previous vertical offset to compensate the displacement of the cavity string with regards to the beam axis during the cool down of the cryomodule.

CONCLUSION

The final design of the LB650 cryomodule has been presented as well as results of mechanical, thermal and thermo-mechanical simulation of some of the main components. Thanks to the strong and fully open collaboration between CEA and Fermilab teams, the LB650 cryomodule benefits from the design and the lessons learnt of the assembly and cold RF tests of the HB650 prototype cryomodule. An important milestone for CEA activities was reached in April 2023 with the Final Design Review of the LB650 cryomodule.

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REFERENCES

[1] R. Stanek *et al.*, "PIP-II Project Overview and Status", presented at SRF'23, Grand Rapids, MI, USA, Jun. 2023, paper MOIXA02, this conference.

[2] N. Bazin *et al.*, "CEA contribution to the PIP-II linear accelerator", presented at SRF'23, Grand Rapids, MI, USA, Jun. 2023, paper MOPMB055, this conference.

[3] V. Roger *et al.*, "HB650 cryomodule design: from prototype to production", presented at SRF'23, Grand Rapids, MI, USA, Jun. 2023, paper WEPWB067, this conference.

[4] N. Bazin *et al.*, "Design of the PIP-II 650 MHz Low Beta Cryomodule", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021. doi:10.18429/JACoW-SRF2021-THPTEV00

[5] J. Drant *et al.*, "Preparation of the assembly of the 650 MHz Low Beta Cryomodules for the PIP-II Linear Accelerator", presented at SRF'23, Grand Rapids, MI, USA, Jun. 2023, paper TUPTB025, this conference.