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DESIGN OF THE PIP-II 650 MHz LOW BETA CRYOMODULE

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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 is responsible for the 650 MHz low-beta section comprising 9 cryomodules, 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. This paper presents the design of the 650 MHz low-beta cryomodules.

INTRODUCTION

The PIP-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 [1].

The CEA contribution to the PIP-II project is mainly on the low beta elliptical cavity cryomodule – also called LB650 cryomodule (Figure 1).

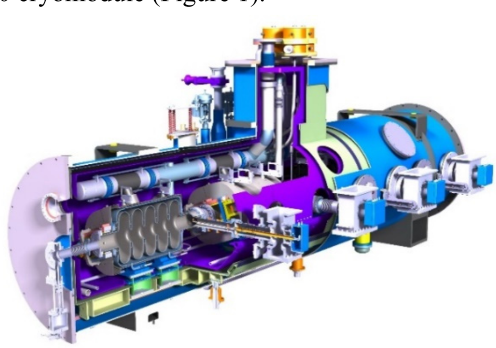

Figure 1: The LB650 cryomodule.

It includes the design of the LB650 cryomodule, the procurement of most of the components (except the cavities, tuning systems, power couplers, instrumentation and related feedthroughs, valves, heat exchanger, JT valve, and auxiliary cryogenic items supplied by Fermilab), the assembly and RF tests of all the cryomodules (one pre-production cryomodule and 9 series ones), and preparation to shipment between France and USA (including the design and manufacturing of the transport frame).

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DESIGN OF THE LB650 CRYOMODULE

The LB650 cryomodule benefits from the experience of the cryomodules previously developed for the PIP-II project (the first spoke cryomodule SSR1 [2]) or under development (the HB650 prototype cryomodule [3]). The concept of the supporting system for the cold mass is identical for the spoke and elliptical cryomodules: it is based on the strongback that stays at room temperature when the cryomodule is cold [4].

Each LB650 cryomodule houses four 5-cell β=0.61 cavities (developed by Fermilab, INFN, and VECC for the preproduction cryomodule [5] and series cryomodules [6]). The frequency tuning systems and the power couplers for the low beta and high beta cavities are identical. They are under the responsibility of Fermilab ([7] and [8]), with CEA contribution on the studies of the power couplers ([9] and [10]). The schematics of the cryogenic lines of the LB650 cryomodule is shown in Fig. 2, Fig. 3 presents the layout. It is similar in design to the HB650 cryomodule described in [11]. Each cavity is connected to 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) and the 5 K line where liquid helium flows inside.

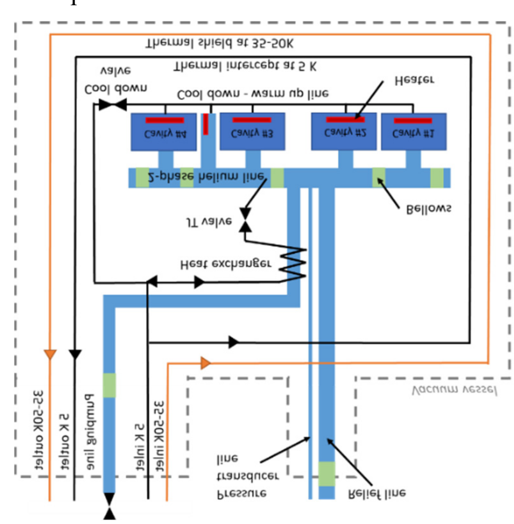

Figure 2: Schematics of the cryogenic lines of the LB650 cryomodule.

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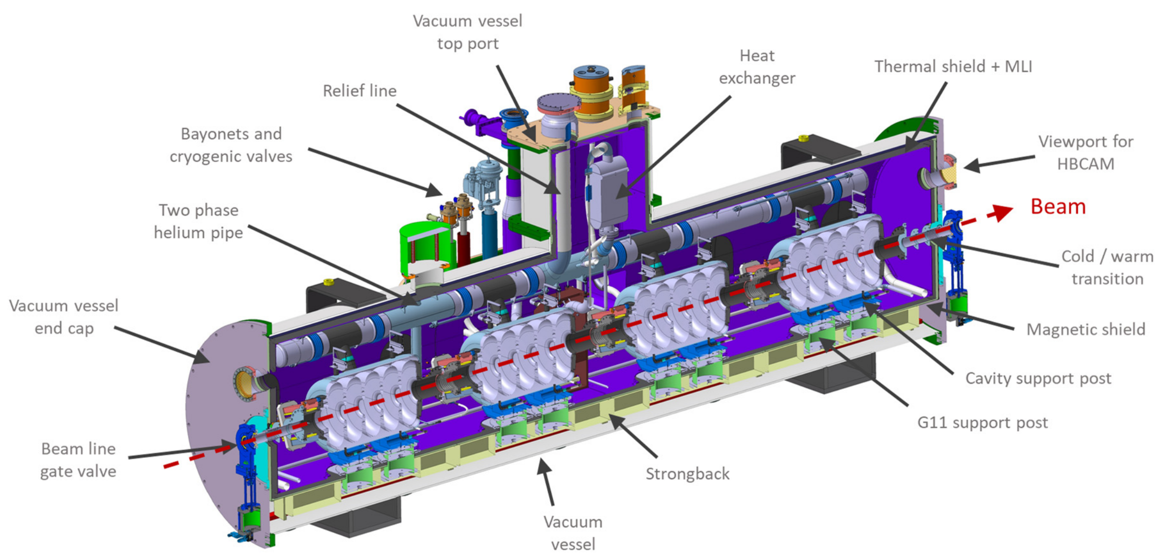

Figure 3: Layout of the PIP-II LB650 cryomodule.

To deal with the difference in thermal contraction coefficients of the materials of the strongback and the cold mass, the cavities are not fixed to the support posts but installed on C-clamp assemblies that allow motion in the horizontal plane. The C-clamp closest to the power coupler does not allow longitudinal motion, to fix the position of the cavity along the beam axis.

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). It is made of five sub-assemblies: the top part of the shield, the bottom part where the cooling channel is welded using finger welds, the top port, the side port and the upstream and downstream panels. Unlike what is planned for the HB650 cryomodule, the top and bottom parts are not welded together during the assembly of the cryomodule, but connected together using bolts. Thermo-mechanical analysis performed using FEM software taking into account the thermal contact resistance between the assemblies shows that the gradients, the deformations and the stress are acceptable during cool down and nominal operation. In steady state, the top port is the warmest part of the thermal shield, 8 K above the temperature of the cooling fluid (see Figure 4).

To protect the superconducting cavities against the ambient magnetic field, two magnetic shields are installed to respect the requirement of 5 mG (0.5 µT) for the residual magnetic field on the cavity surface: a cold local shield that is placed around the helium tank of every cavity, and a global one that is installed between the thermal shield and the vacuum vessel and that stays close to room temperature.

The vacuum vessel is made of carbon steel, which also helps in the shielding of external magnetic field. The flanges are made of stainless steel.

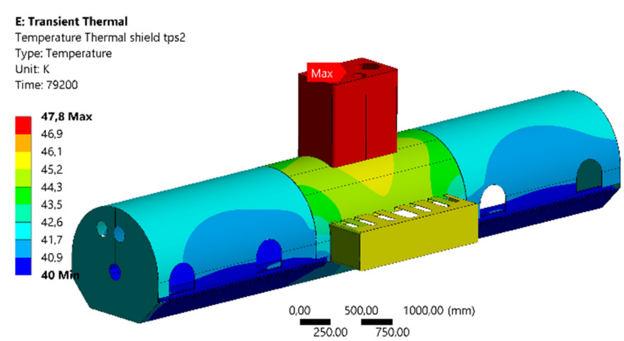

Figure 4: Temperature distribution of the thermal shield in steady state.

The vacuum vessel is around 5250–mm long and 10-mm thick cylinder with two stiffening rings spaced 3630 mm apart. It is designed to keep deformation of the connection points of the strongback and vacuum vessel below 0.5 mm, in order to limit the impact on the alignment of the cavity string (Fig. 5).

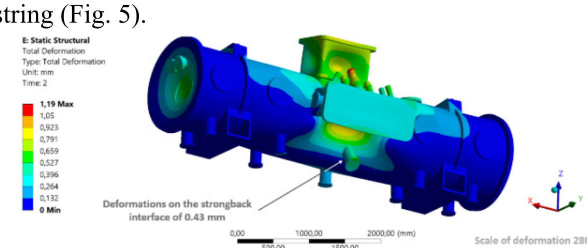

Figure 5: Deformation of the vacuum vessel under external pressure forces and mass of the components.

The port on one side of the vacuum vessel is used to install the bayonets that provide fluids from the cryogenic distribution sysetm. The port on the top houses the heat exchanger, the pressure relief line and the lines and feedthroughs for the cables of the liquid level gauge and the instrumentation placed on the cavites. Helium guards are used to protect the cryogenic circuit in case of a small air leak in a feedthrough.

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In order to standardize the components of the elliptical cavity section, several components are common to both the LB650 and the HB650 cryomodules: in addition to the tuning systems and the power couplers previously mentionned, it includes the support assemblies of the cavities, the cold-warm transitions installed on each end of the cavity string, the cryogenic bayonets, the bellows installed between two cavities, the thermal straps and the instrumentation (sensors, cabling and flanges with feedthroughs).

THERMAL STUDIES OF THE STRONGBACK

The strongback is a key component for the alignment of the cavity string. The cavities are aligned before the insertion of the cold mass inside the vacuum vessel. Because the strongback is meant to stay at room temperature during cool down, the fixed point of the cavities does not move from room to helium temperature. Because the strongback is connected to a hot source (the vacuum vessel) and cold sources (the support posts of the cavities and the thermal shield), it is not obvious that its temperature is the same as the vacuum vessel. Thermal studies have been performed to assess the temperature of the strongback considering all the heat loads applied to it:

- Head loads by conduction from the support posts of the dressed cavities and the thermal shield.
- Heat loads from thermal radiation of the thermal shield at 50 K.
- Heat loads by conduction of the studs that supports the strongback and that are connected to the vacuum vessel that is at ambient temperature.
- Heat loads from thermal radiation of the vacuum vessel.

Two methods have been used to calculate the strongback temperature in nominal operation:

- Analytical calculations like the ones described in [10]. This method gives an average temperature of the whole strongback with the possibility to quickly define the impact of one of the parameters: radiative heat flux from the vacuum vessel and the thermal shield, emissivity, thermal contact (simplified model)…
- FEM (Finite Elements Method) analysis to get the temperature distribution in the strongback and using more realistic boundary conditions (thermal contact resistance, convection with ambient air …). Because of the size of the model and the complexity of the strongback design with the stud assemblies that connect the device to the vacuum vessel, this method is time consuming.

Note that these studies have been done for the LB650 and HB650 cryomodules, and that design improvements described below have been implemented on both cryomodules.

The analytical calculations showed that it is important to have the highest possible emissivity - for the inner surface of the vacuum vessel and the surface of the strongback that faces the room temperature surface (Table 1). It led to a first design improvement: because the mu-metal material used for the warm magnetic shield has a low emissivity (around 0.15), it was decided to place it between the strongback and the thermal shield instead of between the vacuum vessel and the strongback (Figure 6). During the manufacturing of the components, the inner surface of the vacuum vessel will be covered with a white epoxy paint to get an emissivity around 0.7 and the bottom surface of the strongback will be blasted (shot-blast, sand-blast or micro-blast, depending on the contractor) to increase the emissivity of material up to 0.7.

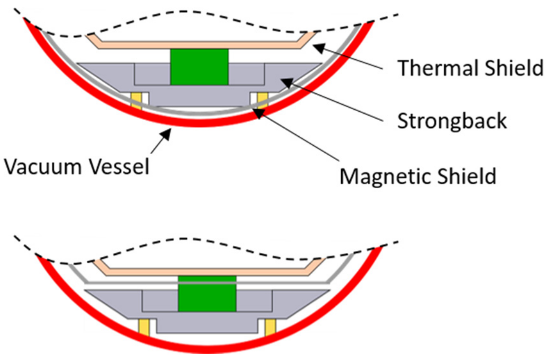

Figure 6: Initial configuration (top): the magnetic shield is placed between the vacuum vessel and the strongback. Improved configuration (bottom): the magnetic shield is now between the strongback and the thermal shield.

Table 1: Temperature of the strongback and emissivity of the materials for the initial and improved configurations from the analytical calculations.

	Initial configuration	Improved configuration
Strongback Emissivity	0.2	0.7
Vacuum Vessel Emissivity	0.1	0.7
Strongback Temperature	283.21 K	291.22 K

The FEM analysis showed that the thermal contact resistance between the studs and the strongback has a negligible impact on the temperature of the strongback. Indeed the contact is done though a single screw that acts as a bottleneck for the heat transfer between the two assemblies. Therefore, as a second design improvement, thermal straps are installed between the vacuum vessel and the strongback to increase the heat loads by conduction. Figure 7 represents the temperature distribution in the strongback for the improved configuration.

CONCLUSION

The design of the LB650 cryomodule for the PIP-II accelerator is similar to the HB650 cryomodule. Thanks to the strong and fully open collaboration between CEA and Fermilab teams, the LB650 cryomodule benefits from the design of the HB650 cryomodule and the experience of

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both teams. The preliminary design phase of the cryomodule is now finished, and the LB650 cryomodule is now entering the detailed design phase.

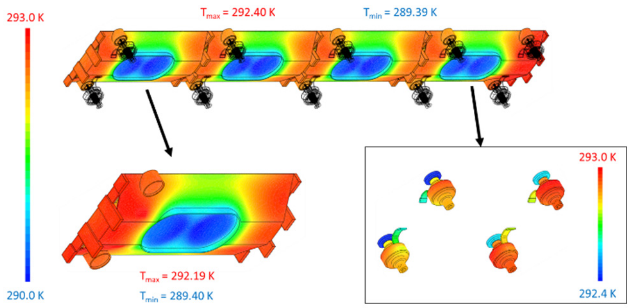

Figure 7: Temperature distribution in the strongback, the studs and the thermal straps using an emissivity of 0.7 for the strongback and the vacuum vessel.

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