ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST011

CEA CONTRIBUTION TO 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 will deliver 10 low-beta cryomodules as In-Kind Contribution to the PIP-II project, with cavities supplied by LASA-INFN and power couplers and tuning systems supplied by Fermilab. This paper presents the CEA scope of work that includes the design, manufacturing, assembly and tests of the cryomodules and the upgrade of the existing infrastructures to the PIP-II requirements.

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 [1].

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 [2].

OVERVIEW OF THE CEA CONTRIBUTION TO THE PIP-II PROJECT

CEA is designing, building, testing, installing and commissioning superconducting linear accelerators (or part of them) for others labs since 20 years. It includes the development of a wide range of cryomodules with different frequencies, different types of cavities (low beta ones – half-wave and quarter-wave resonators – and high beta ones – elliptical cavities), different types of supports and insertion modes of the cold mass: 352 MHz cryomodule for SOLEIL, 88 MHz QWR cryomodules for Spiral2, 1.3 GHz cryomodules for XFEL, 175 MHz HWR cryomodules for IFMIF/EVEDA, IFMIF-DONES and SARAF, 704 MHz cryomodules for ESS [3, 4].

Thanks to this expertise, CEA joined the PIP-II collaboration in 2018. The involvement of CEA in the PIP-II Linac construction was formally approved by the French Ministry of Research in July 2020 with the definition of the scope of work and the budget envelope.

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 (called "LB650" hereafter) according to the PIP-II project specified requirements. This includes:

- The design of the LB650 cryomodule.
- The procurement of most of the components of the cryostat (i.e. the cryomodule without the cavities, the tuning systems, the power couplers and some standard components provided by the PIP-II collaboration).
- The assembly and cold RF tests of the 10 LB650 cryomodules.
- The design of the transport frame for the LB650 cryomodules, fabrication of 2 units and road test of the pre-production cryomodule.
- The preparation for shipment before the transfer title from CEA to the U.S Department of Energy and the overseas transportation from France to the USA.

DESIGN OF THE LB650 CRYOMODULE

The LB650 cryomodule houses four 5-cell β=0.61 cavities (developed by Fermilab, INFN, and VECC for the preproduction cryomodule and series cryomodules [5]). 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, with CEA contribution on the design studies of the power couplers. Each cavity is connected to the 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) and the 5 K line where liquid helium flows inside.

The LB650 cryomodule is similar to the HB650 cryomodule that is being developed by Fermilab [6]. In order to benefit from the HB650 cryomodule to the LB650 one, CEA is part of the integrated design team with Fermilab,

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ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-MOPOST011

UKRI-STFC and DAE and was in charge of the mechanical and thermal design of the strongback and the design of the endcap tooling (based on the one used for the assembly of the ESS cryomodules at Saclay).

The design of the LB650 cryomodule is described in [7]. Figure 1 presents an artist view of this cryomodule.

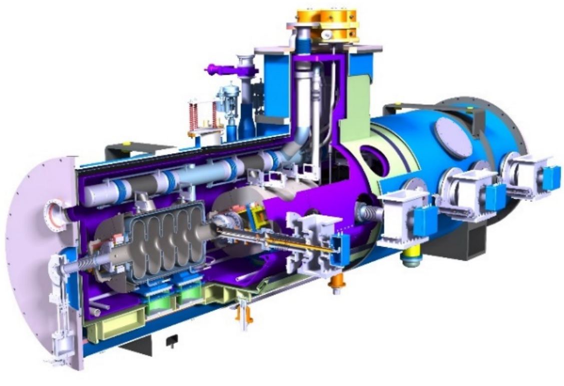

Figure 1: The LB650 cryomodule.

ASSEMBLY OF THE CRYOMODULES

The assembly of the LB650 cryomodules will be performed in the so-called “ESS Village” at CEA Saclay (former “XFEL Village”). The infrastructures and existing equipment will be adapted to the PIP-II components.

Assembly studies have been performed in parallel to the design of the cryomodule in order to define as earlier as possible the required tooling and interfaces between the components and the tools. It also enabled to identify the workstations according to the assembly sequence. Even if the one for the LB650 cryomodule is rather similar to the one for the HB650 cryomodule the difference of infrastructure between CEA Saclay and Fermilab has to be taken into account. Concerning the design of the tooling, the challenge is to adapt the existing one already used for the assembly of the XFEL and ESS cryomodules to the PIP-II components while trying to keep this one compatible as much as possible with the tooling developed by Fermilab for the assembly of the HB650 cryomodules.

Cavity String Assembly

The cavity string is made of four superconducting cavities, four power coupler, three bellows implemented between two cavities and two cold-warm transition with the beam valves that close the beam vacuum. It will be assembled in the 112 m² ISO 4 clean room.

Two workstations have been identified: one for the preparation of the components (including the high pressure rinsing of the bellows and transitions), the other for the assembly of the beam components.

Each cavity is supported by two support posts (Figure 2). Two similar posts are used to install the beam valve on a cold-warm transition. Two assembly support tables have been developed to connect the power couplers and the bellows on the cavities. Every post and tool has adjustment systems to position one component with regards to the other.

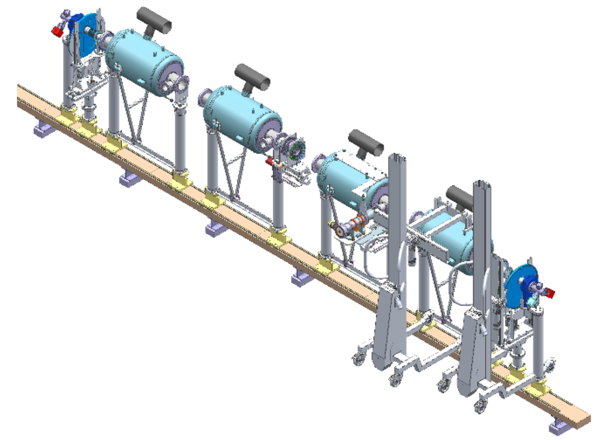

Figure 2: Tooling for the cavity string assembly in clean room.

Post Clean Room Assembly

Three workstations are identified for the assembly operations outside the clean room. At the first one, each cavity is equipped with its tuning system and cold magnetic shield and the inlet and outlet cryogenic pipes are welded to the helium tank.

The second workstation is dedicated to the cold mass assembly and its insertion in the vacuum vessel. It is divided into three working areas, one for the strongback assembly, one for the installation of the cavity string on the strongback and the finalization of the cold mass assembly and the last one for the preparation of the vacuum vessel with the installation of the warm magnetic shield on its inner surface. Once the cold mass is inserted in the vacuum vessel, the two end caps are installed. Most of the tooling used for the operations at this workstation is shown in Figure 3.

The last workstation (CLO) is dedicated to the preparation of the cryomodule before its transfer to the RF test stand that is installed in a building close to the assembly hall.

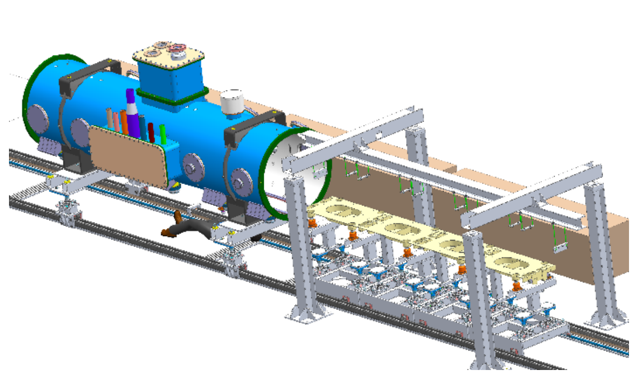

Figure 3: Tooling used for the insertion of the cold mass inside the vacuum vessel.

UPGRADE OF THE RF TEST INFRASTRUCTURE

The existing test infrastructure that is currently used for the qualification at Saclay of some of the ESS cryomodules,

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and that is described in [8], has to be adapted to fulfil the PIP-II requirements. It includes the procurement of four 650 MHz 19kW CW solid-state amplifiers, four RF power circulators equipped with their corresponding RF loads and the waveguide distribution system to power the four cavities of the LB650 cryomodule independently. Concerning the cryogenic system, the existing cold box will be replaced by a more efficient one that delivers supercritical helium (5.5 K / 3 bars) instead of saturated liquid helium at 4.2 K and that allows to cool the thermal shield of the cryomodule with cold pressurized helium gas (between 40 and 60 K) instead of liquid nitrogen. The fluid distribution system will be upgraded: a new valve box is being designed and will be installed on top of the test cave as well as a 500-liter pressurized helium dewar. This one will be used to deliver the extra mass flow for the fast cool down of the cavities (up to 50 g/s required whereas the cold box can deliver up to 20 g/s).

Instrumentation and control cabinets are also being developed for the PIP-II LB650 cryomodule. It includes:

- Control of the cryogenic distribution.
- Fast acquisition of the RF signals, the arc detectors on the RF distribution system, cavity field probes and coupler electron pick-ups.
- Slow acquisition of the vacuum signals and the temperature.
- Control of the frequency tuning system of the cavities.
- Regulation of the RF power frequency and amplitude.
- Control of the safety devices of the test stand and associated interlock signals.

All these cabinets will be near the test cave and close to the control room. The layout of the test infrastructure is presented in Figure 4.

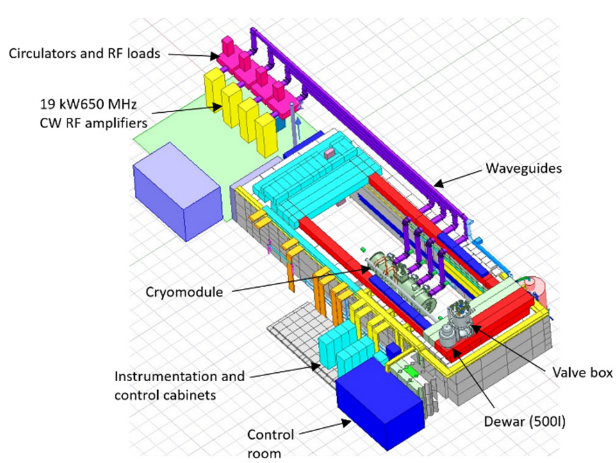

Figure 4: Layout of the PIP-II cryomodule test infrastructure at CEA Saclay.

TRANSPORTATION

The LB650 cryomodules assembled and tested at CEA Saclay in France are to undergo transatlantic shipment by road and air to be installed on the PIP-II accelerator beam line at Fermilab, in the neighborhood of Chicago in the USA. This poses significant risks and required analysis and tests before the transfer of a cryomodule.

CEA is committed to design and manufacture two transport frames for the overseas cryomodules transportation (which is under the responsibility of Fermilab). Theses frames, as well as the studies to be performed on the cryomodules, are similar to what has be development for the HB650 prototype cryomodule [9]. Lessons learnt from the transportation tests of this cryomodule will be implemented, thanks the integrated transportation team consisting of CEA, UKRI-STFC and Fermilab.

In addition to the simulations, a set of road tests will be performed in France: first with a dummy load, then with the pre-production cryomodule.

The preliminary design of the transport frame is shown in Figure 5. Before shipment, the cryomodule is reconfigured: the top port of the cryomodule has to be disassembled to fit in a standard cargo plane and the warm parts of the power couplers are removed.

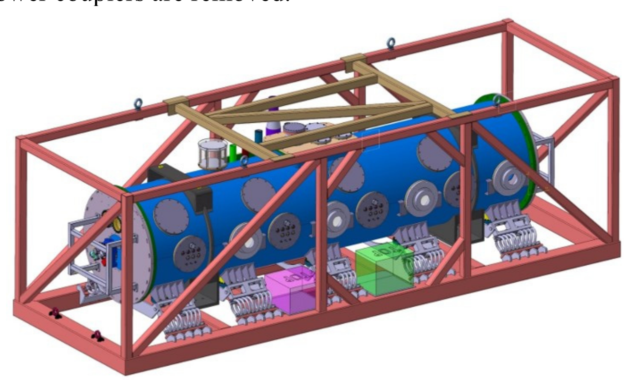

Figure 5: Preliminary design of the transport frame of the LB650 cryomodules.

CONCLUSION

Thanks to its strong expertise in the development of cryomodules for superconducting linac, CEA joined the PIP-II collaboration in 2018 with an in-kind contribution on the LB650 cryomodules. The detailed design of the cryomodules is well advanced thanks to the strong and fully open collaboration between all the partners. Moreover, the LB650 benefits of the lessons learnt of the HB650 prototype cryomodule that is being developed at Fermilab. Meanwhile, the upgrade of the existing infrastructures are in progress, with the design of the tooling required for the cryomodule assembly and the procurement of the first equipment for the test stand.

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