

## CEA CONTRIBUTION TO THE PIP-II LINEAR ACCELERATOR

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### Abstract

The Proton Improvement Plan II (PIP-II) that will be in-stalled at Fermilab is the first U.S. accelerator project that will have significant contributions from international part-ners. CEA joined the international collaboration in 2018, and will deliver 10 low-beta cryomodules as In-Kind Con-tributions to the PIP-II project, with cavities supplied by LASA-INFN (Italy) and VECC-DAE (India) and power couplers and tuning systems supplied by Fermilab. An im-portant milestone was reach in April 2023 with the Final Design Review of the cryomodule, launching the pre-pro-duction phase. This paper presents the status of CEA activ-ities 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 neu-trino beam for the Long Baseline Neutrino Facility (LBNF) and the Deep-Underground Neutrino Experiment (DUNE) located in South Dakota, 1200 km from the neutrino pro-duction in Illinois.

PIP-II will deliver 1.2 MW of proton beam power from the injector, upgradeable to multi-MW capability. The cen-tral 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 interna-tional partners, including India, Italy, France, United King-dom and Poland [1, 2].

### OVERVIEW OF THE CEA CONTRIBUTION TO THE PIP-II PROJECT

CEA is designing, building, testing, installing and com-missioning superconducting linear accelerators (or part of them) for others labs since 20 years. It includes the devel-opment of a wide range of cryomodules with different fre-quencies, 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 SO-LEIL, 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 collabo-ration in 2018. The involvement of CEA in the PIP-II Linac construction was formally approved by the French Minis-try of Research in July 2020 with the definition of the scope of work and the budget envelope.

CEA contribution focuses on the 650 MHz supercon-ducting accelerating section, with the design, fabrication, assembly and test of 1 pre-production and 9 production low-beta 650 MHz cryomodules (called “LB650” hereaf-ter) 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 3 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 (DOE) and the overseas transportation from France to the USA.

### DESIGN OF THE LB650 CRYOMODULE

The LB650 cryomodule houses four 5-cell  $\beta=0.61$  cavi-ties (developed by Fermilab, INFN, and VECC for the pre-production cryomodule and series cryomodules). The fre-quency 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 con-nected to the a supporting system that stays at room tem-perature , 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 inter-cepts, one connected to the thermal shield (cooled around 40 K) and the 5 K line where liquid helium flows inside.

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The LB650 cryomodule is similar to the HB650 prototype cryomodule that was assembled and cold RF tested at Fermilab [5]. In order to benefit from the HB650 cryomodule to the LB650 one, CEA was part of the integrated design team with Fermilab, UKRI-STFC and DAE and was in charge of the mechanical and thermal design of the strongback of the HB650 prototype cryomodule and the design of the endcap tooling (based on the one used for the assembly of the ESS cryomodules at Saclay).

Lessons learnt from the assembly and tests of the HB650 prototype cryomodule have been implemented in the design of the LB650 cryomodule. This one was independently reviewed in April 2023. The Final Design Review, which is an important milestone for the CEA activities, marks the end of the design phase and opens the construction phase of the LB650 pre-production cryomodule.

The design of the LB650 cryomodule is described in [6]. Figure 1 presents an artist view of this cryomodule.

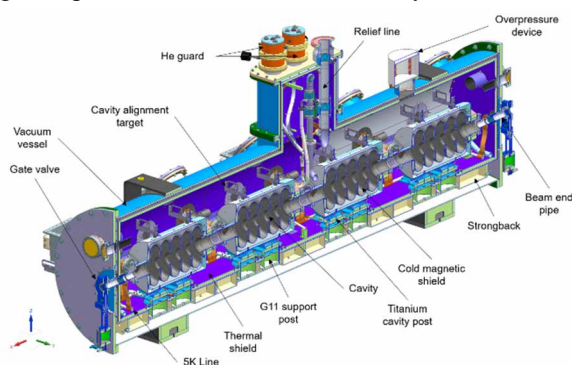


Figure 1: The LB650 cryomodule.

## 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 (Fig. 2). 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 [7].

In addition to the preparation work at Saclay, the CEA assembly team visited Fermilab throughout 2022 to observe the assembly of the HB650 prototype cryomodule. Thanks to the open collaboration between CEA and Fermilab teams, it was an opportunity to discuss procedures, processes, tooling and design elements. Like for the design of the LB650 cryomodule, lessons learnt from the assembly of the HB650 prototype cryomodule have been implemented in the design of the tooling.

One of the challenges of assembling the LB650 cryomodules, in addition to perform a particle-free assembly, is to deal with the multitude of components supplied by the PIP-II collaboration: the cavities will be provided by LASA-INFN (Italy) and VECC-DAE (India), Fermilab will provide the power couplers, the frequency tuning systems for the cavities, the instrumentation (sensors, actuators, internal cabling, flanges with vacuum feedthroughs), the cryogenic valves, bayonets and helium guards. This requires a common management of the interfaces and of the quality control steps that have to be performed when receiving the hardware at CEA to avoid issues during the assembly process. An effort has been made in the past months within the PIP-II collaboration to set the interfaces, the as-delivered configuration of the components with the associated documentation, and the process for acceptance for every component between CEA and Fermilab and the title of transfer of each cryomodule between CEA and DOE.

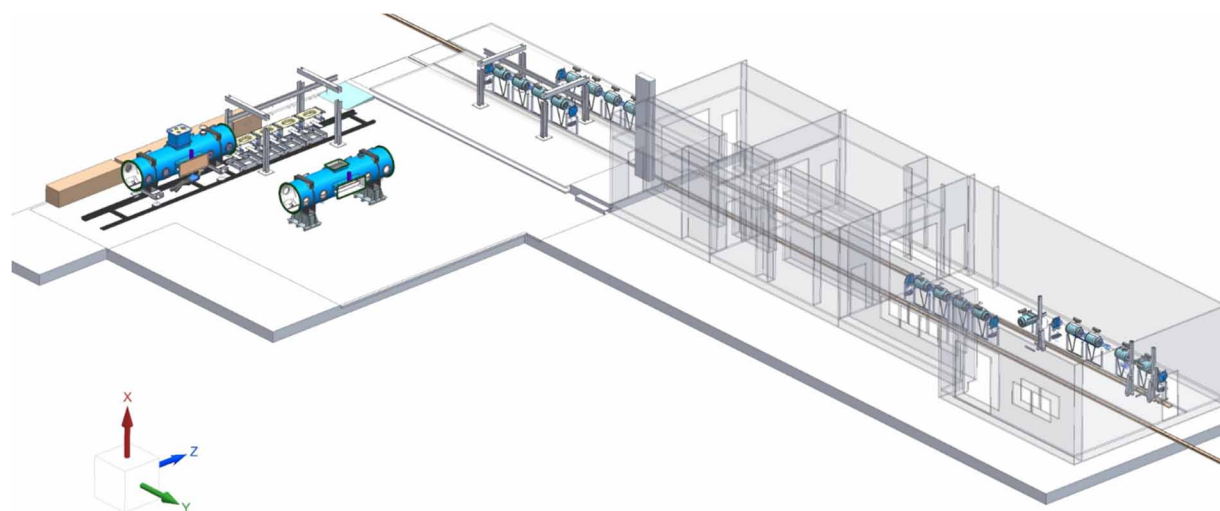


Figure 2: The workstations for the assembly of the LB650 cryomodules in the future “PIP-II Village”.

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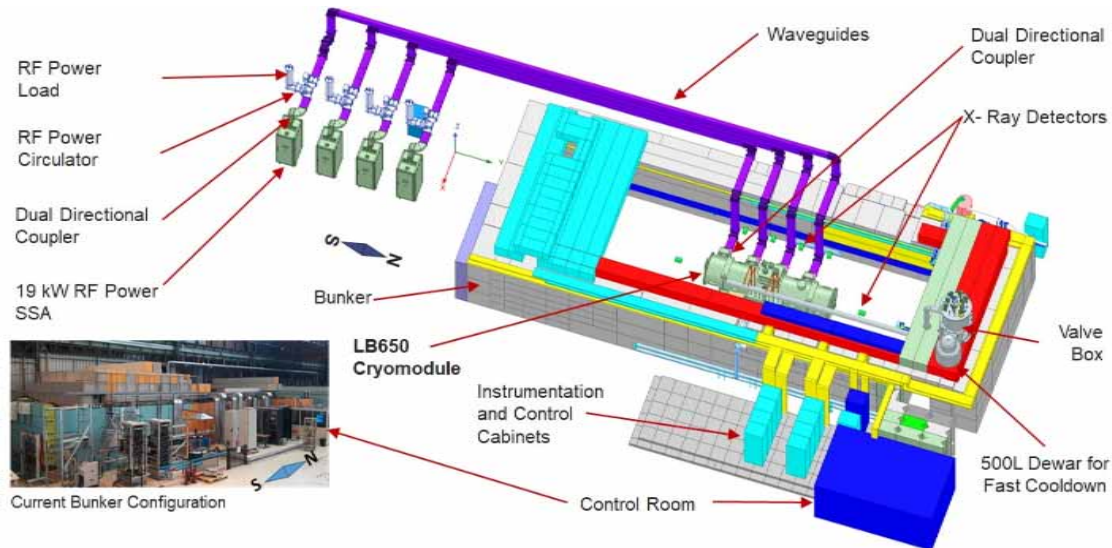


Figure 3: Layout of the PIP-II cryomodule test infrastructure at CEA Saclay.

## 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, 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 (40 K / 14 bars) 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 Fig. 3. More details are given in [9].

## 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 three transport frames for the overseas cryomodules transportation (which is under the responsibility of Fermilab). These frames, as well as the studies to be performed on the cryomodules, are similar to what has been developed for the HB650 prototype cryomodule [10]. Lessons learnt from the transportation tests of this cryomodule have been implemented, thanks to the integrated transportation team consisting of CEA, UKRI-STFC and Fermilab.

In addition to the simulations, a road test will be performed in France with the pre-production cryomodule.

The design of the transport frame is shown in Figure 4. Before shipment, the cryomodule is reconfigured: the top part of the cryomodule has to be disassembled to fit in a standard cargo plane and the warm parts of the power couplers are removed.

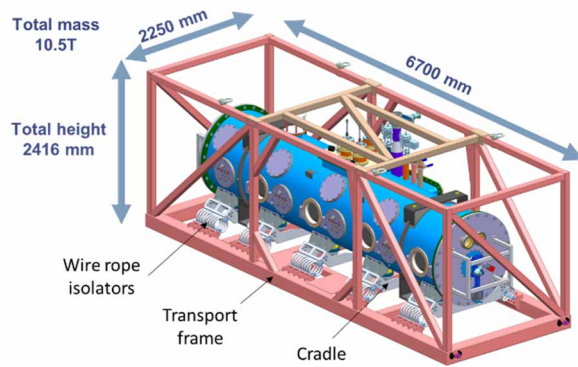


Figure 4: Design of the transport frame of the LB650 cryomodules.

## 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 LB650 cryomodule that benefits of the lessons learnt of the HB650 prototype cryomodule that was developed at Fermilab is completed. The construction phase of the pre-production cryomodule started in April 2023. 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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