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STATUS OF THE CEA CONTRIBUTION TO THE PIP-II LINEAR ACCELERATOR

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Abstract

The Proton Improvement Plan II (PIP-II) project at Fermilab is the first U.S. accelerator project that will have significant contributions from international partners [1]. CEA joined the international collaboration in 2018, and will deliver 10 low-beta cryomodules as In-Kind Contributions 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 important milestone was reached in April 2023 with the Final Design Review of the cryomodule, launching the pre-production phase. This paper presents the status of CEA activities on the construction of the LB650 pre-production cryomodule and the upgrade of the existing assembly and test infrastructures to the PIP-II requirements.

INTRODUCTION

The PIP-II project is an upgrade of the accelerator complex of Fermilab [2] to enable the world's most intense neutrino beam for the Deep-Underground Neutrino Experiment (DUNE) housed in the Long Baseline Neutrino Facility (LBNF) 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.

OVERVIEW OF THE CEA CONTRIBUTION TO THE PIP-II PROJECT

Thanks to the expertise in designing, building, testing, installing, and commissioning superconducting linear accelerators, 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 3 units, and road test of the pre-production cryomodule.
- The preparation for overseas shipment to the USA before the transfer title from CEA to the U.S Department of Energy (DOE).

DESIGN OF THE LB650 CRYOMODULE

The LB650 cryomodule houses four 5-cell β=0.61 cavities (developed by Fermilab, INFN [3], and VECC for the pre-production cryomodule and series cryomodules). 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 a supporting system that stays at room temperature, called 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 LB650 cryomodule is like the HB650 prototype cryomodule that was qualified at Fermilab [4, 5]. To benefit from the efforts in the HB650 cryomodule design to be applied 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 CEA).

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.

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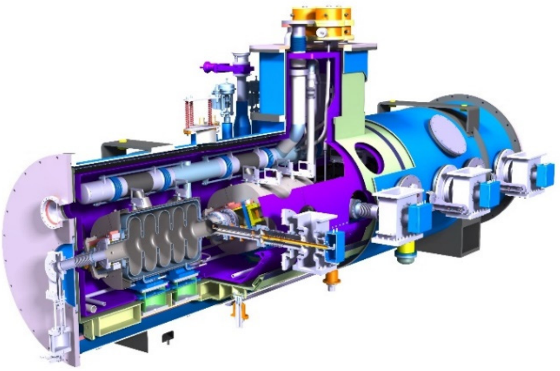

Figure 1: The LB650 cryomodule.

CONSTRUCTION OF THE PRE-PRODUCTION CRYOMODULE

Following the Final Design Review, CEA launched the procurement process of the long-lead high value components. The contracts for all these components are issued for the pre-production and the production cryomodules in a single process divided into two stages (1 set + 9 sets), to retain the same vendor for all the cryomodules and to reduce the procurement time between the pre-production and production phases. Where design uncertainty remained because of the excessive heat loads observed on the HB650 prototype cryomodule, components were excluded from the procurement, and will be ordered later when there is better understanding of the thermal behavior of the HB650 prototype cryomodule.

The manufacturing of the components of the pre-production cryomodule is ongoing. Most of the Manufacturing Readiness Reviews will be completed in the next weeks. Vendors have already placed orders for raw materials with long lead times.

PREPARATION OF THE 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”) that will be become the “PIP-II 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 to define as early as possible the required tooling and interfaces between the components and the tools. It also enabled identifying 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 ones already used for the assembly of the XFEL and ESS cryomodules to the PIP-II components, while trying to keep compatibility as much as possible with the tooling developed by Fermilab for the assembly of the HB650 cryomodules [7]. Most of the tooling is now designed. Part of it has already been delivered and will be used in the next months to perform assembly tests with a cavity and a coupler mock-up to qualify them before the assembly of the pre-production cryomodule.

Like for the ESS assembly of cavity strings in clean room, a cobot will be used to blow the flange holes of the cavities and bellows. The project supports R&D activities to develop the use of the cobot for other operations [8].

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 performing 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 must be performed when receiving the hardware at CEA to avoid issues during the assembly process. A significant effort has been made within the PIP-II collaboration to set the interfaces, the as-delivered configuration of the components with the associated documentation, the process for acceptance for every component between CEA and Fermilab, and the title of transfer of each cryomodule between CEA and DOE.

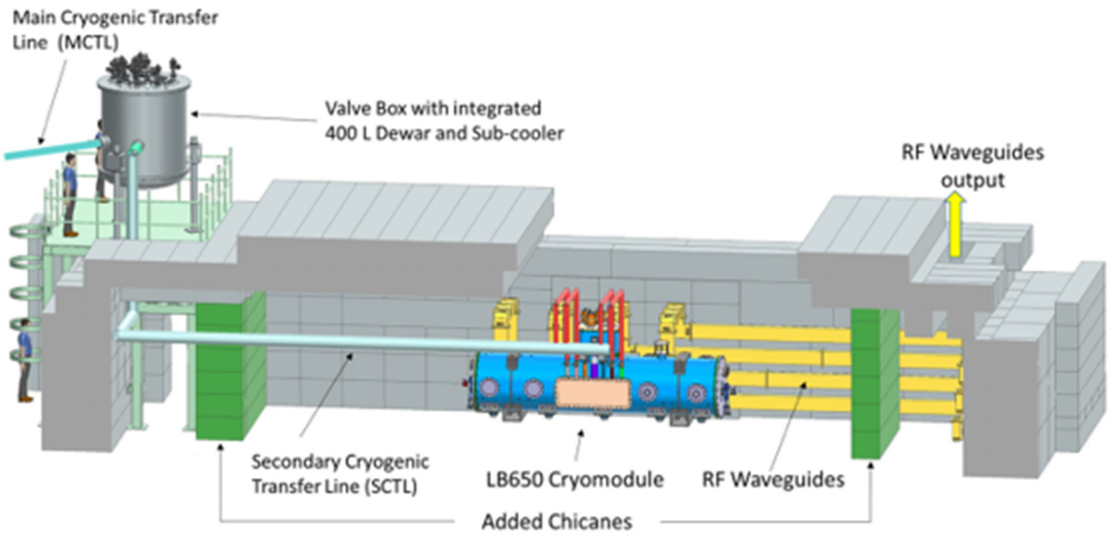

Figure 2: Layout of the PIP-II cryomodule test cave at CEA Saclay.

UPGRADE OF THE RF TEST INFRASTRUCTURE

The existing test infrastructure, which was used for the qualification of the SARAF cryomodules at CEA and some of the ESS cryomodules, has to be adapted to fulfil the PIP-II requirements. It includes the procurement of four 650 MHz 19 kW 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 was decommissioned and will soon be replaced by a more efficient one procured from Air Liquide. This one delivers supercritical helium (5.5 K / 3 bars) instead of saturated liquid helium at 4.2 K and 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 is also upgraded: a valve box that was used for the test of superconducting magnets is being refurbished to the PIP-II needs and new cryogenic distribution lines are being manufactured. This will allow 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).

The layout of the test cave is presented in Figure 2. Details on the test infrastructure, including the radiation shielding efficiency studies, 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 outskirts of Chicago in the USA. This poses significant risks, and required analysis and tests before the transport 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 like what has been developed for the HB650 prototype cryomodule. Lessons learnt from the successful shipment of this cryomodule from the USA to the United Kingdom and back have been implemented [10].

The design of the transport frame is now completed. The procurement of the first unit for the transportation of the pre-production from France to the USA should start by the end of this year.

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, developed at Fermilab, is completed. The construction phase of the pre-production cryomodule started in April 2023 and the components are being manufactured. Meanwhile, the upgrade of the existing infrastructures are in progress, along with the design and manufacturing of the tooling required for the cryomodule assembly and the procurements of the equipment for the test stand.

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