IMPLEMENTATION OF THE TEST BENCH FOR THE PIP-II LB650 CRYOMODULES AT CEA

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Abstract

The Proton Improvement Plan II at Fermilab is the first U.S. accelerator project that will have significant contributions from international partners. As a part of the French In-Kind Contributions to this project, CEA will provide ten 650 MHz low-beta cryomodules (LB650) equipped with LASA-INFN (Italy), Fermilab (USA) and VECC-DAE (India) cavities and Fermilab power couplers and RF tuning systems. CEA is accordingly in charge of the design, manufacturing, assembly and testing of these cryomodules. This paper presents the future implementation of the test stand dedicated to the cryogenic and RF power testing of the LB650 cryomodules. The choice of the equipment and the current status will be detailed, as well.

INTRODUCTION

The Proton Improvement Plan II (PIP-II) project is an upgrade of the accelerator complex of Fermilab, in Illinois, with significant in-kind contributions from international partners. It will 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. The central element of PIP-II is an 800 MeV linear accelerator that will deliver 1.2 MW of proton beam power from the main injector. The superconducting Linac section consists of five different types of cavities and cryomodules, including Half-Wave Resonators, Single Spoke and Elliptical Resonators operating at state-of-the-art parameters [1].

The CEA major contribution is the design [2], fabrication, assembly [3], and cryogenic and RF performances testing of one preproduction and nine production LB650 cryomodules. The scope of the CEA covers other collaboration aspects related to the design harmonisation efforts and the collaborative design activities such as for the 650 MHz power couplers [4] and the HB650 cryomodules [5]. An overview of the CEA contribution to the PIP-II project is given in references [6].

Each LB650 cryomodule will undergo a comprehensive cryogenic and RF test at CEA in order to compare its performances with respect to a defined Acceptance Criteria List (ACL). The cryomodules are expected to be directly operational on accelerator after their validation. Only the first three LB650 cryomodules will be retested after their transportation to Fermilab.

Details about the expected tests for the LB650 cryomodules at CEA, the Test Bench status and the equipment choices will be presented in this paper.

LB650 CRYOMODULE

The LB650 cryomodule activities at CEA use lessons learned from the cryomodules previously developed for the PIP-II project as a result of the design standardization choice adopted by the PIP-II project [7]. The HB650 prototype cryomodule [5], currently under the cold RF testing and validation process at Fermilab, has the most similar design to the LB650 cryomodule [8]. HB650 cryomodules house six 5-cells high-beta cavities [9], while the LB650 cryomodules only include four 5-cells low-beta cavities [10]. Furthermore, the power couplers [11] and the frequency tuning systems [12] are identical for both cryomodule types. The procurement of these three main cryomodules subparts are under Fermilab responsibilities.

The design of the LB650 is detailed in the [2] and partially presented on Figs. 1 and 2.

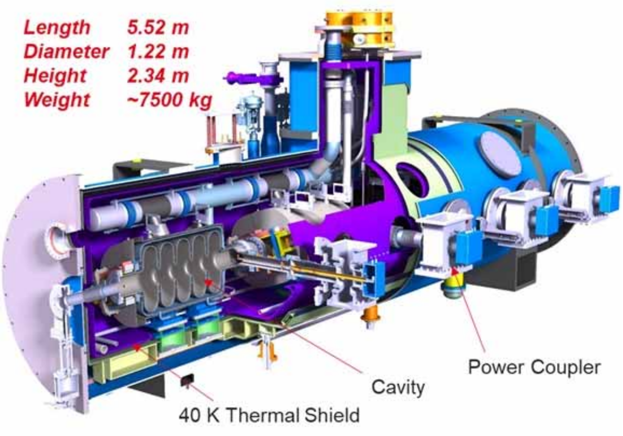

Figure 1: LB650 cryomodule layout.

Figure 2 shows schematics of the cryogenic lines of the LB650 cryomodules. It has a High Temperature Thermal Shield (HTTS) and a Low Temperature Thermal Source (LTTS) both cooled using pressurised GHe at ~ 40 K and ~ 5 K, respectively. The cool down piping shall balance the He flow to each cavity so that it is within 5% of the average cavity flow during the 175 to 90 K and the 45 to 4.5 K phases of the cool down. The cryocircuits associated with cavity cool down must support a “fast cool down” (FCD) of the cavities, at a rate of 20 K /min from 45 K to 4.5 K. This typically requires a LHe flowrate of 50 g/sec. To implement this operation mode, new cryogenic equipment are procured by CEA. Their main technical requirements are detailed later in this paper.

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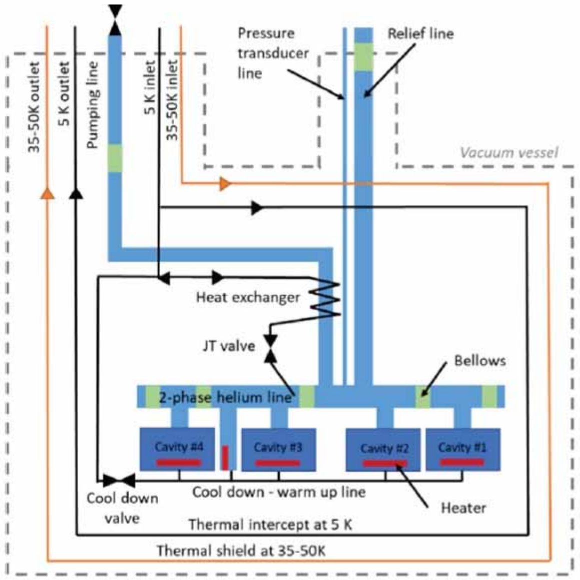

Figure 2: Schematics of the cryogenic lines of the LB650 cryomodule.

EXPECTED CRYOMODULE TEST PLAN

The expected test plan of the LB650 cryomodules at CEA can be summarised in the following main steps. For reasons of clarity and simplification, the order of some of the following steps could be different from their order when performing the test.

- Cryomodule insulation vacuum and beam line volumes pumping performances determination, at Room Temperature (RT) and at cold operation.
- Cryomodule slow cool down by decreasing the temperatures of thermal shield and the cold mass from RT down to 40 K and 4 K, respectively.
- Cryomodule fast cool down by rising the cavities temperature up to 45 K then decreasing it to 4 K with a rate of 20 K/min, while monitoring the magnetic field expulsion during the cavity transition.
- Helium pumping for the 2 K cooling.
- Power coupler test, out of resonance, with HV bias permanently applied on its antenna when RF power is ON.
- Individual cavity conditioning and tests up to 19.5 MV/m in CW operation mode: processing of the cavity multipacting, determination of the field emission, the radiation rate, the Lorentz Force Detuning behaviour, and the potential quench limits.
- Tuners and piezo performances testing.
- Global cryomodule static heat loads determination.
- Individual cavity and coupler dynamic losses determination and Q0 estimation using calorimetric techniques.
- Four cavities simultaneous RF power test testing to reach the cryomodule total voltage acceptance criteria corresponding to 47.6 MV.
- Cryomodule total dynamic heat load estimation and check of its thermal stability in CW operation mode.

The validation of the cryomodule performance is subject to an ACL agreed between CEA and Fermilab.

CRYOMODULE TEST BENCH

The LB650 cryomodule test bench, see Fig. 3, will be installed at CEA-Saclay in a dedicated facility for cryogenic and RF tests of the superconducting accelerator subparts called Supratech Cryo/HF. The cryomodule will be tested in the existing 18 m x 5 m test cave already used to validate several medium beta and high beta cryomodules of the European Spallation Source (ESS) Linac [13]. The existing cryogenic facility will be upgraded to meet requirements for the LB650 tests. Consequently, a new cold box will be procured. Furthermore, a newly designed valve box and cryogenic distribution network will also be implemented to connect the cryomodule to the cold box.

Four RF power sources, operating at 650 MHz, will be needed to test independently and then simultaneously the cryomodule cavities. This requires the use of four RF power circulators equipped with RF loads in order to match each RF amplifier to the RF power line and protect it from the total reflected CW RF power as well as from the peak RF power caused by the transient behaviour of the cavities. A network of four WR1150 parallel waveguide RF power lines will be installed to connect each RF power source to the corresponding power coupler and cavity. Each RF power source will be independently driven by a dedicated RF power generator and equipped with its own frequency feedback loop based on a Phase Locked Loop (PLL) system.

RF power measurement will be carried out in two positions of each RF power line using two Dual Directional Couplers: one placed downstream the circulator, the other inserted close to the power coupler. The latter will be mainly used in SW mode due to mismatch of the cavity in the absence of beam. A high directivity (at least 40 dB in our case) is the required to reduce measurement errors.

The X-Rays generated during the RF tests will be measured with the same detectors, the so-called Fox detectors, used by Fermilab for similar tests, and at equivalent position with respect to the cavities, see Fig. 3. This will allow radiation measurements results to be compared with similar tests carried out within the framework of the PIP-II collaboration.

MAIN CRYOGENIC EQUIPMENT PROCUREMENTS

The main procurements for the cryogenic equipment are the cryogenic distribution transfer lines, the valve box and the cold box. The 2 K superfluid helium will be obtained by using two identical and independent sealed pumping units (oil sealed rotary vane pumps and canned Roots pumps) having an individual He pumping capacity of 2.5 g/s. These two pumps are not part of the PIP-II cryogenic procurements and are already in operation.

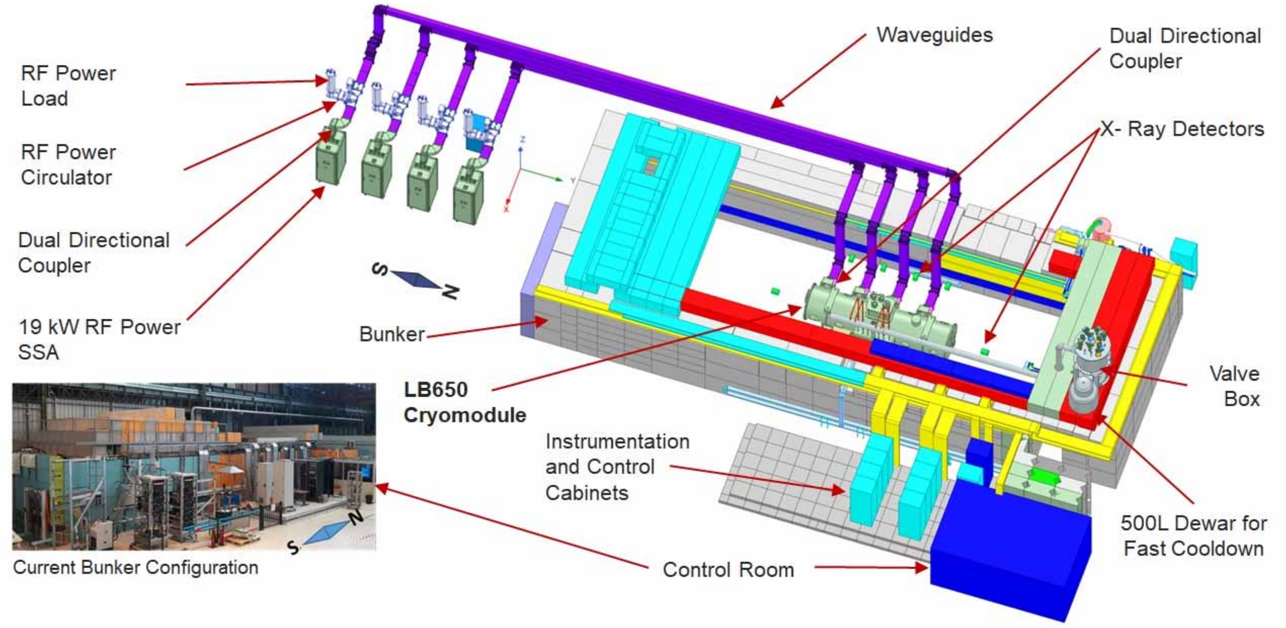

Figure 3: LB650 cryomodule test bench at CEA-Saclay.

Cryogenic Distribution and Valve Box

This equipment is designed to ensure the sequences required for cooling of the cryomodule and transporting the helium to the test area at the nominal temperatures and pressures as described below.

For thermal shielding operation:

- High Pressure (HP) helium (35-50 K inlet in Fig. 2.) delivered by the Cold Box at 14.4 bars and 40 K to cool down and supply the thermal shield of the cryomodule.
- HP Helium leaving the cryomodule shield, cooling the cryogenic distribution shield and returning inside the Cold Box at 14.15 bars minimum and 60 K maximum.
- For LTTS and cavities operation:
- Subcooling at 4.5 K of Supercritical helium (SHe) delivered by the Cold Box at 3 bars at 5.5 K in the Valve Box (GHe/LHe bath HX) before transfer to cryomodule
- Mixing of SHe/GHe for controlled cooling down from 300 K down to 5 K
- Cold Helium gas recovering from the LTTS circuit at 5 K – 6 K and 1.2 bars
- 2 K Cold gas pumping from cavity bath and gas warming up towards the RT pumping units

For Fast Cool down sequence:

- Filling of FCD Dewar (Fig. 4) with Liquid Helium
- Pressurisation of FCD Dewar at 3 bara before quick transfer of 50 g/s helium to CM cavities (from 45 K down to 5 K) during a few minutes

The parts of the cryogenic distribution expected for the LB650 cryomodule tests are presented in Fig. 4 and listed below:

- Main Cryogenic Transfer Line (MCTL)
- Valve Box
- Secondary Cryogenic Transfer Line (SCTL)
- 500 L Dewar for Fast Cool down
- 2 Dewar Transfer Lines
- 4 U-Transfer Lines connected to the cryomodule (2 K pumping line not represented)

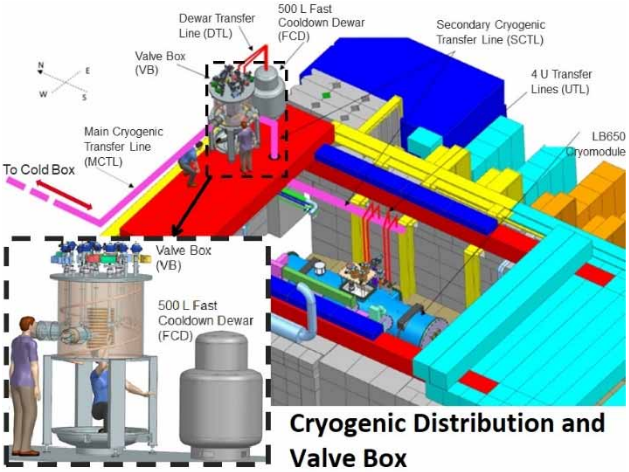

Figure 4: Cryogenic distribution and valve box.

All the cryogenic distribution parts are under procurement process and are expected to be received in 2024.

Cold Box

A new cold box, see Fig. 5, is currently being procured as a part of cryomodule test stand implementation for the PIP-II project. The change of the current cold box was motivated by two main reasons: increasing the LHe production rate and reproducing the nominal operating conditions of the cryomodule. This imposes the use of GHe to cool down the HTTS, instead of the LN2 used for the ESS cryomodule tests at CEA, and the use of Supercritical He for supplying LB650 cryomodule.

The new Cold Box main features are the followings:

- Supercritical He at 5.5 K
- Higher LHe production capacity: > 200 l/h
- Two input/output stages:
  - Cold Box output at 40 K ± 5 K for HTTS with 14.5 bara pressure and 500 W available refrigeration load
  - Cold Box output at 5.5 K ± 0.1 K with 3 bara pressure offering 60 W available refrigeration load for LTTS and the correspondent cryogenic distribution, and an available liquefaction rate of 4.45 g/s @ 2K for cavities testing.
- Achievable slow cool down duration of the cold mass + SCTL is less than 15 h
- Achievable cool down duration of the HTTS+SCTL is about 10 h 30

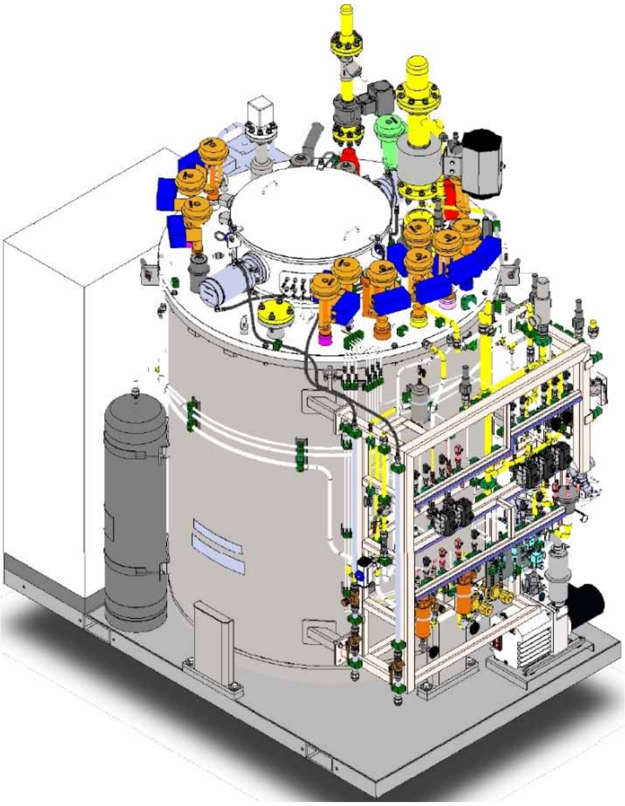

Figure 5: Cold box.

The cold box is already ordered and has passed the final design review. It is expected to be received at CEA premises in the first semester of 2024.

MAIN RF EQUIPMENT PROCUMENTS

The choice of the RF equipment requirements are related to the expected RF test conditions.

RF Power Sources

The LB650 cavities have a nominal accelerating gradient of 16.9 MV/m. The test gradient is 15% higher. The expected Q_{ext} of the power coupler is ~ $10^7 \pm 20\%$. Adding the maximum expected RF losses through the RF power network, the needed power is estimated to 18 kW CW at 650 MHz.

In addition to CW RF mode test, pulsed RF mode will be needed for progressive RF conditioning of the cavities.

Four Solid State Amplifiers (SSA) are in production. Their main technical specifications are the following:

- Operating frequency: 650.0 MHz
- 3 dB bandwidth: ± 3 MHz or higher
- Solid-state class: AB
- Operating mode: CW and pulsed
- Nominal output power at 1 dB compression: 19 kW (CW).
- Operating range: 100 W – 19 kW
- Acceptable output reflected power: up to 1 kW CW at any reflected phase. This corresponds to the worst expected mismatch with the RF power circulator and the worst reverse RF power flowing from the cavity toward the circulator.

RF Power Circulators and RF Power Loads

Reducing the mismatch of the RF power circulator with the RF power network is a major concern as it is a source of errors in estimating the amount of the RF power coupled to the cavity and on the power level measurements during tests. As a consequence, the return losses of the circulator need to be minimised.

In addition to the operating forward power, a maximum peak RF power flowing from the cavity down to the circulator during the tests and corresponding to 4 times the maximum forward power have to be considered. This peak power is generated after each RF power switch off as a result of the exponential decay of the energy stored in the cavity. Consequently, this RF power will flow back through the power coupler toward the circulator.

The main requirements for the circulator listed below take in account additional operational and design margins:

- Frequency: 650 ± 1 MHz
- Power (forward): 25 kW
- Power (reflected): 100 kW for 4.3 ms worst case, 25 kW full reflection
- Insertion loss: ≤0.13 dB @ F0, ≤0.20 dB in bandwidth
- Isolation: ≥30 dB @ F0, ≥26 dB in bandwidth
- Return loss: ≥30 dB @ F0, ≥26 dB in bandwidth

In addition, the circulator will have a Control System aiming to compensate the circulator frequency detuning. It will be also permanently cooled with dedicated water loop to maintain the nominal temperature within ± 05 °C.

Regarding the RF power loads, the technical requirement of the RF load are totally coherent with the circulator performances in terms of RF power operation. The return loss is defined as follows:

- 18°C – 24°C : ≥ 30 dB @ F0 (Nominal test conditions)
- 18°C – 24°C : ≥ 26 dB @ 650 ± 1 MHz

The RF power circulators and loads are provided by the same manufacturers. They are expected to be received at CEA in summer 2023.

RF Control system

For a nominal coupling, the LB650 cavity bandwidth is about 60 Hz. During the cryomodule tests, the mechanical vibrations (microphonics) could detune the cavity frequency by few tens of hertz. A Phase Locked Loop (PLL) will be used in order to maintain a stable RF operation of the cavity.

As a part of the cryomodule validation tests, we expect to maintain the cavity RF gradient, in CW mode, constant for several hours in order to obtain the thermal stability of the cryomodule. To guarantee this condition despite the potential slow variation of the SSA RF output, a power level regulation feedback loop will be used for each RF power chain.

Both the PLL and the power level regulation feedback loop designs are based on adaptations of existing CEA developments already validated on other projects. They will be ready in 2023.

CONCLUSION

The Cold RF Test activity relies on the existing CEA infrastructure already used for cryomodule tests. The design standardization choice made by the PIP-II collaboration offers a great opportunity to take advantage of the experience feedback from design optimizations and validation test protocols carried out on the other cryomodules especially the HB650.

The technical RF requirements for the RF power and cryogenic equipment were defined considering the best practices and the need of reproducing the nominal operation conditions of the LB650 cryomodule, as far as possible. The procurement processes are well advanced. The Cold RF test of the preproduction LB650 cryomodule is expected for 2025.

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