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

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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 in-kind contributions (IKC) from international partners. As a part of the French IKC to this project, CEA will provide ten 650 MHz low-beta cryomodules (LB650) equipped with cavities from INFN-LASA (Italy), Fermilab (USA), and DAE-VECC (India), and power couplers and RF tuning systems from Fermilab. CEA is in charge of the design, manufacturing, assembly, and testing of these cryomodules. This paper presents the progress of the future implementation of the test stand dedicated to the cryogenic and RF power testing of the LB650 cryomodules.

INTRODUCTION

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 [1]. The CEA major contribution is the design [2], fabrication, assembly [3], and testing of ten LB650 cryomodules. An overview of the CEA contribution to the PIP-II project is given in references [4].

The construction of a new test bench dedicated to testing the LB650 cryomodules at the Saclay test facility Supratech Cryo/HF [5] represents one of the most significant activities within the CEA scope [4]. Each LB650 cryomodule will undergo comprehensive cryogenic and RF testing at CEA to evaluate its performance against a defined Acceptance Criteria List (ACL) [6]. Several important procurements have been initiated to meet the requirements of these cryomodule validation tests. An overview of the main procurements and the related key technical requirements is also detailed in the aforementioned reference.

This paper provides an updated overview of CEA's activities related to the procurement of new cryogenic equipment and the associated distribution network, the establishment of the new RF power facility, and the upgrade of the cryomodule test cave previously used for the qualification tests of height ESS cryomodules with elliptical cavities and four SARAF cryomodules with HWR cavities.

CRYOMODULE TEST BENCH

The preparation of the LB650 cryomodule test bench is well advanced. The exact position of the cryomodule has now been finalized (see Fig. 1). This has enabled the completion of the Secondary Cryogenic Transfer Line (SCLT) and RF waveguide path definitions, as well as provided essential input for radiation calculations. These calculations are based on various cavity test configurations, particularly the maximum accelerating gradient tests and the multi-cavity nominal accelerating gradient tests, both conducted in continuous wave (CW) mode.

For a better understanding of the choices explained in this paper, it is highly recommended to see the details giving in [6] about the LB650 Cryomodule design, validation tests and main procurements technical requirements.

MAIN CRYOGENIC EQUIPMENT PROCUREMENTS

The main procurements for the cryogenic equipment are the cryogenic transfer lines, the valve box and the cold box.

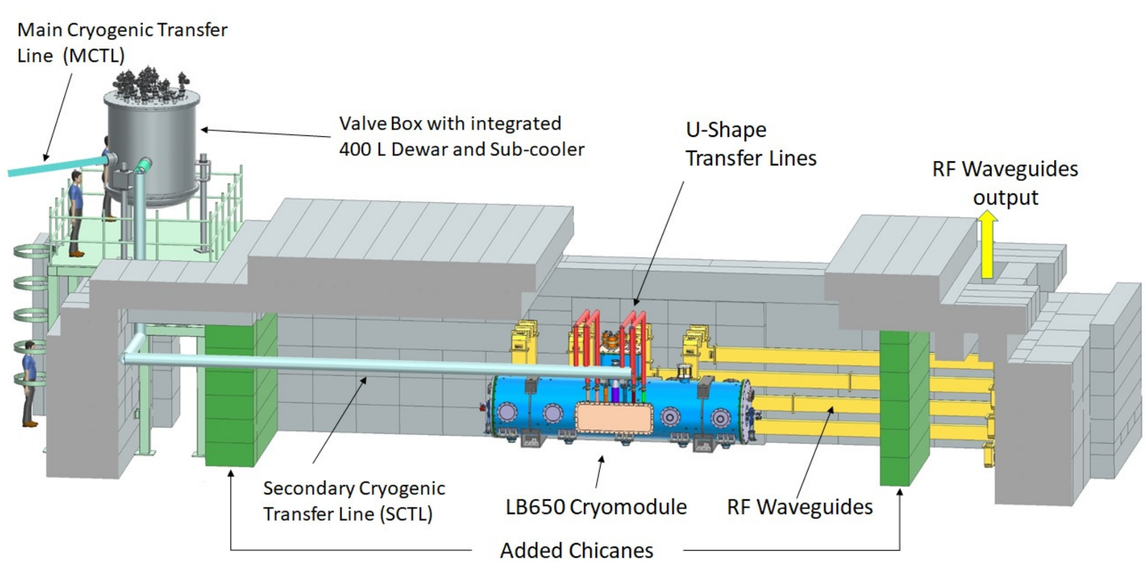

Figure 1: LB650 cryomodule test bench at CEA-Saclay.

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Cryogenic Transfer Lines and Valve Box

In 2024, the CEA decided to withdraw the Valve Box from the global cryodistribution procurement call for tenders. This call originally included the Main and Secondary Transfer Lines (MCTL and SCTL), which connect, respectively, the Cold Box to the Valve Box and the Valve Box to the cryomodule via four U-shaped transfer lines (Fig. 1).

In fact, while the Cold Box manufacturing progressed as scheduled, the cryodistribution call for tenders was deemed unsuccessful. Consequently, CEA reconsidered a technical alternative involving the adaptation and reuse of the "satellite" cryogenic unit from the former W7X experiment located at the CEA Saclay site. Although larger than the initially designed Valve Box, the "satellite" offers the advantage of being modular, with an external enclosure and shield. It has already side line inputs, removable bottom and a top plate that can accommodate various types of instrumentation. Its shielded volume also allows for the integration of a 400 L Dewar, which was initially expected to be external in the previous Valve box design. As a result, it was decided to restructure the cryodistribution implementation procurements as following:

- Cryogenic transfer lines to be outsourced to traditional cryogenic line suppliers. The manufacturing of these parts is already ongoing.
- Valve Box to be assembled by CEA, while the internal Dewar, the subcooler tank, and cryogenic valves sourced from manufacturers.

Delays in the procurement of the cryodistribution system have led to an earlier installation of the Cold Box. As a result, it was decided to modify the test setup to demonstrate that the requirements can be met without relying on the cryodistribution system.

Cold Box

The new Cold Box, shown in Fig. 2, has been delivered at CEA after passing the factory acceptance test (FAT). It will be coupled to the existing cryogenic facility and will then undergo the site acceptance tests (SAT) before the end of 2024. FAT and SAT tests are conducted with the participation of CEA and the manufacturer's representatives.

The Cold Box FAT was primarily based on a detailed review of all deliverables, visual inspections of all external connection interfaces, He leak tests of both internal and external circuits and the instrumentation panel, and a review of all expected performances during the SAT. These performances had already been verified by computational models simulating the different test configurations.

As previously explained, the Cold Box SAT will be conducted prior to the availability the expected cryodistribution system. As a result, the validation of the Cold Box will be based on test setups that simulate its various operational modes and measure the expected performance. The Cold Box SAT will include the following tests:

- Liquefaction mode only
- Mixed mode that simulates the cooling of the 2 K cold mass, the Low Temperature Thermal Source LTTS of the cryomodule and the cooling of the cryomodule High Temperature Thermal Shield (HTTS) in addition to liquefaction.
- Helium leak test to be performed on the Cold Box following its cooldown.

Figure 2: Cold Box.

MAIN RF EQUIPMENT PROCUMENTS

The RF equipment requirements is detailed in [6].

RF Power Sources

Four 19 kW Solid State Amplifiers (SSAs) class AB operating at 650 MHz in CW mode are currently in the procurement process. All SSA subassemblies are available at the manufacturer's premises, with testing and integration already underway. The Factory Acceptance Test (FAT) for the first SSA is expected in November 2024, with the FATs for the remaining three SSAs anticipated by the end of 2024.

The factory tests will primarily focus on the following:

- Measuring the RF output power up to 19 kW as a function of input power.
- Measuring the amplifier bandwidth at nominal output power, including harmonics.
- Operating with reflected power exceeding 1 kW.
- Conducting seven hours of continuous operation at 19 kW in CW mode, with measurements of RF power amplitude and phase stability.
- Testing pulsed RF power operation at various pulse widths and duty cycles.
- Testing the protection system and measuring interlock response times.

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RF Power Circulators and RF Power Loads

The RF power loads and circulators were delivered to CEA at the end of 2023. The FAT and SAT primarily focus on S-parameter measurements. High-power RF testing will only be possible after the RF power sources are delivered, which is expected to happen by the end of 2024, as already mentioned.

The measurements performed on the RF loads showed differences between the FAT and SAT results, likely due to variations in the measurement-equipment calibration. In summary, the low-power RF global performance measured at CEA shows a return loss, *RL*, of ≥25 dB at 650 MHz for water temperature $T = 21 \pm 3$°C.

The RL (= – |S11|) is highly dependent on the water temperature, as shown in Fig. 3. Measurements indicate that the best performance is achieved at water temperatures between 21°C and 24°C. We also observed discrepancies in RL values between different RF loads. To reduce these discrepancies, during RF power operation, we need to optimize the water temperature inside each load. This can be achieved by adjusting the water flow to artificially modify the water temperature inside the load. This optimization is particularly beneficial during long-term operation at a fixed power level, in compliance with the ACL requirements, to accurately measure the whole dynamic losses of the cryomodules.

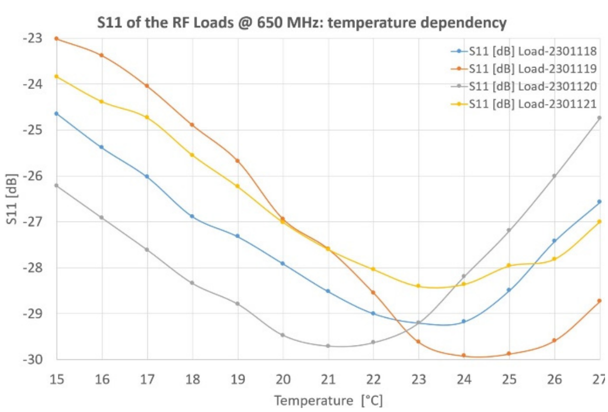

Figure 3: S11 vs. temperature variation.

The following measurements results have been obtained during the SAT of the RF circulators:

- Insertion losses: ≤ 0.13 dB at 650.0 MHz and ≤ 0.2 dB in BW at 26°C
- Isolation: ≥ 30 dB at 650.0 MHz and ≥ 26 dB in BW at 26°C
- Return Losses: ≥ 30 dB at 650.0 MHz and ≥ 26 dB in BW at 26°C

These RF performances are achieved by supplying the appropriate amount of DC current to the compensation coils integrated into the circulator, which corrects for all effects that may degrade RF performance. We also tested a setup with one circulator connected to a RF power load on port 3 (with RF input on port 1 and RF output on port 2). The measurements showed that S22 and S12 were primarily influenced by the load return loss, as expected.

During the high-power RF tests, it is necessary to determine new DC current values to compensate for circulator detuning caused by thermal effects due to power losses. Our measurements have shown that each time we adjusted the circulator's water-cooling temperature, we could significantly mitigate the S-parameter deviation by selecting a new current set point, as shown in Fig. 4. Although the experiment does not fully replicate the heating effects caused by RF power, it provides valuable insights into the potential for circulator tuning.

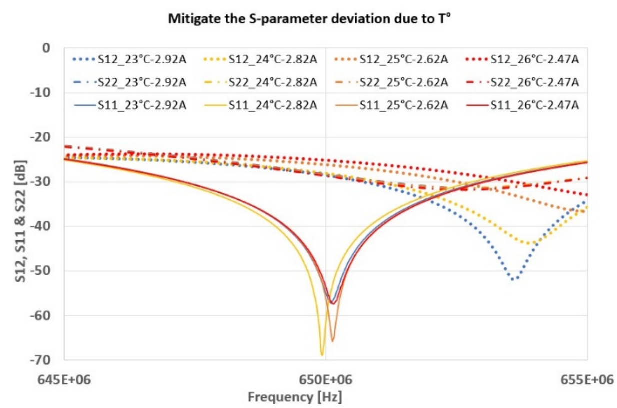

Figure 4: DC current values vs. T°.

RADIATION CALCULATION

Building on top of the high-power CM testing experience with ESS and the development of a Geant4 simulation model [7], a detailed assessment of the characteristics of Field Emission induced radiation was carried out for LB650. The geometrical beta of 0.61 leads to rather inefficient acceleration through the cavities. When all cavities reach the maximum test gradient simultaneously the maximum e- impact energy reaches 18.5 MeV, similar to what was obtained with single high beta ESS cavity (16 MeV), already tested in the same cave. Therefore, a similar Bremsstrahlung energy spectrum is expected.

However, the CW operation leads us to upgrade the radiation shield of our test cave, in order to keep the dose rate in the lab area within public access limits. Specifically, the roof thickness is doubled, and the transmission through openings is been strongly decreased thanks to the addition of a maze at each end of the test cave.

CONCLUSION

The procurement process for the LB650 cryomodule test bench is progressing well. All major equipment is either in the procurement phase or has already been procured. Critical performance tests on key equipment will be conducted within the next few months. In 2025, the test cave will be adapted to meet new radioprotection requirements, which will ensure readiness for the pre-production LB650 cryomodule test.

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REFERENCES

[1] P. Raimondi, "PIP-II: an international endeavor to enable neutrino science", presented at the 32nd Linear Accelerator Conference (LINAC2024), Aug. 2024, paper WEYA003, this conference.

[2] R. Cubizolles *et al*., "Final design of the 650 MHz low beta cryomodule for the PIP-II linear accelerator", in *Proc. 21th Int. Conf. on RF Superconductivity (SRF2023)*, Grand Rapid, Michigan, USA, Jun. 2023, paper WEPWB063. doi:10.18429/JACoW-SRF2023-WEPWB063

[3] J. Drant *et al*., "Preparation of the assembly of the 650 MHz low beta cryomodules for the PIP-II linear accelerator", in *Proc. 21th Int. Conf. on RF Superconductivity (SRF2023)*, Grand Rapid, Michigan, USA, Jun. 2023, paper TUPTB025. doi:10.18429/JACoW-SRF2023-TUPTB025

[4] N. Bazin *et al*., "Status of the CEA contribution to the PIP-II linear accelerator", presented at the 32nd Linear Accelerator Conference (LINAC2024), Aug. 2024, paper THPB010, this conference.

[5] H. Wiese *et al.,* "Strategy for the development of the AMICI TI", Horizon 2020 Research Infrastructures GA, Report no. 101004730, IFAST-D13.1, I.FAST Consortium, Oct. 2023. https://ifast-project.eu/

[6] H. Jenhani *et al*., "Implementation of the test bench for the PIP-II LB650 cryomodules at CEA", in *Proc. 21th Int. Conf. on RF Superconductivity (SRF2023)*, Grand Rapids, MI, USA, Jun. 2023, paper MOPMB057. doi:10.18429/JACoW-SRF2023-MOPMB057

[7] G. Devanz *et al*., "Instrumentation for high performance cavities and cryomodule field emission analysis", in *Proc. 21th Int. Conf. on RF Superconductivity (SRF2023)*, Grand Rapids, Michigan, USA, Jun. 2023, paper FRIBA02. doi:10.18429/JACoW-SRF2023-FRIBA02