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PREPARATION OF THE ASSEMBLY OF THE 650 MHz LOW BETA CRYOMODULES FOR THE PIP-II LINEAR ACCELERATOR

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Abstract

The Proton Improvement Plan II (PIP-II) that is under construction at Fermilab is the first U.S. accelerator project that will have significant in-kind contributions from international partners. CEA's scope covers the supply of the 650 MHz low-beta cryomodule sections with the cavities provided by LASA-INFN (Italy) and VECC-DAE (India) as well as the power couplers supplied by Fermilab. This scope includes the assembly of the 650 MHz low-beta cryomodules. Assembly studies have been conducted based on CEA experience acquired on previous projects, as well as on the feedback of Fermilab on the assembly of the HB650 prototype cryomodule. This paper presents the organization of assembly phases from the cavity string in the clean room and the assembly of the cryostat to the preparation of the cryomodule before its shipment to Fermilab.

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 neutrino production in Illinois [1]. CEA is in charge of the design [2], fabrication, assembly and cold RF tests [3] of the low-beta 650MHz cryomodules (called "LB650" hereafter). The CEA contribution will consist of one pre-production cryomodule [4], whose assembly will start in 2024, and nine series cryomodules, whose assembly will start in 2026. The assembly studies have been conducted in parallel with the design of the cryomodule to allow for potential minor design changes to facilitate assembly steps or to allow for the addition of link interfaces to assembly tooling. The development of assembly tooling is also carried out in parallel with the assembly studies because it is directly impacted by the choice of assembly workflow. Thanks to the CEA experience on cryomodules assembly, the assembly studies are based on feedback from assembly teams who have participated in previous projects. In particular, the similarities between the LB650 cryomodules and the cryomodules of the ESS project (currently still in the assembly phase) allow a simplified transfer of knowledge. The choice to involve the CEA teams from the design of the high-beta cryomodules has resulted in high similarities between the two types of cryomodules [5]. These design similarities are reflected in the transposition of some assembly processes from Fermilab to CEA. This transposition is facilitated by the numerous exchanges with the assembly team at Fermilab (reports, CEA visits, regular meetings).

ASSEMBLY GENERAL WORKFLOW

Based on the feedback from the ESS project teams and the experience from previous projects, it is possible to define the general workflow of the assembly process (see Fig. 1). This process extends from the preparation of the components before their entry in the clean room to the preparation of the cryomodule before shipping to Fermilab.

The first workstation (WAS/PRE) allows the preparation of all the elements assembled in the clean room. This preparation includes inspections, tests and washing operations to limit the risk of non-conformities that are more detrimental to clean room operations. The two following workstations (CAP & BLA) correspond to the assembly, in clean room, of all the elements to obtain the cavity string. The three following workstations (ABE & PAV & PAS) detailed the assembly of the three main component groups of the cryomodule: the beam line, the vacuum vessel and the strongback. The two following workstations (COS & CRY) allow the assembly of the main component groups. The beam line is assembled with the strongback in order to form the cold mass. This set is then inserted into the vacuum vessel to initiate the final assembly steps of cryomodule. The following workstation (CLO) allows, with the last assembly steps, the finalization of the cryomodule before the cold RF test phase (BUN). After the cold RF test, the cryomodule is prepared for shipping to Fermilab. This workstation (EXP) includes the disassembly of some elements for shipping and the assembly of transportation tooling. The disassembly phase has two objectives: to approach the final configuration of the cryomodule (operating configuration of the cryomodule in the accelerator tunnel) and to remove the elements not compatible with the available space for air transport of the LB650 cryomodule. An overview of the cryomodule assembly state after each workstation is presented in Fig. 2.

GEOGRAPHICAL LOCATION OF THE ASSEMBLY WORKSTATIONS

The previous cryomodule assembly projects have enabled the CEA to optimize the available infrastructure. Thus, the assembly of the LB650 cryomodules will be performed in the so-called "ESS Village" at CEA Saclay (former "XFEL Village"). The main objective of the LB650 assembly studies is the adaptation of these infrastructures to the specificities of the assembly of these cryomodules. The organization of the future "PIP-II Village" is presented in Fig. 3. The two main

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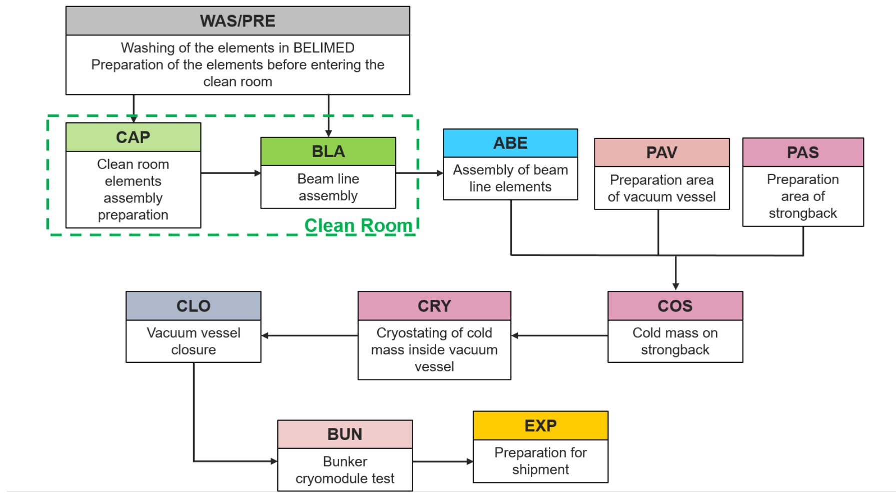

Figure 1: Assembly workstations overview workflow.

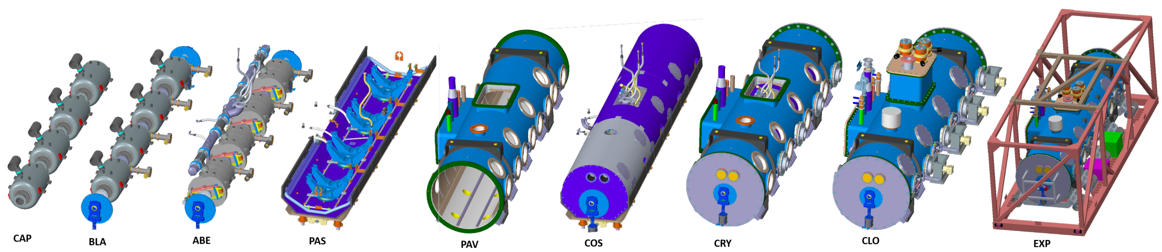

Figure 2: Cryomodule assembly state after each workstation.

components of the infrastructure are the clean rooms and the assembly hall. The clean rooms are composed of ISO7, ISO5 and ISO4 clean rooms. The cavity string will be assembled in the latter (CAP & BLA workstations). The main part of clean room components will be prepared in PRE/WAS workstation. They will enter in ISO4 clean room by two ways: either by the industrial cleaner-dryer (cavities, cold-warm transitions, inter-cavity bellows, …) or through a manual cleaning step through the two other ISO7 and ISO5 clean rooms (cavity post, …). Note that the cold-warm transitions and inter-cavities bellows will receive a final cleaning step by HPR (High Pressure Rinse) before assembly on cavity string. One of the advantages of the CEA assembly infrastructure is the existence of a two-rails system. This system is available in the clean room and for the first workstation after the clean room. It offers flexibility in the assembly steps to cope with unforeseen events. For example, if there is a delay in the supply of components assembled outside the clean room (strongback, vacuum vessel, …), the assembly of a second cavity string from the CAP workstation to the ABE workstation can be realized. This system makes it possible to parallel assembly of a cavity string and a disassembly of another. A second rail system is used for the PAS, PAV, COS and CRY workstations. This equipment facilitates the alignment of the components and the insertion of the cold mass in the vacuum vessel. Finally, for the CLO workstation, the cryomodule will be placed on stands to realize the final assembly steps. In Fig. 3, a temporary workstation is represented. It takes place in the Cryomodule Waiting Area. This workstation has several aims. First, it allows us to free the CLO workstation place when the assembly of a cryomodule is finished and is waiting for a transfer for the cold-RF test. It also allows us to perform the last steps of the CLO workstation if the cryomodule production rate requires it. The objective remains, however, that this area be used as little as possible during the cryomodule production phase. The arrow pointing to the two last workstation of LB650 cryomodule production, BUN and EXP, is directed towards the outside of the assembly hall because these two steps are realized in another building. To ensure the transfer of the cryomodule, an electric trailer is used.

ASSEMBLY TOOLING

The assembly studies also aim to develop the required tooling to achieve the LB650 cryomodules production. Like the determination of the workflow of the workstations, the development of the assembly tooling take place in parallel with the design of the cryomodule to determine or add the necessary interfaces. During the development of assembly tooling, several objectives have been formulated. Firstly, it is necessary to adapt the tooling to the CEA infrastructure (presented in the past section). As an example, the vacuum

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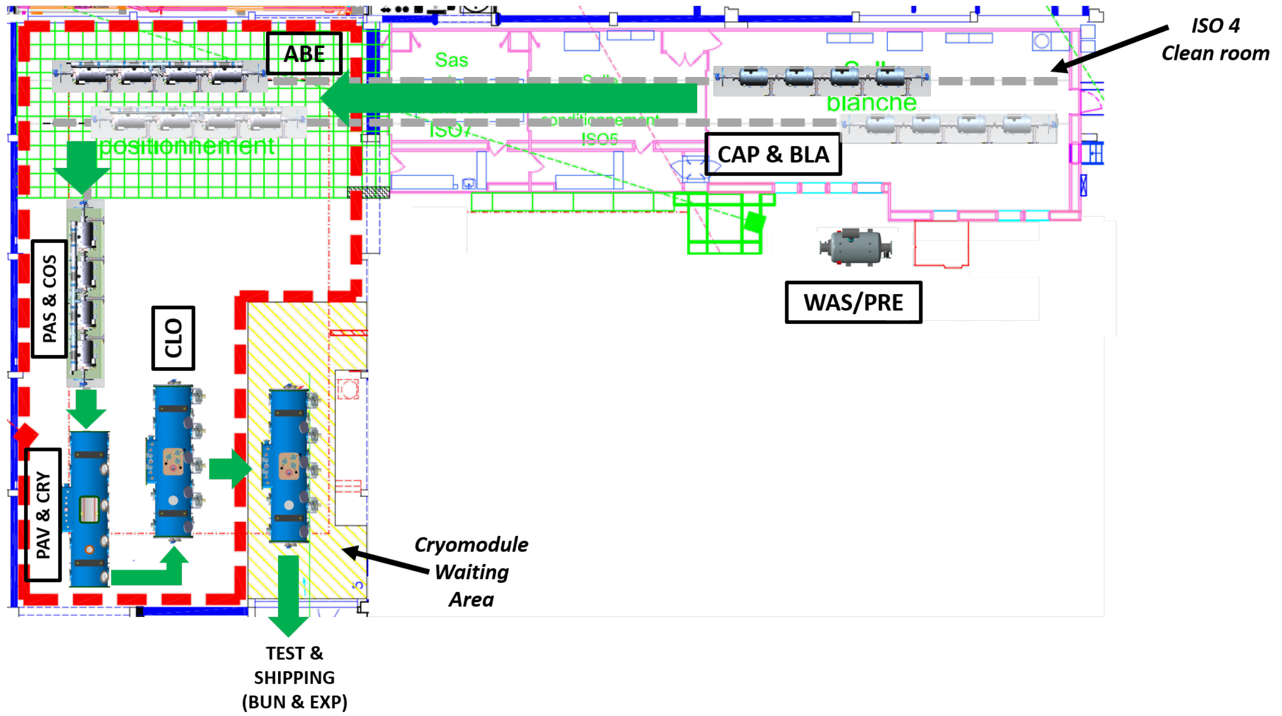

Figure 3: Future PIP-II Village.

vessel supporting tooling must be adapted to the rail system in the assembly hall. Another objective of this study is the maximum re-use of existing tooling from previous projects (XFEL, ESS, …). This objective limits the design work, but most often imposes the design/modification of adaptation parts between the tooling and the cryomodule components. The tooling development relies on two main strengths, the experience acquired by the CEA during previous projects completed by the feedback given by the assembly teams and the lessons learned from the assembly of the HB650 prototype cryomodule at Fermilab. This collaboration is also transcribed in the objective of standardization of tooling between the LB650 and HB650 cryomodules because of their strong similarities in the design. This standardization remains a real challenge due to the differences in infrastructure between the different laboratories. The assembly tooling can be separated in two main groups: inside clean room tooling and outside clean room tooling.

Inside Clean Room Tooling

The assembly steps in the clean room require two types of tooling, the component support tooling and the pre-alignment tooling.

Components support tooling The support of components in the clean room is realized with posts that are mounted on the rail system. The cavity posts, except for the interface with the cavities, are inherited from the XFEL project. For the other posts, their design is inherited from previous projects and feedbacks.

Pre-alignment tooling After the preparation phase of the component for entry in clean room, a pre-alignment step is required. This step aims to reduce the alignment phase before assembly between component (cavity/cavity assembly, cavity/cold-warm transition assembly, ...). To achieve this goal, the adjustment elements of the tooling are preset in their nominal position by means of setting jigs. As an example, Fig. 4 shows the jig (green part) for adjusting the height of cavity posts before assembly of cavity supports.

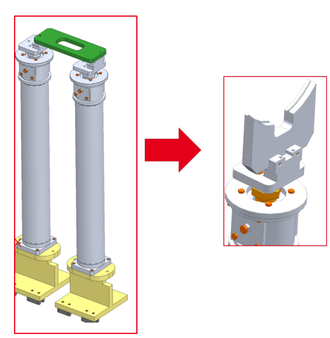

Figure 4: Cavity post height jig.

A second example of pre-alignment step consists on the leveling (roll and pitch) of cavity after positioning on the cavity posts. The tooling developed is similar to the one used by Fermilab for the HB650 cryomodule. It uses a level to adjust the cavity, as presented in Fig. 5.

A jig is also designed to check/correct the distance between couplers before exiting the clean room. This step, limiting the alignment load outside the clean room, is facilitated by the use of the jig shown in Fig. 6. This tooling

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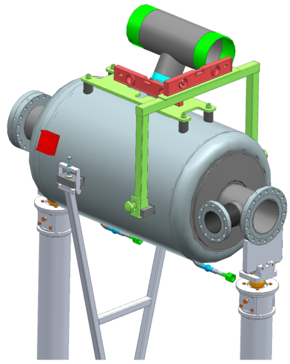

Figure 5: Cavity leveling tooling.

inspired by previous projects at CEA is also standardized with the tooling used by Fermilab for the same step.

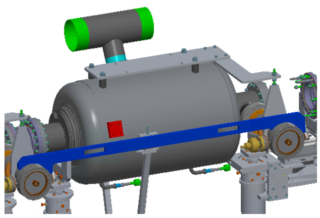

Figure 6: Coupler-Coupler distance jig.

The main alignment tooling used for clean room assembly are the coupler on cavity and bellow on cavity tooling. They are presented in Fig. 7. These two sets use the same table that links to the cavity post. This tooling presents an example of re-use of tooling designed for a previous project (XFEL).

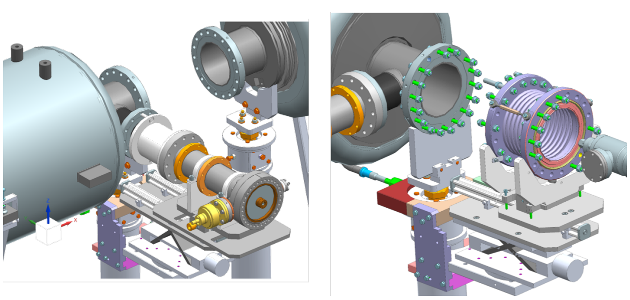

Figure 7: Coupler (left) and bellow (right) assembly table on cavity.

Most of the pre-alignment of the components assembled in the clean room is done with pins to align the screw holes of the flanges and ensure the roll, pitch and yaw adjustment.

Outside Clean Room Tooling

After the assembly in clean room, the cavity string is lifted using a lifting tool. This tooling is under development, but it will be inspired by the lifting tool used during XFEL project. In the objective of re-use, we can thus note that the lifting tool stands manufactured for the XFEL project will be re-used for the LB650 assembly. The lifting tool, by using a crane, is then transferred from ABE workstation to COS workstation to be positioned above the strongback as shown at Fig. 8.

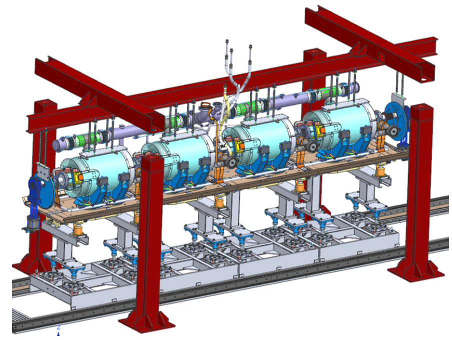

Figure 8: Lifting tool positioned above strongback at COS workstation.

For PAS, PAV, COS and CRY workstations, the support tooling for the strongback and the vacuum vessel is designed as presented in Fig. 9. The main objective of these tooling is to ensure the link between the assembly hall rail system and the components. They also allow the alignment of the strongback and the vacuum vessel for the cold mass insertion phase in the vacuum vessel (CRY workstation).

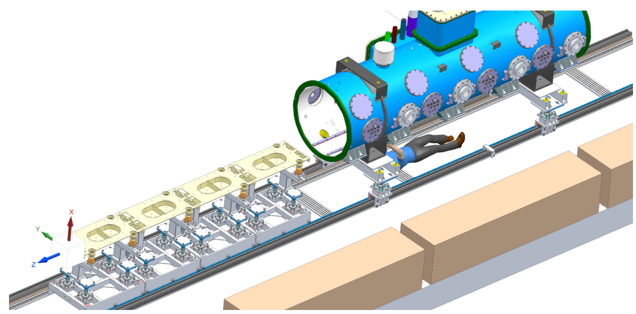

Figure 9: Strongback and vacuum vessel support tooling.

CLEAN ROOM ASSEMBLY PREPARATION

Validation by Dummy Components

CEA's previous projects (IFMIF/EVEDA and ESS) have shown the value of using dummy components to validate assembly studies. Thus, for the LB650 assembly studies, it was decided to use mock-ups as much as possible. This allows us to validate both the assembly procedures and the tooling designed. At first, we choose to focus on the assembly steps in clean room (CAP & BLA). Thus, a dummy cavity and a dummy coupler have been designed to avoid the problems associated with the use of real critical components, as presented in Figure 10. However, all the external interfaces of these components have been reproduced to all realistic assembly operations. Moreover, the presence of all the external interfaces allows the realization of all the assembly steps related to the cavity (cold magnetic shield, tuner, lifting, cryogenic piping welding, …) To support the dummy

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cavity, a cart reproducing a part of the rail system of the clean room will be used as a base. On this cart, two cavity posts will be mounted. It will be possible to test, as in the production of cryomodules, the phases of pre-alignment and the installation of a cavity on the posts. It is then planned to perform a coupler and bellow assembly using the designed tooling, presented in Fig. 7.

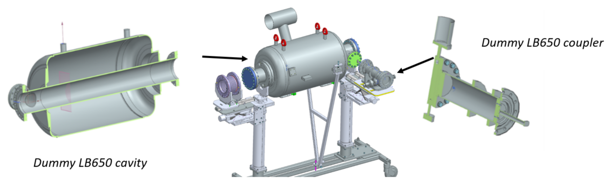

Figure 10: Assembly tests on a cart with dummies components.

Development of Cobotization Assembly

During the ESS project, the use of cobotization for certain clean room operations was studied [6]. This dynamic is continued for the PIP-II project. The gain sought by cobotization can be classified in 2 categories:

- Painful reduction and reliable cleaning process
- Quality improvement by installation or removal of component

The first objective is mainly achieved by the implementation of a cleaning system by blowing ionized nitrogen and counting particles on a robot arm. This system allows to clean the components (flange, cavity, bellow, coupler, ...) before assembly or disassembly. Cleaning programs have been set up during the production of the ESS project, as presented in Fig. 11. For the production of LB650 cryomodules, these programs will be adapted to the specificities of the project, and new programs will be created to develop this objective.

The second point is studied on the ESS project and will be implemented on LB650 cryomodule production by the removal of temporary or transport flanges and assembly of components as inter-cavity bellows or coupler.

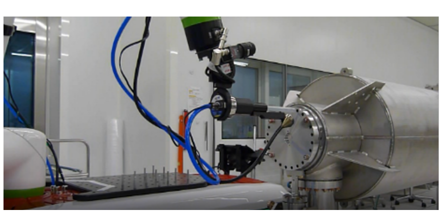

Figure 11: ESS cavity flange cleaning.

CONCLUSION

Based on the experience of the CEA in the assembly of cryomodules and the feedback of Fermilab on the assembly of the prototype cryomodule HB650 MHz, the studies of the assembly of LB650 cryomodules have been performed. Inspired by previous projects, the organization of the workstations was defined from the preparation of the components before their entry into the clean room through the assembly of the cryomodule outside the clean room to its preparation for the transport phase to Fermilab. The development of the main assembly tools has been completed. Their development was facilitated by the parallel design of the cryomodule, which allowed us to add some useful interfaces to the assembly. This development was performed with an objective of re-use of the tooling already designed at the CEA and in a concern of standardization with the other laboratories involved in the project. Finally, the use of dummy components is presented to validate some assembly processes, as well as the development of cobotization for certain assembly operations in clean rooms.

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REFERENCES

[1] R. Stanek *et al.*, "PIP-II Project Overview and Status", presented at SRF23, Grand Rapids, MI, USA, Jun. 2023, paper MOIXA02, this conference.

[2] R. Cubizolles *et al.*, "Final Design of the 650 MHz Low Beta Cryomodule for the PIP-II Linear Accelerator", presented at SRF23, Grand Rapids, MI, USA, Jun. 2023, paper WEPWB063, this conference.

[3] H. Jenhani *et al.*, "Implementation of the test bench for the PIP-II LB650 cryomodules at CEA", presented at SRF23, Grand Rapids, MI, USA, Jun. 2023, paper MOPMB057, this conference.

[4] N. Bazin *et al.*, "CEA Contribution to the PIP-II Linear Accelerator", presented at SRF23, Grand Rapids, MI, USA, Jun. 2023, paper MOPMB055, this conference.

[5] J. Ozelis *et al.*, "HB650 Cryomodule Design: From Prototype to Production", presented at SRF23, Grand Rapids, MI, USA, Jun. 2023, paper WEPWB067, this conference.

[6] S. Berry *et al.*, "Cobotisation of ESS cryomodule assembly at CEA", presented at SRF23, Grand Rapids, MI, USA, Jun. 2023, paper TUPTB024, this conference.