INFN LASA ACTIVITIES TOWARD PIP-II

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Abstract

INFN LASA is advancing its in-kind contribution to the PIP-II project at Fermilab, with significant progress achieved in both cavity production and testing infrastructures. The main activity is the fabrication of 38 five-cell $\beta = 0.61$ superconducting cavities for the LB650 section of the linac. Manufacturing is well advanced, with mechanical production of the series cavities progressing while the two pre-series ones are being used to validate the complete industrial workflow, including surface processing and final preparation, that is mostly entrusted to industrial partners. To ensure compliance with the stringent performance requirements of PIP-II, all cavities will undergo final qualification through a vertical cold tests facility at DESY AMTF (Germany) that is being finalized and commissioned. Lastly, the cavities will proceed with the delivery to CEA Saclay (France) as fully validated components ready for string assembly. This contribution summarizes the status of these activities, presenting updates from the manufacturing of series cavities, results from pre-series qualification and recent upgrades to both LASA and DESY testing infrastructures.

INTRODUCTION

The Fermilab Proton Improvement Plan II (PIP-II) Linac is designed to deliver a 1.2 MW H^- beam, with future scalability to multi-megawatt operation, in support of the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) programs [1].

Once it reached 800 MeV, the beam is transferred to the upgraded Booster Ring and subsequently injected into the Main Injector. The Linac operates with a flexible 0.55 ms, 2 mA beam pulse structure, while its radiofrequency (RF) systems are capable of continuous-wave operation.

A key element of the accelerator is the 650 MHz superconducting low-beta section (LB650), consisting of 36 five-cell elliptical cavities installed in 9 cryomodules and accelerating the beam from 177 MeV to 516 MeV.

The operational target for the LB650 cavities is a quality factor of 2.4×10^{10} at an accelerating gradient of 16.9 MV/m under cryomodule conditions [2], with even higher performance required during vertical cold tests.

THE LB650 CAVITY DESIGN

All 38 superconducting cavities, including 36 series and 2 pre-series units, will be delivered by Istituto Nazionale di Fisica Nucleare (INFN) following successful vertical testing.

The cavities will be fully dressed, equipped, maintained under ultra-high vacuum, and ready for string assembly. INFN LASA developed the electromagnetic and mechanical design of the LB650 resonators [3], including all interfaces with the cryomodule environment, such as ports, flanges, power couplers, tuners, helium vessels, and associated interconnections.

THE LB650 CAVITY SURFACE TREATMENT RECIPE

The cavity surface preparation sequence begins with bulk electro-polishing (EP), providing a total material removal of 140 µm, including a final 20 µm "cold" EP step. Current-voltage measurements are performed during each treatment to ensure process reproducibility and stable reaction conditions throughout production.

Each chemical treatment is followed by ethanol rinsing to remove Sulphur contaminants that could degrade cavity performance and enhance field emission.

A degassing heat treatment is then carried out in vacuum at 900 °C for 3 hours, followed by in-vacuum cooling. This step is combined with frequency and field-flatness tuning, taking advantage of the softened mechanical state of the cavity after high-temperature treatment.

The final surface preparation includes an additional 40 µm electro-polishing, again with the last 20 µm performed in cold conditions, followed by more than 48 hours of exposure to ISO4 clean air to promote complete re-oxidation of the inner surface.

Subsequently, a mid-temperature bake at 350 °C for 3 hours in vacuum furnace is performed to enhance the quality factor at medium and high accelerating gradients. Since this treatment defines the final RF surface properties, it is carried out in a fully qualified furnace capable of guaranteeing state-of-the-art vacuum conditions. The LB650 series will benefit from the significant experience gained in these last few months on executing Mid-T treatment both in a lab environment and in industry [4].

Finally, to preserve the optimized inner surface, cavity tuning and helium-vessel integration are performed in a particle-free argon atmosphere. During the complete integration process, a dedicated flanging and monitoring system derived from the Eu-XFEL Frequency Monitoring System (FMS) [5] is used to continuously control and, if necessary, correct cavity frequency and field flatness.

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CURRENT STATUS

LB650 pre-series cavities

Two pre-series cavities, B61M-ZRI-401 and #402, were foreseen in the contract with the awarded manufacturer, *Zanon Research and Innovation* (Italy) (ZRI), to anticipate and qualify the cavity forming, welding and treatment steps and timely release the qualified stages for the series ones.

Both cavities have been electron-beam welded (EBW) on target for length, dimensions and frequency, and subsequently accepted through the surface processing before Mid-T, preparation that both completed successfully by February 2026.

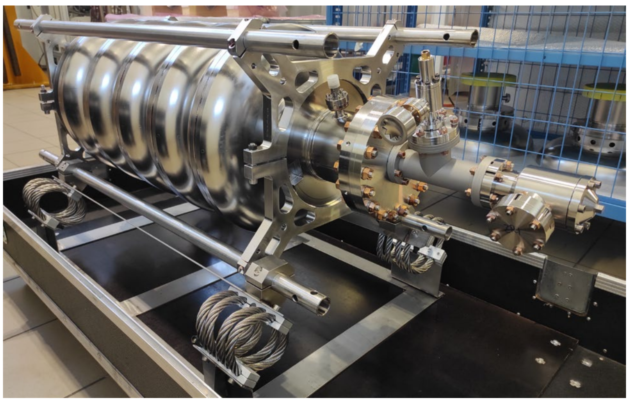

Figure 1: Cavity #401 upon Leaving Toward Fermilab to Receive Mid-T Baking.

During the post bulk-EP visual inspection, cavity #402 showed a few surface features potentially indicating small pits or bumps. Although their minor entity, it has been opted for a mechanical removal by grinding the areas around the defects. The cavity was therefore diverted from its baseline cycle and received, after grinding, an EP-reset of 60 µm removal (40 warm plus 20 cold) before restarting the nominal process with the high-temperature baking.

After final EP and further cleaning by HPR and ethanol rinsing, from March 2026 both cavities were safely moved to Fermilab to receive the Mid-T treatment (Fig. 1) in accordance with the technical provisions mutually agreed by all involved parties and including the following steps:

- Incoming inspection with RF measurements of the cavity, which is travelling with neutral Argon pressure and in its VT hardware, including RF antennas.
- ISO4 clean-room entry, dismounting of flanging hardware, single-pass HPR, 48+ hours drying.
- Clean, double bagging for the transport to vacuum furnace.
- Installation of Niobium foil caps in a soft wall ISO7 clean-room area at the furnace entry (Fig. 2).
- 350 °C 3h vacuum baking following a burn-out cycle on the empty furnace and cryo-pumps regeneration. Cool-down under vacuum.
- Full dressing with the original hardware of the in-air cavity.
- Final RF outgoing checks and crating for shipment.

Cavity #401 suffered from an abrupt interruption of the thermal cycle due to a pressure increase in the furnace chamber that the cryo-pumps could not compensate for. It reached 350 °C and maintained that temperature for about 36 minutes before the heat cycle was stopped in response to the alarm and cooling began.

The cavity was visually inspected, and no abnormal signs were seen on either the external or internal surface. After this incident, further furnace runs and RGA spectrum analyses ruled out air leak as a cause of the pressure increase. Before a second, successful process, the cavity underwent a 15 µm EP removal of the oxygen-enriched layer. SIMS analyses of the samples baked with the cavity supported the decision of removal thickness.

Figure 2: Cavity #401 Ready to Receive Mid-T Baking at Fermilab.

At the time of writing, shipping back to ZRI is being addressed for both cavities to proceed with the final cleaning and the preparation for intermediate vertical cold test.

A preliminary analysis of shock-logger data for both cavity #401 and its box (Fig. 3) through the air transport to Fermilab confirmed that steel wires suspensions system installed in the crate delivers the expected dampening and accelerations experienced by the cavity are comparable to those usually recorded in dedicated road transports.

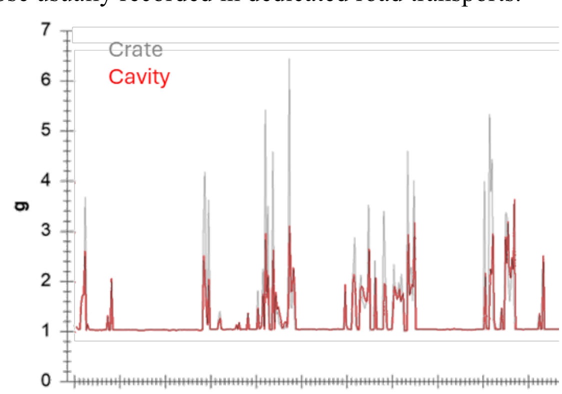

Figure 3: Log of Cavity #401 Shock-Loggers, Crate and Cavity, Readings Along Positive Vertical Axis (+1 g Bias) During its Shipment from ZRI to Fermilab.

LB650 series manufacturing status

Forming and coining of half-cells for the pre-series required extra effort to address residual errors in the RF profile leading to excessive frequency errors and internal equators diameters that were consistently larger than required [3].

As a consequence, the stamping dies for all the three shapes have been slightly modified for the series sub-components. This action proved sufficient to restrain the half-cells equator diameters, but re-shaping process is still required to cancel the frequency bias.

As of today, all HCs for the first cavity batch of 4 cavities have been stamped and final forming is underway. EBW for this first lot is foreseen in June 2026 while manufacturing of sub-components is already authorized for the whole series.

Successful results from the qualification vertical test of the naked pre-series cavities will timely release the surface treatment of the first cavity batch and of all available cavities afterward.

All ancillary sub-components for the naked cavities (pipes, flanges, spool rings) are already available while procurements for all jacketed cavity ancillary items (jackets, bi-metallic joints, tubes) are set and parts are being delivered.

Document management and cavity database

To support cavity industrial production and testing, INFN LASA team is developing QA/QC tools and software infrastructure to handle documents and data flowing to and from companies, partners labs and the project.

Following the successful experience gained with the QA/QC protocol for the ESS in-kind contribution [6], a dedicated document management platform based on INFN Alfresco [7] was implemented. It is organized into a structured folder hierarchy, reflecting the production workflow agreed upon with the industrial partner.

Internally at INFN, a Python-based tool has been developed, and it performs preliminary formal checks on the documents and automatically route the files to the appropriate folders. Once sorted, the script updates each document by adding a signature containing the name of the person who created, approved, or rejected it, together with the corresponding date.

Finally, all relevant information extracted from the documents is stored in a database. The database is built by merging information extracted from Alfresco with LabVIEW output files generated during VT testing at DESY. This tool enables efficient traceability of all cavity components, making it easier to identify correlations with successful or unsuccessful cavity performance and to detect trends throughout the production process.

To monitor the full production chain of the SRF cavities, from the processing of individual subcomponents to the final vertical tests, a Streamlit-based interface capable of parsing and visualizing data from the database is in development (Fig. 4).

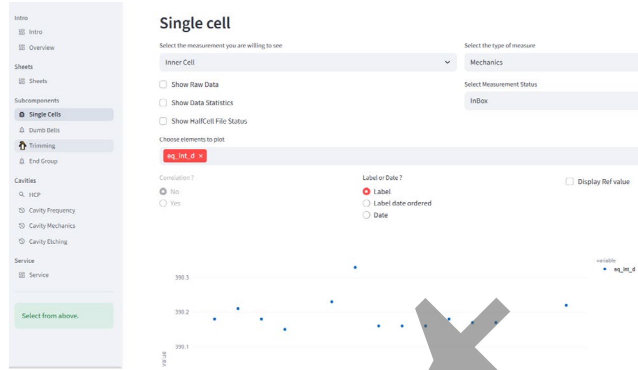

Figure 4: Graphical Interface of the PIP-II Dashboard with an Example of Trend Plot from Actual Template Data

Qualification cold-tests at DESY AMTF

The qualification of the LB650 series will take place at the AMTF facility at DESY, an infrastructure that grants both the required test performance and accuracy as well as the high testing rate needed by the project's schedule.

The first of the two vertical inserts dedicated to LB650 cavity series, capable of hosting two jacketed cavities, is expected to be available in autumn 2026. Regarding the pre-series cavities, the DESY team has confirmed the availability of a solution that will enable the qualification tests to be carried out on the two pre-series cavities in the coming months.

LASA INFRASTRUCTURE UPGRADE

As part of a broader upgrade of the INFN LASA experimental infrastructure [8], the cold-test facility is being refurbished to meet the state-of-the-art requirements for high-Q cavity qualification in terms of cryogenics, magnetic hygiene, and diagnostics.

In parallel, a second insert, previously dedicated to 3.9 GHz cavities, has been upgraded to also support larger multicell resonators such as those for ESS and PIP-II, enabling to proceed with two cavities being simultaneously prepared for cold testing in support of the LB650 series qualification.

The Ultra-Pure-Water production plant and the High-Pressure Rinsing system have both been completely revamped. The whole infrastructure and the related toolings now allow dressing, cleaning and handling large multicell cavities as LB650.

CONCLUSIONS

INFN LASA in-kind contribution to the LB650 section of the PIP-II linac at Fermilab is progressing, pre-series cavities are close to their qualification tests while activities for the series started: subcomponents manufacturing is underway and all collaborations with partner companies and labs are running.

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