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INFN-LASA FOR THE FERMILAB PIP-II

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Abstract

The status of INFN LASA contribution to the PIP-II project at Fermilab is reported in this paper. Experimental results and ongoing activities on prototypes are summarized together with the development of related testing infrastructures. The series production of the 38 INFN LASA designed, 5-cell cavities with beta 0.61 for the LB650 section of the PIP-II linac recently commenced, the status of major procurements and associated activities is here below conveyed. All cavities will be produced and surface treated in industry to reach the unprecedented performances required, qualified through vertical cold test at state-of-the art infrastructures and delivered as linac-ready at the string assembly site.

INFN LASA CONTRIBUTION

The Fermilab Proton Improvement Plan II (PIP-II) Linac [1, 2] is designed to deliver a 1.2 MW H^{-}beam upgradable to multi-MW to enable LBNF and DUNE neutrino physics projects. The 800 MeV beam will be injected into the upgraded Booster Ring via a linac-to-booster transfer line and it will then proceed to the Main Injector Ring.

The PIP-II linac features a flexible time structure for its 0.55 ms, 2 mA beam pulse in order to satisfy different experimental needs, with radiofrequency (RF) repetition rate of 20 Hz pulsed but with components capable of supporting continuous-wave (CW) operations.

A key section of the linac is the 650 MHz superconducting part with geometric beta factor of 0.61 (LB650) that currently encloses 36 five-cell elliptical cavities in 9 cryomodules, accelerating beam from 177 MeV to 516 MeV. Target cavity accelerating gradient is set at 16.9 MV/m with a quality factor higher than 2.4 10^{10}, an unprecedented working point for this type of resonators.

INFN LASA firstly provided a novel electromagnetic and mechanical design for the LB650 cavities [3], fully compatible to the performances and technical interfaces posed by the project as well with beam pipes and flanges, power coupler, helium tank, tuner.

On December 4th, 2018, the U.S. Department of Energy (DOE) and Italy's Ministry of Education, Universities and Research (MIUR) signed an agreement to collaborate on the development and production of technical components for PIP-II [4]. Following this milestone, on June 28th, 2021, INFN president, A. Zoccoli, officially signed the finalized INFN PIP-II Project Planning Document (PPD) [5].

INFN in-kind contribution will cover the needs of the LB650 section of the linac, namely:

- Grand total of 40 SC cavities (36 plus 2 spares, and 2 initial prototypes) delivered as ready for string assembly, equipping a total of 9 cryomodules.
- Qualification via vertical cold-tests provided by INFN either through the LASA test stand or through a qualified cold-testing partner infrastructure.
- Dual Acceptance Review, initially on INFN responsibility upon cold qualification and later under project responsibility at the string assembly site.
- Compliance to the PIP-II Technical Review Plan, the procedure issued by DOE and Fermilab in order to meet PIP-II technical, schedule and budget commitments.

PIP-II LB650 CHALLENGES

A successful cavity design is the result of an interplay of multiple state-of-the-art competences existing at INFN-LASA in electromagnetic, mechanical and technical domains [6].

PIP-II LB650 cavities are themselves among the key scientifical challenges of the whole project, requiring:

- An unprecedented quality factor for these resonators, e. g. more than four times higher than that of ESS cavities at a similar gradient.
- The proper surface treatment recipe, based in Electro-Polishing etching (EP), must be developed and qualified on these low-beta resonators.
- Assessment of High-Order Modes (HOMs) risks so that neither instabilities nor additional cryogenic losses pose critical issues.
- Deep understanding of Lorentz Force detuning, pressure sensitivity and mechanical leading parameters as rigidities, yield limits, stresses [7]. PIP-II operational scenario is an uncharted territory in terms of cavity detuning control, especially in view of foreseen pulsed operation of these high loaded-Q cavities.
- Potential mutual compliancy to both European pressure vessel directives (PED) and U.S. codes (ASME) shall be resolved.

PROTOTYPES AND OTHER PRE-PRODUCTION ACTIVITIES

In total, seven PIP-II LB650 prototype cavities have been produced counting both single and multi-cell, and three of them are shared with Fermilab since early 2020 for a joint development effort (Fig. 1).

The actual status and perspectives of each of these prototype cavities is resumed here below, more insights are instead reported in M. Bertucci at al. at this conference [8].

B61S-EZ-001 Single-Cell

- High-Q recipe at FNAL [9]: *160 μm bulk EP + 900°C heat treatment (HT) for 3 hours +2/0 N-Doping at 800°C + final EP.*

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- Test at Fermilab-VTS, project goals met.
- Next: re-test at INFN LASA in view of the crucial harmonization of testing infrastructure performances and outcomes.

B61S-EZ-002 Single-Cell

- Baseline recipe: *150 μm bulk EP + 800˚C HT for 2 hours + 25 μm final EP + 120˚C bake for 48 hours.*
- Vertical Test (VT) qualified at LASA (Fig. 1) without fast cooling and active residual magnetic field compensation capabilities.
- Next: surface refresh, 900°C HT followed by mid-T bake recipe. Re-test later in 2022.

B61S-EZ-003 Single-Cell

- Target recipe is High-Q treatment with 900°C HT and N-doping.
- VT planned at LASA in 2022.

B61-EZ-001

- Surface treated and successfully qualified at Fermilab VTS both as naked and as jacketed [9]. Now targeted for dressed, horizontal cavity test in Fermilab STC.
- Title transferred from INFN to Fermilab/DOE.

B61-EZ-002

- Prepared by INFN (Fig. 2) with *150 μm bulk EP + 800˚C HT for 2 hours + final cold EP + 300˚C bake for 3 hours*.
- Successful VT at LASA in October 2021 (Fig. 3) without fast cooling and active B-field compensation capabilities.
- Currently being jacketed in industry making use of FMS-like [10] system to preserve the already qualified inner cavity surface during the helium vessel integration process.
- Qualification VT is foreseen at LASA in 2022.

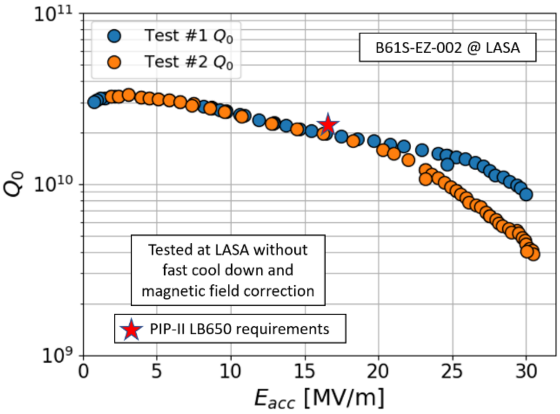

Figure 1: Q-vs-Eacc results for the INFN LB650 single cell cavity test at LASA test stand, compared to PIP-II specifications.

Differently than Fermilab VTS [11], LASA VT infrastructure has its residual magnetic field value minimized only by passive shielding and about 8 mG are left in the cavity region. In addition, current cryogenic transfer lines setup and liquid helium mass flow availability at the LASA infrastructure only allow for a small temperature time rate across transition, about 1 K/min, therefore the reported residual field could be assumed as completely trapped.

Figure 2: INFN B61_EZ_001 LB650 cavity for PIP-II after final electron-beam welding.

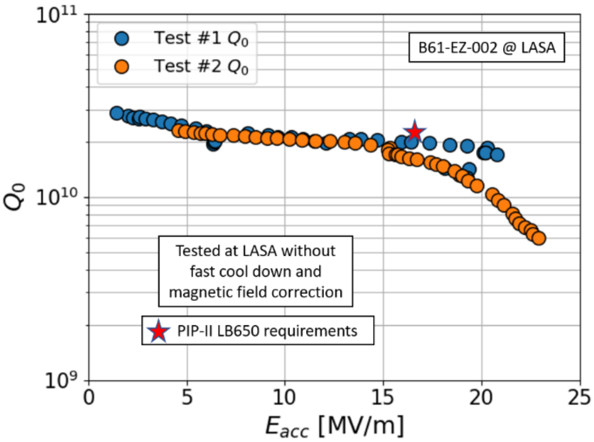

Figure 3: Q-vs-E_{acc} results for the INFN LB650 cavity test at LASA test stand, compared to PIP-II specifications.

LASA INFRASTRUCTURE UPGRADE

LASA cavity vertical cold-test infrastructure has been upgraded in many aspects in view of the LB650 cavities qualification and in order to align to state-of-the-art test facilities in the PIP-II collaboration.

An inner, cylindrical magnetic shield in Cryoperm© has been realized and installed to further reduce the residual magnetic field in the cavity region of the test cryostat.

Cryogenic capabilities of SRF testing facility at LASA have also been expanded on different fronts the goal being a more efficient cold measurement strategy with less downtimes and capable to operate in continuous wave (CW) mode.

- Higher cryogenic power for CW operation has been achieved, from about 40 to 60 W @ 2 K (32 mbar) by upgrading cold gas pumping line and pumps skids.
- Cryostat re-filling systems at 2.0 K – 32 mbar by means of a counter-flow heat-exchanger followed by a Joule-Thomson expander installed and commissioned. Installed below the last copper thermal shield of the vertical insert, this solution is designed to shorten the amount of time used for liquid helium accumulation while also extending, when needed, the cavity testing time.

Further upgrades are also being put in place for the vertical test insert in use for the PIP-II cavities (Fig. 4):

- Faster cool-down rate at SC transition through an optimized distribution of biphasic helium flow toward and around the cavity.
- Active compensation of residual magnetic field through Helmholtz coils, initially installed and commissioned for a LB650 single cell.

Figure 4: LASA VT inserts. On the left the one in use for PIP-II cavities equipped with tube-in-tube heat-exchanger (wrapped in MLI) and Joule-Thomson refilling system.

TOWARD SERIES PRODUCTION

Major procurements for the LB650 production cavities are expected to commence by 2022 starting with the raw Niobium sheets and semi-finished items, whose Production Readiness Review (PRR) has been already closed. This will be followed by cavity manufacturing, that includes cavity treatment and final preparation, and experimental qualification via cold tests.

Two pre-series cavities will be used, with intermediate cold-tests, to qualify the production strategy. Subsequent cavities will be delivered at the string assembly site directly after qualification cold test and ready for string installation after two stages of Site Acceptance Review.

Discussion about the LB650 cavity configuration upon reception at string assembly site already commenced involving INFN, CEA and Fermilab technical teams. Finalized cavity Acceptance Criteria and Interfaces Description documents will be soon released as outcome of this effort.

Production LB650 cavities are targeted to be delivered in 9 batches, 6 units for the first batch and 4 for the following ones, starting from 2024.

Quality Assurance and Control, Risks

The INFN Quality team released the INFN Assurance Plan document (QAP) jointly with Fermilab experts. This document captures the set of preventive as well as control actions put in place by INFN to ensure that project requirements are met throughout the entire cavity cycle and changes or non-conformances are properly handled.

The Quality Assurance and Control strategy includes, for instance, defining quality requirements for procurement, manufacture, assembly and testing processes, maintaining necessary documentation, monitoring production quality performance and identify opportunities for improvement or review quality procedures.

An INFN PIP-II Quality Planning Workshop is to be held this month to consolidate expectations and resources in both teams.

The INFN Risk Management Plan document has also been released together with a Risk register tailored to the INFN scope of work.

A substantial effort is being put by INFN and partners' teams in the scope of harmonizing quality controls at various laboratories by means of a Quality Control Alignment Matrix and through the collaborative activity of the PIP-II Quality Control Coordination Group.

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