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STATUS OF THE INFN-LASA CONTRIBUTION TO THE PIP-II LINAC

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Abstract

The international effort for the PIP-II project at Fermilab has been joined by INFN with its planned contribution to the PIP-II proton linac in the low-beta section. INFN-LASA is finalizing its commitment to deliver in kind the full set of the LB650 cavities, 36 plus spares resonators with 5-cell cavities at 650 MHz and geometrical beta 0.61. All cavities, designed by INFN-LASA, will be produced and surface treated in industry to reach the unprecedented performances required by PIP-II, qualified through vertical cold test at state-of-the art infrastructures and delivered as ready for the linac at the string assembly site. The status of INFN contribution to PIP-II, the development of infrastructures and prototypes as well as the ongoing activities toward the start of series production are summarized in this paper.

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 beam pulse in order to satisfy different experimental needs, with RF repetition rate spanning from 20 Hz pulsed to continuous-wave (CW).

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 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, INFN-LASA is finalizing the layout of its in-kind contribution aiming to 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-test provided by INFN either through the LASA test stand or through a qualified cold-testing partner infrastructure.
- 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.

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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 [5].

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 must be developed and qualified addressing at first the challenges of Electro-Polishing (EP) etching 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 [6]. PIP-II operational scenario is actually 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 required to both European (PED) and U.S. (ASME) pressure vessels codes.

R&D AND PROTOTYPE 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).

Figure 1: INFN B61_EZ_001 LB650 cavity for PIP-II after final electron-beam welding.

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One of single-cell (B61S_EZ_002) (Fig. 2) has been surface treated and prepared for vertical test by INFN at Zanon Research and Innovation company [7] and used to put to test a baseline recipe (150 μm bulk EP + 800˚C Heat Treatment + final cold EP + 120˚C) together with the upgraded Electro-Polishing plant and with the dedicated process diagnostic [8].

Figure 2: INFN B61S_EZ_001 LB650 cavity installed on the LASA vertical insert before the cold-test. Second sound and temperature sensors are visible around the cell.

A second INFN single-cell cavity (B61S_EZ_001) has been surface treated and prepared by Fermilab following the state-of-the-art High-Q recipe (180 μm bulk EP + 900 ˚C Heat Treatment +Nitrogen-Doping + final cold EP). In its last cold-test in Fermilab VTS infrastructure this resonator performed excellently and exceeded project requirements [9].

Plot presented in Fig. 3 reports and compares the quality factor Q versus the accelerating gradient E_{acc} for both single-cell vertical tests measurements, at LASA and Fermilab VTS. An analytical extrapolation is also shown for the B61S_EZ_002 data set in order to better compare the two different cavity environment during superconducting transition. At Fermilab VTS in fact residual magnetic field is actively tied close to zero by means of Helmholtz coils, flux-gate sensors and a regulating loop [10] while at LASA its value is minimized by passive shielding only and about 8 mG are left in the cavity region. In addition, current cryogenic setup at LASA only allows for a small temperature time rate across transition, about 1 K/min, therefore the reported residual field could be assumed as completely trapped.

More details on the performances of the cavity tested at LASA are reported in [11], together with a description of the assumptions and the procedure for the rescaling of Q-vs-E_{acc} at zero external magnetic field.

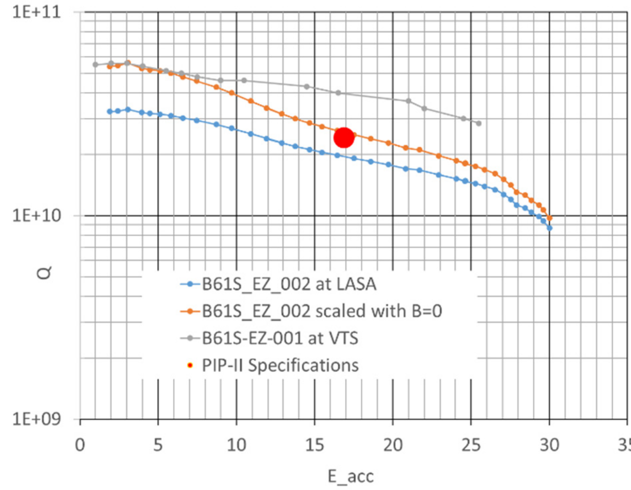

Figure 3: Q-vs-Eacc results for the two INFN LB650 single cell cavities, compared to PIP-II specifications.

Following initial development activities on single cells, two fully compliant, 5-cells LB650 prototype cavities have been manufactured by INFN in early 2020 to complete the qualification process for the cavity package.

An intense development effort is currently ongoing at both INFN and Fermilab premises, sharing one LB650 cavity each, and both prototypes are expected to be qualified via vertical tests at their respective test facilities within few weeks from now [12].

Specifically, for the one to be qualified at LASA, the Electro-Polishing plant at Zanon Research and Innovation is being upgraded and qualified. This LB650 cavity already successfully received a bulk EP with about 150 mm removed, as cross-confirmed by charge, weight and thickness measurement result, and an 800 °C 2 h heat-treatment.

Once surface treatment will be completed the cavity will be immediately prepared for the vertical test, targeted to take place at LASA in July.

Details concerning the effort ongoing at INFN toward the optimal High-Q surface treatment and about the innovative diagnostic for the EP process developed are also reported in [8, 11].

Fluid-Dynamics Test Bench

Uncertainties in the solution of computational fluid dynamics (CFD) simulations are not negligible due to the complex geometry of a SRF cavity and thus without an experimental validation, results from this type of simulations cannot be confidently used to improve the process (Fig. 4).

To this aim an experimental study has been started at INFN, in the framework of the activities on LB650 prototypes for PIP-II, to investigate the fluid-dynamics of the chemical etching process by means of Particle Image Velocimetry (PIV) technique on a hollow, scaled and transparent model of a LB650 cavity die manufactured in a silicon elastomer. Introduction to this subject and preliminary results are reported in [13, 14].

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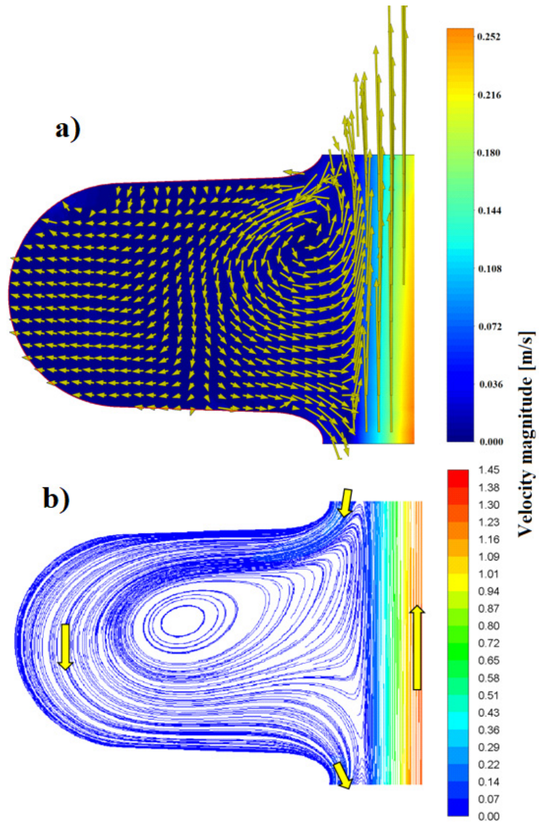

Figure 4: Side-by-Side comparison of a) PIV experimental and b) CFD simulation results for the acid flow within a low beta cell.

Preliminary experimental set up confirmed the possibility to actually analyze qualitatively and quantitatively the flow field inside an elliptical cavity and, to a first approximation, the overall complex behavior predicted by CFD simulations has been consistently verified. Further measurements are required to fully validate CFD simulations for this specific cavity shape, this tool could be then used to optimize treatment parameters and setup.

Horizontal cavity treatments, as for instance EP or even rotational BCP, will be then addressed together with multi-physics simulations to include the electro-chemical aspects of the etching processes.

OPTIMIZED HPR NOZZLE HEAD

The flat side walls and the large equator diameter of low-beta elliptical cavities as the PIP-II LB650 represent a potential float in the effectiveness of the inner surface cleaning by means of High-Pressure water Rinsing (HPR).

In this respect a novel design for the HPR nozzle head has been developed at INFN-LASA, conceived to be promptly compatible with the existing HPR facility at Zanon and to make use of the widely proven sapphire threaded nozzles.

The spraying head features (Fig. 5) four pairs of jets at different angles in order to improve the jet patterns on flat side-walls as well as equatorial regions of the cavity surface. Azimuthally, the four pairs span over the full circle with 90 degrees between each couple.

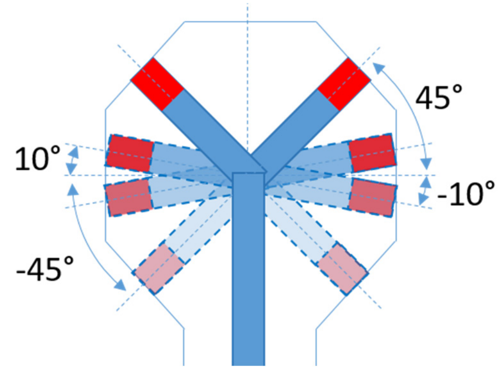

Figure 5: Schematic layout of the revised HPR nozzle head for low-beta cavities. The end of each channel (in blue) is equipped with a nozzle (in red) featuring ISO M8 thread and sapphire round orifice.

This HPR nozzle head with revised design has been already successfully used for the rinsing of B61S-EZ-002 cavity. Moreover, it's efficiency has been proven with even more emphasis through the re-treatment of M006 cavity from the ESS series for which a strong multipacting barrier has been basically cured [15].

LASA INFRASTRUCTURE UPGRADE

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

Inner Magnetic Shielding

An inner, cylindrical magnetic shield in Cryoperm© has been realized and installed in order to further reduce the residual magnetic field in the cavity region of the test cryostat (Fig. 6).

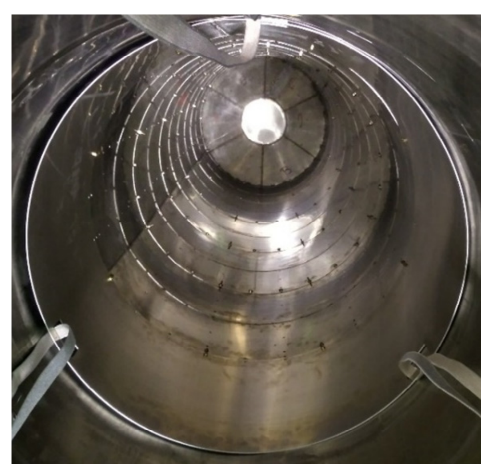

Figure 6: Cryoperm© magnetic shielding in place inside the vertical testing cryostat. A second, external shield at room temperature is placed (not visible here) around the cryostat.

Preliminary installation within the cryostat allowed for a first evaluation of the inner shield effect on the remnant field. Figure 7 shown measured vector amplitude values with and without the inner shield as a function of the cryostat vertical axis (starting at the bottom). Positions of

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LB650 cavity equators during cold-test are also noted at the bot-tom of the plot for reference.

Overlapping joints of outer and inner shields apparently allow magnetic field to leak into the enclosed volume, a tighter connection between sectors is indeed currently being provided to enhance the overall field reduction.

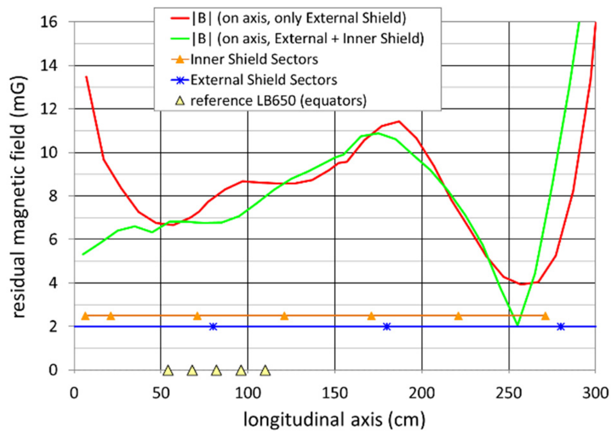

Figure 7: Magnetic field vector amplitude as measured along the LASA cryostat vertical axis in different shielding configurations.

Cryogenic System

In the past months, cryogenic capabilities of SRF testing facility at LASA have 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, currently expected to reach up to 70 W @ 2 K (32 mbar). Achieved via an expanded throughput of primary pumping skid and a new gas transport piping with larger diameter.
- Cryostat filling at 2.0 K – 32 mbar by means of a counter-flow heat-exchanger followed by a Joule-Thomson expander (Fig. 8) [16], both 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.
- Faster cool-down rate at SC transition through an optimized distribution of biphasic helium flow toward and around the cavity.

In view of the qualification of a larger series of cavities with higher test rate required, a third qualified infrastructure (aside LASA and FNAL VTS) that could be potentially selected as partner is being discussed. This goes along the successful strategy put in place by INFN for the ESS series cavity procurement through a contract with DESY for the use of the excellent AMTF facility [17].

IN-KIND CONTRIBUTION DOCUMENTS

The Project Planning Document (PPD) for the INFN in-kind contribution to PIP-II has been finalized. It accounts for the compliance to the PIP-II Technical Review Plan, for

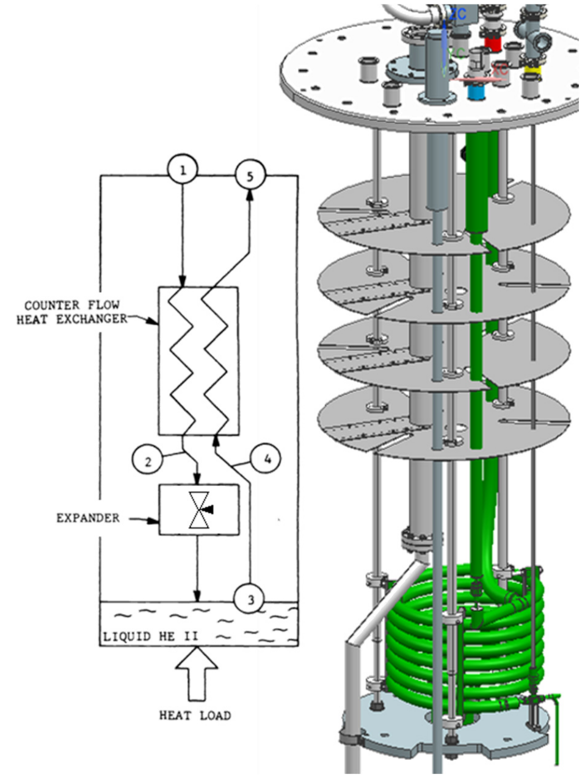

Figure 8: CAD view of Heat-Exchanger, J-T valve and related process lines on the LASA LB650 vertical insert.

the scope of work, the deliverables, the milestones and the project schedule. INFN PPD received US DOE approval and it has been recently signed by INFN.

The INFN Quality Assurance Plan document (QAP) is also in an advanced stage. This document captures the set of preventives 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.

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

SERIES PRODUCTION PLANNING

Major procurements contracts for the LB650 production cavities are expected to be placed by 2022 starting with the raw materials procurement and shortly followed by cavity manufacturing and experimental qualification via cold-testing.

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.

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Production LB650 cavities are targeted to be delivered in 9 batches, 6 units for the first batch and 4 for the following ones, from May 2024 up to July 2025 [18].

CONCLUSIONS

INFN and the LASA SRF group are going to contribute to the US flagship project PIP-II at Fermilab addressing the numerous scientifical challenges of the LB650 section of the linac.

Preparatory activities on prototypes, infrastructures and treatment recipes are proceeding toward their conclusion in view of the Final Design Review of the LB650 cavity package at the end of 2021.

LB650 prototypes built by INFN are being used to qualify the cavity production and preparation strategy jointly with industry. LASA cold-test infrastructure are also being upgraded in order to allow for LB650 cavity testing aside a partner test infrastructure qualified for series production testing rate.

Once the design of LB650 cavity package is finalized and reviewed, the procurement of production cavity series is expected to commence leading to the delivery of last cavity batch by 2025.

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