

STATUS OF THE PIP-II ACTIVITIES AT INFN-LASA

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Abstract

INFN-LASA joined the international effort for the PIP-II project in Fermilab and it is expected to build the 650 MHz superconducting cavities required by the low-beta section of the 800 MeV front-end proton linac, as recently signed by US DOE and Italian MIUR.

After developing the electro-magnetic and mechanical design, INFN-Milano started the prototyping phase by producing five single-cells and two complete 5-cells cavities. In a joint effort with Fermilab the road for the optimal surface treatment for such low-beta resonators has started in order to approach the existing state-of-the-art performances of beta 1 cavities.

This paper reports the status of PIP-II activities at INFN-LASA, summarizing manufacturing experience and preliminary experimental results.

INTRODUCTION

The Fermilab Proton Improvement Plan II (PIP-II) Linac [1] is designed to deliver an average H⁺ beam current of 2 mA at a final kinetic energy of 800 MeV, thus doubling the injection energy into the Booster Ring. The beam will be then injected into the Main Injector Ring to finally serve the Fermilab's flagship LBNF/DUNE neutrino program.

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 spanning from 20 Hz pulsed to continuous-wave (CW).

One key section of the linac is the second-to-last 650 MHz superconducting part with geometric beta factor of 0.61 that currently encloses 33 five-cell elliptical cavities, accelerating beam from 185 MeV to 500 MeV (named as low-beta section or LB). Target cavity accelerating gradient is set at 16.9 MV/m with a quality factor of $2.15 \cdot 10^{10}$.

INFN-LASA initially provided a novel design for the LB650 cavities [2], fully plug compatible with the technical interfaces posed by Fermilab: beam pipes, power coupler, helium tank, tuners etc.

On December 4th, 2018, the U.S. Department of Energy (DOE) and Italy's Ministry of Education, Universities and Research (MIUR) signed an agreement [3] to collaborate on the development and production of technical components for PIP-II.

Following this milestone, INFN-LASA is expected to in-kind contribute to the PIP-II linac with the complete set of superconducting cavities of the low-beta section, delivered as fully jacketed and qualified, ready for the stage of string assembly.

INFN CAVITY DESIGN

EM Cavity Design

Seeking for a high energetic efficiency, as expressed by the R/Q ratio, is always crucial in view of a CW operational mode. A high R/Q principally requires small iris aperture and small wall-angle; this may lead to difficulties in field flatness tuning, cleaning and cavity surface treatment.

Therefore, INFN RF cavity design has been primarily driven by the pursue of the optimal trade-off on a wider range: balancing shunt resistance, electromagnetic performances and formability/tunability of the final resonator according to INFN experience in the field.

Rationales for the key design features of the INFN LB650 cavity can be then outlined as follows:

- Cell coupling kcc driven by the optimization, assuming TESLA-type cavity as a reference, of the quantity $N^2/(\beta k_{cc})$ [4]. N being the number of cells and β the relative velocity.
- End Cell frequency tuning achieved by increasing the diameter of the whole terminal cell thus preserving its round shape and symmetry (as done for the SNS cavities).
- Maximize G factor while preserving sidewall angle at 2° avoiding potentially negative value during the cavity field flatness tuning stage.
- Achieve a large frequency separation between π and $4/5 \pi$ modes.

Table 1 finally resumes main RF parameters for the resulting cavity design.

To complete the electromagnetic design, the HOM spectra and sensitivity to geometry as well as the multipacting have been addressed in detailed simulations [2].

Mechanical Cavity Design

The relatively small beam current of PIP-II results in an external Q of the cavity as high as 10^7 that in turns implies a narrow bandwidth of the accelerating mode. In order to have a stable beam acceleration, an extremely strict control of the Lorentz Force Detuning (LFD, or pulsed RF) and

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microphonic is required: the PIP-II operational scenario reveals to be an uncharted territory in terms of detuning control, as expressed by the ratio LFD/bandwidth [5].

Starting from 4.4 mm sheets, the cavity wall thickness after treatments has been set for simulations at 4.2 mm assuming Niobium material mechanical parameters well-established from previous projects. This is meant as a convenient balance between cavity stiffness and heat conduction toward Helium bath.

We apply single stiffening rings both at end cells and at inner cells to provide enough suppression of detuning. The double stiffening ring option has been discarded due to the substantial negative impact of such choice on manufacturing quality and tunability.

Table 1: RF Design Parameters of INFN LB650 Cavity

Parameters	INFN LB650
$\beta_{geometric}$	0.61
Frequency	650 MHz
Number of cells	5
Iris diameter	88 mm
Cell-to-cell coupling, k_{cc}	0.95 %
Frequency separation $\pi-4\pi/5$	0.57 MHz
Eq. diameter - IC	389.8 mm
Eq. diameter - EC	392.1 mm
Wall angle – Inner & End cells	2 °
Effective length ($10 * L_{hc}$)	704 mm
Optimum beta β_{opt}	0.65
E_{peak}/E_{acc} @ β_{opt}	2.40
B_{peak}/E_{acc} @ β_{opt}	4.48 mT/(MV/m)
R/Q @ β_{opt}	340 Ω
G @ β_{opt}	193 Ω

The study conducted [6] highlighted the interplay among geometrical parameters, a trade-off must be found between mutual minimization of LFD and pressure sensitivity coefficients, with the latter requiring larger stiffening rings radius. Finally, a radius of 90 mm is chosen.

The mechanical design parameters for the cold cavity, based on the previous discussed considerations, are summarized in Table 2.

Table 2: Mechanical Parameters of INFN LB650 Cavity

Parameters	INFN LB650
Inner cells stiffening radius	90 mm
External cells stiffening radius	90 mm
Longitudinal stiffness	1.8 kN/mm
Longitudinal frequency sensitivity	250 kHz/mm
LFD coefficient	
k_{ext} at 40 kN/mm	-1.4 Hz/(MV/m) ²
Pressure sensitivity	
k_{ext} at 40 kN/mm	-11 Hz/mbar
Maximum Pressure	2.9 bar
VM stress at 50 MPa	
Maximum Displacement	1.5 mm
VM stress at 50 MPa	

A key role on final figures is played by the effective spring rate of the whole cavity mechanical constraint,

external stiffness k_{ext} , as showed in Fig. 1. Design of helium jacket, tuner and their interfaces toward cavities are under finalization to fulfil PIP-II challenging requested specifications.

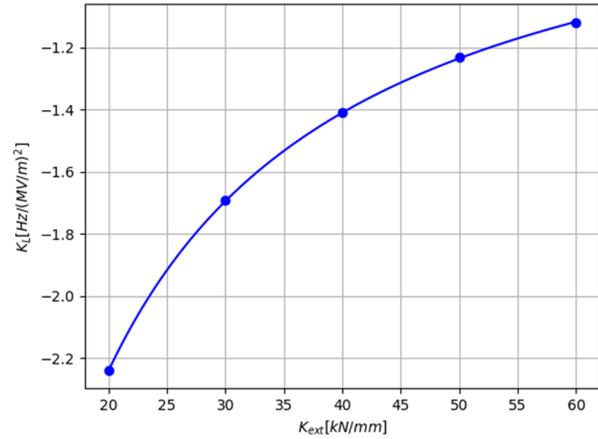


Figure 1: Lorentz force detuning (LFD) coefficient as a function of external cavity stiffness, cold cavity.

SINGLE-CELL PROTOTYPES

In order start validating cavity design, fabrication procedures and surface treatments, 3 single-cell cavities have been already manufactured and 2 more are under production. These prototype resonators are made by two end cells from the multi-cell cavity end-groups and allowed at first the qualification of the deep-drawing die for this specific design and thickness.

The higher effort is now set on the optimization of the electro-polishing surface finishing that is expected to be the baseline treatment for LB650 cavities. The large cavity size and its squeezed cell shape are expected to significantly change the process behaviour.

Specific tools are being developed and the process recipe, mostly used in the past for XFEL and LCLS-II 1.3 GHz cavities, is being optimized for the steeper geometry. For this to occur, produced prototypes are going to be shared with Fermilab for their experts to proceed in parallel with INFN staff and industrial partners.

In the latter case, preliminary and successful experimental results have been achieved on a PIP-II FG001 single-cell at the EP plant at the E. Zanon (Fig. 2) [7].

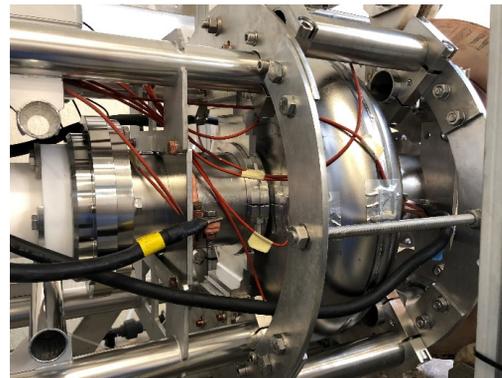


Figure 2: PIP-II FG001 single-cell during preliminary EP treatment at E. Zanon.

Once surface treatment technique is established, single-cell prototypes are going to be qualified by vertical test at both INFN and FNAL VTS test stands.

More specifically, the state-of-the-art features of VTS at Fermilab [8] in terms of active cancelation of residual magnetic field and fast cooldown will allow for the in-depth characterization of magnetic flux expulsion performances of the Niobium material of these prototypes. The two single-cell units currently under production will feature the same Niobium specifications of the incoming multi-cell prototypes, these results will serve as a basis for the joint definitions of the material parameters for the production.

MULTI-CELL PROTOTYPES

Two completely dressable prototypes are also currently under fabrication (Fig. 3), fully compliant to the current state of cavity interfaces as per Fermilab specifications.

These cavities will be delivered tuned to frequency and field-flatness, thus allowing the qualification of all manufacturing intermediate steps and tools:

- Half-cells and dumb-bells deep-drawing, RF measurement and machining.
- EB welding and ancillary tools
- Tuning machine for cavity preparation at the required frequency and field-flatness

The two prototypes will help completing the development of surface treatments for the PIP-II goals and will be vertical-test qualified independently at Fermilab and INFN. Its then expected to proceed with jacketing and dressing up of at least one of these cavities so to conclude this prototyping phase with the qualification via horizontal test of a dressed cavity (with power coupler) in STC at Fermilab.



Figure 3: View of the prototype cavity under production.

TOWARD SERIES PRODUCTION

In view of the expected responsibility for the PIP-II LB650 series cavity production, INFN is providing all the necessary step to initiate and sustain the task.

INFN is involved with the PIP-II community in the ongoing joint effort to issue the optimal Niobium material specifications and thus commence the related procurements.

Moreover, modifications and upgrades to INFN vertical cold test infrastructure at LASA are taking place. The min-

imization of the residual magnetic field in the existing cryostat, currently at about 8 mG, has been firstly addressed: an additional cylindrical cryo-perm shield is under procurement in order to halve this value and an active compensation through Helmholtz's coils is under studying to locally cancel even this small remnant field.

Additionally, over a longer time span, current cryogenic capabilities of LASA facility will be expanded seeking for more cryo power and faster cooldown rate, as of today limited to about 45 W and 0.5 K/min at transition respectively.

In view of the qualification of a larger series of cavities with higher test rate required, a third qualified infrastructure (beside 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 [9].

CONCLUSIONS

INFN is shaping its contribution to the US flagship project PIP-II at Fermilab based on the ongoing activity at LASA.

First single and multi-cell prototypes are being delivered thus concluding the preparation phase in view of the final DOE approval. They will serve as basis for the development of the optimal surface treatment recipe tailored to the challenging PIP-II specifications.

The detailed strategy for the close-out of the prototyping phase toward the start of procurement of jacketed and qualified LB650 series cavity is being issued in a joint effort of INFN, Fermilab and all the international partners of the PIP-II project.

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