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INFN-LASA FOR THE PIP-II PROJECT

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Abstract

INFN-LASA joined the international effort for the PIP-II project in Fermilab to build the 650 MHz superconducting cavities realizing the low-beta section of the 830 MeV proton linac.

After developing the electro-magnetic and mechanical design, INFN-LASA started the prototyping phase by producing five single-cells and two complete five-cells cavities.

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

INFN-LASA CONTRIBUTION

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 36 five-cell elliptical cavities, accelerating beam from 185 MeV to 530 MeV (named as low-beta section or LB). Target cavity accelerating gradient is set at 16.9 MV/m with a quality factor of $2.15\ 10^{10}$.

INFN-LASA provided a novel design for the LB650 cavities [2], fully plug compatible with the technical interfaces posed by Fermilab: 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.

Following this milestone, INFN-LASA is expected to in-kind contribute to the PIP-II covering the full cavity need of the LB650 section of the linac, namely:

- 40 SC cavities (36 plus contingency) delivered as ready for string assembly, equipping a total of 9 cryomodules.
- Qualification via vertical cold-test provided by INFN through a qualified cold-testing infrastructure acting as a subcontractor. Following ongoing experience with AMTF at DESY providing qualification tests for INFN cavities for the ESS project
- Compliance to the PIP-II Technical Review Plan, the procedure issued by Fermilab in order to meet PIP-II technical, schedule and budget commitments.
- Engagement of INFN-LASA and Fermilab technical teams to ensure that final cavity design properly interfaces with all external components.

ELECTROMAGNETIC 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, the RF design of INFN-LASA cavity 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 k_{cc} driven by the optimization, assuming TESLA-type cavity as a reference [3], of the quantity $N^2/(\beta k_{cc})$. 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 ANALYSES

In order to swiftly converge to a functional LB650 prototype, INFN-LASA and Fermilab agreed to adopt for helium tank the design originally developed by Fermilab for

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the high-beta cavity. As a consequence, the mechanical design of INFN-LASA cavity addressed mostly the RF part of the resonator.

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.

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 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 [4].

We apply single stiffening rings both at end cells and at inner cells to provide enough suppression of detuning. The double stiffening rings option for the inner cells 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 π-4π/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

Table 2: Mechanical Parameters of INFN LB650 Cavity

Parameters	INFN LB650
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 *VM stress at 50 MPa*	2.9 bar
Maximum Displacement *VM stress at 50 MPa*	1.5 mm

The study conducted [5] 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 geometry, based on the previous discussed considerations, are summarized in Table 2.

For the Niobium Young's module, a about 10% increase is assumed for the cold state, leading to the final value used in simulation of 118 GPa.

For what concerns instead elastoplastic limit of the cavity the ranges, both in strain and pressure, are computed as a reference to a Von Mises (VM) stress of 50 MPa where a safety coefficient of 2/3 is applied to the typical value of 70 MPa. It's although assessed that Niobium yield limit at cold extends by a factor of 6 to 8 at cryogenic temperature thus values shown in Table 2 are meant as a limit to room temperature operations on cavity (tuning, pressure tests etc.).

A key role on final figures is played by the effective spring rate of the whole cavity mechanical constraint, external stiffness or k_{ext}, that is generated by the series of elements in the helium jacket and the interfaces to cavity.

The impact of final external stiffness on two crucial cavity mechanical figures, the vacuum sensitivity k_p in terms of Hz/mbar and the frequency shift due to Lorentz Force detuning (LFD) Δf_{LFD} is shown in Fig. 1 for a range spanning across the design value of 40 kN/mm.

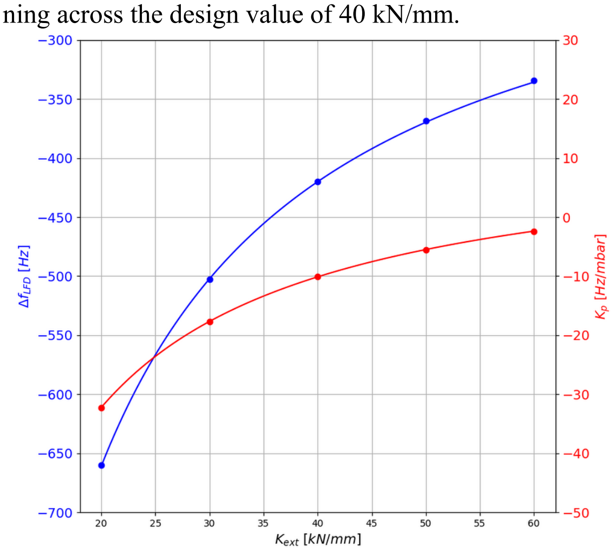

Figure 1: LFD frequency shift (blue) and pressure coefficient (red) as a function of external cavity stiffness for a cold cavity.

Values reported in the plots above are computed by two different means: the solid dots are the results of a direct electromagnetic and mechanical simulation while the solid line results from a more general analytical approach employing the following Eq. (1) for the LFD detuning:

$$\Delta f_{LFD} = \left(k_{L0} - \frac{k_T R_L}{k+k_{ext}}\right) E_{acc} \quad (1)$$

While Eq. (2) is used for the pressure sensitivity:

$$k_p = k_{p0} - \frac{k R_p}{k_{cav}+k_{ext}} \quad (2)$$

In the above equations:

- k_{cav} is the cavity stiffness
- k_{ext} external stiffness
- k_T tuning sensitivity

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- k_{p0} limit vacuum sensitivity related to a fully constrained cavity in terms of *Hz/mbar*
- R_p constraint reaction related to k_{p0}
- k_{L0} limit LFD coefficient related to a fully constrained cavity in terms of *Hz/(MV/m)²*
- R_L constraint reaction related to k_{L0}

In order to anticipate any potential issue generated by the final helium jacket design missing its target stiffness value, further mechanical analyses are ongoing for cavity interfaces to helium vessel.

Focusing only on key components, the cavity external stiffness is determined by the series of the extremely rigid tank tube itself with the frequency tuner, on pick-upside, and with the transition spool ring on the main-coupler side.

While cavity tuner effective stiffness is under evaluation at Fermilab [4], results of cavity-to-tank interface study are shown here below.

An infinitely stiff constrain has been set at the end of the round end cap in order to evaluate the reaction of this cavity section individually to the compressing reaction force of the radiation pressure. Results are visually summarized in Fig. 2 and highlight how the spool transition ring rigidly rotate (visual magnification factor of 30000 in the picture), increasing internal stresses at pivot points.

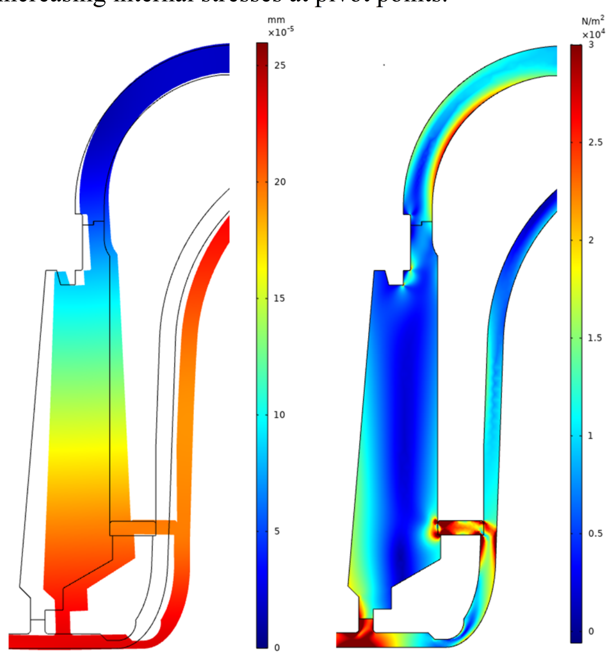

Figure 2: FEM analysis (strain on the right, VM stress on the left) of the spool transition ring while withstanding the reaction force of 10 MV/m cavity field. Peak values in the colour code are 0.25 µm and 0.03 MPa, respectively.

The stiffness of this specific part of the interface resulted to be about 60 kN/mm. To mitigate the worsening of LFD coefficient in case the series of this section to the tank and the tuner generates a final external stiffness lower than design value, a few options could be considered.

Reinforcing ribs could be welded between beam pipe and the upper part of the spool ring and in this case the benefit in terms of LFD sensitivity is estimated in about 10%. Up to 20 % reduction could be instead achieved in case these ribs are extended up to the tank round end-cap, but this would imply a re-design of most of the cavity tools and frames.

SINGLE-CELL PROTOTYPES

In order start validating cavity design, fabrication procedures and surface treatments, 3 single-cell cavities have been already manufactured (Fig. 3) 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.

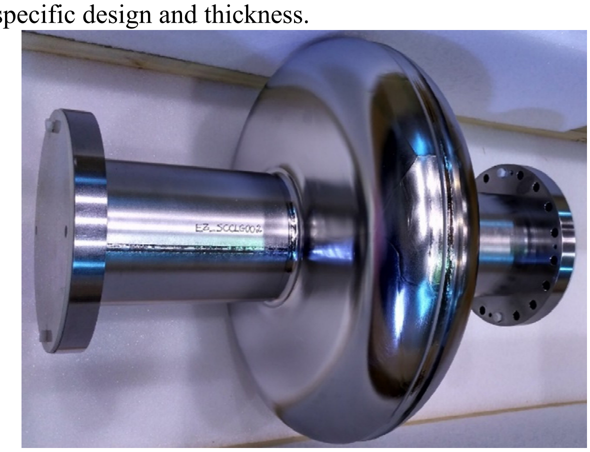

Figure 3: PIP-II LG002 single-cell.

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.

Successful experimental results have been already achieved on a PIP-II single-cell at the EP plant at the E. Zanon (Fig. 4) [6].

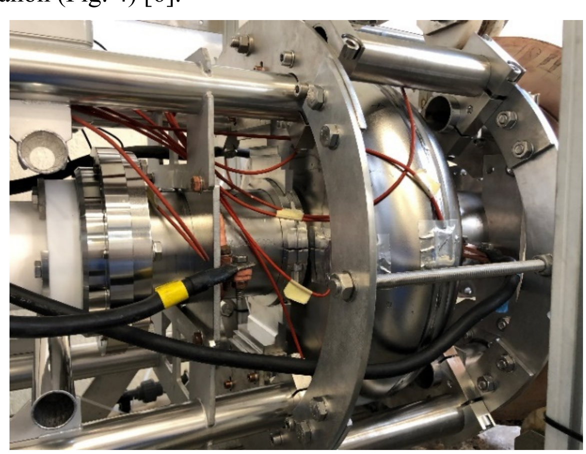

Figure 4: PIP-II FG001 single-cell during preliminary EP treatment at E. Zanon.

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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.

MULTI-CELL PROTOTYPES

Two completely dressable prototypes are also currently under fabrication (Fig. 5), 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.

NIOBIUM MATERIAL SPECS

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

A first set of specifications has been issued for the ongoing manufacturing of prototypes. It's still widely based on assessed physical and chemical values from E-XFEL and ESS productions but it's introducing, for the first time, a harder constrain in the allowed ASTM grain size. Each Niobium sheet shall still be fully recrystallized, exhibit uniform size and equal axed grains with predominant size ASTM 5 (0.065 mm) but it's requested to have no grains larger than ASTM 4 (0.090 mm) as well as no grains smaller than ASTM 6 (0.045 mm).

The first test bench for these specifications will be the cold qualification test of INFN-LASA prototypes at the VTS facility at Fermilab [7]. With its state-of-the-art active cancelation of residual magnetic field and fast cooldown capabilities VTS will allow for the in-depth characterization of magnetic flux expulsion performances of the Niobium material.

The two additional single-cell cavities 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.

INFRASTRUCTURES UPGRADE

INFN-LASA activities for PIP-II will benefit from the modifications and upgrades to LASA vertical cold test infrastructure that are taking place.

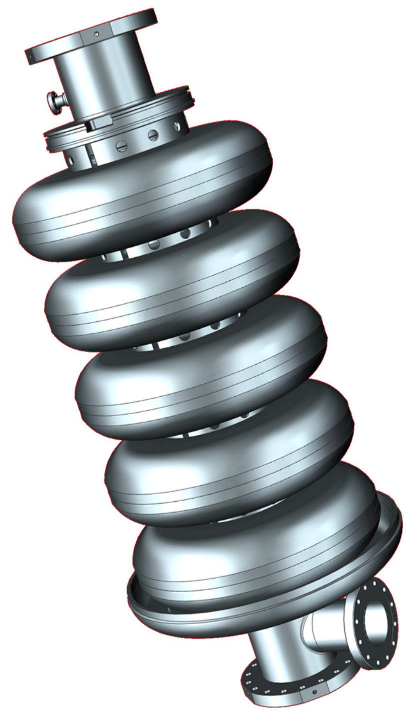

Figure 5: View of the prototype cavity under production

The minimization of the residual magnetic field in the existing cryostat has been firstly addressed. As of today, a typical value of 8 mGauss is measured at cavity level with limited variation around equators of each cell (Fig. 6).

A cylindrical cryo-perm shield, placed inside the cryostat, is under procurement and it will aside the existing one that is installed outside the vessel. It's expected this new shielding geometry to halve the residual field value in the cavity axis direction and furthermore reduce orthogonal components.

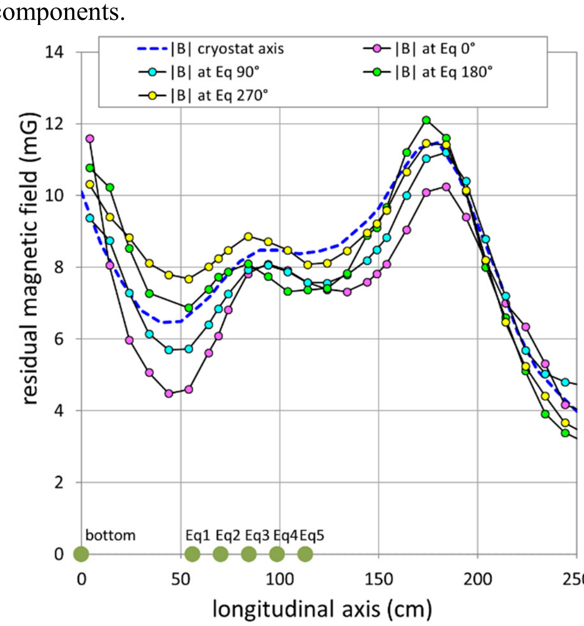

Figure 6: Measurement of the vector amplitude of residual magnetic field in the vertical cryostat at LASA. Horizontal axis starts at cryostat bottom, green dots visually report the heights of each cavity equator.

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In this upcoming scenario, the exact cancelling of remnant longitudinal field component might be achieved by active compensation through Helmholtz's coils around the cavity. Such local compensation would be then driven via closed loop by fluxgate sensors installed at cavity equators so that magnetic field is vanishing when SC transition occurs.

Additionally, in the next months, current cryogenic capabilities of LASA facility will be expanded on different fronts the goal being a more efficient, CW capable cold measurement strategy with less downtimes.

- Higher cryogenic power for CW operation, now limited to 40 W @ 2 K: redesign of cryostat pumping elements and vacuum chain is under studying in order to push it to about 70 W @ 2.0 K
- Cryostat filling at 2.0 K – 32 mbar: this will allow shortening the amount of time used for liquid helium accumulation while also extending, when needed, the cavity testing time. The setup under development makes use of a counterflow heat-exchanger followed by a Joule-Thomson expander (Fig. 7), both installed below the last copper thermal shield of the vertical insert.
- Faster cooldown rate, now at 0.5 K/min at SC transition: the cryostat and the process lines will be redesigned in order to allow for a short transient of high mass flow and gas throughput.

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 [8].

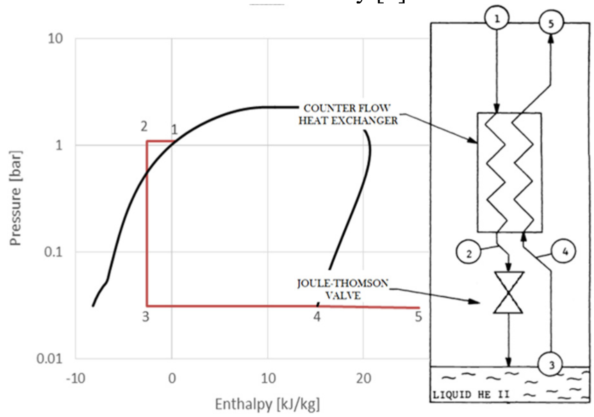

Figure 7: Conceptual layout of the 2 K refilling system for the LASA facility and corresponding points in the pressure-enthalpy graph of helium [9].

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 as well as for the qualification of involved test infrastructures.

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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