

STATUS OF THE HIGH Q-HIGH G R&D ACTIVITIES ON SRF CAVITIES AT INFN LASA*

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Abstract

INFN LASA started an R&D activity dedicated to the development of the knowledge needed to understand how to improve SRF cavity performances to reach High Q and High G values to accomplish the sustainability and cost reduction requests, as needed for the future large particle accelerators. This R&D activity, funded by INFN, is also enriched by synergies with other LASA activities like the PIP-II low beta cavity production, the participation to ILC Technology Network, and by the LASA experience in SRF cavity industrialization developed during the large-scale production of the Eu-XFEL and the ESS SRF cavities. The first results obtained on 1.3 GHz single and multi-cell cavities, and the status of the upgraded LASA infrastructures for Vertical Test are here presented.

INTRODUCTION

Next-generation facilities, such as lepton colliders and advanced light sources, require accelerator technologies that surpass current limits in energy and beam quality. Achieving these goals also demands improved sustainability and reduced costs.

A major contribution to these improvements comes from advancements in accelerating components, in particular Superconducting Radio Frequency (SRF) cavities, as emphasized in the 2020 European Strategy for Particle Physics (ESPP) [1]. Targeted R&D on cavity surface preparation and thermal treatments is therefore crucial to achieve both high-quality factors (Q) and high accelerating gradients (G).

The INFN Milano–LASA SRF group has extensive expertise in the design, prototyping, and industrial production of bulk niobium based superconducting cavities and related components, with strong efforts toward technology transfer. This approach has been successfully validated through in-kind contributions to major international projects such as the European XFEL, ESS, and PIP-II [2-5].

To sustain and expand this expertise, INFN launched in 2023 a multi-year program focused on future large-scale projects including ILC, Muon Collider, and FCC. Similar initiatives are pursued worldwide within international

collaborations we are participating to, such as the ILC Technology Network (ITN), which targets high gradients (31.5 MV/m) while maintaining high Q_0 ($\geq 1 \cdot 10^{10}$) in line with its pulsed operation design goals [6].

OUR R&D STRATEGY

To address these challenges, the strategy we have developed is structured in two main phases. The first focuses on R&D using 1.3 GHz single-cell cavities—the reference frequency for these studies—with the goal of developing surface and thermal treatments that extend high-Q performance into the high-gradient regime. Once these processes are consolidated, the second phase aims to transfer them to multicell cavities and, critically, to make them compatible with industrial production in view of future large-scale applications. This approach is fully synergic with our ongoing programs dedicated to future collider projects (ILC, Muon Collider, FCC, etc.), as previously outlined.

Moreover, the R&D activities described here - particularly those focused on High-Q performance - will strongly benefit from ongoing studies carried out in the framework of optimizing the treatments of PIP-II low-beta cavities, operating at 650 MHz which is the first subharmonic of 1.3 GHz [7]. These efforts are especially relevant given the very high Q requirements of the project, despite the relatively modest accelerating gradients associated with their continuous-wave (CW) operation.

Over a 3–4 years horizon, we will deliver a focused, results-driven program built on 1.3 GHz technology:

- **High-Q / High-Gradient process development:** We will optimize two single-cell cavities starting from a proven European XFEL-like baseline treatment (150 μm bulk EP, 900 °C annealing, 10–20 μm final EP, 120 °C 48h baking), and advance performance through innovative methods such as mid-temperature and two-step baking. Rigorous validation at LASA and partner laboratories (e.g., CEA) will ensure robust cross-comparison and rapid process qualification.
- **Scalable technology transfer:** We will extend the validated process to two 9-cell cavities, demonstrating reliable performance at the multicell level while establishing industrialization workflows, including integrated quality assurance and control (QA/QC) protocols, to support future large-scale production.
- **Targeted R&D on enabling systems:** In parallel, we will strengthen key ancillary technologies—such as tuners and magnetic shielding—to guarantee full

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compatibility with high-performance cavities and maximize overall system reliability.

The strategy presented here will be also in parallel pursued in the framework of the ITN collaboration [8]. In fact, synergically, ITN activity will mainly concentrate on reaching the high gradient required by ILC project with high quality factor (Q_0). In this context we will also study the harmonization of pressure vessel codes and the differences in performance, and in mechanical properties, of cavities realized with Fine Grain Niobium but also with the less costly Medium Grain Niobium in view of the overall project cost reduction.

R&D ACTIVITIES STATUS

In this section, we present the status of the R&D activities at LASA dedicated to studies related to High Q, in the context of the PIP-II program and, more specifically, High Q – High Gradient.

The upgrade of the LASA infrastructure required for these activities is presented in a dedicated section afterwards.

High Q Studies

High-Q activities at INFN LASA were initiated within the PIP-II project [4], where LASA is responsible for producing 38 superconducting 650 MHz cavities ($\beta = 0.61$) for the low-energy section of the linac, targeting $Q_0 = 2.4 \times 10^{10}$ at 16.9 MV/m. Although the operating gradient is moderate, the acquired expertise is highly relevant for High-Q/High-G programs.

To achieve such high Q_0 , advanced surface treatments are required. A mid-temperature (mid-T) bake was selected due to its simplicity and the absence of a final electropolishing (EP) step, unlike nitrogen doping [8]. The initial process (150 μm EP, 800°C annealing, 5 μm EP, 300°C bake) was applied to a 5-cell prototype, yielding $Q_0 = 2.1 \times 10^{10}$ at 16.9 MV/m, slightly below target, partly due to modest flux expulsion under non-ideal cooldown conditions [9].

Subsequent R&D focused on improving both surface treatment and magnetic environment. The EP process was improved by proper tuning of the process parameters and hardware components [10]. An investigation was carried out to evaluate the feasibility of transferring the mid-T process to the industry by tests on INFN single cells and a MSU multicell sharing comparable geometrical and RF characteristics [11].

In parallel, active magnetic field compensation using a Helmholtz coil system was developed to suppress remanent fields. While a single coil is sufficient for single-cell cavities, multicell configurations require multiple coils to ensure field uniformity. Both single and multiple coils were implemented in our Vertical Test setup, improving significantly the measured Q_0 .

The enhanced processing techniques, magnetic control, and testing capabilities developed at LASA now form a strong foundation for ongoing High-Q/High-G R&D programs.

High Q – High Gradient Studies

Within INFN’s ESPP R&D project—aimed at systematically understanding the impact of different cavity surface treatments on the quality factor (Q_0) and accelerating gradient, and at developing the capability to tailor these processes to the requirements of future approved projects—two 1.3 GHz single-cell fine-grain niobium cavities have been successfully manufactured at Research Instruments (RI), as shown in Fig. 1, applying a QC as the one used for the large series production.

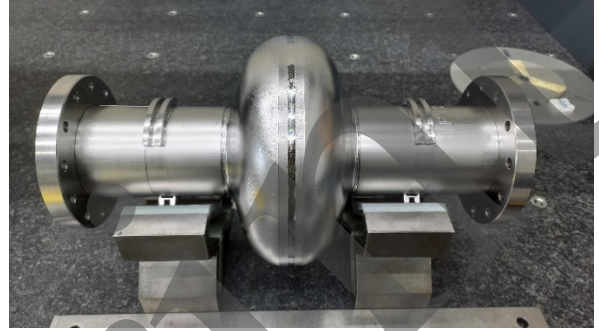


Figure 1: Single cell cavity during dimensional control after mechanical fabrication at RI.

Both cavities have already undergone initial surface treatments, 160 μm “warm” bulk EP ($T < 22^\circ\text{C}$) and 900 $^\circ\text{C}$ for 3 hours, and are currently in the final processing stage, which includes a 20 μm final “cold” EP ($T < 7^\circ\text{C}$) and a 120 $^\circ\text{C}$ bake for 48 hours. This treatment sequence represents the “modified” (900 $^\circ\text{C}$ followed by “cold” EP) and it represents our baseline. These two single cell cavities will be ready by beginning June 2026 for cold RF testing. In Figure 2 show two pictures acquired during the inner visual inspection campaign conducted at RI before and after 160 μm Bulk EP are shown.

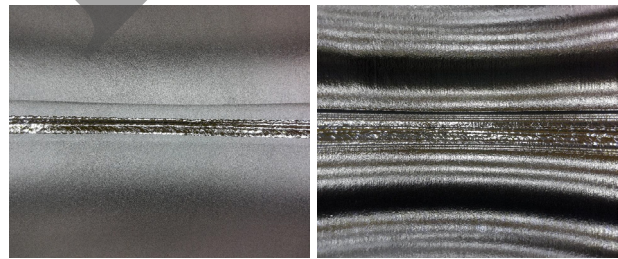


Figure 2: Inner visual inspection after EBW (left), after 160 μm Bulk EP and 900 $^\circ\text{C}$ annealing.

After the qualification test, we will introduce advanced and promising techniques such as mid-temperature (mid-T) baking at around 300 $^\circ\text{C}$ and the two-step baking process (75 $^\circ\text{C}$ for 4 hours followed by 120 $^\circ\text{C}$ for 48 hours). These approaches are expected to provide critical insights into performance optimization, particularly in minimizing temperature-dependent surface resistance and enhancing high-field performance.

RF characterization at 2 K will be carried out at LASA using the newly commissioned dedicated cryostat, ensuring stable and reproducible testing conditions. To strengthen the reliability of the results and enable

international benchmarking, measurements will also be independently verified at leading laboratories such as CEA and DESY, allowing for robust cross-comparison and validation of the treatment processes.

In parallel, the procurement of a 9-cell cavity in industry is currently in progress. This activity marks a key step toward the second phase of the R&D program, where the optimized treatments developed on single-cell cavities will be extended to multicell structures. The objective is to demonstrate scalability, confirm reproducibility, and support the transition toward industrialization and potential large-scale production.

LASA INFRASTRUCTURE UPDATE

The need to measure high Q_0 and high gradient required a substantial update of our test infrastructure to enhance measure capability with less liquid helium usage per test.

New R&D Cryostat

Our new cryostat design, delivered in 2025 [12], was driven by three main objectives:

- To provide a state-of-the-art test facility with optimal cool-down rates and excellent magnetic hygiene.
- To enable a faster and more efficient cavity testing cycle thereby increasing throughput.
- To accommodate either two single-cell cavities or one 9-cell TESLA-type cavity.

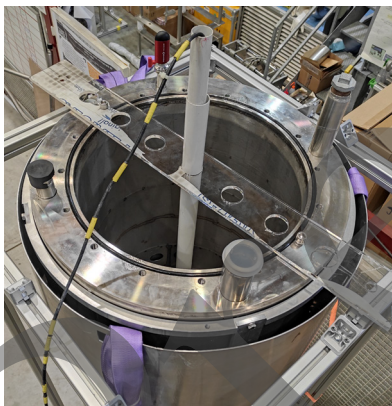


Figure 3: Mapping of Residual Magnetic Field Inside the Cryostat Once Inserted in its Outer Magnetic Shield.

The cryostat assembly includes both passive and active magnetic shielding: a Cryoperm® outer cylinder for passive protection, and a movable Helmholtz coil system positioned between the outer cylinder and the external cryostat walls, for active compensation.

The cryostat is currently undergoing qualification and commissioning tests and, a simplified, preliminary cold test is planned in July 2026 with the main purpose of qualifying cryogenic performances. As of today, the outer shield has been installed around the cryostat and the residual magnetic field is being mapped (Fig. 3) to identify, and possibly cure, areas of field inhomogeneity and thus optimizing active cancellation performance.

The cryostat vertical insert structure is going to be equipped with a comprehensive set of cryogenic

diagnostics, including fast-response thermal sensors, second-sound detection, X-ray radiation monitors, and both fluxgate and AMR magnetometers for detailed magnetic field mapping.

Currently the clean vacuum line for the cavity pumping manifold is being built (Fig. 4), it will host all required pumping devices (SIP, turbomolecular), dedicated diagnostics (full-range BA gauge, RGA) as well as safety and connection elements.

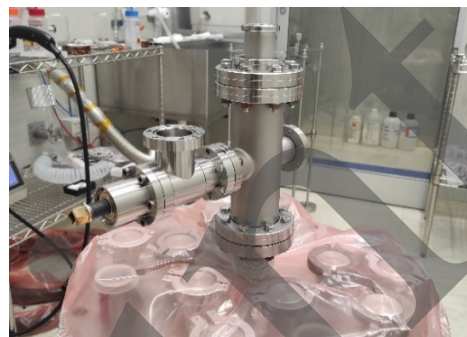


Figure 4: Top Flange of Vertical Insert During Assembling of Cavity Vacuum Components in Cleanroom.

RF System

A new RF chain is being developed for cold testing of 1.3 GHz cavities in the R&D cryostat. It includes an in-house made, mixed analog-digital PLL and a wideband amplifier to operate in both fundamental and HOM bands, enabling also studies of plasma cleaning. A fully digital FPGA-based PLL under development will complement the existing setup to allow for the active cancellation of spurious modes.

Finally, low-noise cryogenic amplification and a high-dynamic-range signal analyzer have been integrated to support dark photon research, allowing sensitive monitoring of field transfer between coupled cavities.

CONCLUSION

R&D on high-quality factor (High-Q) and high-gradient (High-G) SRF cavities is essential for next-generation accelerators, where reducing costs, footprint, and environmental impact is critical.

Within national and international programs such as ESSP-SRF and ITN, our activities target these goals through a structured 3–4 years plan. The program begins with 1.3 GHz single-cell cavities—the SRF benchmark—and progresses to multicell structures, with a clear focus on scalability and large-scale production.

In parallel, ongoing work on PIP-II single and multicell cavities is delivering encouraging results, providing a solid foundation for further optimization of surface treatments and high-Q performance testing.

To support these efforts, the LASA test infrastructure is being significantly upgraded.

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