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R&D ON SRF AT INFN LASA

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Abstract

Sustainability and cost reduction are key factors for the development of future large particle accelerators. This motivated INFN LASA to initiate an INFN-funded R&D program dedicated to improving the performance of SRF Nb cavities in terms of quality factor (High-Q) and accelerating gradient (High-G).

The R&D program will start by exploiting state-of-the-art surface treatments on 1.3 GHz single-cell prototypes, in view of a possible industrialization process for large-scale productions.

Integrating part of this program is the upgrade of our vertical test facility to enable qualification of such high-performance cavities. Ongoing activities include the construction of a new dedicated cryostat, which minimizes Liquid Helium consumption, reduces the impact of trapped magnetic flux and provides a wide range of diagnostics for quench, field emission, and magnetic flux expulsion studies.

INTRODUCTION

The SRF group of INFN Milano - LASA has a long experience in the field of niobium (Nb) superconducting (SC) cavities and related accessories, with research and development activities also dedicated to the industrialization of this technology aimed at in-kind contribution to international projects such as E-XFEL, ESS and, recently, PIP-II [1-4].

Maintaining and reinforcing this excellence and expertise is important in view of future high-performance accelerators (such as lepton colliders and light machines) that aim for even better performance for SRF cavities to meet greater sustainability, cost reduction and short footprint (as for example stated by the ESPP - European Strategy for Particle Physics) [5]. Therefore, R&D programs dedicated to the study and improvement of cavity surface and thermal treatments to achieve High-Q and High-G performance prove to be crucial activities.

The demonstration of how this approach is shared by many worldwide parties is supported by similar 3-4 years programs financed not only nationally as by INFN (with main focus on future projects as ILC, Muon Collider, FCC, etc.), but also by international collaboration as ITN (ILC Technology Network) that aim to reach High-G with good Q_0 at the ILC goal [6]. In this context, FCC is aiming for 20 MV/m with 3E10 while ILC expects 31.5 MV/m with 1E10 in operation. In particular ITN, that is still under formal finalization between all the partners, is a worldwide technology network that aims to study some critical aspects highlighted in IDT (ILC Development Teams) during the preparatory phase of ILC. For ITN, INFN contributes to SRF themes (cavities, cryomodules and ancillaries) working with our colleagues from EU labs involved and coordinated by CERN. Among the various tasks, we will take care of the development and optimization cavities treatments, of their industrialization, and we will work on the harmonization of the EU/US pressure vessel code (PED and ASME) with the Japanese HPGS (High Pressure Vessel Code), that will allow installing up to two European cavities in the demonstrator cryomodule that it will assemble at KEK. This activity is important in view of the future international projects where it will be essential to have world-wide contributions compliant with local regulations.

Furthermore, a four-year EAJADE EU Marie Curie program plays a crucial role in these activities since, sponsoring staff exchange between young EU researchers and well-known labs and universities in US and Japan, will enrich and improve the knowledge exchange in the SRF fields.

OUR R&D STRATEGY

The strategy we propose consists of an R&D phase based on single cells at 1.3 GHz (reference frequency for these activities) for the development of treatments that allow the High-Q to be extended towards the high gradient. Once these treatments will be consolidated, an essential step will be their transfer to multicell cavities in view of a possible large-scale production. This activity is synergic with the SRF group's current program towards future colliders (ILC, Muon Collider, FCC, etc.).

Moreover, the R&D activities here described, in particular the High-Q part, will be synergic and it will profit of the on-going developments and studies in our group for the optimization of the 650 MHz (1^{st} sub harmonic of 1.3 GHz) PIP-II cavity treatments, that asks to reach a very high Q_0 but at modest accelerating gradient.

Within our reference time frame (3-4 years), the plan for developing the activities we propose, based on 1.3 GHz technology, can be summarized in:

- High-Q/High-G recipe development on 2 single-cell cavities. This activity will start from baseline process (E-XFEL like) and then it will include further treatments such as two-step baking, mid-T baking, etc. Moreover, we will test the cavities not only at LASA but also in other laboratories (i.e. CEA) for performance cross-check.
- Transfer of selected treatments to multicell, with 2 9-cells, addressing the industrialization and QA/QC process implementation in preparation for a future large-scale production.

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- Research and development on auxiliary cavity systems (tuners, magnetic shields, etc.).

The strategy presented here will be also in parallel pursed in the framework of the ITN collaboration. In fact, synergically, ITN activity will mainly concentrate on reaching the high gradient required by ILC project with high Q_0. In this context we will also study the harmonization of pressure vessel codes and the difference in performances, and in mechanical properties, of cavities realized with Fine Grain Nb but also with the less costly Medium Grain Nb in view of the overall project cost reduction [7].

R&D ACTIVITIES ON HIGH Q_0

The season for High-Q/High-G activities at the INFN-LASA laboratory has been initiated through participation in the PIP-II project [4]. INFN-LASA took on the responsibility for producing 38 low-β cavities of the proton linac, operating at 650 MHz with $\beta = 0.61$, targeting a $Q_0 = 2.4E10$ at the gradient E_{acc} of 16.9 MV/m. The participation into this project allows acquiring the know-how to achieve high Q_0 that will be later integrated with high gradient in 1.3 GHz cavities.

First and foremost, achieving such a High-Q target required the development of state-of-the-art surface treatments. Amongst the existing recipes, mid-T bake was chosen for its simplicity, as it does not require a final electropolishing (EP) treatment [8] as instead needed by nitrogen doping. These treatments were conducted in the industry to benefit of an existing and tested infrastructures with specific adaptation for our cavity geometry and size.

The initial version of this recipe was applied to a 5-cell cavity prototype and included the following steps:

- 150 μm bulk EP (“warm”)
- 800°C annealing for 2 hours in High Vacuum
- 5 μm final EP (“cold”)
- Mid-T bake (3 h at 300°C in High Vacuum).

This cavity was tested at the LASA facility, before and after tank integration, in an average residual field of 10 mG, with poor flux expulsion due to a cooldown rate of less than 1 K/min and a 0.2 K/m temperature gradient. Under these circumstances, the measured trapped flux efficiency was 0.92. The jacketed cavity reached a Q0 of 2.1E10 at 16.9 MV/m. The result, albeit encouraging, is slightly below the target project value, motivating us to perform an additional double R&D effort: first, to ameliorate the mid-T bake recipe and, second, to improve the cryostat magnetic environment.

From the treatments point of view, several modifications were introduced in the process. First, the EP voltage has been increased from 17 to 20 V to improve the surface smoothness, which is essential to grant high performances [9]. The annealing temperature was increased to 900°C to enhance the magnetic flux expulsion capabilities of the material [10]. Finally, the light EP following the annealing was extended to 40 μm, with 20 μm of this applied at cold.

From the cryostat magnetic point of view, a Helmholtz compensation coil was introduced in the cryostat. This setup allows for the local cancellation of the remanent magnetic field through precise regulation of the coil current.

To address the field in the equatorial zones, where the RF dissipated power density is higher, a single coil can theoretically eliminate most of the trapped flux residual resistance for a single cell cavity (see Fig. 1).

However, for a multicell cavity, multiple coils are required to achieve a more uniform field profile along the entire cavity axis. This has been also developed and it will be tested soon.

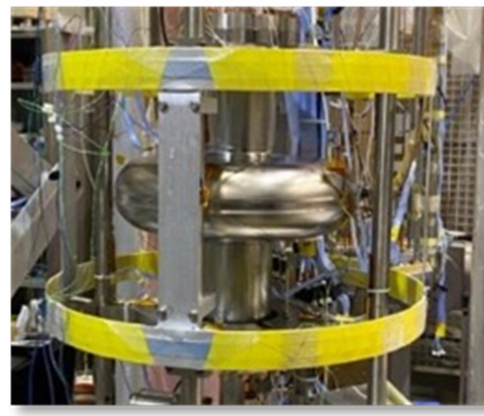

Figure 1: The PIP-II single cell prototype with Helmoltz coil installed on the frame.

The new version of mid-T bake recipe was applied on a single cell cavity, which was then tested with active field cancellation (on average 0 mG in the equator zone) through a single Helmholtz Coil. The cavity reached a Q_0 of 3.1E10 at 16.9 MV/m, which is well above the target value of 2.4E10.

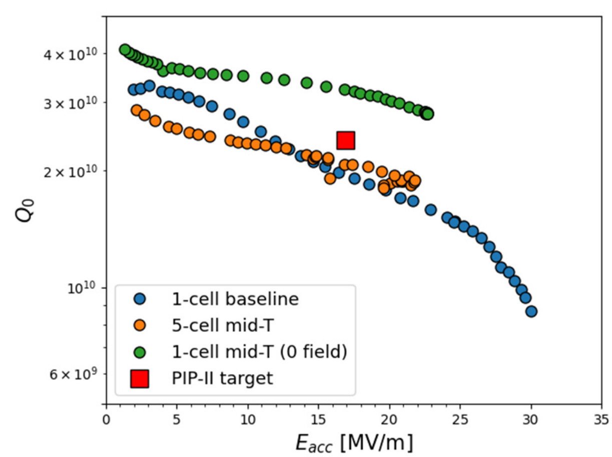

Figure 2: Vertical test results of PIP-II cavity prototypes tested at LASA facility. A significant improvement on the cavity performances is observable on the results of the 1-cell mid-T cavity w.r.t. the baseline one. The PIP-II project target is shown for reference.

Figure 2 shows the results of PIP-II prototype cavities tested so far at the LASA facility. The first is a single-cell cavity treated with the "baseline" E-XFEL type recipe,

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based on electropolishing (EP) for surface removal and a low-temperature bake at 120 °C (1-cell baseline). The other two cavities are the multicell cavity treated with the initial version of the mid-T bake recipe (5-cell mid-T) and the single-cell cavity treated with the improved mid-T bake recipe and tested with active field cancellation (1-cell mid-T 0 field). A big improvement in cavity performance is evident with the introduction of the new mid-T bake version and with active field cancellation procedure.

The overall improvement of the cavity performances and the vertical test facility capabilities, combined with the extensive experience in many topics related to achieving high Q_0 cavities will undoubtedly be valuable for the dedicated R&D program on High-Q/High-G. We are indeed already developing a Helmholtz coils setup for single cell 1.3 GHz, along the same lines of the aforementioned activities on PIP-II cavities.

THE NEW R&D CRYOSTAT

As part of the R&D activity, we have also ordered a new cryostat dedicated to 1.3 GHz cavities.

This cryostat is smaller than the actual one and is being realized to fit into the empty second dewar position inside the LASA test bunker.

The rationale behind its design has been two-fold:

- Ensure the state-of-the art test environment in term of cool-down rate and magnetic hygiene.
- Allow for a shorter and optimized cavity test cycle to improve testing rate. Up to two single-cell or one 9-cells TESLA type cavities can be installed.

With about its 3 m overall height and ID of 610 mm, less than one 450 L dewar of liquid helium will be required for a single cavity test. This will be a significant improvement since it will be only about ¼ of the inventory that nowadays must be available for a test in our large cryostat currently in use.

The cryostat assembly will feature a passive magnetic shielding (external Cryoperm® cylinder) and an active compensation system (movable Helmholtz coils setup external and close by cryostat walls).

The cryostat will be equipped with usual cryogenic diagnostic, fast thermos-sensors, second sound, X-ray detector and fluxgates for magnetic field mapping.

A simple sketch of the cryostat and its insert is shown in Fig. 3 where both single- and 9-cells configurations are visible. As mentioned before, two single-cell cavities can be tested simultaneously in one test session.

CONCLUSIONS

The R&D towards High-Q/High-G is an essential activity for all future accelerators based on the SRF technology. The request for reduce cost, limited footprint and sustainability is mandatory for any large accelerator complex that will be built in the future.

At INFN Milano – LASA, within an international context, we have launched an R&D that will maintain and strengthen our expertise in the SRF physics and technology.

Some activities have already started, also in the framework of other programs we contribute to, and others have been launched or they will start shortly. In this paper we have presented the most recent. In parallel, we are also starting the procurement of key component as cavities, RF components, diagnostics. The present plan is to commission the new cryostat in spring 2025 and to have the first results on single cell cavities by the end of 2025.

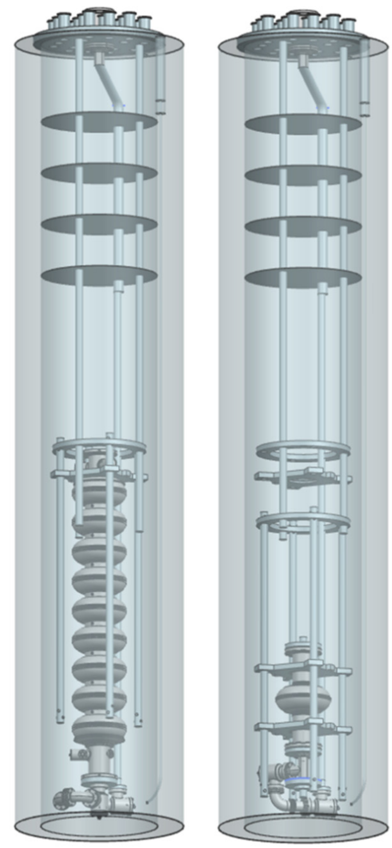

Figure 3: Sketch of new designed R&D cryostat with insert for two different configurations: single-cell and 9-cells cavities.

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