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INFN-LASA R&D ON HIGH-Q CAVITIES FOR THE PIP-II PROJECT

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Abstract

As the series production of PIP-II 650 MHz Low Beta cavities approaches, INFN-LASA R&D activities on cavity prototypes are ongoing. Different surface treatments have been exploited in a joint effort between INFN and FNAL, to establish the series cavity recipe. Meanwhile, the vertical test facility has been upgraded for the test of high-Q cavities, by increasing its capability to reduce the trapped magnetic flux and by developing of a magnetic mapping system suitable in the cryostat environment. Here, we report the latest experimental results.

INTRODUCTION

The Fermilab Proton Improvement Plan II (PIP-II) [1] Linac is designed to deliver a 800 MeV H- beam, which will be injected into the Booster Ring and then transferred to the Main Injector ring, eventually granting a 1.2 MW beam power to the LBNF and DUNE neutrino physics experiments.

INFN LASA is responsible for the production of 40 650 MHz $\beta = 0.61$ superconducting cavities for the low-beta (LB) section of the PIP-II Linac [2]. Specifications for operation in the machine are $E_{acc} = 16.9\,\mathrm{MV\,m^{-1}}$ with a $Q_0 \geq 2.4 \cdot 10^{10}$. A "high-Q" surface recipe is therefore needed to grant such high level performances. Several different recipes has been exploited so to find the best solution in terms of cavity performance and cavity mechanical stability. One must for instance assure that target values for Q_0 and E_{acc} are preserved after the Helium tank Jacketing and the installation in the cryostat, without significant drifts in the operating frequency and cavity field flatness. All this requirements lead us to define an optimized cavity processing sequence suitable in the context of a cavity series production.

CURRENT STATUS OF PIP-II LB650 CAVITY PROTOTYPES

In parallel with the activities performed by FNAL, INFN-LASA conducted an analogous R&D effort on PIP-II LB650 cavity prototypes. Overall, 3 single-cell cavities and 4 multi-cell cavities have been manufactured at the company Zanon Research & Innovation Srl. 2 cavities were shared with FNAL [3]: single cell cavity B61S-EZ-001 underwent a high-Q recipe based on N-doping (160 µm bulk EP + 900 °C HT for 3 hours + 2/0 N-doping at 800 °C + final EP); multicell cavity B61-EZ-001 underwent a baseline treatment (160 µm bulk EP + 800 °C HT for 2 h + final EP + 120 °C 48 h bake), and then has been jacketed with helium tank. In both cases, the project goals were met.

Single cell cavity B61S-EZ-002 and multicell cavity B61-EZ-002 were surface-treated at the company, with the goal of optimizing the already operating infrastructures to the specific case of LB650 cavities, so to demonstrate the feasibility of high-Q treatments of LB650 cavities in the industrial context.

Cavity B61S-EZ-002

B61S-EZ-002 was used to adapt the Electropolishing plant to the different size and geometry of PIP-II LB650 cavities. The treatment parameters were optimized so to improve smoothness, removal rate and iris/equator removal ratio [4]. Aluminum cathode enlargements were installed in correspondence of the center of cells so to increase the removal rate at equators. The same cavity was then used to test a baseline treatment sequence (150 µm bulk EP + 800 °C HT for 2 h + 25 µm cold final EP + 120 °C 48 h bake) which will serve as a reference for forthcoming high-Q treatments. The "cold" regime was employed in the final EP treatment, in which the average temperature on cavity surface is maintained below 12 °C so to grant a smoother surface. The vertical test results at 2 K are affected by poor flux expulsion regime due to the slow cooldown rate of LASA-INFN cryostat (approximately $1\,\mathrm{K\,min^{-1}}$ at the transition temperature corresponding to a 82% measured trapped flux efficiency). Despite this, a $Q_0 = 2 \times 10^{10}$ was achieved at the target E_{acc}=16.9 $\mathrm{MV\,m^{-1}}$ [5]

Cavity B61-EZ-002

Multicell cavity B61-EZ-002 was treated with the mid-T bake recipe (150 µm bulk EP + 800 °C HT for 2 h + 5 µm cold final EP + 300 °C 3 h bake). In this case, the cavity is kept at 300 °C for 3 hours in the same furnace used for high-temperature annealing in UHV conditions ($P \approx 10^{-7}$ torr). Such treatment allows the redistribution of oxygen in the subsurface layer, then preventing additional losses due to hydride segregation [6]. After that, the cavity was exposed to air to allow the regrowth of the Nb_2O_5 layer.

In the first test at 2 K the cavity experienced field emission above 20.8 $\mathrm{MV\,m^{-1}}$, with the abrupt rise of radiation level and a Q-degradation. In a second power rise, the onset of radiation lowered down to 14 $\mathrm{MV\,m^{-1}}$, with a simultaneous drop of the Q_0, until the cavity quenched at 23 $\mathrm{MV\,m^{-1}}$. This behavior is due to the irreversible activation of a field emitter [5]. In this case, a $Q_0 = 1.9 \times 10^{10}$ was achieved at the target $E_{acc} = 16.9\,\mathrm{MV\,m^{-1}}$. After the vertical test, the cavity was

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equipped with a full set of diagnostics for measuring flux expulsion (temperature sensors and 3 fluxgates) and dressed with the Helium tank. A future vertical test of the dressed cavity is planned at DESY AMTF facility so to check cavity performances in a high cooldown rate regime.

LASA ACTIVITIES TOWARDS THE CAVITY SERIES PRODUCTION

While the prototyping phase is still ongoing, the strategy for cavity series production is now under definition. In synergy with FNAL, the experimental data so far collected with the prototype tests have been carefully analyzed and many conclusions have been already drawn.

Definition of Cavity Surface Recipe

Amongst all the high-Q treatments, the mid-T bake recipe is a promising choice, because it requires no additional final EP to tune the impurity content to the desired exposed RF level. However, as for the N-doping treatment, an increase in residual resistance was also noticed, due to an increase in trapped flux sensitivity. A $T \geq 900\,°C$ annealing is needed to recover the magnetic flux properties of the material. This in turn may affect the mechanical stability of the cavity. Even in this frame, mid-T baked cavities experience a reduction of BCS resistance but also a simultaneous increase of residual resistance due to improved trapped flux sensitivity. According to recent findings [7], 300 °C mid-T baked TESLA-type 1.3 GHz cavities experience a 1.5 nΩ mG^{-1} sensitivity at low field, which is more than three times higher with respect to ordinary 120 °C low temperature baking.
The impact on the mid-T baked cavity B61-EZ-002 of the slow cooldown conditions of the LASA-INFN cryostat was evaluated assuming a conservative value of 1 nΩ mG^{-1} for trapped flux sensitivity. Considering an average residual field of $B \approx 6$ mG and a trapped flux efficiency $\eta \approx 80\%$, one obtains a residual resistance $R_{t.f} = \eta \cdot S \cdot B = 4.8\,n\Omega$. Figure 1 shows the experimental Q_0 vs E_{accc} for Cavity B61-EZ-002 and the theoretical Q_0 assuming full flux expulsion, namely subtracting 4.8 nΩ from the experimental surface resistance. This result is consistent with experimental results obtained for similar cavities in high flux expulsion conditions [8].
The optimization of the treatment parameters is ongoing also for the Electropolishing (EP) plant. The same facility is expected to be used for both warm and cold EP treatments, by operating with a maximum temperature setpoint on cavity walls of 20 °C and 12 °C, respectively. The cold EP temperature set-point is achieved thanks to external water chillers [4]. A supply voltage of 18 V was used in all INFN-LASA EP-treated LB650 prototypes, due to limitations in the maximum available supply power. Recent findings [9] demonstrated that a smoother surface finishing can be obtained with a 23 V supply, which corresponds to the plateau region in the I-V polarization curve. An upgrade of the plant power capabilities is foreseen so to allow EP in the full polishing regime. This is expected to further improve the cavity Q-value by limiting dissipative mechanisms due to surface roughness.

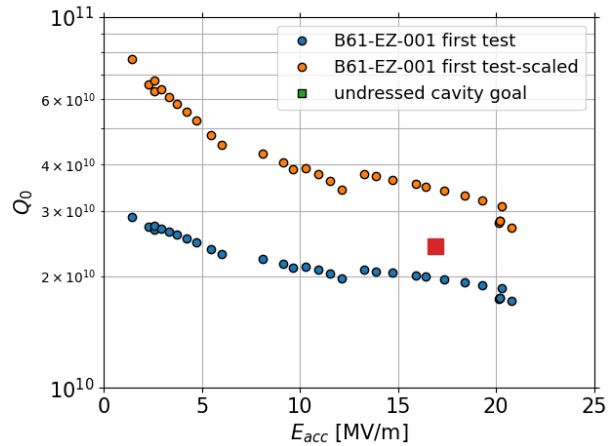

Figure 1: Q vs E_{accc} for Cavity B61-EZ-002 at 2K: experimental Q_0 and recalculated Q_0 assuming full flux expulsion with a 1 nΩ mG^{-1} sensitivity.

Definition of Cavity Final Configuration

Through an interplay among the different partners involved, the cavity shipment and testing configuration is being thoroughly discussed. A second access port to cavity vacuum has been designed in agreement with requirements of the string assembly team. It's hosting a separate all-metal CF16 valve and an UHV compliant micrometric filter and it will provide a dedicated cavity venting line, safe from the standpoint of particle contamination and Q_0 degradation after string assembly. Overall, compatibility with activities planned upon string assembly at CEA has been secured. Figure 2 shows the INFN LB650 cavity as it is currently configured upon delivery at CEA.

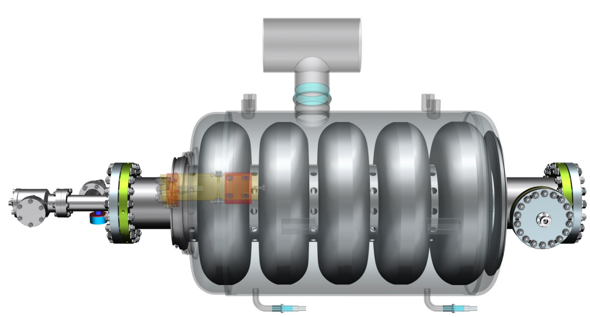

Figure 2: INFN LB650 cavity in its current configuration upon delivery at CEA. Additional venting line is visible on the left in between main CF40 valve and cavity.

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Preparation of Series Vertical Testing Strategy

The full pace vertical testing of production LB650 cavities is planned as a collaboration with DESY and will exploit AMTF infrastructure along a scheme already successfully adopted for the ESS project [10]. Two devoted inserts with two cavities each will be put in place to achieve the peak desired rate of 4 LB650 cavities vertically tested each 5 weeks. No active compensation of residual magnetic field will be realized while a consistent fast cool-down procedure will be defined by calibrating cryo-system data (e.g. outer wall temperatures, liquid helium mass-flow) against LB650 prototypes equipped with *ad hoc* diagnostics.

Upgrade of LASA Vertical Test Facility

LASA vertical test facility is being upgraded in view of the tests of high-Q treated cavities. For the PIP-II LB650 testing purposes it can side DESY infrastructure by testing undressed cavities that require additional evaluation. LASA facility is indeed equipped with a wider set of cavity diagnostics allowing to better understand possible mechanisms of performance limitation.
At the present state, the LASA cryostat does not allow high cooldown rate at the transition temperature, but an upgrade is currently under way. From the point of view of Helium transfer dynamics, LASA cryogenic plant resides on dewars for the liquid helium mass-flow during cool-down and level build-up. Hence, the temperature drop rate at transition will be maximized through a devoted re-design of transfer lines, heaters and spraying nozzles around the cavity.
In the same time, an external field active compensation apparatus is currently under development. This setup is constituted by two Helmholtz coils and a central single coil that are operated with separate current sources. The coil position and currents must be set in such a way to obtain the lowest possible residual field at the cavity equator sites. Such optimization has been carried out considering coils center positions and currents as free parameters and then minimizing the analytical superposition of the coil fields and residual cryostat field at the equator sites. Figure 3 shows the results of such optimization procedure for a residual field of 10 mG. The optimum solution is found with a 22 cm distance between single coil and Helmholtz coils, a 0.26 A current for the two Helmholtz coils, and 0.14 A for the center single coil. The absolute value of residual field on cavity surface is calculated by means of the magnetostatic solver of CST Microwave Studio. The typical residual field at the cavity surface is less than 1 mG and never higher than 2 mG. This in turn would allow the reduction of $R_{t.f.}$ by a factor 10. The active compensation system will also be equipped by a set of magnetic sensors allowing to monitor in real time the residual field level in several points of interest of cavity surface.

Finally, an integrated, fully digital and FPGA-based Phase-Locked Loop (PLL) system is under development to side the analog cavity control system currently in use. The new control crate, similar to those developed for the same task at UKRI or Fermilab, will allow for high flexibility (seamlessly working across different frequencies) and will simplify the harmonization of cavity control and test data acquisition across different labs in the PIP-II collaboration.

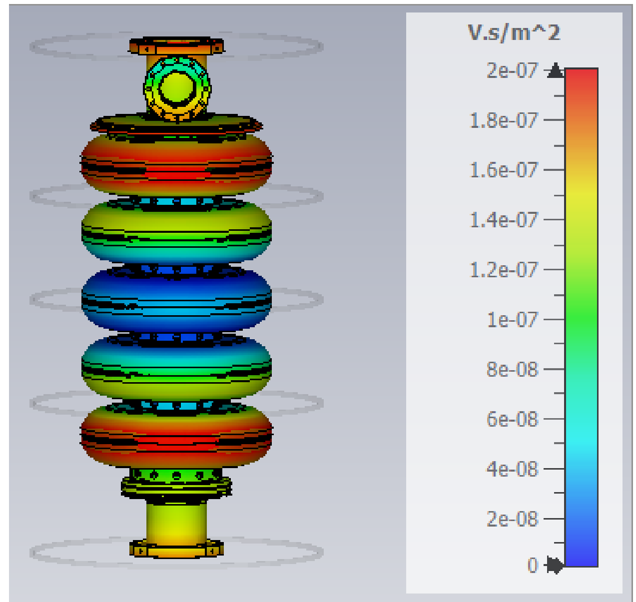

Figure 3: Residual magnetic field along cavity surface employing 2 Helmholtz coils and a single central coil after parametric optimization.

CONCLUSIONS

This paper reports the latest LASA-INFN activities towards the series production of PIP-II LB650 cavities. These consisted in the development of some single and multi-cell cavity prototypes to setup the processing recipe in the industrial context. Besides the definition of the cavity surface treatments, LASA-INFN is also preparing the forthcoming series production. Cavity testing configuration has been defined and the vertical test strategy finalized.
Aiming to test high-Q cavities, the LASA-INFN facility is being upgraded in order to minimize the residual resistance due to trapped magnetic flux. This facility will be used as a backup solution for testing undressed LB650 cavities in case of need.

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