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TOWARD QUALIFICATIONS OF HB AND LB 650 MHz CAVITIES FOR THE PROTOTYPE CRYOMODULES FOR THE PIP-II PROJECT *

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Abstract

High-beta (HB) and low-beta (LB) 650 MHz cryomodules are key components of the Proton Improvement Plan II (PIP-II) project. In this contribution we present the results of several 5-cell HB650 cavities that have been processed and tested with the purpose of qualifying them for the prototype cryomodule assembly, which will take place later this year. We also present the first results obtained in LB650 single-cell cavities process optimization. Taking advantage of their very similar geometry, we are also analyzing the effect of different surface treatments in FRIB's 5-cell medium-beta 644 MHz cavities. Cavities processed with N-doping and mid-T baking showed very promising results in term of both Q-factors and accelerating gradient for these low-beta structures.

INTRODUCTION

The Proton Improvement Plan II (PIP-II) project aims to upgrade the Fermilab accelerator complex to power the world's most intense high-energy neutrino beam for the Deep Underground Neutrino Experiment (DUNE). The high-power proton beam will also enable muon-based experiments and a broad physics research program [1].

PIP-II includes the construction of a 215 m superconducting linear accelerator that will accelerate protons up to 800 MeV by using 5 different types of superconducting cavities: Half-Wave-Resonators (HWR), Single-Spoke-Resonators (SSR1 and SSR2), low- and high-beta 650 MHz elliptical cavities (LB650 and HB650) [2]. The project relies on significant international contributions, from cavities to cryomodule assembly for many of these sections [3].

This proceeding focuses on the status of 650 MHz cavities qualification for which Fermilab partners with RRCAT (India), VECC (India), UKRI (United Kingdom) and INFN (Italy) [4, 5].

Several HB650 pre-production bare cavities have been qualified in vertical tests at Fermilab and are being jacketed, awaiting now for qualification for the prototype-CM assembly which will start in fall this year. LB650 cavities are currently undergoing a processing optimization phase, currently involving both single-cell and 5-cell cavities.

We are also studying the effect of different surface treatments in FRIB 644 MHz medium-beta cavities which show very similar design. This effort started in the framework of an Accelerator Stewardship in collaboration between Fermilab, Michigan State University (MSU) and Argonne National Laboratory (ANL) and is now being carried out in collaboration with the PIP-II project.

HB 650 MHz CAVITIES: QUALIFICATION FOR pCM ASSEMBLY

After a first phase of processing optimization that involved a large number on single-cell high-beta 650 MHz cavities [6], the processing was then transferred to bare 5-cell cavities that were tested in the Vertical Test Stand (VTS) at Fermilab. Cavities that met PIP-II specifications ($Q_0 = 3.3 \times 10^{10}$ at 18.8 MV/m) were jacketed with He-vessel and tested again for the final qualification for cryomodule assembly. Some of the cavities were also instrumented with temperature and magnetic sensors before being jacketed in order to allow for the monitoring of temperature and magnetic field during the cryomodule testing. Some of the cavities are also tested horizontally in the Spoke Test Cryostat (STC) which has been modified to allow for 650 MHz cavities testing [7].

Fermilab has a total of seven HB650 prototype cavities: four $\beta = 0.9$ that were procured several years ago and three $\beta = 0.92$ that were recently received from RRCAT (India).

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Additional three $\beta = 0.92$ HB650 cavities are being procured by Fermilab and expected to be delivered in fall 2021. The RF design of the $\beta = 0.9$ and $\beta = 0.92$ HB650 cavities is very similar allowing to use both of these cavities type together in the prototype cryomodule (pCM) [8, 9]. According to the final PIP-II linac design, only $\beta = 0.92$ HB650 cavities will be procured during the production phase.

After the study conducted in single-cell cavities, the processing protocol for the HB650 cavities has been set as follows: bulk electro-polishing (EP), 800°C (or 900°C if needed to improve flux expulsion efficiency) for 3 hours in ultra-high vacuum, followed by 2/6 N-doping (2 minutes at 800°C with ~25 mTorr of nitrogen and 6 minutes without nitrogen) and then by 7 µm of cold EP. Amount of final EP removal was set to 10 µm after having transferred the processing to 5-cell cavities. A summary of the vertical test results are shown in Fig. 1. Looking at the graph it is possible to notice that when post-doping removal is around 10–13 µm, specifications are largely exceeded in terms of both Q-factor and accelerating gradient.

Currently, five cavities have been jacketed after their qualification in vertical test. Four of them have initial design of $\beta = 0.9$. One of these jacketed cavities (B9A-AES-009) has been also qualified for cryomodule assembly. During the jacketing process of the first cavities, we observed the deformation on the end cells and a degradation in the field flatness (FF) to below the >90% specification. This is likely due to thermal stresses on the cavity end cells generated during the welding of the helium vessel to the niobium-titanium cavity transition. Based on the experience of the first two cavities, the last two cavities were proactively detuned to compensate for the expected FF degradation during helium vessel integration. As a result, the FF after jacketing was within specifications. No FF change was instead observed during jacketing of the $\beta = 0.92$ cavity. In Table 1 the current status of the 5-cell HB650 cavities is summarized.

During this qualification phase, field emission has been one of the major limitations. In addition, there have been frequent cold leaks, resulting in very high reprocessing rate. The assembly procedure and the high-pressure-rinsing (HPR) facility at Lab2 in Fermilab are therefore being reviewed and optimized.

One jacketed cavity (B9A-AES-010) has been already tested horizontally with the goal of commissioning the Spoke Test Cryostat (STC) for 650 MHz cavities testing. This test also validated the 650 MHz coupler and tuner designs [10]. At this time the project is planning to test two HB650 cavities horizontally in STC after vertical test qualification, before their assembly in the pCM. These horizontal tests will allow optimization of cool-down parameters for flux expulsion and high-Q preservation in cryomodule environment.

LB 650 MHz CAVITIES: PROCESSING DEVELOPMENT

Three single-cell β=0.61 LB650 cavities has been received at FNAL, one from INFN (Italy) and two from VECC

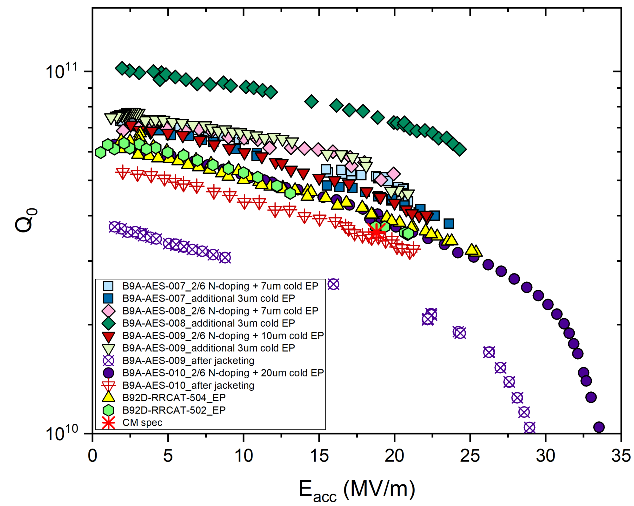

Figure 1: Q-factor versus accelerating field curves of the 5-cell HB650 cavities that are being tested at Fermilab toward their qualification for CM assembly. Two cavities were tested after jacketing and one qualified for CM assembly. All the data reported in the graph are acquired at 2 K.

(India) to validate their fabrication and optimize processing protocol. These cavities were baselined with bulk electro-polishing (EP), high-T baking (800°C for 3 hours) and light EP. The RF tests of the cavities at 2 K can be seen in Fig. 2. B61S-VECC-002 was tested again after 120°C baking and after subsequent HF rinsing to characterize how performance changes with these treatments. After 120°C baking the Q-factor improved only at high field, mitigating the high-field-Q-slope. The subsequent HF rinse improved substantially Q-factor at low field but only slightly at medium and high field, while preserving gradient. B61S-EZ-001 was instead re-set with 60 µm EP, baked again at high-T (this time 900°C for 3 hours) and N-doped (2/0 N doping at 800°C followed by 7 µm of cold EP). It is possible to notice how after the N-doping Q-factors clearly improved reaching Q-factors higher than 3×10^{10} even above 20 MV/m, far exceeding specifications.

We also measured flux expulsion properties of both cavities in order to verify if baking at higher temperature was needed to obtain good flux expulsion.

Flux expulsion data are shown in Fig. 3 and it is possible to notice that the cavity B61S-EZ-001 almost trapped all the field even when larger thermal gradients were achieved along the cavity after that it was baked at 800°C for 3 hours. The cavity B61S-VECC-002 showed instead an improvement of flux expulsion as larger thermal gradients are reached after same heath treatment. B61S-EZ-001 significantly improved flux expulsion properties after being baked at 900°C for 3 hours. A combination between RF and material studies are on-going to better understand how to optimize flux expulsion without degrading mechanical properties of these cavities. RF measurements at room temperature were conducted on B61S-EZ-001 to determine how mechanical property of the cavity changed before and after the 900°C heat treatment.

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Table 1: Summary Status of the 5-cell HB650 Cavities

Cavity name	β	Jacketed	Instrumented	Qualified for CM assembly
B9A-AES-007	0.9	X		
B9A-AES-008	0.9	X	X	
B9A-AES-009	0.9	X		X
B9A-AES-010	0.9	X	X	
B92D-RRCAT-502	0.92	X	X	
B92D-RRCAT-504	0.92			
B92E-RRCAT-506	0.92			

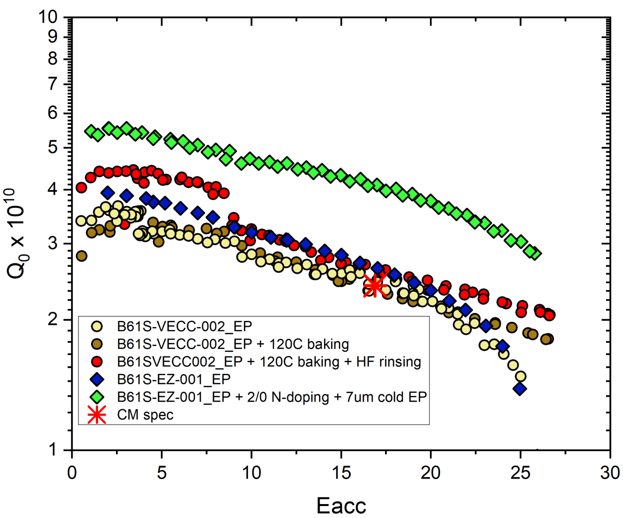

Figure 2: Q-factor versus accelerating field curves of the single-cell LB650 cavities measured at 2 K after they have been processed with different surface treatments. N-doping maximises performance at medium field also maintaining high values of quench field.

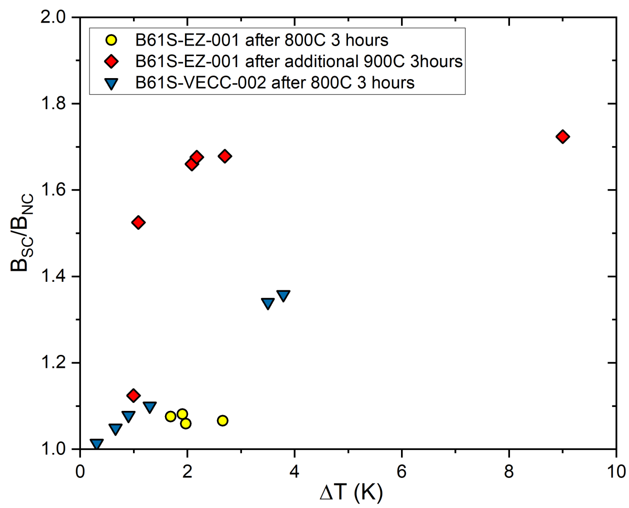

Figure 3: Flux expulsion ratio (magnetic field measured after the superconducting transition over the one measured before) versus thermal-gradient along the cavity during the superconducting transition. The two cavities show different flux expulsion efficiency after being both treated at 800°C for 3 hours. This is due to the different micro structural properties of the Niobium sheets used for their fabrication. As expected, flux expulsion efficiency of B61S-EZ-001 increased after heat treating the cavity to 900°C for 3 hours.

We observed that after stretching the cavity by 500 kHz, the residual frequency shifted of about 15 Hz before the 900°C baking and of about 80 Hz afterwards. On the other hand, before 900°C baking, the residual frequency shifted was only by 45 Hz after stretching the cavity by 800 kHz. Additionally, frequency of the cavity was shifted by +2.6 MHz after baking. This is a clear indication of the reduction of yield stresses after 900°C baking. More study will follow to verify if the cavity mechanical properties are still acceptable.

A 5-cell LB650 cavity has also been received at FNAL from INFN (Italy) in order to being qualified in vertical test for jacketing. Also in this case the cavity has been processed with bulk EP, high-T baking (800°C for 3 hours) and light EP. The RF measurements are still on-going since tests performed so far were limited to ~12 MV/m due to the excitation of a parasitic mode (4pi/5) with frequency very closed to the cavity fundamental mode. Since the excitation of this parasitic mode is most likely due to electron activity, the cavity has received light EP again to get rid of any possible field emitter, and is awaiting testing.

As mentioned in the introduction, we are also working in collaboration with Michigan State University (MSU) and Argonne national Laboratory (ANL) in order to optimize performance of 644 MHz β=0.65 5-cell cavities within the framework of an Accelerator Stewardship. Because of the similar geometry of these cavities with PIP-II LB650 ones, lessons learned from the processing and testing of these cavities will be useful for the project. While more results are reported elsewhere [11], in Fig. 4 summary results acquired by performing sequential studies in one of these cavities are shown. As it can be noticed from the graph, N-doping did not substantially improve performance. The cavity was then reset and processed with mid-T baking treatment (300°C for 3 hours) [12, 13]. Also in this case performance are only slightly improved compared to EP baseline. However, this treatment is the best performing treatment so far for these cavities. More studies are to follow to better optimize this treatment for this frequency range.

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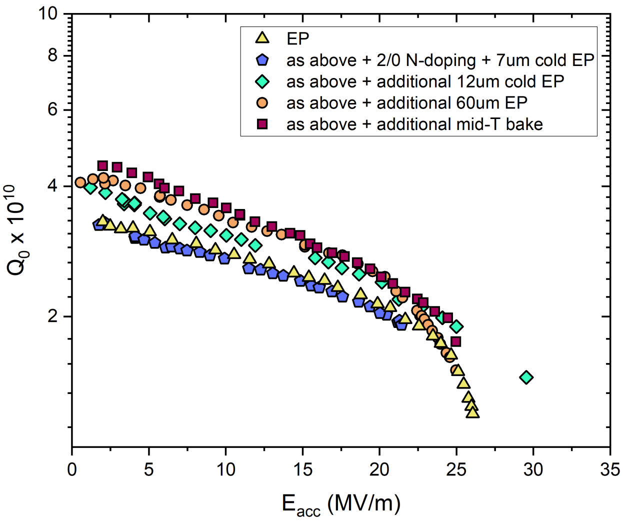

Figure 4: Q-factor versus accelerating field measured at 2 K on a FRIB 5-cell medium-beta 644 MHz cavity after sequential surface treatments. Mid-T baking gave best results in terms of Q-factor at medium gradient and will be study more in details to optimize it for these low- and medium-beta structures.

CONCLUSIONS

Cavity qualification for the PIP-II HB650 prototype cryomodule is ongoing and the first jacketed cavity has been qualified for CM assembly. Additional three jacketed cavities are now awaiting vertical testing and qualification. Cavity assembly and high-pressure-rinsing set-up for both HB and LB 5-cell 650 MHz cavities is under optimization to reduce the re-processing rate due to field emission and cold leaks. Processing optimization is currently on-going in LB650 cavities. Improvement of Q-factor in single-cell LB650 cavities has been verified, and mid-T baking has been identified as a potential treatment for these cavities.

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