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SARAF-PHASE 2 LOW-BETA AND HIGH-BETA SUPERCONDUCTING CAVITIES QUALIFICATION

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Abstract

CEA is committed to delivering a Medium Energy Beam Transfer line and a superconducting linac (SCL) for SARAF accelerator in order to accelerate 5 mA beam of either protons from 1.3 MeV to 35 MeV or deuterons from 2.6 MeV to 40 MeV. The SCL consists in four cryomodules. The first two identical cryomodules host 6 half-wave resonator (HWR) low beta cavities (beta= 0.09) at 176 MHz. The last two identical cryomodules will host 7 HWR high-beta cavities (beta = 0.18) at 176 MHz. The low-beta prototypes was qualified in 2019. Low-beta series manufacturing is on-going. The high-beta prototype was first tested in 2019 but failed. A new prototype was tested in the end of 2020. This contribution will present the results of the tests for low- and high-beta SARAF cavities, series and prototypes.

INTRODUCTION

In 2014, CEA (Commissariat à l'Energie Atomique et aux Energies Alternatives, Saclay, France) was committed to delivering a Medium Energy Beam Transfer line and a superconducting linac (SCL) for SNRC (Soreq Nuclear Research Center, Soreq, Israel), on the SARAF (Soreq Applied Research Accelerator Facility) site [1].

This new accelerator, called Saraf-Phase II, was designed to accelerate 5 mA beam of either protons from 1.3 MeV to 35 MeV or deuterons from 2.6 MeV to 40 MeV. CEA is currently driving the manufacturing of this new accelerator, called to be installed by SNRC and CEA at Soreq, Israel [2]. The commissioning of the MEBT began in 2021, and CEA planned the end of the commissioning of the last cryomodule for 2023.

In order to keep the existing RFQ of SARAF-Phase I, the frequency of the full accelerator was fixed to 176 MHz. During the pre-studies of this new accelerator, the beam dynamics fixed the optimal "geometric betas" to 0.09 and 0.18. The SARAF-Phase II accelerator contains 13 superconducting cavities with $\beta_{opt} = 0.09$, called low-beta (LB) cavities, and 14 superconducting cavities for $\beta = 0.18$, called high-beta (HB) cavities [3].

At this frequency, HWR (Half Wave Resonators) technologies seemed to be the most suitable [4]. Moreover, this technology showed good results for a previous CEA project: IFMIF [5]. It was also the technology chosen for the previous SARAF-Phase I prototype accelerator [6]. It is planned to use the superconducting cavities only at 4.45 K, at 1200 mbar. No operation is planned at lower temperature.

These two HWRs, LB and HB cavities, were designed in 2016 [7]. Research Instrument was chosen in 2017 to manufacture these cavities. CEA qualified the prototypes and the LB cavities series from 2018 to 2021 [8, 9]. The qualification of the HB cavities series is ongoing.

DESIGN

The design of both cavity kinds began in 2016 and was described in [7]. SNRC defined the frequency for the superconducting LINAC to 176 MHz, in order to keep the RFQ [6]. Thus, the superconducting cavities had to be tuned at 176 MHz. The expected maximal beam losses defined the aperture diameters of the beam ports: 36 mm and 40 mm for the LB and HB cavities respectively. The beam dynamics defined the required β_{opt} for both types of cavities: 0.09 and 0.18 [3]. The beam dynamics also fixed the accelerating voltage of the cavities to 6.5 and 7.5 MV/m for LB and HB cavities respectively. However, in order to keep some margin on the design, we designed them as if SNRC would have used them at 7.0 and 8.1 MV/m. It allows compensating potential lower performances of some cavities along time.

The beam dynamics defined the position of the cavities in the cryomodule. Considering the other components of the cryomodule (frequency tuner, couplers, thermal and magnetic shields, cold mass, etc. [10]), the cavity without helium tank had to be smaller in diameter than 200 mm and 320 mm for LB and HB cavities respectively (excluding the beam and coupler ports).

The peak magnetic and electric fields were optimized in accordance to these requirements. Based on the literature [11] and previous CEA projects [12, 5], it seemed possible to reach surface magnetic fields up to 140 mT and surface electric fields up to 70 MV/m, at the cost of a very high cryogenic power consumption. The test of PXIE HWR cavities demonstrated later that cavities could even reach surface electric fields up to 90 MV/m and 95 mT without quench or excessive field emission [13].

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We defined as maximal acceptable electric and magnetic surface fields 40 MV/m and 70 mT respectively, at the designed accelerating field. This corresponds to about half the previous achievable fields.

Table 1 presents the final performances for these accelerating fields as mentioned in [8]. This table shows that the initial requirements, i.e. E-peak lower than 40 MV/m and B-peak lower than 70 mT are verified. The RF power consumption is given at 45 nΩ, which seemed achievable at 4.45 K.

Table 1: Performances According to Final RF Simulations

	Low β cav.	**High β cav.**
β_{opt}	0.091	0.181
Design E_{acc} (MV/m)	7	8.1
Epk_{max} (MV/m)	34.5	35.8
Bpk_{max} (mT)	65.6	65.3
Target Q_0 @ 4.45 K	8.10^8	$1.2.10^9$
R/Q @ β_{opt} (Ω)	189	280
Stored Energy (J)	5.7	16.8
Max. RF power consumption @ 4.45 K (W)	7.9	15.5

Figure 1 presents the final design of the LB cavity with its helium tank. Both inner and outer conductors are cylindrical. Figure 2 presents the final design of the HB cavity with its helium tank. Contrary to the LB cavity, the inner conductor is conical.

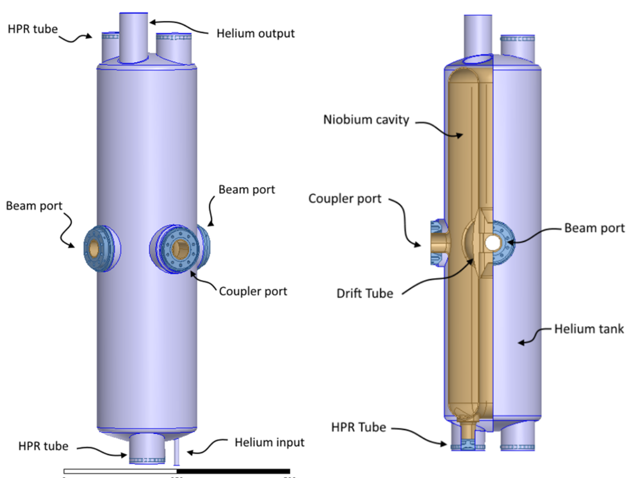

Figure 1: LB SARAF Cavity.

A lot of parts were designed to be manufactured with niobium rods instead of sheets. Especially, drift tubes, beam ports and large parts of the HPR ports were designed to be manufactured with large niobium rods, for both LB and HB cavities. This increased significantly the cost in niobium, but it allowed to define very tight tolerances on these critical parts. It also allowed to optimize the mechanical design to reach a better rigidity and better resistance to overpressure.

The RF pick-up antenna was designed to be installed in one of the HPR ports. It is a simple loop made in copper razed on a ceramic on one side, and on an HPR flange on the other side, as shown in Figure 3. The system is installed in one of the HPR ports (the four HPR ports are identical).

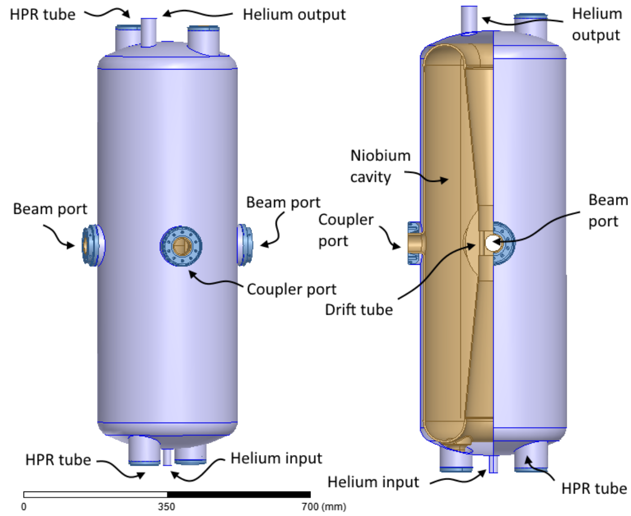

Figure 2: HB SARAF Cavity.

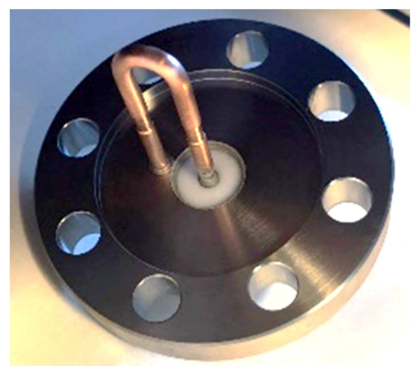
Figure 3: Picture of the RF pick-up loop.

The mechanical design was presented in [14]. Both cavities were mechanically designed to be in compliance, to the best extent, to the rules of Unfired Pressure Vessels NF-EN 13445 (1-5) standards. For this purpose, it was necessary to define different scenarios. According to the simulations, the worst scenario appears at room temperature, during the pressure test. Due to the maximal reachable pressure in the helium vessels, 2 bars, and due to the standard defining the test pressure as 1.43 times the maximum pressure, it was necessary to verify that the cavity with its helium tank was able to bear up to 2.86 bars at room temperature. Another scenario is described in [14] with frequency tuner system (FTS) fully engaged at 4.45 K.

The mechanical simulations demonstrated that some parts were very critical, especially the beam ports, where the FTS is attached, and the HPR ports, where the stress between the cavity under vacuum and the helium tank, under helium pressure, is maximal. Figure 4 shows an example of simulation of the HB cavity with FTS.

Other parts of the equipped cavity include the coupler and the frequency tuner system (FTS). The coupler was simply designed with a stainless steel outer tube with copper coating, a bulk copper antenna, a large flange to be connected to the cryomodule, and three small tubes to connect

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one photomultiplier, one electron pick-up probe and one vacuum gauge.

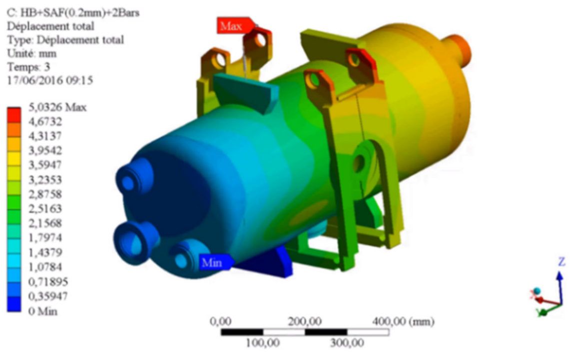

Figure 4: Displacement field of the HB cavity with FTS.

The FTS is based on the tuner system already designed for IFMIF [5]. Two lever arms are connected on one side to a titanium block, and on the other side on an eccentric shaft driven by a motor fixed to an endless screw. The system is similar to a nutcracker, the cavity being the nut. By deforming the shape of the cavity in the electric area, the frequency can move. Compressing the cavity allows reducing the frequency of it.

Figure 5 shows the LB cavity with coupler and FTS. Figure 6 shows the HB cavity with coupler and FTS.

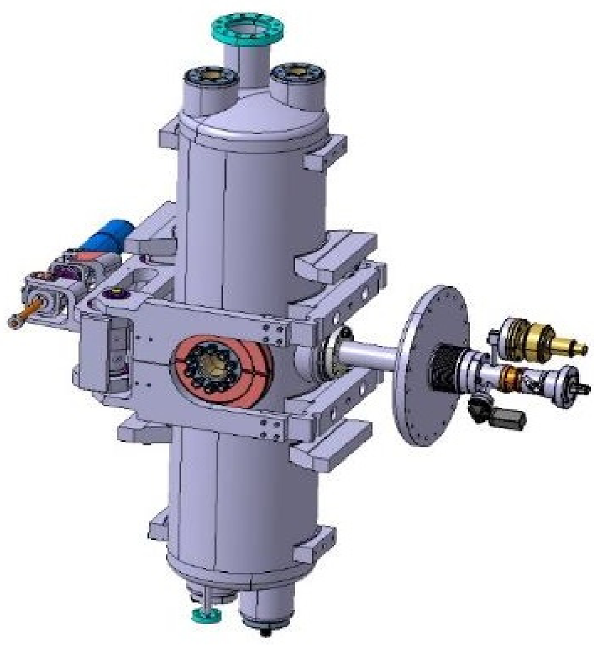

Figure 5: LB equipped cavity with coupler and frequency tuner system.

FIRST PROTOTYPES

LB Prototype

A first series of prototypes was launched in 2017. Especially, concerning the cavities themselves, Research Instrument (Germany) was chosen for manufacturing. We chose Canon Electron Tube Devices (Japan) for couplers, and Gavard et Cie (France) for Frequency tuner systems.

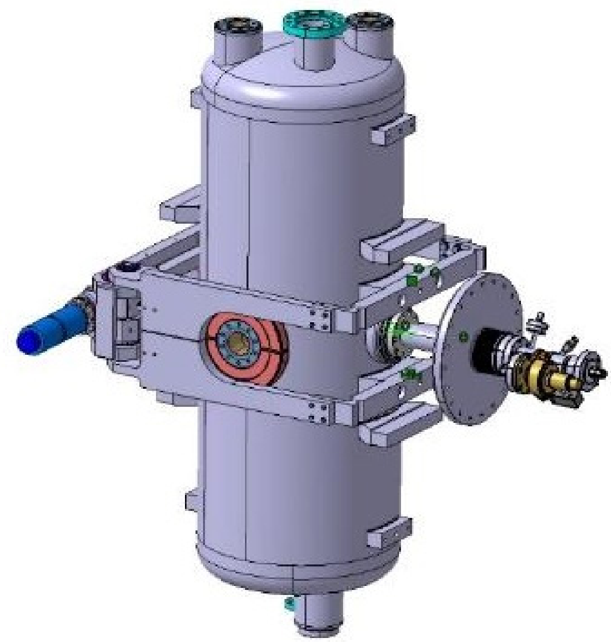

Figure 6: HB equipped cavities with coupler and frequency tuner system.

The first preparation procedure was defined as follow:

- 120 µm BCP of the bare cavity (Ultra-sound degreasing was systematically done before each BCP),
- 6 hours HPR,
- First test in vertical cryostat at 4.2 K,
- Heat treatment (650°C under vacuum),
- 10 µm BCP,
- 6 hours HPR,
- Second test in vertical cryostat at 4.2 K,
- Welding of the helium tank,
- 10 µm BCP,
- 6 hours HPR,
- Final test in vertical cryostat at 4.2 K.

This procedure was first tested on the LB prototype. Unfortunately, we had some difficulties with the HPR, and the 6 hours HPR could not be done as expected due to a failure. The result was that it did not work (tests QFT #1 and QFT #2 in Fig. 7). Multipactor was very high for an accelerating field around 1 MV/m and at low field (around 20 kV/m). A quench appeared first at 4 MV/m (QFT #1), and then at 1 MV/m after warm-up and new cool-down (QFT #2). Electrons and X-ray emissions showed strong field emission for these first tests.

We tried to apply the heat treatment, even if the performance was far too low as it was not possible to apply a new HPR quickly. After this heat treatment, we did a new cleaning with a new 120 µm BCP and a new HPR (that was repaired at this time). The result was greatly improved (QFT #3). But the average surface resistance was a bit higher than 45 nΩ.

We decided to continue the defined procedure with the welding of the helium tank, and again BCP and HPR. A new test was done (QFT #4), showing no difference with the previous test before helium tank welding, as expected.

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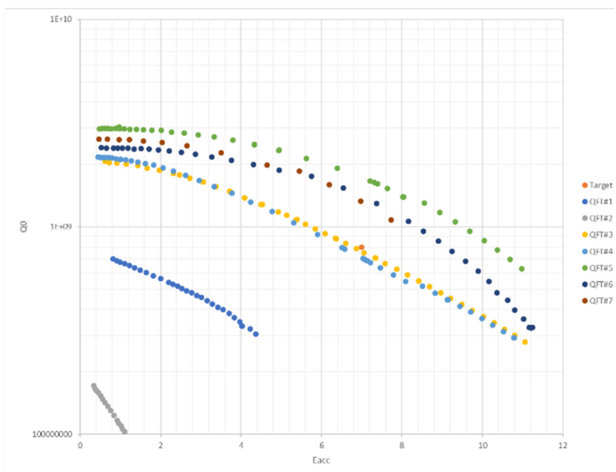

Figure 7: Set of Q_0 tests for the LB SARAF prototype in vertical cryostat and ECTS.

At this stage, we decided to try to add baking in the procedure, in order to improve the performances, according to [15]. We applied a 3-days 120°C treatment on the cavity under vacuum, and we did a new test. The performance was far better and the average surface resistance decreased to about 20 $n\Omega$ at 7 MV/m, better than expected (QFT #5).

At this stage, all tests were done with straight pick-up antennas inserted in one of the beam tubes. In order to validate the loop pick-up design (see Figure 3), we did a new test by removing one of the HPR flange to replace it by this loop antenna. The result showed a slightly lower performance, but far better than the target (QFT #6). The difference is maybe due to the fact that we had to open the cavity under clean room air before changing the pick-up antenna, what could have reduced a bit the efficiency of the baking process.

Finally, the cavity was tested in a dedicated cryomodule test stand called ECTS (Equipped Cavity Test Stand). Details about this test stand can be found in [9]. Performances in this cryomodule, with the FTS was as expected (QFT #7). A last test was done with FTS and coupler. The estimation of the Q_0 was done by measuring the cryogenic consumption without and with RF in the cavity. Even if the error margin is higher in this configuration, it was enough to fully validate the LB cavity. At least, for now…

HB Prototype

In parallel, the HB cavity was tested. Results were far lower than expected. Figure 11 shows the performance of the HB prototype before baking (no test was done after baking for this prototype). A quench appeared at an accelerating field of 5.4 MV/m. No electron was detected, no X-ray. We tried new BCP and new HPR, without success, and without changing the quench field. Tests were done with 16 temperature probes around the 4 HPR ports, showing that one of the HPR ports was heating abnormally. Investigations by endoscopy was difficult due to the shape of the HPR port and the torus. Finally, it was decided to cut the torus and look at the HPR ports.

After having cut the tori, it was clear that the welds of the HPR ports to the tori were defective. These welds (see diagram in Fig. 8) were supposed to be done in two steps (inside and outside weld) and were classified from the beginning on as very challenging. Due to the geometrical boundary conditions the wall thickness varied from 4.4 mm to around 10 mm and inclination angle from 90° to around 20° when performing the circular welds. During fabrication it turned out, that many EB welding parameters had to be varied simultaneously with welding penetration and inclination angle of the beam to the welding surface varying very significantly resulting in potentially lack of fusion in the bulk of the welds. It turned out that even X-ray investigations could not resolve such lack of fusion defects. After heavy BCP, the voids were detected and most probably responsible for the early quench.

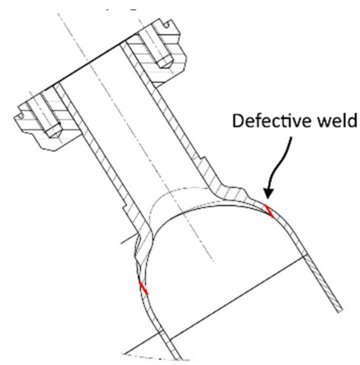

Figure 8: Schematic of the defective weld.

Following these observations, the approach chosen turned to be not practical and it was decided to abandon the initial approach of welding bulk HPR ports into deep drawn tori and to apply a more conventional extrusion of the HPR ports. Moreover, it was decided also for the LB cavities series to proceed with this more conventional approach.

However, as it made the cavity less rigid, we had to verify the compliance with the PED at 2.86 bars. Simulations showed that it did not generate any critical risk for the LB cavity, but it was dangerous for the HB cavity. In order to limit the stress on the HB cavities, we also decided to add bellows between the helium tank and the HPR flange (see Figure 9). In this way, overpressure does not create any critical stress on the HPR ports.

A new set of cavity prototypes was ordered. Concerning the HB prototype, it was decided to reuse inner and outer conductor and to produce new tori and HPR ports. Concerning the LB prototype, the first of series would be a new prototype for the series.

SECOND PROTOTYPES

For the second set of prototypes, the preparation process was significantly modified. Here was the new process:

- 120 µm BCP of the bare cavity (Ultra-sound degreasing was systematically done before each BCP),
- 6 hours HPR,
- Optional: Test in vertical cryostat at 4.2 K,
- Heat treatment (650°C under vacuum),
- Welding of the helium tank,
- 10 µm BCP,

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- 6 hours HPR,
- 3-days baking at 120°C,
- Final test at 4.2 K.

Figure 9: Bellow between the HPR port and the helium tank.

The new LB prototype, shown in Fig. 10 (SLN 101), was successfully tested with this new process. After second test, the performance was the same than for the prototype. As expected, the design modification had no consequence on the RF performances. As for the first prototype, we observed a factor 2 to 2.5 between Q_0 before and after baking. This proves that the 120°C baking is very critical to reach the required performances. In Fig. 11 SLN100_Baked represents the performance of the first prototype after baking, and SLN101_Baked represents the performance of the second prototype after baking.

A new test was done in ECTS [9], with same results as for the first prototype. Contrary to the first prototype, this one was slightly deformed during manufacturing to easily reach the 176 MHz frequency with the frequency tuner system (the first prototype was tested at 176.8 MHz). In this way, it was possible to test it with the final Low-Level RF electronic at the nominal frequency.

We applied exactly the same process for the new HB prototype. One test was done before heat treatment, as for the LB first of series. Figure 11 shows the results for the new HB prototype before and after baking. The new HB prototype was successfully tested with this new design. As for the LB cavities, baking increases the Q_0 factor by a factor close to 2.5. Baking is required to reach the target performances.

Figure 10: LB cavity with its coupler for ECTS test.

We applied exactly the same process for the new HB prototype. One test was done before heat treatment, as for the LB first of series. Figure 11 shows the results for the new HB prototype before and after baking. The new HB prototype was successfully tested with this new design. As for the LB cavities, baking increases the Q_0 factor by a factor close to 2.5. Baking is required to reach the target performances.

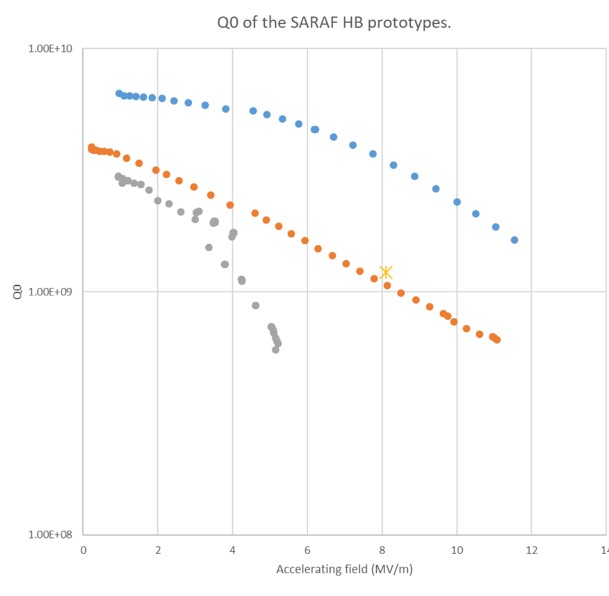

Figure 11: Performance of the HB prototypes.

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SERIES

The second LB prototype is now considered as first of series as it reached the expected performances. The next cavities have been manufactured and tested with the same process. The only change is that all cavities are mechanically tuned during the helium tank welding process to reach 176.050 MHz in the cryomodule at 4.2 K. Concerning the 6 next LB cavities (SLN 102 to SLN 107), tests after helium tank welding and baking are shown in Fig. 12. Cavities SLN102 to SLN106 were tested before heat treatment and helium vessel welding. Among them, cavities SLN103, SLN105 and SLN106 quenched before 7 MV/m during the first test (between 5 and 6.5 MV/m). Cavities SLN103 and SLN105 received an extra 10 µm BCP and HPR, and perfectly worked after that. For cavity SLN106, heat treatment and welding of the helium tank was done despite the low performances during the first test. No problem was detected during final tests. For following cavities, we decided to not do any intermediate cryogenic test.

It seems like two HPR are required to avoid field emission with high probability, but the second HPR can be done after helium tank welding and short BCP.

The test of cavities SLN 108 to SLN 114 is on-going. Concerning HB cavities, the manufacturing of bare cavities is on-going.

CONCLUSION

We successfully validated both superconducting cavities, after some initial difficulties. After few tests, it seems like we found an easy and efficient process for the preparation of cavities with Q_0 about twice higher than the initial requirement we defined.

Now, the LB series manufacturing is successfully ongoing. The first LB cryomodule with 6 cavities is being prepared.

The HB series is being manufactured by RI Research Instrument GmbH. Most of the cavities should be ready in the end of the year, and final assembly of the last cryomodule should finish in the middle of 2022.

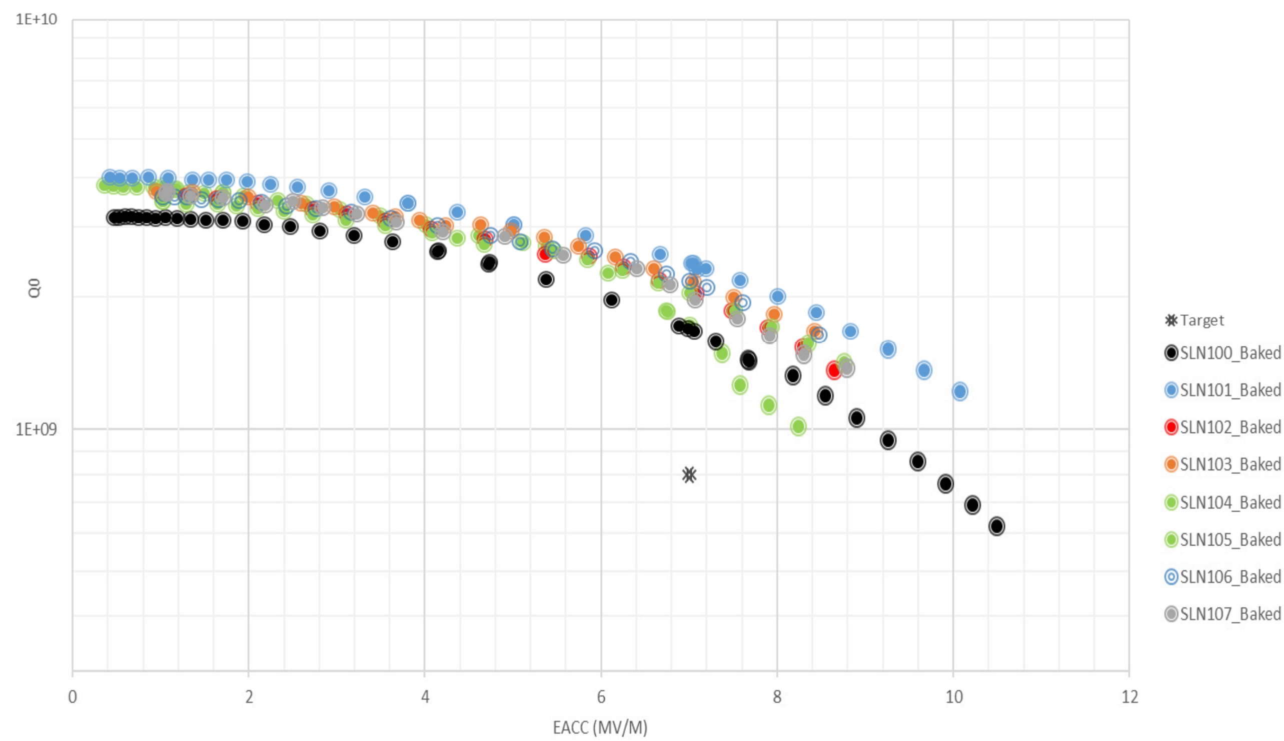

Figure 12: Performance of the LB cavities.

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