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INFN- LASA MEDIUM BETA CAVITY PROTOTYPES FOR ESS LINAC

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Abstract

INFN-LASA, in the framework of INFN contribution to the European Spallation Source, has developed, produced and tested 704.42 MHz Medium Beta (β = 0.67) cavities. Mode separation and avoidance of HOM excitation by machine line frequencies have driven the cavity design. The production at the industry, also in view of the INFN in-kind contribution of series cavities, has been done "build-to-print" and we have implemented our own quality control process, based on our XFEL experience, from raw material to cavity ready for test. The cavities have been then cold tested in our upgraded Vertical Test Facility. In this paper, we report on our experience on the different phases of the cavity production and test processes.

INTRODUCTION

The Medium Beta (MB) section of the European Spallation Source (ESS) Linac is composed of 36 six-cell elliptical superconducting (SC) cavities (β = 0.67) [1]. As a part to the in-kind contribution of Italy to the ESS project, INFN-LASA is in charge of the development and of the industrial production of the whole set of 36 resonators [2]. Two cavity prototypes, with same geometry but different materials, have been produced in order to verify and optimize all the fabrication and treatment processes for the 36 series Medium beta cavities. One cavity is made by Fine Grain niobium (FG, MB001), i.e. the standard technology for SC cavities and the other is built using Large Grain (LG, MBLG002) niobium. The main motivation to build cavities based on LG niobium is to explore both the physical potential benefit due to higher achievable thermal stability coming from the "phonon peak" in the thermal conductivity and the cost benefit due to lower bare material prices. The Medium beta cavity prototypes have been completely designed by INFN LASA team and built by Ettore Zanon S.p.A, a qualified (XFEL, FRIB, LCLSII, etc.) superconducting cavity vendor in Schio (Italy), under our constant supervision. Indeed, a quality control protocol has been issued to follow every step of the cavity fabrication with tests to be fulfilled and passed before accessing to the successive construction phase. Once the subcomponents were ready and passed the quality controls, they were assembled vertically on a dedicated frame in preparation for the final Electron Beam Welding (EBW) equatorial operation.

After the welding procedure, the cavities underwent the following main production steps:

- Dimensional control and data record with the CMM (Coordinate Measuring Machine), inner and outer visual inspections (surfaces, weld beads).
- Frequency tuning (pre-tuning) before treatments.
- Dimensional control and data record with the CMM machine after pre-tuning.
- Bulk Buffered Chemical Polishing (BCP) (~ 200 μm surface removal), divided in three steps.
- 600° annealing to eliminate material internal stresses and degassing the cavity.
- Final frequency tuning and field flatness correction up to at least 95% of field profile uniformity.
- Dimensional control and data record with the CMM, inner and outer visual inspections (surfaces, weld beads).
- Final (Flash) BCP treatment (~ 20 μm surface removal), 12 h HPR, assembly of accessories and final checks (leak tightness and vacuum quality, RF spectrum).

Between each Bulk BCPs a High Pressure Rinsing (HPR) procedure of two hours was made. This procedure consists in washing the cavity surface with high pressure jets (100 bar) of Ultra Pure Water (UPW) to assure both the full removal of chemicals residuals and the cleanliness of the cavity itself. After the Final BCP and before making the vacuum inside the cavity, the High Q and the pick-up antennas, for the RF cavity vertical tests, were assembled in clean room and a long HPR of 12 hours was made.

Both prototypes (FG and LG cavities) were delivered, under vacuum condition and ready for the test at cold, to LASA within the end of 2016 and they were tested at the LASA Vertical Test Facility. As a consequence of the FG cavity good results, well above the ESS requirements, and in view of its assembly in the prototype ESS Medium Beta section cryomodule (M-ECCTD), in 2017 this cavity was equipped with its He-tank and prepared at the industry for a new cold RF test at LASA. Finally, this second test showed no performance degradation, validating the full integration process.

CAVITY CONSTRUCTION

The MB cavities are fabricated using INFN design and are plug-compatible with CEA design boundary conditions, including helium tank, fundamental coupler, flanges and tuner connections.

From Subcomponents to Cavities

The base cavity components are the Half Cells with three different geometries, labelled respectively as Inner Cell (IC), Pen Cell (PC) and End Cell (EC). HCs are used to produce the Dumb Bells (Inner Dumbbell (ID) and two terminal Dumb Bells respectively PD and CD and the End Groups (EGT and EGC). Main quality control steps for

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HCs, DBs and EGs are mechanical measurements (with also 3D surface controls) and RF measurements at different stages of their production, in order to get the final cavity resonant frequency and length inside ESS specs. While the industry has the responsibility of the full fabrication, INFN is in charge of the DBs and EGs composition and trimming instructions, and of the sequencing of the subcomponents composing the cavity. Figure 1 shows a sketch of main subcomponents used for the fabrication of the ESS medium beta cavity.

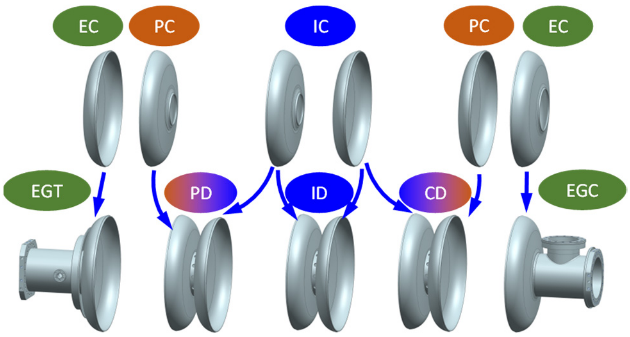

Figure 1: The cavity subcomponents.

For the Fine Grain niobium prototype production, 4.6 mm niobium sheets are cut with a water jet cutter and then HC is obtained by deep-drawing with male and female stamps. 3D measurements allow improving the final HC shapes.

Irises and equators are lathed keeping 0.35 mm and 2 mm respectively of extra metal to compensate for weld shrinkage and set the cell frequency by further trimming operations. The iris and equator surface planarity is ± 0.05 mm.

The RF controls have been done using a dedicated INFN tool, optimized by the company. The frequency of the component is recorded using a Vector Network Analyzer (VNA), taking the average of two successive measurements. The frequency difference of the two measurements must be less than 200 kHz. In addition, the quality factor is acquired as an index of the quality of the measurement: we typically require Q higher than 3000 for DBs.

The device is such the HC (DB, EG) is placed between two plates. The plates are made of niobium to avoid any component contamination before welding. A good RF contact, especially at the equator, is crucial for the frequency measurement. Therefore, a pushing device must be used to properly press the equator and the iris against the contact plate. In addition, to improve the contact RF, fingers must be cut on the external borders of the niobium plates.

Figure 2 shows a Dumb Bell installed inside the RF tool. The same device is used both for DBs and HCs. Below the bottom-side Half Cell, "fingers" of the niobium plate are visible to compensate for non-planarity of the component. The same figure shows also one of the rings used to apply pressure on that DB to improve the RF contact.

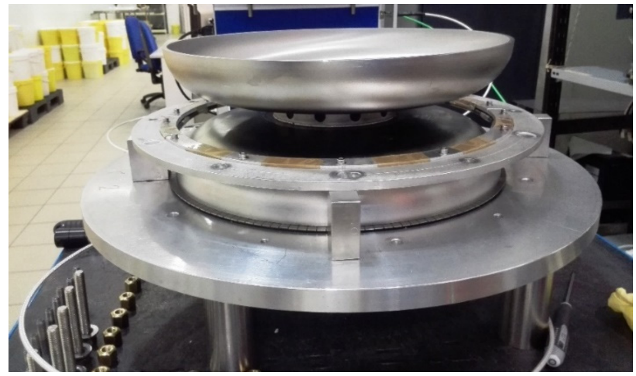

Figure 2: Installation of a dumb bell on the set up for RF check.

The HC RF test is mainly an indication of the quality of components production and is useful for choosing the HC pairs to form the DBs. Due to non-ideal RF contacts and the imperfections of mechanical machining, especially occurring for the LG HCs, the measurement is complicated. Indeed, the HC frequencies are largely scattered around an average value, as shown in Fig. 3.

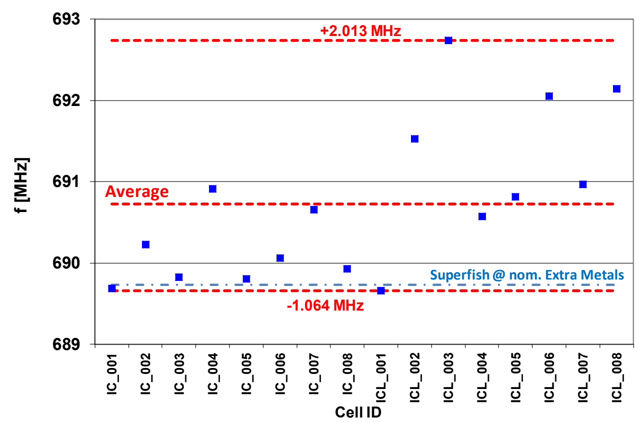

Figure 3: HC frequency distribution. The dotted light blue line is the simulated frequency value from Superfish, keeping into account the cell extra metals at iris and equator.

Moreover, the DB and EG RF results are used, together with their geometrical dimensions, to assess the necessary trimming of extra metal to achieve the final cavity frequency and length.

The successful procedure we have followed for the prototypes will be extended to the series subcomponents preparation, where, given the larger number of items, a dedicated strategy of control and QA/QC is going to be implemented for the production process.

Main Cavity Treatments

After the EBW welding of the components into a cavity, the resonator is measured both RF and geometrically. For the prototypes, the cavities where tuned to reach a field flatness larger than 90 %, to allow easier measurement of Field Flatness (FF) variation during the chemical treatments. For these prototypes, the Bulk BCP process was done in three steps (flipping the cavity upside-down at each

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step for a better uniform removal) while keeping the foreseen final surface removal. Between each step, the cavity was properly UPW and HPR rinsed and it was weighed when dry to obtain the average surface removal. Moreover, we measured the RF spectrum and FF to study the Ir/Eq removal rate and the uniformity of the removed layer during chemistry. To better understand the BCP process, the temperature of the outer cells was monitored during the treatment. This allowed us to define the proper starting temperature of the BCP barrel to obtain a well-controlled etching process [3].

After the chemical treatment, a 600 °C annealing process (10 h) was performed in a UHV oven. The vacuum quality was monitored during the full process by an RGA to study the gases evolution, with care for the H_2 concentration.

As for the subcomponents, the prototypes allowed highlighting keys parameters to monitor during etching and annealing processes in view of the series production.

Cavity Tuning

After the main treatments, the cavity is tuned to the goal frequency with field profile uniformity higher than 95%, using a dedicated tuning machine. The cavity field profile acquisition is based on the measurement of the electric field profile in each cell for all TM_{010} modes, through a metallic bead on a nylon string, placed on the beam axes (where magnetic field is zero) that perturbs the cavity resonant frequency and then using the known property that $\delta f \propto E^2$. Figure 4 shows the scheme of the tuning set up used for prototype tuning and field flatness.

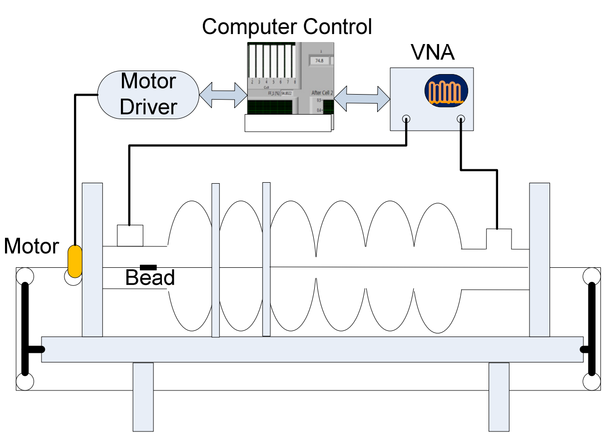

Figure 4: Tuning setup block diagram.

The electric fields in each cell is acquired as a function of the bead position along the longitudinal axis of the cavity. A VNA, set in phase mode, traces the frequency shift of the cavity with respect to the unperturbed cavity's resonant frequency. A computer program controls the network analyzer, reads and plots the resonant frequency for all the TM_{010} modes, then through a transducer moves the bead and traces and plots the field profiles. This process is run for all the six TM_{010} modes in the cavity. The data acquired are then used to determine the tuning needed by each cell to achieve the final cavity field flatness at the correct frequency. Cells are deformed by pushing or pulling their sides. The cell deformation stops when the cavity resonant frequency equals the one indicated by the control program with an error of ± 5 kHz. The same process is applied to all six cells until the cavity π-mode frequency is equal to the goal frequency (maximum error ± 30 kHz) with the field profile flatness higher than 95%.

Figure 5 shows the FG prototype cavity installed on the tuning machine. The cavity beam flanges are placed on Teflon supports. In the picture is also well visible the moveable frame that host the cell deforming plates and the gears used to move them. The operator moves the frame rotating the black steering wheel.

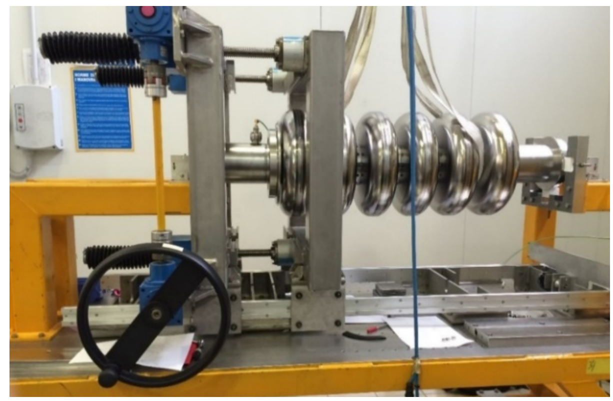
Figure 5: MB prototype cavity placed on the tuning machine.

The field flatness of the MB001 cavity after welding was about 80%. We did a first tuning (pre-tuning) before the chemical treatment and brought the FF to 97%. After the bulk BCP the FF went down to 91.5%. After the final tuning, the FF raised to 97.5%, as shown in Fig. 6.

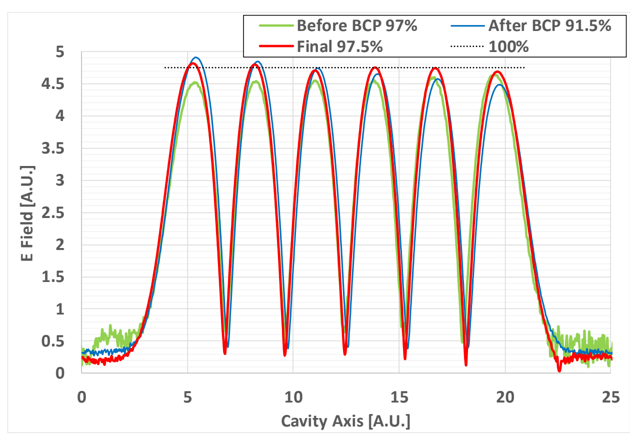

Figure 6: MB001 cavity field profile evolution before and after "Bulk BCP" and after final tuning.

The LGMB002 cavity had a similar behaviour, reaching a final FF of about 98%.

For the series production, the cavity will be tuned only after the Bulk BCP and the annealing processes. In the production steps that will follow, we will monitor the cavity frequency and the final FF will be re-measured after He-Tank integration.

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VERTICAL TEST FACILITY

Figure 7 shows the MB001 cavity installed on the vertical test insert ready for the cold test. The insert top flange (not visible in figure) hosts all the ports and feedthroughs to connect the instrumentation needed for the test and an UHV (Ultra High Vacuum) line for the cavity. A Sputter Ion Pump (SIP) is permanently installed on the insert top cover and connected to the cavity vacuum. The UHV line is also equipped with a Turbo Molecular Pump to be used in case of He-leak. The insert is also equipped with diagnostic devices to monitor the cavity during the cold test.

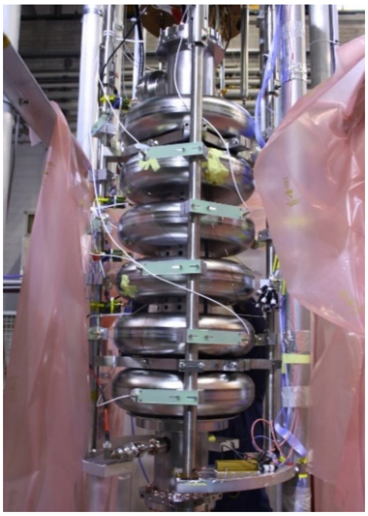

Figure 7: MB001 cavity installation on the insert.

The cavity is first assembled on the vertical insert using a portable clean room to perform the vacuum connection. The insert vacuum line is then slowly pumped and leak checked before switching on the SIP. Only after the vacuum level is below 10^{-5} mbar the cavity valves are opened, after isolating the fore-vacuum system of the vertical insert line. The warm RF cables are then tested and the cavity frequencies checked before moving the insert into the cryostat. At this stage, also quench diagnostic tools are installed around and on the cavity like Second Sound Detector and thermometers.

The Vertical Test Facility has been upgraded for testing ESS Medium Beta cavities. In particular, given the large Q_0 of these cavities w.r.t. the previous tested 3.9 GHz resonators [4], we have decreased the residual magnetic field in the cryostat to reduce its contribution to the residual resistance.

RF CAVITY CHARACTERIZATION

For the power test at 2 K temperature, the cavity is inserted in a PLL where a precise RF source drives the cavity at its resonant frequency and an amplifier provides the necessary power. The input, reflected and transmitted powers are read by high dynamic power sensors connected to the cavity ports via calibrated RF cables. For further details refer to [5].

The MB001 cavity was tested in November 2016. During sub-cooling from 4.2 K to 2 K, we monitored the surface resistance against the bath temperature, performing measurements at moderate field levels (typically between 0.2 and 1 MV/m of accelerating gradient (E_{acc})). At 2 K, the surface resistance R_s was close to 10 nΩ. Figure 8 shows R_s, trend during the subcooling operation.

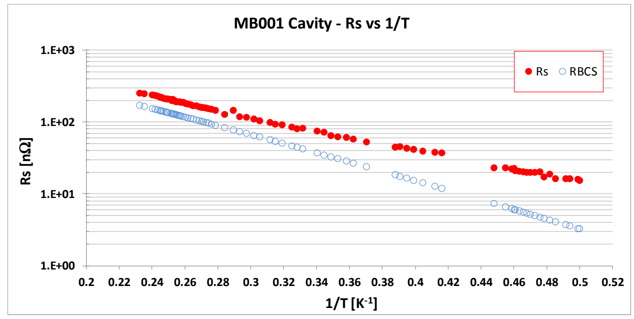

Figure 8: MB001 R_s behaviour during sub-cooling from 4.2 K to 2 K.

The MB001 power test was successful. Figure 9 shows that the Q_0 versus E_{acc} measurements (power rise), of the first MB prototype cavity, are well above the ESS requirements of E_{acc} = 16.7 MV/m @ $Q_0 > 5{\cdot}10^9$. E_{acc} higher than 22 MV/m (@ $Q_0 > 5{\cdot}10^9$) has been reached and, at ESS goal accelerating gradient, the quality factor was $Q_0 \sim 1.5{\cdot}10^{10}$.

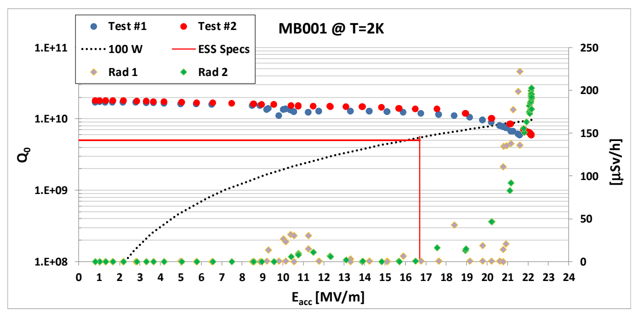

Figure 9: MB001 first test result. The plot shows Q_0 vs E_{acc} and the corresponding radiation measured on the top cover of the cryostat.

Throughout this first test, two power rises were performed. During the former, we found soft multipacting barriers for E_{acc} between 9 and 10 MV/m, overcome after few minutes of RF processing. During the second power rise, the multipacting has been passed without processing. Field Emission (FE) has been observed at higher E_{acc} values. The X-ray radiation dose measured was slightly above 200 µSv/h at maximum gradient, though some conditioning is evident during the second power rise. During both power rises the cavity began quenching at field above E_{acc} = 22 MV/m.

Once passed the qualification test, the MB001 cavity was sent to ZANON to be integrated inside the He-Tank. After the pressure test needed for installation in a cryomodule the cavity sustained additional final BCP treatment followed by the last 12 h HPR cycle and it was sent back to LASA to be cold tested again. The integrated cavity repeated the previous good performances, as reported in Fig. 10: the cavity outperformed the ESS requirements and quenched again at about E_{acc} = 22 MV/m, with $Q_0 \sim 2{\cdot}10^{10}$ at low gradient. Neither multipacting nor X-ray radiation

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have been recorded during the second test, evidence that field emission has been cured by the second cycle of treatments (final BCP + 12 h HPR) that followed the cavity integration.

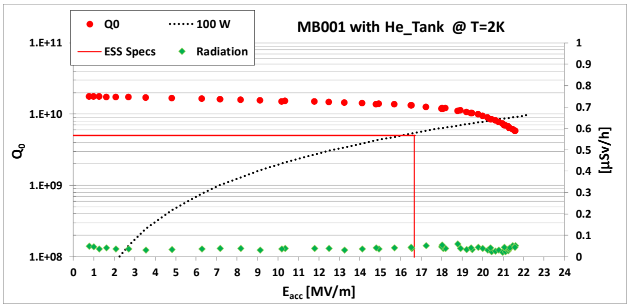

Figure 10: Performances of MB001 integrated in the He-Tank.

Table 1 reports a summary of the MB001 cavity performances (2nd test), compared to the ESS requirements.

Table 1: MB001 Performances and ESS Requirements.

	MB001	ESS Specs
f_π [MHz]	704.213	704.2 ± 0.1
f_π closest f [MHz]	703.449	f_π ± 0.45
Max E_{acc} [MV/m]	21.6	> 16.7
Q_0 @ ESS E_{acc}	$1.3\cdot10^{10}$	$> 5\cdot10^{9}$
Q_0 @ Max E_{acc}	$6\cdot10^{9}$	
Q_I (input Q_{EXT})	$6\cdot10^{9}$	
Q_T (PU Q_{EXT})	$9\cdot10^{10}$	$2\cdot10^{11}$
FE@ Max E_{acc}	0.043 µSv/h[1]	

[1]Note: ground dose level

Large Grain Cavity Test

The Large Grain Medium Beta cavity (MBLG002) test was performed in the second half of December 2016. The cavity received the same preparation processes of the MB001. The Q_0 at low field was again close to $2\cdot10^{10}$, but the cavity quenched at lower field than expected, as shown in Fig. 11.

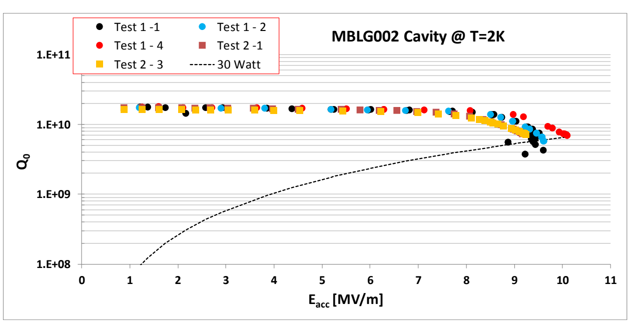

Figure 11: MBLG002 four power rises together with the equi-power line at 30 W.

Four power rises were executed during this test. In the first one, multipacting barriers were observed around E_{acc} = 2 MV/m and E_{acc} = 9 MV/m. Once these were processed, the cavity quenched at E_{acc} = 9.6 MV/m, far from the ESS specifications. In addition, significant FE was observed, with X-ray radiation above 1 mSv/h at the maximum E_{acc}, with a peak of 1.8 mSv/h during multipacting. As shown in Fig. 12, during the other three power rises, the FE has been partially processed, down to less than 1 µSv/h in the 4th power rise, but the accelerating gradient reached just above E_{acc} = 10.1 MV/m before quench.

The MBLG002 cavity was sent back to the factory for additional processing, trying to remove field emitter and improve gradient performances. After a final BCP and 24 h HPR the cavity has been tested again, but without gradient improvements. However, after the re-treatment, no evidence of multipacting has been recorded and the FE was measured below the ground level.

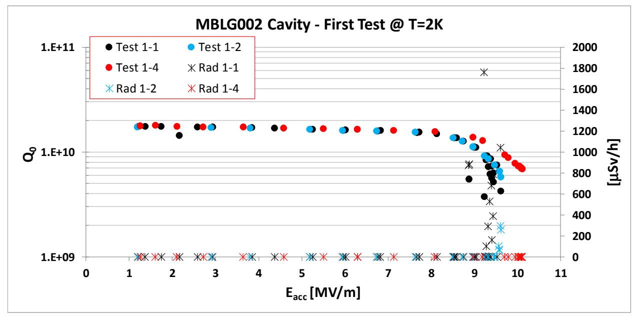

Figure 12: MBLG002 Q_0 vs E_{acc} plots showing FE.

CONCLUSION

Two MB cavity prototypes have been designed and produced by INFN LASA in preparation to the series production of 36 cavities as Italian in-kind contribution to the ESS project. The fine grain cavity, MB001 has been successfully tested and integrated inside its He-Tank. Having fulfilled the ESS requirements, it has been inserted in the M-ECCTD, together with three other MB cavities designed and produced by CEA Saclay. Furthermore, a call for tender for the industrial production of 38 fine grain Nb cavities based on MB001 design has just been issued.

The Large Grain Niobium prototype cavity has a good Q_0, but has not reached yet the ESS requirements for E_{acc}. The further steps towards gradient optimization are still under discussion inside our group.

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