FABRICATION AND TREATMENT OF THE ESS MEDIUM BETA PROTOTYPE CAVITIES

L. Monaco†, A. Bellandi, M. Bertucci, A. Bignami, A. Bosotti, J.F. Chen, P. Michelato, R. Paparella, D. Sertore, INFN Milano - LASA, Segrate (Mi), Italy
S. Pirani, ESS, Lund, Sweden, on leave at INFN Milano - LASA, Segrate (Mi), Italy
C. Pagani, University of Milano & INFN Milano – LASA, Segrate (Mi), Italy

Abstract

In view of the Medium Beta series cavities production at the industry for the European Spallation Source project, INFN Milano - LASA design prototypes have been fully produced at Ettore Zanon S.p.A. with our supervision. Based on our experience on the production of 1.3 GHz and 3.9 GHz E-XFEL series cavities, we set-up and applied an "external" quality control activity of the overall production of the prototype cavity, starting from the row materials to the ready to be tested cavity. In this paper, we report the strategy we have adopted on the overall production, mechanical and surface treatments, frequency measurement of subcomponents and cavities and the obtained results.

INTRODUCTION

For the European Spallation Source (ESS) [1] that will be built in Lund, INFN Milano – LASA is in charge to produce 36 RF SC cavities at 704.42 MHz for the Medium beta (β = 0.67) linac section, as part of the Italian in-kind contribution to the project [2]. We adopted the "build-to-print" concept in the successful construction at the industries of 800 1.3 GHz and of 20 3.9 GHz cavities for the European XFEL project [3, 4]. For the ESS project, we will follow a similar strategy in the fabrication process requiring to the industry a strict adherence to our specifications but not specific product performances. This forces INFN to prepare a detailed list of requirements and specs and, a continuous monitoring of key steps of the production process, the so-called "external" Quality Control (QC), using documents that the industry provides to the INFN experts for their approval. Moreover, the definition of Acceptance levels (Als) to be overcome by the industry and the recording of non-conformances, documented with the Non-Conformity Reports (NCRs), completes the "external" QC that revealed to be essential to guarantee the high quality reached in the EXFEL project.

In view of the large-scale production of the ESS series cavities, we set-up the "external" QC already for the prototypes production, with the aim to use the feedback from these two cavities to ameliorate and optimize the overall QC. In this paper, we present a short description of the quality control strategy set up for the series fabrication and the results of the prototypes fabrication and treatment process. The feedback from the prototype cavities production has been used to improve the foreseen external "QC" for the series cavities.

† laura.monaco@mi.infn.it

THE EXTERNAL QUALITY CONTROL

As already mentioned, a large effort has been spent in the definition of the production cycle of the cavity, starting from raw material up to the cavity ready for test, together with the definition of parameters and processes to be carefully monitored during the full fabrication process.

We foresee five Acceptance levels along the cavity production cycle. Al1 up to the cavity mechanical fabrication, Al2 reached after main surface treatments, i.e. bulk etching and annealing, and the tuning operation, Al3 after He-tank integration and cavity preparation for cold RF test. The series cavities, once overcome the third acceptance level (Al3), will be delivered to DESY for the cold RF test (Al4) and then sent to CEA (Al5) for the final assembly in the cryomodule string.

For each acceptance level, a detailed list of controls and procedures to be performed by the industry has been prepared. Once an acceptance level is reached, the industry send all documents relative to this Al to INFN for expert acceptance (or rejection) and, only after the INFN release, the cavity can proceed to the steps foreseen in the next acceptance level. In case of non-conformance, an NCR is emitted and repair actions are proposed by the industry to INFN. In the following subsections, we present a short description of activity and control towards the first three acceptance levels.

Towards a "Naked" Cavity (Al1)

Figure 1 shows a sketch of main subcomponents used for the fabrication of the ESS medium beta cavity.

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).

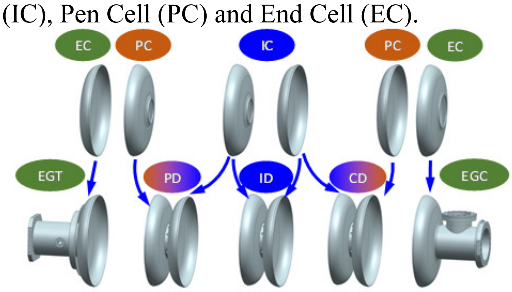

Figure 1: The cavity subcomponents.

HCs are used to produce the Dumb Bells (Inner Dumbbell (ID) and two terminal Dumbbells respectively PD and CD) and the End Groups (EGT and EGC). Main quality control steps for HCs, DBs and EGs are mechanical measurements (with also 3D surface checks) and RF

ISBN 978-3-95450-182-3

measurements at different stages of their production. 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.

Once assembled, the "naked" cavity is subject to several controls (mechanical, frequency, visual, vacuum) to assure the quality of the fabricated product. Particular care is applied to the inner surface inspection to reveal defects (droplets, scratches) that can be easily cured at this stage of the production as shown by the EXFEL experience [3, 4, 5].

"Naked" Cavity Surface Treatments (AI2)

Once overcome the AI1 level, the cavity can start with the surface treatments, including the etching and thermal processes, up to the RF tuning operation. In Table 1 main steps are summarized.

Table 1: Main Production Steps of the "Naked" Cavity

Operation	Description	Where
Bulk BCP (1:1:2)	100+80 µm, rinsing (12 MΩ cm, HPR)	ISO 7
Annealing (with RGA)	600 °C, 10 hours	UHV oven
Tuning process	Field Flatness > 95%,	Tuning area

To be noticed that the "Bulk BCP" treatment is done in two steps, turning the cavity upside-down to improve the homogeneity of the removed layer. As for AI1, the industry at this stage is in charge for the cavity frequency measurements and also for its tuning. During this production phase, the "naked" cavity is subject to several controls (mechanical, frequency, inner visual inspection, leak tightness) and the quality of treatments is monitored collecting and analysing relevant processes parameters.

"Dressed" Cavity Ready for Vertical Test (AI3)

After the final tuning, the cavity is integrated in its He-tank and prepared for the cold RF test. In Fig. 2 a sketch of the dressed cavity in its final configuration for the cold test is shown, while in Table 2 the main steps belonging to this production stage are summarized.

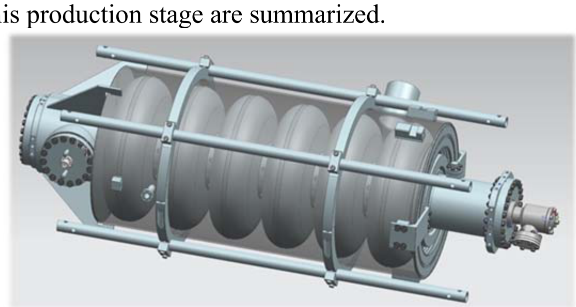

Figure 2: the "dressed" cavity (He-tank transparent to see the inner cells) equipped for the cold RF test.

After the He-tank integration and before the "Final BCP", several tests are done as pressure test at 1.5 barg, mechanical measurements to check the interfaces constrains, and leak checks (volume between the outer of the cavity and the inner of the tank, cavity volume). As a last step, the FF is measured and must be ≥ 94%. As the cavity is prepared for cold test, the industry will emit the "outgoing" inspection, a detailed report describing the final status of the cavity (mechanical, visual, RF, vacuum, etc.) that will complete the AI3 documentation.

Table 2: Main Production Steps of the "Dressed" Cavity

Operation	Description	Where
He-tank integration	Welds and tests	
Final BCP (1:1:2)	20 µm, rinsing (17 MΩ cm, HPR)	ISO 7 & ISO 4
Assembly of all accessories	PU, MC, flanges, leak check	ISO 4
Final HPR	12 hours, 100 bar	ISO 4
Final Leak check and RGA	$< 10^{-10}$ mbar·l·s^{-1}	ISO 4
Final RF spectrum		
Outgoing document		

Only after the release of all documents, the cavity will be ready to be delivered to the qualified laboratory (DESY) for the cold RF test.

PROTOTYPE PRODUCTION

E. Zanon S.p.A. in Schio has fabricated the two medium beta ESS prototype cavities. For the HCs we have used Fine Grain (FG) Nb sheets (from OTIC) and Large Grain (LG) Nb disks (from CBMM) [6, 7]. RRR measurements have been done on several samples extracted from sheets to check the Nb quality, showing values of about 450 for the FG material. RRR measurements have been done also along all the main surface treatments to validate the processes. Besides the controls needed for the "external" QC, for prototypes we have introduced further steps to have better control of the process at this stage and to, supposedly, implement these into the series QC. In next sections, we will be concentrated on the FG cavity production, since details relative to the LG one are available in [8].

Subcomponents and "Naked" Cavity Fabrication

The three HC shapes have been obtained by deep-drawing with male and female stamps improving their shapes by using 3D shapes measurements as feedback [9]. The RF controls have been done using a dedicated INFN tool, optimized by the company. All data, collected in the dedicated templates constituting the subcomponents documentation needed for the overcome of the AI1, had allowed the INFN experts to asses DB and EG composition and trimming, as well as cavity composition. As an example of the available data, Figure 3 reports the 0-mode and π-mode frequency spread of DBs after trimming. After the equatorial EB welds, the cavity has then been measured mechanically and the RF spectrum has been recorded. A pre-tuning stage was added reaching a FF > 90 % in view of dedicated measurements to be performed during the bulk BCP operation (see next paragraph).

ISBN 978-3-95450-182-3

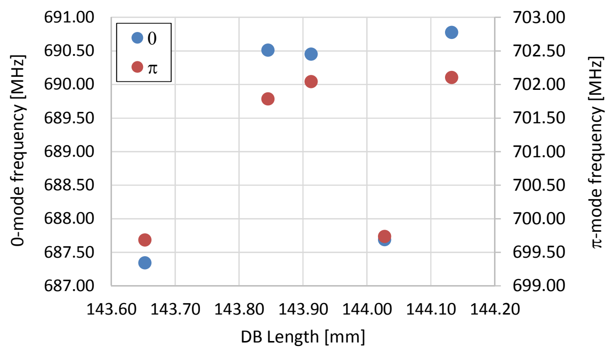

Figure 3: DB modes frequency spread after trimming.

As a last step, inner and outer optical inspection have been done and the cavity vacuum leak tightness measured.

"Naked" Cavity Surface Treatments and Test

To have a better control of the bulk BCP process, done for the first time in an industry for a Medium beta cavity, we have increased, while keeping the total amount of material removal, the foreseen steps of the FG cavity, while the LG cavity was treated in two steps simulating the series process. Moreover, for these prototypes, we have measured in clean room cavity weight, RF spectrum and FF with a dedicated bead-pull tool after each of these steps to study the average surface removal, the removal ratio Ir/Eq and changes of the frequency and field profiles due to the etching process. Figure 4 shows, as an example, the mean etching rate vs total removed weight.

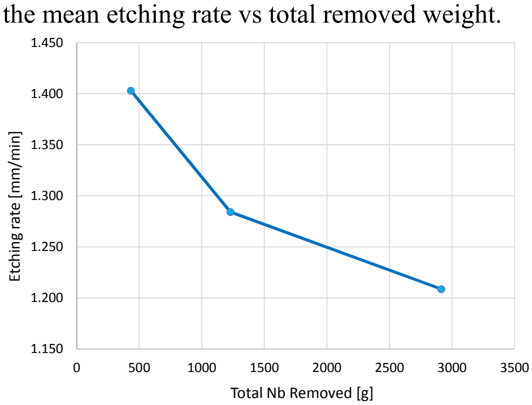

Figure 4: Etching rate versus total removed Niobium.

These studies show that the bulk BCP does not significantly change the FF profile at least up to 200 µm of average surface removal (corresponding to about 3 kg). We have also monitored the cavity cells temperatures during the etching process to avoid overheating of the cavity walls. With a starting temperature of the acid of 5 °C, the maximum temperature reached on the cavity wall was 29.9 °C, while the acid temperature at the outlet was below 16.7 °C. These results are consistent with our specification for the treatment of the series cavities, where we require the acid to be precooled to 5 °C and that the output temperature of the acid is ≤ 15 °C during the whole process, allowing only a short temperature rise-up to 22°C at the beginning.

After the BCP, the cavity was heat treated at 600 °C for 10 hours, monitoring the vacuum composition with an RGA with special attention to the H_2 peak. This measurement, together with RRR measurements on Nb samples, confirmed that this heat cycle is appropriate for removing hydrogen embedded during the BCP process. Finally, the cavity has been tuned to proper frequency and Field Flatness (FF around 98% for both prototypes). The cavity length was measured within tolerance.

Differently from series cavities, we have foreseen to test at cold the "naked" cavity to validate all the treatments done so far before He-tank integration. For this reason, this cavity went through the Final BCP of 20 µm and the preparation for cold test. After the outgoing inspection (similar to the one in AI3), the cavity was delivered to LASA in a FlightCases type prototype transport box designed in view of the series production. The successful result of this test is extensively reported in [10].

"Dressed" Cavity Surface Treatments and Test

In view of its integration into the M-ECCTD [11], the FG prototype has been integrated into the He-tank allowing debugging also of AI3 and partly AI4 and AI5 for the incoming and outgoing inspections. During the integration process, the frequency was monitored in many phases to check possible changes. After the integration, a pressure test at 1.5 barg was performed, two leak checks and the cavity was then mechanically measured and the RF spectrum acquired. The overall frequency change during the integration process was about 30 kHz.

The cavity was then moved into the clean room for the final surface treatments. A refresh of the surface was done performing the Final BCP of 20 µm, followed by rinsing and HPR. After the accessories assembly a 12h HPR was done, the cavity was slow pumped and leak checked, with RGA recording. As for the naked, the dressed cavity was delivered to LASA in the FlightCases type box this time equipped with two acceleration sensors with loggers for monitoring the vibrations during transportation. The maximum acceleration was below the limit of 3 g.

The test of the "dressed" cavity confirmed the excellent results of the previous test [10] and, therefore, that the He-tank integration has no effect on cavity performance. This also support the effectiveness of the "external" QC we have implemented.

CONCLUSION

Two ESS medium beta prototypes have been produced at the industry applying, from the beginning, "external" QC to the "build-to-print" strategy. The main parameters were set-up before starting the fabrication and optimized using prototypes measurements and performances as feedback. The FG prototype was also used to qualify the He-tank integration and cavity transportation. This allowed to have a review of the full QC cycle that will involve not only the INFN and the industry but also DESY (as qualification laboratory) and CEA (for the cavities acceptance and installation in the cryomodule).

ISBN 978-3-95450-182-3

REFERENCES

[1] ESS, https://europeanspallationsource.se

[2] P. Michelato *et al.*, "INFN Milano – LASA activities for ESS", *in Proc. 17th Int. Conf. RF Supercond. (SRF2015), Whistler, Canada, Sep. 2015, paper THPB010, pp. 1081-1084.*

[3] W. Singer *et al.*, "Production of superconducting 1.3-GHz cavities for the European X-ray Free Electron Laser", *Phy. Rev. Accel. Beams.*, vol. 19, no. 9, p. 092001, Sep. 2016.

[4] P. Pierini *et al.*, "Fabrication and vertical test experience of the European X-ray Free Electron Laser 3.9 GHz superconducting cavities", *Phy. Rev. Accel. Beams.*, vol. 20, no. 4, p. 042006, Apr. 2017.

[5] D. Reschke *et al.*, "Performance in the vertical test of the 832 nine-cell 1.3 GHz cavities for the European X-ray Free Electron Laser", *Phy. Rev. Accel. Beams.*, vol. 20, no. 4, p. 042004, Apr. 2017.

[6] Ningxia Orient Tantalum Industry Co. Ltd, http://www.nniec.com

[7] CBMM: Companhia se Metalurgia e Mineracao, www.cbmm.com.br

[8] D. Sertore *et al.*, "Experience on design, fabrication and testing of a large grain ESS medium beta prototype cavity", presented at the 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, paper MOPVA068, this conference.

[9] P. Michelato *et al.*, "ESS medium and high beta cavity prototypes", *in Proc. 7th Int. Particle Accelerator Conf. (IPAC'16), Busan, Korea, May 2016, paper WEPMB011, pp. 2138-2140.*

[10] A. Bosotti *et al.*, "Vertical tests of ESS medium beta prototype cavities at LASA", presented at the 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, paper MOPVA063, this conference.

[11] C. Darve *et al.*, "ESS superconducting RF collaboration", presented at the 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 2017, paper MOPVA090, this conference.