UPDATE ON ESS MEDIUM BETA CAVITIES AT INFN LASA

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Abstract

INFN LASA is involved in the delivery of four Medium Beta cavities to ESS ERIC as part of the Italian In-Kind Contribution to the "Operation Phase".

The cavities have been fabricated and tested bare before the integration into the helium vessel. After successful performance verification, the cavities will be integrated and finally validated at DESY AMTF before their delivery to CEA for installation into the cryomodule. We report the results of the fabrication and tests as well as lessons learned so far.

INTRODUCTION

The European Spallation Source (ESS) linear accelerator employs superconducting radio-frequency (SRF) cavities to accelerate the proton beam to its final energy of 2 GeV, corresponding to world record power of 5 MW beam on target [1].

The Medium Beta ($\beta = 0.67$) section is based on six-cell elliptical cavities operating at 704.42 MHz and provides acceleration between 256 MeV and 571 MeV. INFN Milano-LASA completed the production of 36 Medium Beta cavities as part of the ESS in-kind contribution program to the "Construction Phase" [2].

Following the completion of the series production and the qualification campaign [3], ESS identified the need for additional qualified cavities to support the assembly of a spare cryomodule and to increase operational flexibility over the machine lifetime. Four additional Medium Beta cavities were therefore requested as part of the Italian contribution to the "Operation Phase" of the ESS accelerator. Beyond addressing this operational requirement, the activity was also intended to confirm the maturity and robustness of the production and surface treatment workflow developed during series production.

This paper presents the status and the results of the first vertical RF tests of these four new cavities, with particular emphasis on RF performance, field emission behavior, and process reproducibility.

CAVITY DESIGN AND PARAMETERS

The cavities adopt the standard ESS Medium Beta elliptical design and are then fully compatible with the existing cryomodule infrastructure. No changes to cavity geometry, RF parameters, or interfaces were introduced with respect to the series production. The main cavity parameters are summarized in Table 1.

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Table 1: Main Parameters of the ESS Medium Beta Cavity

Parameter	Value
Frequency	704.42 MHz
Geometry beta	0.67
Number of cells	6
Operating temperature	2 K
Active length	0.855 m
Optimum β, β_{opt}	0.705
Max R/Q at β_{opt}	374 Ω
E_{acc} at β_{opt}	16.7 MV/m
Q_0 at nominal gradient	$\geq 5 \times 10^9$

PRODUCTION AND SURFACE PREPARATION

Niobium Material and Quality Control

High-purity niobium sheets were procured by ESS by Ningxia Orient Tantalum Industry Co., Ltd. (OTIC). Before shipment, we inspected all the sheets at the vendor premises to identify possible visible defects that could be removed before shipment.

Moreover, the Nb sheets underwent Eddy Current Scanning at DESY to identify potential inclusions or subsurface defects not identify by the visual inspection. All Nb sheets satisfied the acceptance criteria and were then released for cavity fabrication, ensuring full traceability throughout the production chain.

Cavity Fabrication

Cavity fabrication was carried out at Zanon Research and Innovation S.r.l (ZRI) following the ESS-qualified manufacturing workflow [4, 5]. The process started with the deep drawing of the half-cells. The measurements done after this stage indicated a problem with the drawing process which resulted in out of shape components. This issue was quickly identified and resolved by the manufacturer, who implemented corrective actions to restore the process control and ensure that the half-cells were within the required dimensional tolerances.

Half-cells were then trimmed, and electron-beam welded into dumbbells. Intermediate RF frequency measurements were performed after each welding step to control cumulative errors. End groups, including the fundamental power coupler and pickup antenna ports, were subsequently welded.

Based on dimensional and RF measurements, we combined the different subcomponents to form the final four cavities and proceed with the Electron Beam welding. The new welded cavities were then subjected to RF and dimensional measurements.

Unexpectedly, all four cavities exhibited a shorter length than expected. Further investigations revealed that the root cause of this issue was a change in the welding parameters that was not communicated before the trimming stage. This resulted in increased shrinkage of the cavity during welding, which was not taken into account during trimming. For this reason, all the four cavities were at the edge of the acceptance criteria for the cavity length. This implied a careful choice of the subsequent treatment steps to maintain the cavity within the expected tolerances.

Surface Treatment and Heat Treatment

The four cavities underwent the standard surface treatment and heat treatment sequence developed for the last cavities of the series production [3], based on the experience of the PIP-II prototypes [6]. Before integration into the helium tank, they were subjected to a first vertical RF test in the bare cavity configuration. Based on the experience gained during series production, electropolishing (EP) was adopted as the baseline bulk surface treatment.

Compared to buffered chemical polishing, EP has demonstrated improved surface smoothness despite a less predictable frequency response of the cavity. Indeed, as already observed during the last cavities of the series production, the variation of the etching sensitivity was less reproducible than for the BCP process, resulting in a $1.61 \pm 0.28\,\mathrm{kHz\,\mu m^{-1}}$. The expected etching sensitivity for a uniform removal along the cavity wall is $3.3\,\mathrm{kHz\,\mu m^{-1}}$ that, compare to the measured one, it indicates a larger material removal at the iris than at the equator.

The full processing sequence consisted of:

- Bulk EP with 120 µm–140 µm material removal
- Heat treatment at 600 °C for 10 h for hydrogen degassing. The temperature is limited by the Titanium connection ring to the helium tank that is already welded to the cavity.
- RF frequency tuning and field flatness correction (required FF > 94 %)
- Light EP (~ 20 µm)
- High-pressure rinsing (HPR) with ultrapure water
- Cleanroom assembly for vertical testing under ISO 4 conditions
- Final HPR and cleanroom exit

For the preparation of the four cavities for vertical test, we chose to use EP again. This will not be possible after helium vessel integration where BCP will be used instead.

VERTICAL TEST SETUP

The first RF qualification tests were performed on bare cavities at the DESY Accelerator Module Test Facility [7] as done in the past for the series cavities.

The cavities were tested in pairs in a vertical cryostat at 2 K. The ESS qualification requires achievement of at least 16.7 MV/m accelerating gradient, compliance with Q_0 specifications, and absence of field emission up to the target field.

Radiation monitors above and below the cavities were used to detect field emission events during the power rises.

FIRST TEST RESULTS

The four cavities were tested in two batches of two cavities each.

All four cavities exceeded the ESS qualification gradient during their first Vertical Test (VT). All of them were tested twice to confirm the results and to check the reproducibility of the performance. The results of the second test were consistent with the first one, confirming the good reproducibility of the process.

All four cavities exhibited similar RF performance, with a narrow spread in both maximum gradient and Q_0 values, as shown in Fig. 1. Maximum accelerating gradients ranged between 25.0 and 26.5 MV/m with Q_0 in the interval 7.0×10^9 to 9.3×10^9. Measured Q_0 values at the nominal gradient of 16.7 MV/m fell in the range 1.58×10^{10} to 1.88×10^{10}.

The limiting mechanism at the highest field was identified as a reproducible thermal quench for three of the cavities, while the fourth one (MB045) was limited by available RF power.

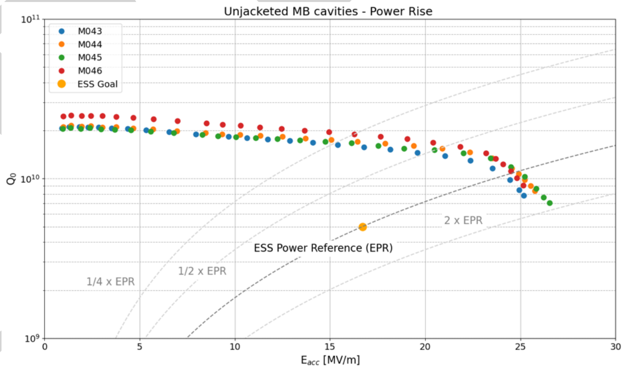

Figure 1: Measured Q_0 versus accelerating gradient at 2 K for the four new Medium Beta cavities during the first VT. The ESS nominal operating gradient and expected Q_0 are indicated for reference.

Another important parameter for the acceptance of the cavities is the level of field emission measured during the vertical test. For all the four cavities, besides few random bursts at low gradient in the first power rise, field emission was absent for all the cavities up to the maximum achieved gradient. This is a clear indication of the smoothness of the inner cavity walls and of the effectiveness of the final cavity preparation steps (cleanroom assembly and HPRs) performed by the cavity vendor.

The consistency of the results demonstrates good process control and confirms the effectiveness of the adopted fabrication and surface treatment strategy.

LESSONS LEARNED AND PROCESS MATURITY

The production of the four additional cavities up to the bare cavity test benefited from the experience accumulated during series fabrication. After a relatively long interruption following the series production, the preparation of the subcomponents initially suffered from shape deviations beyond tolerances. This issue was promptly identified and corrected by the manufacturer through appropriate reprocessing. Following this initial difficulty, production proceeded smoothly, with good reproducibility and no further major issues.

The most significant issue encountered was the not communicated change in welding parameters, which resulted in increased shrinkage and consequently shorter cavity lengths. This required careful adjustment of subsequent processing steps to maintain compliance with dimensional tolerances. The surface and heat treatment sequence was executed successfully, with good reproducibility and no need for corrective reprocessing, aside from careful control of material removal to preserve cavity length and frequency within specifications.

Overall, these results confirm that the fabrication and preparation workflow is stable, reproducible, and suitable for spare cavity production, provided that proper communication and quality control are ensured.

DISCUSSION

The RF performance of the four new cavities, at the stage of bare cavities, is consistent with that achieved during the final phase of series production. The systematic use of EP as the main bulk removal process resulted in smoother finishing of the internal cavity wall with high Q_0 during qualifications. The final preparation sequence, including the light EP after heat treatment, was executed without any issue and resulted in excellent RF performance during the first vertical test, with all cavities exceeding ESS specifications. Despite the lesson learn during the production process, the narrow spread in maximum gradient and Q_0 confirms a high degree of reproducibility and indicates that the production workflow has reached a mature state.

These results also confirm that no additional recovery or reprocessing steps are required to achieve ESS specifications, simplifying logistics and reducing overall production effort for spare components.

STATUS AND NEXT STEPS

Following bare cavity qualification, the cavities are proceeding to helium vessel integration and dressed cavity processing. The four cavities have been retuned and, the field flatness has been corrected to be above 94 %. This step is necessary because a change in field flatness and cavity length was observed between the last measurement before preparation for VT test and the incoming inspection after test.

The helium vessel integration of the four cavities is now progressing at Zanon, where the bellows have been already welded.

Afterward, the cavities and He tanks will be leak-checked, undergo pressure testing, and finally be prepared for the vertical test by performing a light BCP followed by HPR and accessory assembly.

A second vertical test will be performed after helium vessel integration to confirm that the cavities maintain their performance after integration. After successful qualification of the dressed cavities, they will be delivered to CEA-Saclay for integration into the spare cryomodule. The four cavities are expected to be delivered to CEA by end of July 2026.

CONCLUSION

Four new Medium Beta cavities have been successfully fabricated and tested bare as elements for a spare module for the ESS superconducting linac. All four bare cavities exceeded ESS qualification requirements during the first vertical test, exhibiting excellent RF performance and reproducibility. Besides some issues encounter during fabrication, these results validate the maturity of the production and surface treatment workflow and support the availability of fully qualified cavities for ESS spare cryomodules.

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