ESS MEDIUM BETA CAVITIES AT INFN LASA

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Abstract

INFN Milano - LASA contributes in-kind to the ESS ERIC Superconducting Linac supplying 36 cavities for the Medium Beta section of the proton accelerator. All the cavities have been mechanical fabricated, BCP treated and, for most of them, also qualified with vertical test at cold at DESY. We present the result of the cavities already qualified and delivered to CEA, discussing the lessons learnt so far. For remaining cavities, we discuss the actions taken and the plans foreseen to recover them to full specifications.

INTRODUCTION

The European Spallation Source (ESS) ERIC will be the most intense neutron source in the world [1]. ESS make use of a superconducting linac section (see Fig. 1) to accelerate a 62.5 mA proton beam to an energy of 2 GeV. This powerful beam will then be delivered to a target station for producing the neutron beams by the spallation process [2].

The 5 MW beam will be pulsed at 14 Hz with each pulse being 2.86 ms long. This long pulse operation is a real challenge and, to save in cost, superconducting cavities need to be operated at high gradient.

INFN Milano - LASA contributes, as part of the Italian In-Kind, to the Medium Beta Section of the ESS Superconducting Linac with thirty-six cavities that will boost the proton beam energy from 216 MeV up to 571 MeV [3, 4]. Table 1 reports the key parameters of the INFN MB cavities. Ref. [5] reports a detailed discussion on the choices made for the electromagnetic and mechanical design of the cavity.

In this paper, we briefly present the status of the mechanical production and then we will report on the results of the cavities tested so far. A dedicated section is reserved for discussing the not yet qualified cavities and our approach towards their recovery to specification.

CAVITY FABRICATION

The fabrication of the ESS cavities follows a quite traditional process based on Buffered Chemical Polishing (BCP) main treatment, assuring that the fabrication is done according to the Pressure Equipment Directive (PED) art. 4.3, i.e. pressure test and recording of "best engineering practice" and consequent certifications.

Fabrication Workflow

Sheets from OTIC were scanned at DESY with Eddy Current [6] before being deep drawn to form the half cell (HC) at Ettore Zanon (now Zanon Research & Innovation). We have three different types of HCs, namely End Cell, Pen Cell and Inner Cell. While the latest type is used for the middle dumb bells, the Pen Cell is used to match the Inner Cell to the End Cell having it a slightly larger diameter. The DumbBells and End Groups are then welded together to form the cavity.

Table 1: ESS Medium Beta Cavities Main Parameters

Parameter	Value
R_{iris}	50 mm
Geometrical β	0.67
π-mode Frequency	704.42 MHz
Acc. length	0.855 m
Cell-to-cell coupling k	1.55 %
π-$5\pi/6$ mode sep.	0.70 MHz
Geometrical factor G	198.8 Ω
Optimum beta, β_{opt}	0.705
Max R/Q at β_{opt}	374 Ω
E_{acc} at β_{opt}	16.7 MV/m
E_{peak}/E_{acc}	2.55
E_{peak}	42.6 MV/m
B_{peak}/E_{acc}	4.95 $\frac{mT}{MV/m}$
Q_0 at nominal gradient	$>5 \times 10^9$
Q_{ext}	7.8×10^5

The cavity is then BCP treated to remove about 180 µm into two steps, flipping the cavity at half of process to get more uniform final removal. A treatment at 600 °C for 10 h is done to remove hydrogen after the BCP process and to release the mechanical stress [7–9]. This low temperature treatment has been forced having the cavity already welded the Nb-Ti end plate necessary for integrating the He-Tank.

Afterwards, the cavity is tuned to goal frequency and field flatness before being integrated into the He-Tank. Finally, the cavity is prepared for Vertical Test (VT) with the "Final" BCP of 20 µm and long HPR. It is then shipped to DESY for qualification in AMTF or to INFN LASA for special cases [10].

Quality Control and Assurance

Based on the experience that our group developed during the European-XFEL cavities production, a specific Quality Control and Assurance (QC/QA) plan has been developed to follow all the fabrication phases from the reception of the sheets to the delivery of the cavity to CEA for integration into the module.

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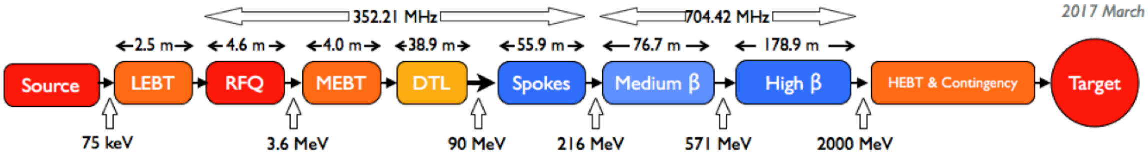

Figure 1: European Spallation Source linac layout.

The QC is sectioned in five Acceptance Levels (AL) corresponding to different phases of the cavity workflow:

- AL1 - Cavity mechanical fabrication
- AL2 - Cavity after treatments and tuning
- AL3 - Cavity integrated and ready for VT
- AL4 - Cavity VT tested and qualified
- AL5 - Cavity accepted by ESS and delivered at CEA

The last two levels are dedicated to the qualification test of the cavity at DESY the first and, the delivery of the cavity at CEA the second. After the successful qualification at DESY, the cavity (with all the necessary documents attesting conformity to ESS requirements) is handed over to ESS before its shipment to CEA. INFN has the duty to take care of the transportation to the final destination.

To follow such a complex process and the related documents (nearly 200 documents for each cavities), different tools have been developed in collaboration with INFN-LNS and within the European Program BrightnESS. The back bone is the INFN Alfresco document server that hosts all the documents. An automatic approval process has been implemented on top of it to allow monitoring documents, their approval as well as documents exchange with the collaboration partners (ESS, DESY, CEA) and the cavity vendor.

To monitor the cavity fabrication process quasi on-line, key parameters are automatically extracted from the documents and store in a database. A web-based dashboard [11] displays these parameters and the status of the documentation approval process allowing a prompt reaction in case of significant deviation from the requirements (see Fig. 2).

	M030	M031	M032	M033	M034
Al1	100% (7/7)	100% (7/7)	100% (7/7)	100% (7/7)	100% (7/7)
Al2	121% (39/32)	143% (46/32)	121% (39/32)	162% (52/32)	121% (39/32)
Al3	100% (44/44)	100% (44/44)	159% (70/44)	156% (69/44)	104% (46/44)
Al4	100% (6/6)	100% (6/6)	100% (6/6)	100% (6/6)	116% (7/6)
Al5	89% (17/19)	89% (17/19)	78% (15/19)	78% (15/19)	94% (18/19)

Al1

19/07/2019 08:35:42 - X_HCP (01) - Cavity Composition
29/08/2019 11:43:27 - X_M01 (01) - Mechanical Check after EBW
29/08/2019 15:04:56 - X_V02 (01) - Inner Visual inspection after EBW
29/08/2019 16:30:53 - X_V01 (01) - Outer inspection after EBW

Al2

09/09/2019 12:17:00 - X_F01a (01) - RF spectrum before 1st step Bulk BCP
09/09/2019 13:07:31 - X_ESS02 (01) - Cavity weighing
09/09/2019 21:29:03 - X_ESS01 (01) - US cleaning and rinsing (open)
11/09/2019 11:03:00 - X_ESS08_TempBCP_01_M031

Al3

20/11/2019 10:33:00 - X_F05 (01) - RF spectrum before He-tank assembly
21/11/2019 15:17:00 - Y_F01 (01) - RF spectrum after EBW of the bellow
28/11/2019 15:16:00 - Y_F02 (01) - RF spectrum after tack welding of He-Tank
02/12/2019 08:07:00 - Y_F03 (01) - RF Spectrum after He-tank welding

Al4

10/02/2021 10:03:31 - Y_F16_M033 (02) - RF spectrum after arrival at DESY (in vacuum)
17/02/2021 12:51:57 - Y_F17_M033 (02) - DESY Cold Measurements (VT, RF spectrum, HOM)
23/03/2021 13:23:36 - Y_F18_M033 (02) - Final RF spectrum before shipping to CEA (in vacuum)
24/03/2021 10:10:00 - Y_Al4_M033 (Al4) - Request Acceptance Level 4 - Hold Point 4

Al5

20/11/2019 11:00:24 - X_M02a (02) - Mechanical check after tuning
10/02/2020 14:49:08 - Y_P01 (01) - Pressure Test after He-Tank integration
11/02/2020 15:53:24 - Y_L01 (01) - Leak check of volume (I) between the inner He-tank and the outer cavity

Figure 2: Web based dashboard to monitor approval status of documents from AL1 to AL5.

CAVITY TESTING

The cavity qualification at cold is the final step in the cavity production process. As already reported in previous paper [10, 12], the MB cavities are tested at DESY in the AMTF facility. A pair of cavities can be tested on a single run, optimizing the cavity throughput.

For special cavities requiring more diagnostics, we use the infrastructure at LASA equipped with second sound and fast thermometry for quench detection and photodiodes at cold and scintillators at warm for X-Ray diagnostic [13].

The ESS requirements for cavity qualification are:

- π-mode frequency at 2 K in the range 704.00 to 704.25 MHz
- E_{acc} = 16.7 MV/m with a quality factor $Q_0 = 5 \times 10^9$
- monopole High Order Modes at least 5 MHz away from integer multiples of the beam-bunching frequency (352.21 MHz) for modes below the beam cut-off frequency
- 5/6 π to π mode separation larger than 0.45 MHz

The qualification at DESY then includes not only the measurement of the quality factor versus accelerating gradient, but also low power characterization of the HOM spectra around the 5th machine line where a possible monopole mode could show up. Up to now, this has never been the case and not dangerous HOM modes have been detected.

All the thirty eight cavities (36 series + 2 spares) have been tested either at DESY or at LASA. In the next section we will discuss in more detail the results of these tests and the final properties of the qualified cavities.

QUALIFIED CAVITIES

The cavity qualification at DESY is the final test before handing over the cavity to ESS for installation into the cryomodule at CEA. As reported in the previous section different criteria need to be satisfied for cavity acceptance and, in the section below, we present few of them.

π-mode Frequency

The π-mode frequency is surely one of the important parameters to control to have a working cavity. We have a double check on its value, one at the end of the preparation process at the cavity vendor and one when the cavity is at 2 K for the Vertical Test at DESY.

The measurement of the frequency at the cavity vendor is our "Reference" frequency and it is part of the Acceptance Level 3 criteria. This measurement is done in Clean Room (ISO-4) before the final 12 h HPR. As shown in Fig. 3

there has been an adjustment of the frequency along the production to better match the target frequency range 702.740 to 702.990 MHz. Over the whole production, the π-mode cavity frequency has been (702.85 ± 0.05) MHz

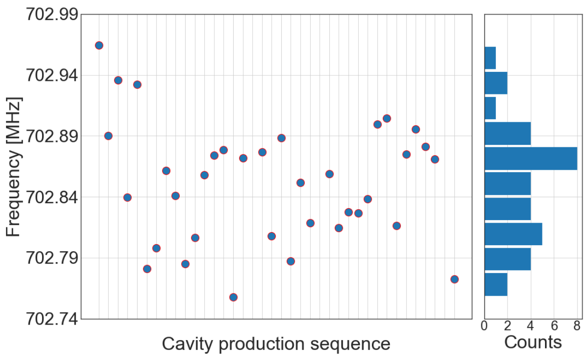

Figure 3: Reference frequency versus cavity. The cavities have been fabricated nearly in a sequence that follow their number. We have made use of the first bunch of cavities to tune the frequency to be within the acceptable range.

Figure 4 reports instead the distribution of the π-mode frequencies for the cavities when they are at cryogenic temperature in the VT cryostat. The cavity frequency, at this stage, is below the operative value (704.420 MHz) because is necessary, during the assembling at CEA, to preload the system cavity-tuner for its optimal operation. All the cavities have the fundamental π-mode frequency within the acceptance range reported in the previous section.

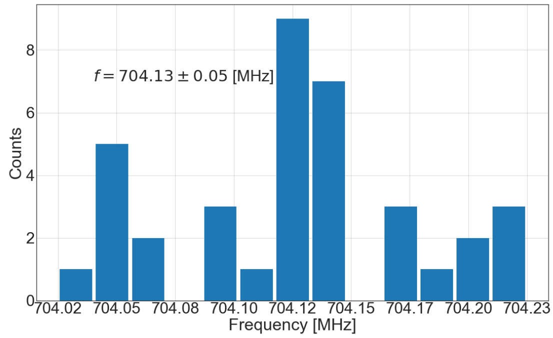

Figure 4: Histogram of the π-mode frequency at 2 K during qualification test.

Field Emission

Field emitted current might be dangerous for the operation of a machine like ESS which runs nearly to pure CW operation. In this operation mode, any current not related to the beam might be accelerated out of phase and energy and might be dumped on critical components like SC cavities and/or activate components or even damage them permanently.

For this reason, we have followed a sort of self limitation based on the know-how present at LASA and shared with the European-XFEL experience. During all the tests performed at DESY in the AMTF facility, we recorded the X-Ray radiation that is directly connected to the field emitted current in the cavity. The radiation is measured at two location, upwards an downwards w.r.t. to the cavity. Clearly the sensitivity of the two detectors is different due to their positioning w.r.t. the cavity. The "down" sensor is the most sensitive to the emitted X-Rays being the closest one [14]. Moreover, we have also observed asymmetries in the emission intensity probably due to the position of the emitter in the cavity.

Nearly 80 % of the qualified cavities have no FE emission at all during the power rise test. About 14 % suffered of FE at the ESS accelerating qualification field and the remaining 7 % showed appearance of field emission above the ESS goal. The summary is shown in Fig. 5.

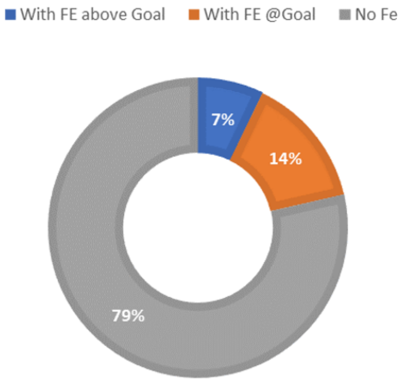

Figure 5: Field emission distribution within the qualified cavities.

Power Rise

The cavity quality factor versus accelerating gradient is a key measurement for the cavity qualification. The measurement process has been described before and here we report the results for the twenty-eight cavities qualified so far.

Figure 6 shows the results of the qualified cavities tested at DESY. As a reference, the ESS goal (E_{acc} = 16.7 MV/m at $Q_0 = 5 \times 10^9$) is reported and it is clearly visible that all the MB cavities overcome the specifications in term of quality factor. In term of static cryogenic dissipated power, the ESS Reference Power (ERP, corresponding to the power dissipated at the nominal ESS parameters) is reported in the plot together with quarter, half and double power curves. If we extrapolate to the ESS accelerating gradient, the quality factor of the cavity qualified so far would correspond to an ERP between one third and half of the project one.

Figure 7 shows the distribution of the Q_0 at the reference field and indeed shows that the mean value is about three times larger than the planned one.

As shown in Fig. 8, within this set of qualified cavities about 90 % of the cavities have been qualified after the first

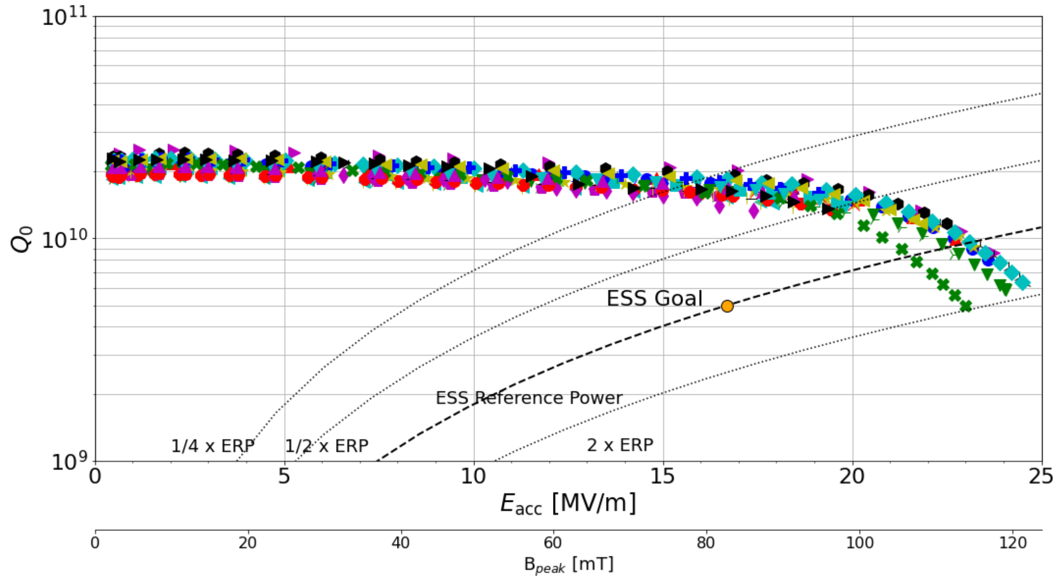

Figure 6: Power rise of the twenty-eight cavities qualified so far. As a reference, we report the ESS goal parameters and the corresponding static dissipated power and some of its multiples.

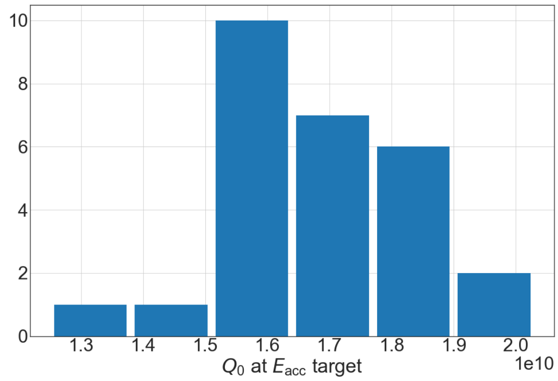

Figure 7: Quality factor distribution at the ESS reference accelerating gradient. Al the cavities have Q_0 nearly three time higher than the ESS planned ones.

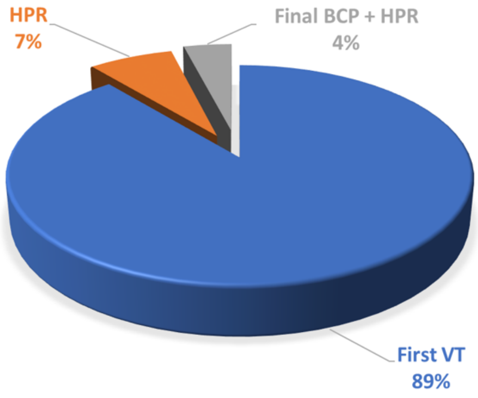

Figure 8: Statistic of the qualified cavities retreatment. Only 11 % of the cavities needed an HPR or BCP+HPR while the rest passed the qualification test at first test.

test, 7 % have been reprocessed with High Pressure Rinsing (HPR) and the remaining 4 % with "Final" BCP+HPR. This last treatment was applied to one cavity that passed the qualification but, during the disassembling, was accidentally vented. The HPRs were instead use to cure few cavities with field emission as it will be discussed in the following section.

CAVITY RECOVERY

Along the qualification process, three cavities did not reach the specifications mainly due to either field emission limitation or quench with field emission and multipacting.

To recover these cavities, we have reviewed and optimized the HPR head to improve the jet footprint on the cavity walls as well as the cavity coverage. M006 was retreated with this new head and it was successfully recovered. This cavity was limited already at the first test by strong field emission and presented a multipacting barrier in range 8 to 12 MV/m while quenching at 18 MV/m. After integration into the He-tank, the strong field emission remained while the multipacting barrier move up in the range 11 to 14 MV/m. This cavity was set in quarantine not being operable in the Linac, since the multipacting barrier was not conditionable. More recently, it was treated with only HPR with new head and was fully recovered both from field emission and multipacting and it is now part of the qualified cavities.

Of the remaining ten out the thirty-eight cavities that did not reached the ESS specifications, we are working to qualify them. Up to now, we have no clear indication of the reason for their performances. They have a good quality factor at very low field well above 1.5×10^{10}. Two of them have a nearly constant Q_0 up to quench field at about 13 MV/m. The other cavities instead suffer by a strong Q-drop that limit the maximum accelerating field below 10 MV/m. All the cavities do not show any radiation during the power rise neither multipacting. Due to the low quench field, we doubt that the eventually generated electrons have not enough energy to generate detectable X-Rays.

CONCLUSION

About two third of the Medium Beta Cavities for the Superconducting Section of the ESS Linac has been successfully handed over. All of them overcome the requirements set by the project with quality factor exceeding by two to three times the target. Moreover, the level of field emission for these cavities are quite low.

An intensive work is now in progress to recover the cavities that have not overcome the qualification process. Different solutions are under investigations whose outcome will be available in the near future.

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