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ESS MEDIUM BETA ACTIVITY AT INFN LASA

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Abstract

The industrial production of the 36 resonators (plus 2 spares) for the ESS linac is steadily progressing. Cavities are delivered by industry as fully surface-treated and dressed to AMTF facility at DESY for their qualification via vertical cold-test. This paper reports the current status of the manufacturing process from subcomponents to processing of the complete cavity inner surface. It also reviews the cavity performances demonstrated so far as well as the documental control strategy deployed to preserve the fulfillment of ESS requirements.

INTRODUCTION

The European Spallation Source (ESS), now in the installation phase at Lund in Sweden, will accelerate high current proton beams up to 2.0 GeV to produce, by the spallation process, neutrons to investigate fundamental process ranging from material science to basic physics research.

The ESS Linac accelerator complex is composed of different sections and the INFN LASA contribution is focused on the Medium Beta (MB, $\beta = 0.67$) cavities [1], used to accelerate the proton beam from 216 to 571 MeV. In collaboration with CEA Saclay, our cavities will be integrated into cryomodules in France before being delivered to ESS for the installation into the tunnel.

INFN LASA has started working on the ESS MB cavity by developing its electromagnetic and mechanical design. The rationale of our design has been to improve the cell-to-cell coupling factor to improve HOM extraction and mode separation at the expense of a slightly higher E_{peak}/E_{acc} and reductions of R/Q [2]. Moreover, an extensive work has also been done to identify trapped monopoles modes below the cut-off frequency of the beam pipes, not having this type of cavity any HOM absorber [3].

Based on our studies, a prototype has been fabricated in collaboration with the industry to establish a validated procedure for the upcoming series production. The results obtained have been extremely encouraging, largely overcoming the ESS specifications [4]. The prototype has been afterwards integrated, together with other three CEA designed cavity prototypes, in the demonstrator module M-ECCTD assembled and successfully tested at CEA [5].

In 2016, we have launched the international call for tenders for the procurement of the Niobium materials and for the cavities fabrication. The tenders were selected and the contracts awarded about six months after tenders issue. Hereafter, we report on the status of the production and test of cavities and related components fabricated up to time of the Conference.

NIOBIUM

All the Niobium components needed for the fabrication of the ESS cavities have been delivered by OTIC Ningxia. 482 sheets have been delivered in three lots for the production of the 38 cavities plus spares for contingency.

All Nb sheets have been eddy current scanned at DESY to detect mainly inclusions of foreign materials but also geometrical imperfections (scratches, thinner sheets, etc.). An important outcome of this analysis has been the determination of the best side to be exposed to RF during the Half Cell fabrication process.

Figure 1 reports the results of the overall scanning, with indication of the causes of sheets non-conformities and their percentage on the total. None of the sheets have inclusions, few of them have some geometrical scratches and only one was thinner than the requested tolerances. More than 80 % of the sheets have been accepted after the scan of the first side only. The remaning sheets needed the analysis of the second side and few of them further analysis (3D microscope and SEM analysis) to exclude presence of foreign materials. The overall acceptance level (i.e. one sheet side good for RF) is larger than 98 %, above our expectations. The sheets that have geometrical imperfections have been recovered by proper grinding. At the end only one sheet was not usable being too thin.

CAVITY FABRICATION

Fabrication and Preparation for Vertical Test

Based on the experience of the European XFEL (E-XFEL) series cavities, a "built to print" process has been chosen also for the ESS MB cavities production. This process consists in setting stringent requirements on the specifications for the

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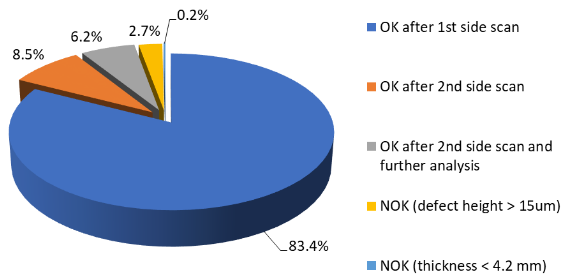

Figure 1: Niobium Sheets eddy current results.

cavity production while not claiming granted performances from the producer. The tender for the cavity fabrication was won by Ettore Zanon S.p.A., a company with a long and solid experience in fabrication of Superconducing RF accelerating structures, already qualified for E-XFEL cavity production.

The cavity fabrication process starts by water jet cutting the square sheets to circular shape and then deep drawing them to form the half cells. Our cavity design foresees three types of Half Cells (HCs), namely Inner (IC), Pen (PC) and End (EC).

The HCs are then electron beam welded (EBW) to form Inner (ID) and Terminal Dumb Bell. The End Cells are EBW to the end tube group to form the End Group. See Ref. [6] for a more detailed description of the cavity assembly process. After mechanical and RF measurements, every component is trimmed to ensure reaching the proper frequency and length of the final cavity. The present status of the subcomponents mechanical fabrication and cavities after welding is summarized in Table 1.

Table 1: Present Status Of The Mechanical Production From Subcomponents to Cavities

Component	Produced	Expected	Percentage
Half Cells	304	304	100 %
Pen Cells	76	76	100 %
End Cells	76	76	100 %
Inner DB	72	114	50 %
Terminal DB	48	76	63 %
End Groups	61	76	80 %
Cavities	21	38	55 %

After mechanical fabrication, the cavity is chemically etched to remove the damage layer of the inner cavity surface. The treatment consists of a total of 200 µm "bulk BCP" etch, 90 µm with the coupler down and the remaining with the coupler up to reduce the asymmetry due to the different chemical etching of the acid while flowing in the cavity. Afterwards, the cavity is heat treated in vacuum at 600 °C for 10 h. It is then tuned to the proper frequency and field flatness before being integrated into the He-tank. The final step is a "final BCP" of 20 µm to prepare the cavity for the test and then the installation of the accessories (pick antenna, main coupler high Q antenna, flanges, etc.). More details on the chemical process of the ESS MB cavity are presented at this conference (see Ref. [7, 8]).

Figure 2 reports a typical frequency variation along the full cavity preparation cycle. The high frequency of the cavity after mechanical production is needed to compensate for the "bulk BCP" process that reduces consistently the cavity frequency (sensitivity 2.9 kHz/µm). The final Field Flatness of the cavity is required to be larger than 93 % as requested from ESS specifications.

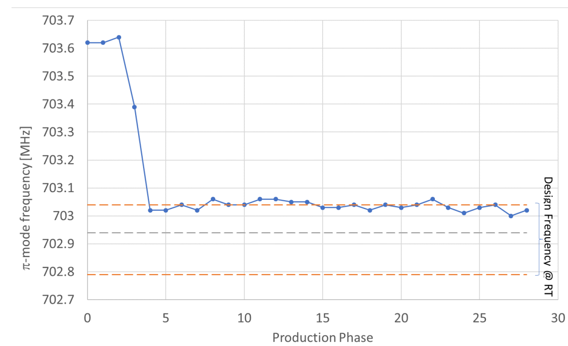

Figure 2: Frequency evolution during the cavity production cycle. The large variation at the beginning is due to the "bulk BCP" process.

At present all the six lots of subcomponents (corresponding to parts for 32 cavities) have been produced. Figure 3 shows the frequency evolution and distribution for the PCs of the whole production. The distribution mode is only less than 200 kHz distant from the expected value.

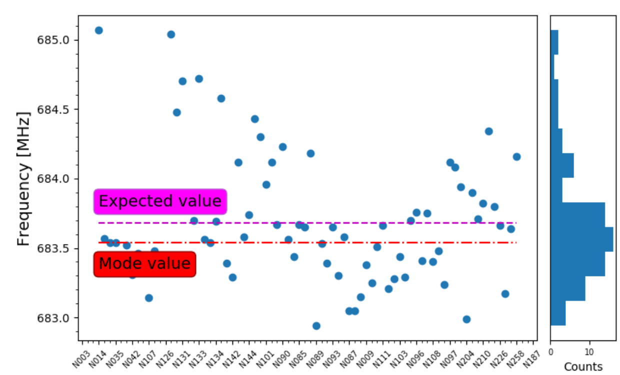

Figure 3: Frequency evolution and distribution for the Pen Cells of the whole ESS MB cavities production.

21 cavities have been EBW and 15 of these have been treated up to the "bulk BCP" stage. Up to now, eight cavities have reached the "final BCP" and they have prepared for to the following test phase at cold at DESY.

CAVITY SHIPPING TO DESY

Cavity transportation from Zanon to DESY is a key topic because we need to preserve the cavity vacuum and avoid production and/or motion of particles.

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We ship the cavity with a dedicated (point-to-point) transportation. To avoid damages during this transportation, a proper box with foam absorbers and provided with soft rubber dumpers supporting the cavity, has been studied and realized. To monitor the cavity during transportation, shock loggers are installed in the box and on the cavity, before starting the shipping, to register eventual shocks above 3 g. A picture of the M001 cavity prepared for leaving Zanon towards DESY is shown in Figure 4.

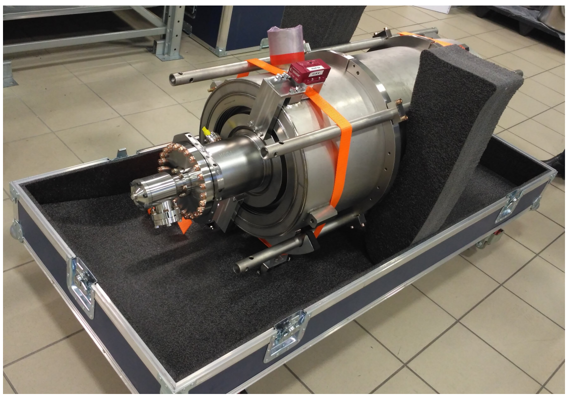

Figure 4: M001 cavity prepared for leaving Zanon. A shock logger (purple box) is visible on the top of the He-tank, above the orange security strap.

Moreover, we issued a detailed protocol that the sender (Zanon) and the receiver (DESY) must accomplish every time a cavity is shipped and/or received. It consists of cavity inspections and testing and compilation of two reports, one with mechanical and inspection measurements and the comparison with reference values, the second with RF measurements. In particular, with regards to the RF measurement, the company before shipping the cavity has to measure, at room temperature, the frequency and the transmission values of the six modes of TM010 band and to acquire the spectrum of the 1720 to 1770 MHz band (Outgoing Inspection). This room temperature test has to be repeated by DESY at the cavity arrival (Incoming Inspection) and compared to the Zanon values ensuring that the following acceptance criteria are fulfilled [9]:

- Max π mode frequency difference = ± 0.1 MHz.
- Max π mode RF power transmission value = −100 dB
- Min π mode RF power transmission value = −130 dB
- Max Mean Spectrum Freq. Deviation = 10 kHz

If any of these acceptance criteria is not met, a nonconformity procedure must be issued and a decision about further actions is taken by LASA experts.

VERTICAL TEST AT DESY

After successful incoming inspection, the cavity is prepared for its qualification in cryogenic conditions at AMTF at DESY [10–12]. A vertical insert allows to test a pair of cavities. Each single cavity is tested up to its limits in order to assess the performances at the ESS working point and the maximum accelerating gradient attainable. Moreover, the frequencies of the first monopole passband mode at cold and the HOM spectra are measured as part of the qualification before installation.

Four dressed cavities have been successfully qualified at DESY up to now (four more expected by end of July). We have also tested naked cavities if subject to operations outside from the standard production cycle [13]. The first ESS series cavity test was in November 2018 and it was cavity M001 installed on the insert with MBLG002 large grain prototype cavity without tank, which already sustained many tests and acted as a reference. In Figure 5 (left) cavities M001 and MBLG002 are installed on the DESY vertical insert, while M003 and M005 are shown on the insert on the right side.

Figure 5: M001 and MBLG002 (left) and M003 and M005 (right) installed on vertical insert at DESY.

The four cavities performances were well above the ESS requirements. ESS specification are summarized in Table 2, where they are compared to cavity performances. Test values column shows the min-max measured values for each parameter in the four tests.

Table 2: First Four MB Cavity Performances And ESS Requirements

	ESS Spec.	**Test Values**
f_π [MHz]	$704.15^{+0.1}_{-0.15}$	704.19 – 704.23
f_π closest f [MHz]	$f_\pi \pm 0.45$	703.45 – 703.49
Max E_{acc} [MV/m]	$>$ 16.7	23.5 – 24.1
Q_0 @ ESS E_{acc}	$>$ 5 10^9	1.6 10^{10} - 2 10^{10}
Q_0 @ Max E_{acc}		6 10^9 - 8 10^9
Q_I (input Q_{Ext})		6 10^9
Q_T (PU Q_{Ext})	2 10^{11}	3.5 10^{11} - 5 10^{11}
F.E. [mGray/min]		< 8.4 10^{-4}

Figure 6 summarizes the results of the dressed cavity tested up to now. Note that all cavities largely overcame 20 MV/m gradient. Cavity M001, M002 and M003 quenched at maximum field, while cavity M005 reached input power limit.

We recorded limited field emission for E_{acc} values between 9 to 11 MV/m, typical multipacting region for these

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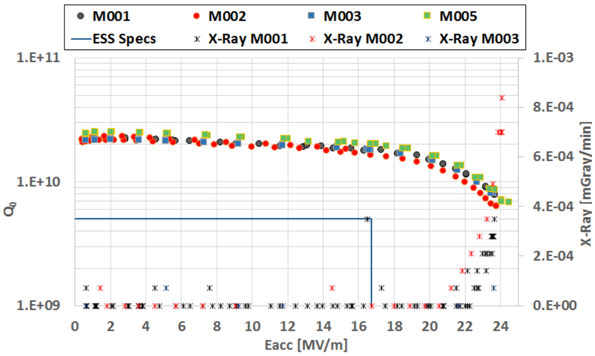

Figure 6: Summary of "dressed" MB cavity vertical test performances at T=2 K. The emitted radiation scale is reported on the right vertical axis.

kind of cavities [14], which disappeared after some minutes of conditioning and was again visible, though modest, towards maximum gradient, except for cavity M005 that showed no radiation.

Along the production, few cavities have shown some not negligible defects on the inner walls. In these cases, either if they are removed or not, we decided to test them without tank and to proceed to tank integration only if project specifications were met. For example, we tested at LASA cavity M006 undressed. This cavity had local grinding of the inner cavity equatorial regions due to round spots (pits) in the region between the cavity weld area and the heat affected zone. M004 undressed has been instead tested at DESY. This cavity was grinded locally for a not-full penetrated equatorial welding. Finally, undressed cavity M010, showing spots of smaller size w.r.t. the latter two, has been tested at DESY without having been grinded, reaching E_{acc} = 20 MV/m. These cavities vertical test results are shown in Figure 7, where it is shown that their performances also overcome ESS requirements and so they are going to be integrated in the He tank.

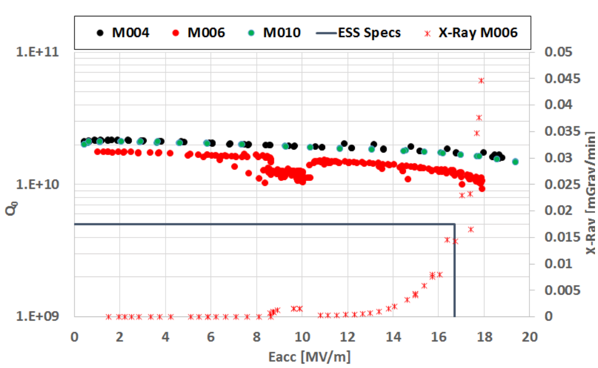

Figure 7: Performances of M004, M006 and M010 undressed cavities.

Cavity High Order Modes

To fulfil the ESS performance requirements, the MB cavity needs to be designed such that all HOMs are at least 5 MHz away from machine lines (i.e. harmonics of beam bunch frequency, 352.2 MHz). If a monopole mode is resonantly excited by lying on a machine line, the induced voltage can degrade the beam quality and also increase the cryogenic losses. The ESS elliptical cavities have no HOM damping antennas so, for a reliable machine operation, it is mandatory to have a cavity design where HOMs are not only away from machine lines by design but also where the fabrication tolerances will not shift HOMs near to these lines. Table 3 [3] shows nominal frequencies (CST simulations) of the $5\pi/6$ mode (of the first cavity passband), accelerating mode and the closest cavity modes to ESS machine lines which have probability of being trapped inside the cavity due to end tubes and iris dimensions. The most probable dangerous HOM is a monopole mode of 3rd passband which ideally it is supposed to be at 1742.5 MHz, 19 MHz away from 5th machine line, namely 1761.05 MHz. The position of this mode is tracked at ambient temperature after cavity tuning and after final BCP treatment, even if the detection of this mode, poorly coupled, is challenging. The accurate measurement of this frequency is done during cold test, where the spectrum of the 1720-1770 MHz band is acquired at 2 K temperature.

Table 3: Cavity Dangerous HOMs Close To Machine Lines (ML) And Related Comments

Freq. [MHz]	**Comments**
703.61	> 0.8 MHz from π mode ($5/6\pi$ mode)
704.42	Accelerating mode (π mode)
1029.6	> 26 MHz from 3rd ML, dipole mode
1376.7	> 32 MHz from 4th ML, quadrupole mode
1742.5	> 19 MHz from 5th ML, monopole mode

For the first four MB cavities there is no evidence of this mode in the region ± 5 MHz from the 5th machine line harmonic frequency. In Figure 8, we show the HOM spectrum of M005 cavity, as an example. This monopole mode is indicated by the red arrow in Figure 8.

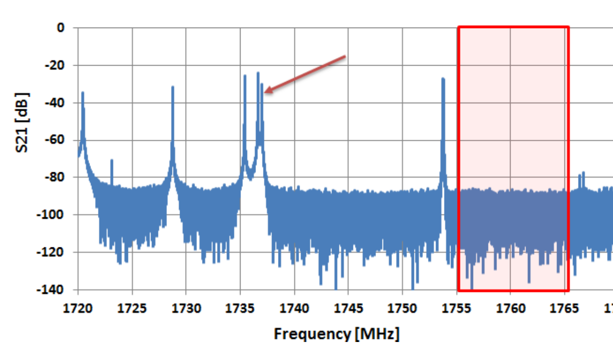

Figure 8: M005 cavity HOM spectrum at 2 K, typical for the four cavities of the series. The "red zone" represents the dangerous area where no monopoles have to show up.

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CAVITY SHIPPING TO CEA

As for the transportation from Zanon to DESY, the final transportation from DESY to CEA follows the same strategy concerning the transportation issues (vibration control, damping, etc.) as well as reports preparation. In particular, to guarantee a safe transportation the RF cavity parameters are measured at room temperature before shipping the cavity and checked again at the cavity reception at CEA. Here, a full check is done on the cavity (mechanical, vacuum, RF) and, if successful, the cavity proceeds to integration into the cryomodule.

QUALITY ASSURANCE AND CONTROL (QA/QC)

The production of the ESS MB cavities needs the supervision and quality control of many components. A critical task is assuring and controlling the production from the Half Cells to the final cavity ready to be delivered for test and installation. For this purpose, we have developed specific procedures and tools to monitor the evolution of the production and to follow single components.

In Ref. [9], we have already reported on the strategy we have developed and applied to ensure proper QA/QC of the production process and how we have extended it also to the test phase at DESY and to the delivery at CEA. To briefly summarize it, we have developed control sheets and detailed reports that the company and the involved laboratories needs to fill and follow that allow cross checking different phases of the cavity cycle. Five acceptance levels (ALs) correspond to hold points where the results and the related documentation is controlled and, if they are conform to specifications the cavity proceeds to the next level. Table 4 reports the ALs and the corresponding cavity delivery phases.

Table 4: Acceptance Levels For The ESS MB Cavities

AL	Description
AL1	Cavity after EBW welding, ready for treatments
AL2	Cavity after tuning, ready for integration
AL3	Cavity fully assembled, ready for shipment to DESY
AL4	Cavity after successful VT test and ready for shipment to CEA
AL5	Cavity accepted and ready for installation at CEA

The most significant information contained in the control sheets are afterwards extracted and collected into a database. A graphical interface (ESS Dashboard [15]) allows having an overview of the production process at a glance both for subcomponents and for cavities. Figure 9 shows an example of the cavity summary panel where the status of the cavity with respect to its advance in the production process is shown as well as its AL status.

The database allows also the analysis of the production nearly on-line to monitor trends and, eventually, a deviation with respect to the standards. As an example, Figure 10 reports the evolution of the length of the ICs before the final trimming. The large step of ID lengths is due to the change of the dies used for these subcomponents deep drawing. After this change, the components are now within the expected tolerances (yellow band) except for few components that have been accepted only after the notification of non-conformity reports (NCRs) and a more detailed analysis on the possible consequences in using these items for the cavity composition. Up to now, about hundred NCRs have been issued during the production process but only few were related to the cavity/cryomodule interfaces as agreed with ESS/CEA and hence might have impact on the cavity installation. All of them have been positively resolved and accepted by ESS after discussion with our colleagues at CEA allowing installation of these cavities.

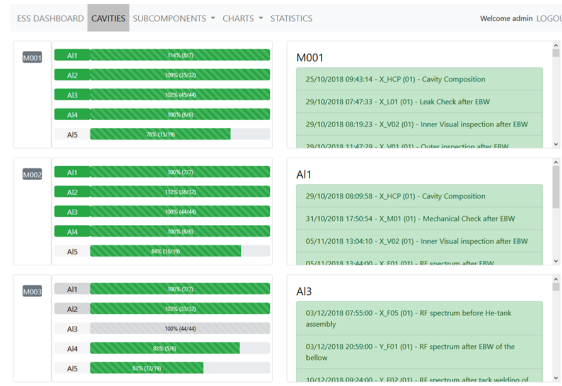

Figure 9: ESS dashboard with detailed information about the status of the cavities.

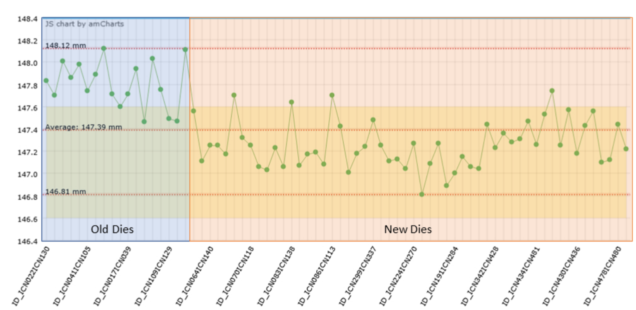

Figure 10: Example of scatter of measurements on length of Inner Dumb Bell before trimming. This is a typical plot available on the ESS Dashboard.

CONCLUSIONS

We have presented the status of the ESS Medium Beta cavity production. We have produced so far mechanical subcomponents for more than half of the full production and half of the cavities. The treatment process has highlighted some defects that have been cured and preventive actions have been identified. Before summer, eight more cavities will be tested and delivered to CEA as foreseen by the ESS schedule and the other are expected to be on time.

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