

## VERTICAL TEST OF ESS MEDIUM BETA CAVITIES

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### Abstract

The Medium Beta ( $\beta=0.67$ , MB) section of the European Spallation Source (ESS) Linac is composed of 36 six-cell elliptical superconducting (SC) cavities [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 plus two spares [2].

The production activity is now ongoing at Ettore Zanon S.p.A. To qualify the cavities, power tests in vertical cryostat have been committed to DESY. During the qualification tests, the cavities provided with He tanks are pushed to their electromagnetic limits, recording their main parameters such as quality factor  $Q_0$  vs  $E_{acc}$ . In this paper we report about the qualification tests performed on the first part of the cavity production.

### INTRODUCTION

During a superconducting cavity qualification test, the measurement of its electromagnetic parameters at cryogenic temperature (2 K) is done installing the resonator on a proper vertical insert, whose top flange hosts all the ports and feedthroughs to connect the instrumentation needed for the test and a pipe to connect the cavity with the vacuum pumps [3]. Due to its narrow bandwidth, less than 0.1 Hz ( $Q_0$  is higher than  $10^{10}$ ), the cavity must be inserted in a Phase Locked Loop (PLL) to be tested.

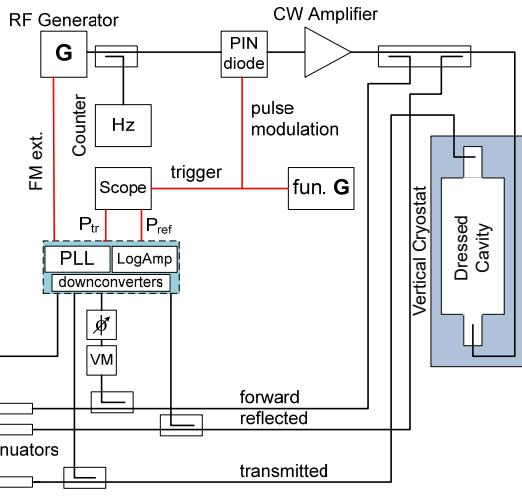


Figure 1: Block diagram of DESY RF setup.

The VCO (Voltage Controlled Oscillator, usually a commercial frequency synthesizer) is frequency modulated by a signal proportional to the phase difference between the

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input and transmitted cavity powers. To set up the PLL working point, i.e. the cavity resonance, to the desired mode, this phase difference is adjusted until we get maximum accelerated field ( $E_{acc}$ ) in the cavity. The envelope of pulsed reflected power is used in this case. The cavity quality factor is computed acquiring the time constant from the exponential discharge of the transmitted power envelope. The conceptual scheme of the DESY cavity test facility is shown in Fig. 1.

Our MB prototype cavity (MB001) has been developed and successfully qualified at LASA, where  $E_{acc}$  higher than 22 MV/m (@  $Q_0 > 5 \cdot 10^9$ ) has been reached, when the ESS requirements are  $E_{acc} = 16.7$  MV/m @  $Q_0 > 5 \cdot 10^9$ . At the ESS goal accelerating gradient, the quality factor was  $Q_0 \sim 1.5 \cdot 10^{10}$ . The MB001 cavity has been then shipped to CEA and integrated, as part of the four cavities package, in the M-ECCTD cryomodule demonstrator, this latter also tested successfully at the end of the last year [4]. Now the M-ECCTD cryomodule is at the ESS site at Lund (Sweden) where is being assembled in the ESS LINAC facility to be re-tested.

After the successful test of the MB001 cavity, INFN contracted Zanon for the production of 38 dressed cavities (cavity +He tank + ancillaries). Cavities are produced in groups (lots) of six devices each. Up to now the firm is producing the cavities of the third lot and the components of the fourth lot. The required cavity production rate is two cavities every three weeks. The last cavity is expected by February 2020. Details of MB cavity production, together with cavity RF properties, can be found in another paper presented at this conference [2]. Due to this high rate, that is over LASA testing capability (one two-cavities test every three weeks), DESY, under INFN responsibility, performs the cold tests of the 38 cavities with tank in their adapted Vertical Test Infrastructure at Accelerator Module Test Facility (AMTF). For this purpose, two 1.3 GHz cavity inserts have been modified to host two ESS MB 704.4 MHz cavities. Few accelerating cavities can also be tested at LASA facility if needed, as well as cavities presenting criticalities, before their integration in the He tank.

### CAVITY SHIPPING TO DESY

Cavity transportation from the factory to DESY is a key topic. Cavity comes out from the factory with all the ancillaries installed and under vacuum condition, ready to be installed on the cold test insert. The shipping is by means of a dedicated (point-to-point) transportation by a standard Courier Service Company. 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.

A picture of the M001 cavity leaving Zanon towards DESY is shown in Fig. 2.



Figure 2: M001 cavity leaving Zanon. A shock logger (purple box) is visible on the top of the He Tank over the orange strap.

In addition to this, we issued a detailed protocol that the sender and the receiver must accomplish every time a cavity is shipped and/or received, consisting on 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  $TM_{010}$  band and to acquire the spectrum of the 1720 – 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 ones ensuring that the following acceptance criteria are fulfilled [5]:

- Maximum  $\pi$  mode frequency difference  $dF_{\text{limit}} = \pm 0.1$  MHz.
- Maximum  $\pi$  mode RF power transmission value  $T_H = -100$  dB.
- Minimum  $\pi$  mode RF power transmission value  $T_L = -130$  dB.
- Maximum Mean Spectrum Frequency Deviation  $\Delta F_{\text{limit}} = 10$  kHz.

If any of these acceptance criteria is not met, a non-conformity procedure must be issued and a decision about possibly cavity rejection is taken by LASA experts. The test of  $\pi$  mode frequencies and the acquisition of the spectrum of 1720 – 1770 MHz band is then repeated at 2K as reference values for cavity installation.

## VERTICAL TEST AT DESY

Four dressed cavities of the first lot have been successfully qualified at DESY up to now. The first ESS series cavity test was in November 2018 and was about dressed M001 cavity installed on the insert with MBLG002 large grain prototype cavity without tank, which already sustained many tests, to be used as a reference. In Fig. 3 (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 3: 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 1, where they are compared to cavity performances, also summarized in Fig. 4. Note that all cavities largely over-come 20 MV/m gradient. Cavity M001, M002 and M003 quenched at maximum field, while cavity M005 test was stopped for reaching input power limits. Test values column shows the min-max measured values for each parameter in the four tests.

Table 1: First Four MB Cavity Performances and ESS Requirements

|                                 | ESS Spec           | Test Values                           |
|---------------------------------|--------------------|---------------------------------------|
| $f_{\pi}$ [MHz]                 | $704.2 \pm 0.1$    | $704.19 - 704.23$                     |
| $f_{\pi}$ closest $f$ [MHz]     | $f_{\pi} \pm 0.45$ | $703.45 - 703.49$                     |
| Max $E_{\text{acc}}$ [MV/m]     | $> 16.7$           | $23.5 - 24.1$                         |
| $Q_0$ @ ESS $E_{\text{acc}}$    | $> 5 \cdot 10^9$   | $1.6 \cdot 10^{10} - 2 \cdot 10^{10}$ |
| $Q_0$ @ Max $E_{\text{acc}}$    |                    | $6 \cdot 10^9 - 8 \cdot 10^9$         |
| $Q_I$ (input $Q_{\text{EXT}}$ ) |                    | $6 \cdot 10^9$                        |
| $Q_T$ (PU $Q_{\text{EXT}}$ )    | $2 \cdot 10^{11}$  | $3.5 \cdot 10^{11} - 5 \cdot 10^{11}$ |
| F.E. [mGray/min]                |                    | $< 8.4 \cdot 10^{-4}$                 |

We recorded limited field emission for  $E_{\text{acc}}$  values between 9 and 11 MV/m, typical multipacting region for these kind of cavities [6], 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 integration only if project specs 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 Fig. 5, where it is shown that their performances also over-come ESS requirements and so they are going to be integrated in the He tank.

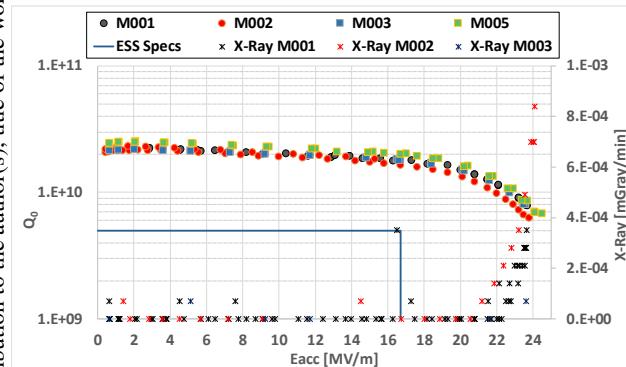


Figure 4: Summary of "dressed" MB cavity vertical test performances at  $T=2K$ . The emitted radiation scale is reported on the right vertical axis.

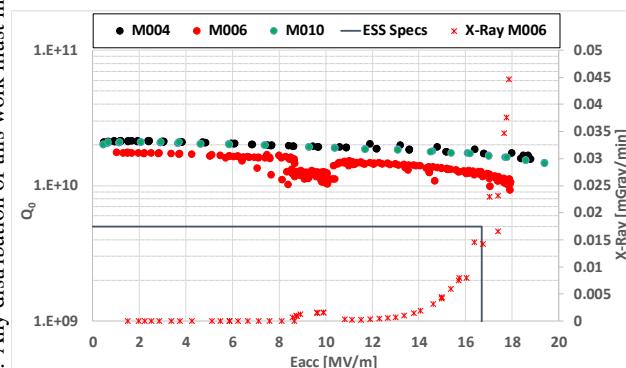


Figure 5: Performances of M004, M006 and M010 undressed cavities.

## CAVITY HIGHER ORDER MODES

To fulfill 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 2 [7] 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 possible dangerous HOM is a monopole mode of 3<sup>rd</sup> passband which ideally it is supposed to be at 1742.5 MHz, 19 MHz away from 5<sup>th</sup> 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 2K temperature.

Table 2: Cavity Design HOMs Close to Machine Lines

| Frequency (MHz) | Comments   |
|-----------------|--|
| 703.61          | > 0.8 MHz from accelerating mode ( $5/6\pi$ mode)          |
| 704.42          | Accelerating mode ( $\pi$ mode)                            |
| 1029.6          | > 26MHz from 3 <sup>rd</sup> machine line, Dipole mode     |
| 1376.7          | > 32MHz from 4 <sup>th</sup> machine line, Quadrupole mode |
| 1742.5          | > 19MHz from 5 <sup>th</sup> machine line, Monopole mode   |

For the first four MB cavities there is no evidence of this mode in the region  $\pm 5$  MHz from the 5<sup>th</sup> machine line harmonic frequency. In Fig. 6, we show the HOM spectrum of M005 cavity, as an example. This monopole mode is indicated by the red arrow in Fig. 6.

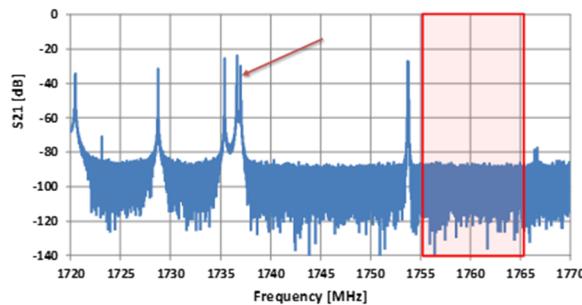


Figure 6: M005 cavity HOM spectrum, typical for the four cavities of the series. The "red zone" represents the dangerous area where no monopoles have to show up.

## 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.

## CONCLUSION

The first four dressed cavities produced have been successfully qualified and are under installation in the first ESS module at CEA laboratory at Saclay. Next two dressed cavity shipment to DESY will be in the first decade of June.

Tested cavities with repaired non conformities have also shown gradient and quality factor performances sufficient to proceed with their integration in the He tank. The testing activities will proceed following Zanon rate of production.

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