ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-TUCOZBS06

CRYOMODULES FOR THE MAINZ ENERGY-RECOVERING SUPERCONDUCTING ACCELERATOR (MESA)*

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Abstract

Two superconducting radio frequency acceleration cryomodules for the new multiturn ERL facility MESA (Mainz Energy Recovering Superconducting Accelerator) at Johannes Gutenberg-Universität Mainz have been fabricated by industry and are undergoing rf tests at the Helmholtz Institut Mainz (HIM) currently. The modules for MESA are modified versions of the ELBE modules at Helmholtz Center Dresden-Rossendorf. The design energy gain per module and turn is set to 25 MeV. Acceleration is done by in total four TESLA/XFEL cavities, which have been vertically tested at DESY, Hamburg, Germany before being integrated in the MESA modules. In order to validate the performance of the fully dressed cryomodules a test stand has been set up at HIM. Within this contribution we report on the necessary modifications of the modules for high current ERL operation as well as on vertical and horizontal rf test results.

INTRODUCTION

For the main linac of the Mainz Energy-Recovering Superconducting Accelerator MESA [1-3], currently under construction at Johannes Gutenberg Universtität Mainz, two ELBE/Rossendorf-type [4] cryomodules have been produced by industry in Germany [5]. Each module consists of two TESLA/XFEL cavities running on an operation frequency of 1.3 GHz in continuous wave (cw) mode. For electron acceleration a gradient of 12.5 MV/m in each cavity is required to suit the experimental needs of the MESA facility. The dynamic losses of the cavities are limited due to the maximum available cooling power of the cryo-plant. Therefore, the unloaded quality factor of each cavity running on the operating gradient of 12.5 MV/m needs to exceed a value of 10^{10} at the operating temperature of 1.8 K. If MESA is run in ERL mode, a beam current of up to 1 mA needs to be accelerated and decelerated two turns each, yielding to a total sum of 4 mA electron beam in cw inside the accelerating cavities. To suit these needs of MESA, modifications on the module needed to be applied. In particular, the cooling of the HOM antennas was optimized and a fast eigenfrequency tuner (XFEL/Saclay type) based on Piezo actuators for an optimized microphonics compensation has been integrated [6,7].

* This work has been supported by DFG through the PRISMA+ cluster of excellence EXC 2118/2019.
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MESA CAVITIES

Specifications

The performance goals for the MESA cavities and cryomodules have been specified beforehand and the vendor guaranteed parameters for the total energy gain per cryomodule and the static and dynamic cryogenic losses. Table 1 gives an overview on the target values to be verified in the horizontal acceptance tests at HIM.

Table 1: Specifications of fully dressed cryomodule performance in horizontal test operated at 2 K [8]

Variable	Specified Value
Energy Gain	25 MeV
Static Losses	< 15 W
Dynamic Losses @ 25 MeV (cw)	< 25 W
$\propto Q_0$ @12.5 MV/m	$> 1.25 \cdot 10^{10}$

Vertical Test Results

After cavity production a XFEL standard treatment procedure has been applied to the cavities. To check the performance of each cavity after being welded into their Helium vessels, a vertical test at DESY has been carried out. Goals of this test have been the measurement of the quality factors at 2 K and 1.8 K and the determination of maximum gradients and performance limits. The test results have already been discussed in detail in [7,8]. Nevertheless, for giving the possibility to compare the results with the horizontal ones, the results will be presented briefly again. All cavities have achieved test results within specification at 2 K (see Fig. 1).

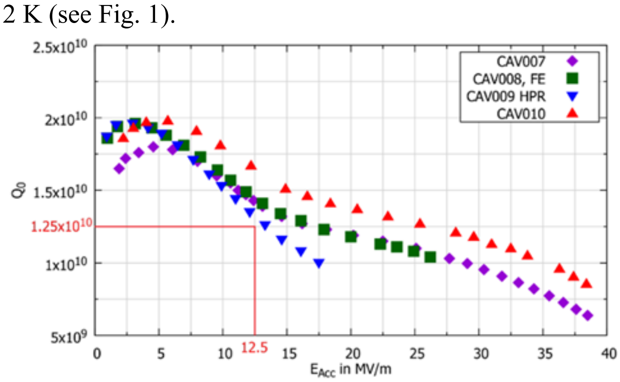

Figure 1: Vertical test results at 2 K operation for all MESA cavities. The measurements have been done at DESY AMTF. All cavities are above specification (red box). CAV 008 showed field emission above 26 MV/m [8].

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Two out of four cavities have shown an excellent behaviour (CAV 007 and CAV 010). The third one (CAV 008) performed acceptable but suffered from light field emission above 26 MV/m. The fourth cavity (CAV 009) fulfilled the specification but needed an additional high pressure rinsing treatment. The quench limit has been measured to 16 MV/m which is lower than the limits of the other three cavities but still exceeding the acceptance limit for full MESA gradient (12.5 MV/m). After vertical testing, the cavities have been integrated into two cryomodules. Cryomodule 1 consists of CAV007 and CAV008, while cryomodule 2 is equipped with CAV009 and CAV010.

MESA CRYOMODULES

HOM Antenna Cooling

If MESA is operated in ERL mode, every cell of each cavity is filled with two bunches, either accelerating or decelerating. The high beam current aimed for at ERL operation (1 mA initially, later 10 mA) interacts with the cavity fields and can excite higher order modes (HOMs), which may be rather long living due to the high quality factor of the SRF cavities. Due to the recirculating design of the accelerator, the beam is sensitive to field disturbances and may close a feedback loop with any of the HOMs, which can cause beam break up (BBU) in the worst case. BBU threshold current depends on the HOM spectra and recirculation optics. BBU limitations have been simulated for MESA using the measured HOM spectra from vertical and horizontal tests of all four cavities. Threshold current for BBU at MESA exceeds 10 mA and BBU is not considered to be the limiting factor for MESA beam current [9,10].

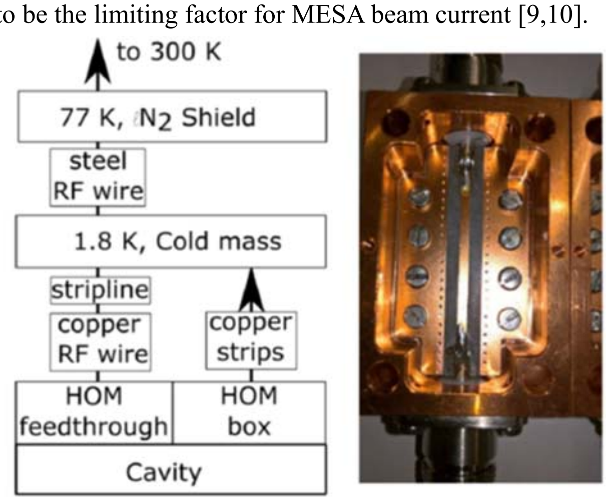

Figure 2: Left side: cooling concept for the inner conductor of the MESA HOM absorbers. Right side: stripline coupler allowing the thermal attachment to the cold mass of the module at 2 K [6,7].

On the other hand, HOMs excited by the high intensity beam need to be damped by the installed HOM absorbers and can result in heating of the antennas. If the cooling of the antennas is not sufficient, a quench can occur and cause the complete cavity to quench. For that reason, the thermal connection of the inner conductor of the antennas to the cold mass have been improved by two measures. First, the feedthrough has been replaced with a version using sapphire as insulator instead of a ceramic with poorer heat conductivity. Second improvement is the use of a stripline coupler for direct cooling of the inner conductor [6,7]. For benchmarking the new system, extensive temperature diagnostics has been integrated to the MESA cryomodules. Cooling concept and a photography of the stripline coupler can be seen in Fig. 2. During cold rf tests no heating of the HOM antennas could be observed. But for a concluding evaluation of the system high current beam tests are necessary as foreseen in the MESA@bERLinPro collaboration [11].

RF Coupling and Horizontal Test Setup

Each MESA cavity will be driven by a 15 kW solid state power amplifier (SSPA) running in cw at 1.3 GHz [12]. For horizontal testing at HIM one SSPA, designed as prototype for rf generation at MESAs normal-conducting and superconducting cavities, was used. The input couplers are capable to accept full power of the amplifier in cw and have been conditioned up to 20 kW in cw operation before module integration [7]. External coupling of the input couplers has been chosen to $Q_L = 1.38 \cdot 10^7$ suiting both MESA operation modes, external beam and ERL [7]. After module completion the resulting coupling at operation temperature has been measured. The values at 2 K range from $Q_L = 1.15 \cdot 10^7$ to $Q_L = 1.66 \cdot 10^7$, which is acceptable for MESA operation. With the maximum power from SSPA, an additional microphonic reserve of 5 kW and the given coupling, the maximum gradient for each cavity can be calculated (see Fig. 3) [8]. Without beamloading, which is the case in ERL operation, the cavities can be stable operated at maximum gradients between 21 MV/m and 25 MV/m using 15 kW forward power and considering the reserve for microphonic detuning, which is well above the 12.5 MV/m design gradient. For rf tests using a phase locked loop (PLL) setting and thus not needing a microphonic reserve, the cavities can be tested up to a range of 25 MV/m to 30 MV/m using the maximum allowed forward power [8]. Therefore, only cavities CAV 008 and CAV 009 can reach their quench field limits from vertical testing in cw in the present horizontal setup.

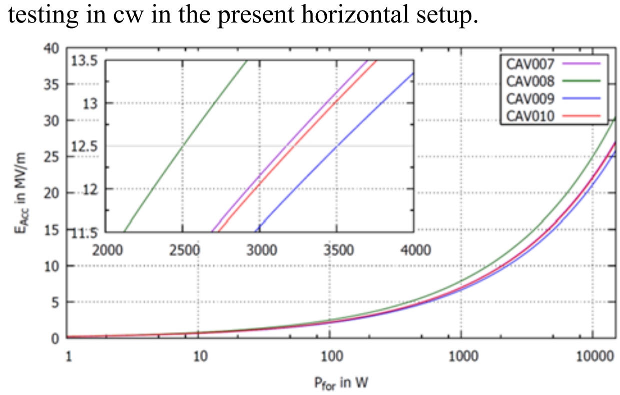

Figure 3: Acceleration gradient at given forward power [8]. The solid state amplifier is limited to 15 kW. The different curves take the measured Q_L for each cavity into account.

ISBN: 978-3-95450-217-2 doi:10.18429/JACoW-ERL2019-TUCOZBS06

Horizontal Test Results

Due to the strongly over coupled cavities, the cw measurement of unloaded Q_0 in the horizontal tests needed to be done using calorimetric methods. Therefore, two approaches for measuring the dissipated power through the amount of evaporated helium have been applied. In the first method the helium flow rate has been detected and compared to measurements with calibrated heaters. For the second method the pressure rise inside the Helium vessel has been measured and again calibrated with runs on defined heater settings. At the time of each measurement all inlet valves into the helium vessel have been closed for creating stable conditions. The Helium flow rate dependent of the accelerating gradient was measured over a period of 5 min in each run and can be compared with a series of heater measurements for flow calibration. The calibration measurement has been used to determine static losses of the modules as well by evaluating the fit function of the calibration run data.

To measure dissipated power by pressure rise, the exhaust valves of the Helium vessel have been closed and the pressure rise inside of the closed volume was measured and again compared to heater measurements for calibration. This method has been described in [13] already. The time per measurement is set to 30 sec. In that time the pressure rise is clearly detectable but not as high as corrections on Helium temperature need to be applied. The dissipated power in each measurement method can be calculated by:

$$P_{Diss} = \left(\frac{x_{RF}-x_{static}}{x_{heater}-x_{static}}\right) P_{heater} \tag{1}$$

Here, the value x can stand for the pressure rise (dp/dt) or the measured flow rate ϕ respectively. The unloaded quality factor Q_0 can be calculated by inserting the results for the dissipated power from Eq. 1 at each accelerating gradient into the following formula:

$$Q_0 = \frac{E_{acc}^2}{\frac{R}{Q} P_{Diss} L^2} \tag{2}$$

The known values [14] for normalized shunt impedance (R/Q = 1030 Ω) and the active resonator length (L = 1.038 m) of the TESLA resonators needed to be inserted as well. In the following figures we present the horizontal test results of both cryomodules.

Cryomodule 1 The resulting quality factors for both cavities can be found in Fig. 4. The horizontal test results of CAV 007 are in compliance with the vertical test results. No field emission has been observed while running the cavity in cw. The measurements of CAV 008 assume to show a higher Q_0 in module test than in vertical test on the first glance. At a detailed revision of the test set-up an unwanted interference of a newly installed µTCA LLRF test set-up [15] with the PLL used for the measurement have been identified. Therefore, the quality factor measurement of CAV 008 need to be done again. Nevertheless, no field emission was present at any time and the Helium flow rates clearly indicated a quality factor above specification at design gradient. The static losses of the module yielded P_{static} = 9.0(23) W, which is within specification.

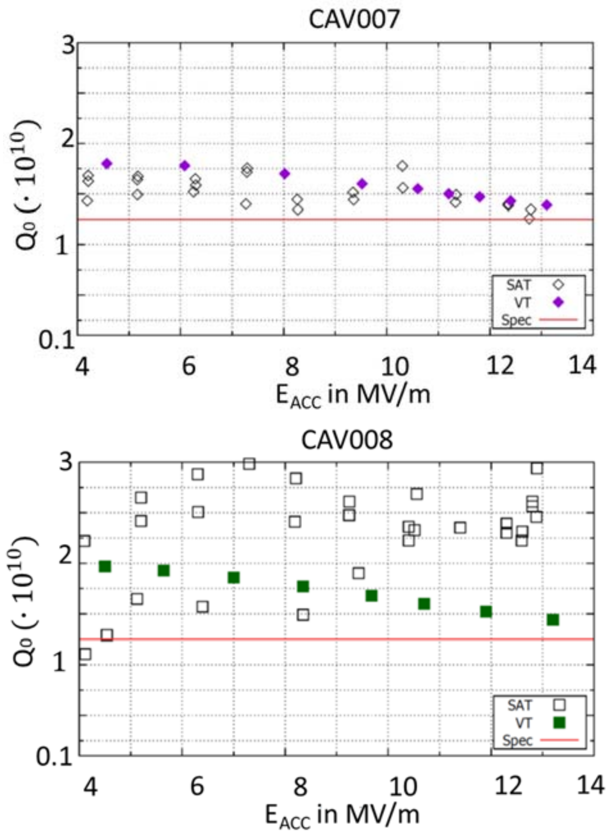

Figure 4: Horizontal test results for the first MESA module [8]. The achieved values for CAV 007 are compliant to the vertical test results and above specification. During measurements on CAV 008 interferences on the rf system caused an uncertainty on the measurement of the accelerating gradient and therefore of the quality factor. These measurements need to be repeated [8].

Cryomodule 2 During measurement of the quality factors of the cavities in cryomodule 2 severe problems with radiation showed up. The test results are plotted in Fig. 5. Both cavities showed radiation from field emission starting with 2 mSv/h at 2 MV/m up to several Sv/h at 10 MV/m [8]. Radiation measured inside and outside of the test bunker limited the operating gradient in cw to below 10 MV/m. A pulsed processing was tried to mitigate the radiation, but a processing effect couldn't be observed. Tests to identify a single field emitter with a matrix of dosimeters attached on the outside of the vacuum vessel showed no pint like source of radiation but a scattered radiation. So a single field emitter could be ruled out to be the reason for the observed radiation [8]. One hypothesis for the unexpected behaviour can be particulate contamination. After delivery of the module a not correctly closed valve between cavity string and a blind flange has been found at visual inspection. This valve at the cavity vacuum was in an indifferent state. After applying pressured air, it closed.

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Due to the vibrations during the transport from the vendor to JGU Mainz, an unwanted movement of the valve disk could have produced particles. Those particles may spread through the nitrogen atmosphere all over both cavities and act as a diffuse pattern of field emitters in the tests. One indicator for this hypothesis is the slightly higher Q_0 of CAV 010. This cavity is located farther away from valve. Static losses of the cryomodule 2 are calculated to P_{static} = 5.61(35) W, which is within specification again. The module is under refurbishment at present including a complete disassembly. Therefore, the static losses have to qualified again in course of the next horizontal acceptance tests.

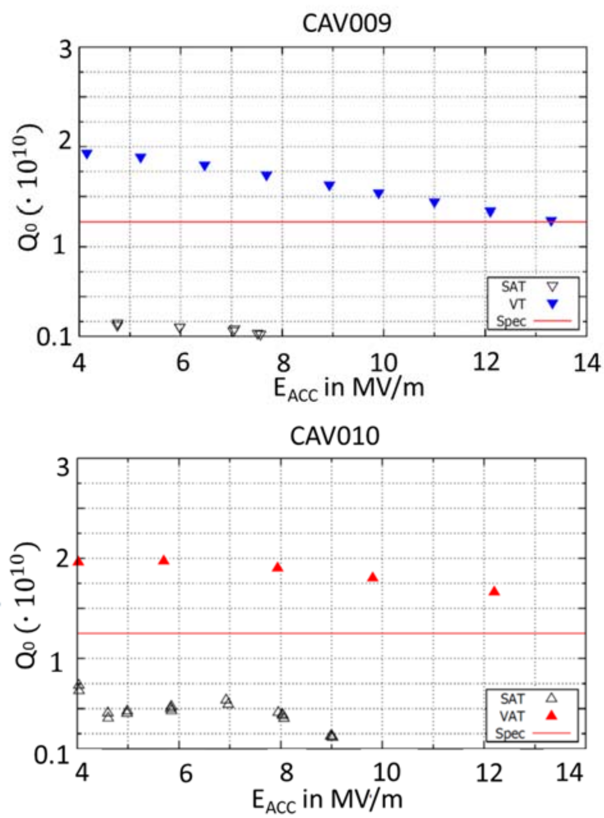

Figure 5: Horizontal test results for the second MESA module [8]. Strong field emission limited operating gradients and resulted in a significant reduced quality factor compared to the vertical tests for both cavities. The module is under refurbishment at the vendor currently. Next horizontal tests are envisaged to take place in end 2019.

CONCLUSION AND OUTLOOK

Both cryomodules for the MESA facility have been fabricated by industry and were tested at 2 K at HIM. Cryomodule 1 could be accepted already showing test results above specification. Nevertheless, further tests are planned in the future on that module up to higher operating cw gradients. Cryomodule 2 showed severe radiation from field emission in both cavities starting at low fields already and was sent back to the vendor for refurbishment. As a possible particulate source, a loose valve disk was identified. Because of the shipping under nitrogen atmosphere, the particulates could float all over the cavities and produced a diffuse radiation pattern. A future shipment under vacuum condition could reduce the risk of particulate transportation inside the cavity vacuum.

In order to verify the improved HOM antenna cooling, experiments with high current electron beam would be necessary. Such tests are planned to happen in course of the MESA@bERLinPro collaboration [11].

ACKNOWLEDGEMENTS

We kindly thank the Helmholtz Institut Mainz, in particular the groups ACID 1 and ACID 2 for providing their rf testing infrastructure for the horizontal tests.

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