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# REFURBISHMENT OF AN ELBE-TYPE CRYOMODULE FOR COATED HOM-ANTENNA TESTS FOR MESA*

P. S. Plattner†, F. Hug, T. Stengler
Institut für Kernphysik der JGU Mainz, Mainz, Germany

*Abstract*

The Mainz Energy-Recovering Superconducting Accelerator (MESA), an energy-recovering (ER) LINAC, is currently under construction at the university Mainz. In the ER mode a continues wave (CW) beam is accelerated from 5 MeV up to 105 MeV with a beam current of up to 1 mA. This current is accelerated and decelerated twice within a cavity. For future experiments, the beam current limit has to be pushed up to 10 mA. An analysis of the MESA cavities has shown that the HOM antennas quench at such high beam currents due to the extensive power deposition and the resulting heating of the HOM coupler. To avoid quenching it is necessary to use superconducting materials with higher critical temperature. For this purpose, the HOM antennas will be coated with NbTiN and $Nb_3Sn$ and their properties will be investigated. For use in the accelerator, the HOM antennas will be installed in the cavities of a former ALICE cryomodule, kindly provided by STFC Daresburry. This paper will show both the status of the refurbishment of the ALICE module to suit MESA, and the coating of the HOM antennas.

## INTRODUCTION

Research on the adequate damping of Higher Order Modes (HOMs) in superconducting radio-frequency (SRF) cavities is a fundamental aspect of advancing Energy Recovery Linacs (ERLs) in terms of beam currents and energy capabilities. To address these obstacles in the MESA project, the MESA Enhanced ELBE-type Cryomodules (MEEC) was developed [1]. The MEEC was designed that the two 9-cell TESLA cavities have a field gradient of 12.5 MV m$^{-1}$ at a $Q_0 = 1.25 \times 10^{11}$. To achieve the requirements the commercial available ELBE/Rossendorf-type cryomodules (CM) needed to be modified in three major parts: the tuner, HOM feedthrough and Helium supply. MESA is designed for 1 mA cw current in the beginning. But based on calculations considering MESA stage 2 beam currents as high as 10 mA, it has been determined that the power levels in the MEEC's HOM dampers will exceed their designed limits [2]. To address this issue, a cryomodule from the decommissioned ALICE ERL[1] [3] is currently undergoing refurbishment in Mainz. Once the cavities have been refurbished, they will be utilized to conduct tests on coated HOM antennas, aiming to enhance the cavities' performance under high beam currents. Table 1 presents a comparison of the key parameters between the MESA and ALICE systems. Since both accelerators operate at the identical frequency, the goal of the refurbishment is first to achieve quality factor which are acceptable for MESA. The reassembled and modified ALICE cryomodule can be used as a platform for SRF-research and spare cryomodule for MESA.

Table 1: Comparison of the Key Parameters of ALICE and MESA

| Parameter | MESA | ALICE |
|---|---|---|
| $Q_0$ | $1.25 \times 10^{10}$ | $5 \times 10^{9}$ |
| Field gradient | 12.5 MV m$^{-1}$ | 12.9 MV m$^{-1}$ |
| Beam current (ERL) | 1(10) mA | 13 µA |
| RF Frequency | 1.3 GHz | 1.3 GHz |
| Cavities | 9-cell XFEL/TESLA | 9-cell XFEL/TESLA |

## MAINZ ENERGY-RECOVERING SUPERCONDUCTING ACCELERATOR

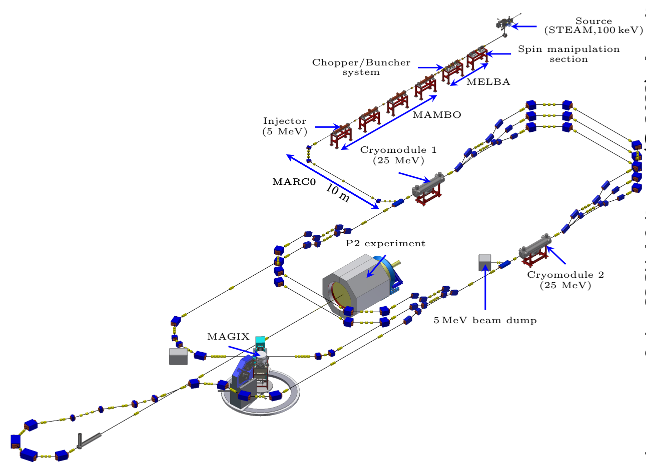


Figure 1: The MESA lattice.

In Fig. 1 is shown the lattice of MESA [4], which has an normal conduction pre-accelerator and a superconducting main accelerator. MESA is a continuous wave multiturn LINAC, which operates at a frequency of 1.3 GHz and can be operated in the Energy Recovering (ER)-mode or in the External Beam (EB) mode. For MESA are planned two electron sources: A Small Thermalised Electron Source at Mainz (STEAM) [5], which provides polarised electrons at a beam current of 150 µA up to 1 mA and the

* The work received funding by BMBF through 05H21UMRB1.
† pplattne@uni-mainz.de
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MESA-Injector Source Two (MIST) [6]. It will provide an average beam current of 10 mA. The MESA Low Energy Beam Apparatus (MELBA) [7] prepares the beam in bunches and the MilliAMpere BOoster (MAMBO) accelerates the bunches up to the injection energy of 5 MeV. After a normal conducting pre-accelerator the 5 MeV electron bunches will be injected into the main accelerator, which is driven by two MEECs which provide an energy gain of 25 MeV each. In EB mode the electrons will recirculate for 3 turn and have an energy gain of 150 MeV and MESA at 150 µA. In ER-mode the electrons recirculate for to turns to have an energy gain of 100 MeV and are fed back in the acceleration, after the interaction with MAGIX, with a phase shift of 180° for two recirculations and are decelerate to 5 MeV for MESA at 1(10) mA.

## REFURBISHMENT OF AN ELBE-TYPE CRYOMODULE FOR MESA

A refurbishment of the ALICE CM and modifications, were necessary to meet the requirements to work as a future spare CM for MESA [8]. However, an unexpected maintenance phase of the clean room infrastructure at the Helmholtz Institute Mainz (HIM) has resulted in a delay in the high-pressure rinse (HPR) treatment. The clean room treatment of the cavities is now scheduled for the summer of 2023. Due to existing oil contamination in the Helium tank of the first cavity, a pre-clean room cleaning procedure consisting of three steps was necessary. In the initial step, the tank was filled with a mixture of ultra-pure water and Tickopur R33 to eliminate the oil residues. The mixture contained a 5% concentration of Tickopur R33. This mixture was circulated for 24 hours and heated to a temperature of 40 °C.

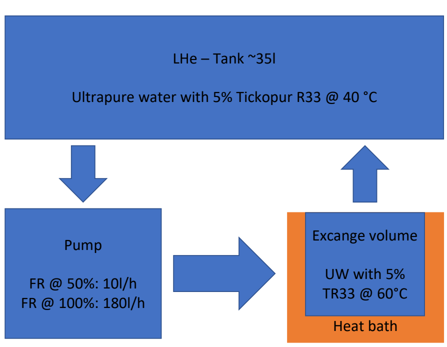


Figure 2: Schematic of the setup for cleaning the Helium tank. Including a pump, heat bath to heat up the circulating water in the exchange volume all connected with the Helium tank.

Figure 2 illustrates a schematic of the setup. The pump speed was set to 100%, corresponding to a flow rate of 180 L h$^{-1}$, ensuring that the total volume of 35 L was exchanged over 100 times. Subsequently, the tank was circulated with ultra-pure water to remove any remaining oil and Tickopur residues. The pump speed was reduced to 50%, equivalent to 10 L h$^{-1}$, and the volume exchanges were reduced to 7. This process was conducted for 24 hours, and following an inspection of the outflowing water, it was evident that a second rinse was required to eliminate additional residues. However, noticeable oil spots were still present after the second rinse cycle. Therefore, the next step involves cleaning the inner surface of the Helium tank with Acetone to completely remove the remaining traces of oil and Tickopur. This measure aims to prevent contamination of the ultrasonic bath in the clean room at HIM. Additionally, the Helium tank of the second cavity will be cleaned before it is introduced into the clean room. This decision was made due to the unexpectedly higher level of oil contamination. Figure 3 depicts the cavity mounted to the transportation cage, which can then be attached to a lifter. Subsequently, the tank will be filled with 10 L of Acetone and rotated to ensure thorough cleaning of the entire surface inside the Helium tank. For the second cavity, a single cleaning cycle using Acetone was sufficient to clean the cavity, as the outgoing Acetone had the same color as unused Acetone. The next step will involve bringing the cavities into the clean room at HIM, where the inner surface will undergo refurbishment with a HPR. Following this, the performance of the cavity will be evaluated through a vertical cold test.

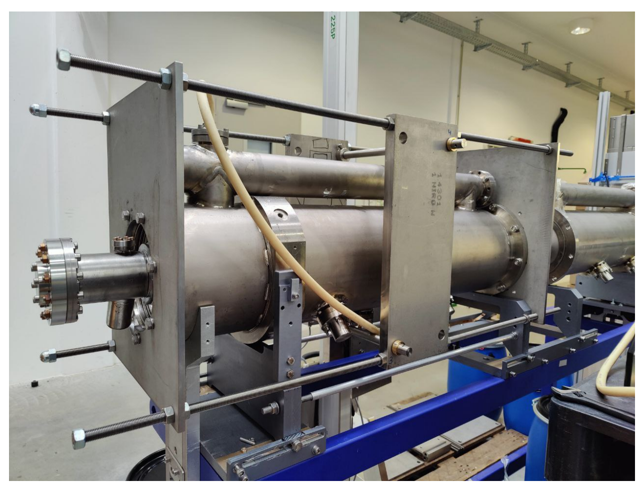

Figure 3: Cavity mounted to a transportation cage and hanging on the lifter. Ready for the Acetone treatment.

## THIN FILMS ON HOM ANTENNA

### *Power Limit at the HOM Antenna Tip*

An approach to estimate the power limit of the HOM feedthrough is to calculate the dissipated heat loss from the magnetic field $H_{\perp}$ which is perpendicular to the HOM antenna surface [9]. The magnetic field $H_{\perp}$ in the area of the antenna tip can be estimate to have 30% of the $H_{peak}$ [10] in the cavity. From $H_{peak}$ = 56.55 mT for an accelerating

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field of $E_{acc}$ = 12.5 MeV m$^{-1}$ follows that $H_{\perp}$ = 16.97 mT. With that can be calculated the heat loss $W_{loss}$ at the surface of the HOM antenna as follows [9]:

$$W_{loss} = \frac{1}{2} R_{S(BCS)}(T) \int |H_{\perp}|^2 dS. \quad (1)$$

Here is $R_{S(BCS)}(T)$ the BCS resistance plus the residual resistance of the surface material and has a temperature dependency. It is growing exponentially for T getting closer to $T_C$ of the material. In Ref. [10] calculated the heat loss of a Niobium and a $Nb_3Sn$ tip. It shows that the tip with $Nb_3Sn$ will be thermally more stable, so that the tip can tolerate an increased power load. The thermal dependency of $R_{S(BCS)}(T)$ can be approximated by the following phenomenological formula from [11]:

$$R_{S(BCS)}(T) = 1.643 \times 10^{-5} \times \frac{T_C}{T} (f(GHz))^2 e^{-\frac{1.92 \times T_C}{T}}. \quad (2)$$

This formula simplifies the dependencies to the operational frequency f, temperature T of the super conductor (sc) and the critical temperature $T_C$ of the sc. $R_{S(BCS)}$ also depends on material properties of the sc, like the London penetration depth $\lambda_L$, mean free path $l_{mfp}$, energy gap $\frac{\Delta(0)}{k_B T_C}$, coherence length $\xi_{BCS}$ and normal state DC resistivity $\rho_n$. Ref. [11] showed that the phenomenological formula is sufficient to describe the temperature dependency of Nb. Now one can assume that the there were materials which have Nb like material properties and only differ in the critical temperature. One can assume 16 K like NbTiN and 18 K like $Nb_3Sn$. So that with equation 2 the BCS resistance of these materials can be estimated.

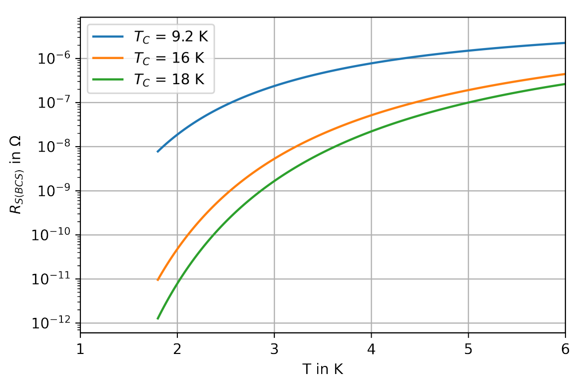


Figure 4: Calculated $R_{S(BCS)}$ for different $T_C$ assuming Nb like material properties.

In Fig. 4 is shown the surface BCS resistance for different $T_C$. The difference at the operational temperature at 1.8 K is in the region of 3 magnitudes, while it becomes smaller for higher temperatures. Since Nb, $Nb_3Sn$ and NbTiN are type 2 sc they will transit at some point in the Shubinkov-phase which means that the normal conducting part increases exponential in this phase until reaching $T_C$. This behavior is also neglected in the phenomenological formula. In Fig. 5

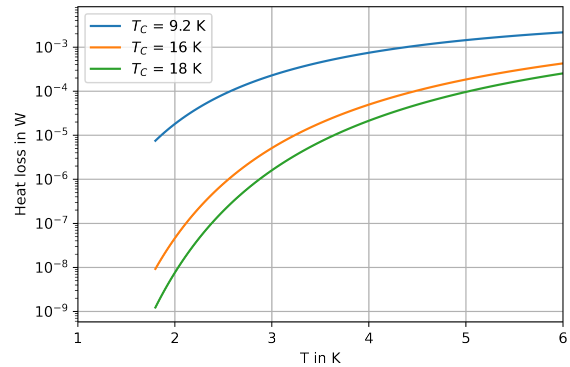


Figure 5: Calculated $P_{heatloss}$ for different $T_C$ assuming Nb like material properties.

is the heat loss at the antenna surface calculated through Formula 1. It shows the same behavior like the surface BCS resistance and for the higher $T_C$ material a significant lower heat loss can be estimated. Also the higher $T_C$ material will be more resistance to a temperature increase.

This approach assumes a heat input only from the input power forwarded to the cavity. The recirculating electron bunches will induce HOMs inside the cavity and store power in them. This power will manipulate the following electron bunch and impure the beam quality. In a worst case scenario this could lead to a beam loss. For MESA the beam current of 10 mA is the specification to achieve no beam loss. However a significant part of the power in HOMs will be coupled out from the cavity by the HOM-couplers and this will generate a heat loss at the HOM antenna. Through this additional thermal load the HOM antenna could be quenching and induce a quench of the whole cavity. For TESLA cavities an improvement could be achieved by using an sapphire feedthrough which improved the thermal coupling of the antenna up to a heat load of 43 mW [12]. However, this will be not sufficient for the beam currents of 10 mA. A further modification of the MEEC was an installation of an stripline coupler for direct cooling of the inner conductor of the HOM feedthrough [8]. With the addition of the stripline coupler the power limit could be improved up to 95 mW in simulations. To achieve an estimation for the stored power from the beam in the fundamental and longitudinal mode [13] presents a formula:

$$P = NqkI_{average} \quad (3)$$

where N is the number of beams in the cavity which is 4 in total in the ER mode for MESA, q is the bunch charge, k = 10 V pC$^{-1}$ the loss factor of the superconducting cavity and $I_{average}$ is the average beam current in the cavity. Table 2 presents beam induced HOM power. It is assumed that 30% of the stored power is transferred to the HOM antenna [13]. From that number it can be derived that 1000 mW will be present at the HOM antenna tip. This is more than a factor 10 larger than the value from the simulations. Nevertheless it

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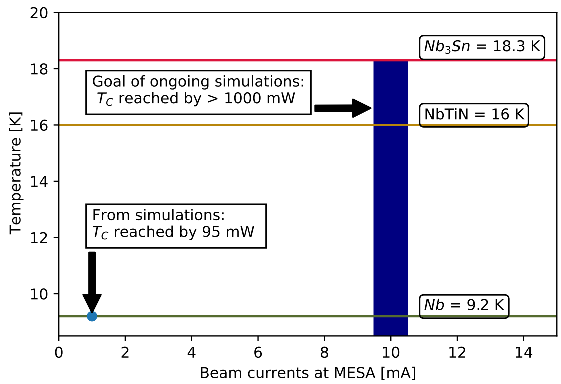


Figure 6: Simulation of power limits of HOM antenna tips. The currents DESY design fulfills the requirements for the ER mode at 1 mA. The quench is expected at 95 mW from simulations. The simulations are ongoing for the coated HOM antennas with $Nb_3Sn$ ($T_C$=18.3 K) and NbTiN ($T_C$=16 K). It is expected, that the coating will prevent a quench at beam currents of 10 mA.

is not fully understood if all of this power can be interpreted as pure heat load to the antenna tip. Figure 6 shows that the current HOM feedthrough design from DESY fulfills the requirements for MESA at 1 mA. For the beam currents the design needs to modify. Since the geometrical constrains are not changeable a thin film of $Nb_3Sn$/NbTiN could improve the power limit of the HOM feedthrough.

Table 2: Calculated power limits for two beam currents at MESA. The step to 10 mA leads to an increase of a factor of 100 for power stored in HOMs. This will cause an extensive power deposition at the HOM antenna tip and heating.

| $I_{average}$ mA | bunch charge pC | HOM power mW |
|---|---|---|
| 1 | 0.77 | 30.8 |
| 10 | 7.7 | 3080 |

### *Coating of $Nb_3Sn$ and NbTiN*

Given the constraint that the MEEC utilizes the DESY HOM coupler design, making significant geometric changes is not feasible without a complete redesign. However, one viable approach to enhance performance is to optimize surface properties such as increasing the critical temperature ($T_C$) and reducing the surface resistance ($R_{S(BCS)}$). This objective can be achieved by applying coatings of $Nb_3Sn$ or NbTiN on the HOM antenna tip. Since both of these materials exhibit higher $T_C$ values compared to pure Niobium, it is expected that HOM heating will be improved. Figures 4 and 5 present the anticipated effects on $R_{BCS}$ and heat loss at the antenna surface resulting from the utilization of higher $T_C$ superconductors. The coating will be done within a collaboration with University Hamburg and Technische Universität Darmstadt. At the University of Hamburg, the antennas will be coated with NbTiN using the Plasma-enhanced Atomic Layer Deposition (PEALD) technique [14]. On the other hand, at Technische Universität Darmstadt, a thin film of $Nb_3Sn$ will be applied to the antennas through magnetron sputtering [15]. These advanced coating methods are expected to significantly enhance the performance of the HOM antennas in the MEEC.

### *Copper as Core Material*

An alternative approach to address the existing challenges involves replacing the existing Niobium antenna with an antenna fabricated from Oxygen-Free High thermal Conductivity (OFHC) Copper. Subsequently, a coating of $Nb_3Sn$ or NbTiN would be applied to the Copper antennas. This integration of a superconducting thin film on the Copper substrate enables efficient management of the high induced surface currents at the antenna tip, while the Copper core facilitates enhanced thermal coupling. Notably, OFHC Copper exhibits superior thermal conductivity characteristics compared to Niobium. At a temperature of 1.8 K, the thermal conductivity of OFHC Copper exceeds that of Niobium by a factor exceeding 100 [16]. This significant disparity in thermal conductivity underscores the potential advantages of utilizing OFHC Copper as the antenna material in terms of improved thermal dissipation and heat management within the system.

## SUMMARY

The refurbishment of the ALICE cavities is ongoing. The removing of oil residuals in the helium tanks was for both cavities successful, so that the clean room treatment at the HIM will be done this summer. Calculations shown that a performance improvement is needed for the HOM feedthroughs in an upgrade phase of 10 mA at MESA. In this context, the implementation of coated HOM antennas appears to be a viable solution to achieve the desired performance improvements.

## OUTLOOK

After the clean room treatment of the cavities, a performance test is planned in a vertical cold test. In the same time new HOM feedthrough will be ordered. When the coating of the new HOM antennas was successful a performance test with the coated antennas will be done to measure the performance improvement. However, to comprehensively study the behavior of Higher Order Modes (HOMs) in a realistic operational scenario, it is crucial to perform a test by using a fully assembled cryomodule with an electron beam. As the installation of the MEECs is planned for the upcoming year and they are currently unavailable, this test can be conducted utilizing the reassembled spare cryomodule from the MESA facility. This approach ensures a practical evaluation of the HOM behavior and allows for valuable insights to be gained prior to the deployment of the MEECs.

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