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OPERATIONAL EXPERIENCE WITH TURN-KEY SRF SYSTEMS FOR SMALL ACCELERATORS LIKE MESA*

T. Stengler†, K. Aulenbacher, F. Hug, P.S. Plattner
Institute for Nuclear Physics, Johannes Gutenberg-Universität Mainz, Mainz, Germany

Abstract

New SRF-based accelerator development at sites without long-term experience in SRF development is a major challenge. Especially in-house development of cryomodules is an almost impossible obstacle to overcome for small projects. To minimize such obstacles, turn-key SRF systems provided by industry can be of great importance. For the multiturn ERL MESA, which is currently under construction at Johannes Gutenberg-Universität Mainz, two turnkey cryomodules have been purchased from industry and successfully tested. The specifications of a design gradient of 12.5 MV m^{-1} in CW operation with an unloaded Q of $1.25 \cdot 10^{10}$ at 1.8 K had to be met. Since the design of the modules had to be modified for high current CW operation, a close cooperation with the manufacturer was of great importance. By purchasing such a turn-key SRF system, the MESA project successfully established the SRF accelerator technology at the site within six years. This was achieved through close monitoring of the manufacturing process and close cooperation with the manufacturer. An overview of the experience with the successful technology transfer of a complete turn-key SRF system for small accelerators will be given.

INTRODUCTION

The development and operation of accelerators based on superconducting radio frequency (SRF) technologies is a major challenge. In particular, small institutes that want to develop smaller accelerator facilities for research and development often lack long-term experience and resources, which makes entry into the technology difficult. Especially in-house development of cryomodules is an almost impossible obstacle to overcome for small projects. Cryomodules play a crucial role in SRF-based accelerator systems, providing the necessary cooling and RF infrastructure for efficient operation. However, the design, fabrication, and integration of cryomodules require specialized expertise and significant financial investments. Small institutes often lack the necessary infrastructure, equipment, and technical know-how to undertake such complex endeavors independently. Consequently, they face significant barriers in realizing their ambitions for SRF-based accelerator development. Collaboration with established institutions, industry partners and research centres can provide a potential pathway for small projects to access the necessary expertise and facilities to meet this challenge and contribute to the advancement of SRF technology.

To gain a better understanding of these challenges, this paper analyses the integration of SRF technology within the framework of the MESA project at the Institute for Nuclear Physics, Johannes Gutenberg University Mainz. The MESA project serves as a case study to examine the difficulties and successes encountered in implementing SRF-based accelerators within a small institute.

MAINZ ENERGY-RECOVERING SUPERCONDUCTING ACCELERATOR (MESA)

The Mainz Energy-recovering Superconducting Accelerator (MESA) is an electron accelerator designed as an Energy Recovering Linac (ERL) which is currently under construction at the Institute for Nuclear Physics, JGU Mainz [1].

MESA has been specifically designed to meet the requirements of experiments [2–4] aimed at verifying the Standard Model of particle physics. These experiments demanding moderate beam energies up to 155 MeV but high beam currents up to 1 mA (CW). Ongoing research efforts are focused on exploring additional modifications to push the beam current limit up to 10 mA [5].

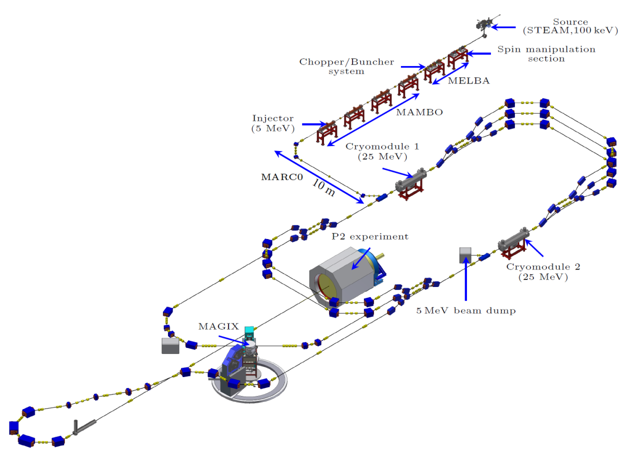

Figure 1: Layout of MESA. A normal-conducting pre-accelerator injects a 5 MeV CW beam into the recirculating main accelerator. Two cryomodules accelerate the beam. In external beam mode for the P2 experiment a 150 mA beam is recirculated thrice to a energy of 155 MeV and dumped afterwards.For the ERL experiment MAGIX 1 mA is recirculated twice up to 105 MeV. Afterwards the beam is decelerated in the main accelerator down to 5 MeV.

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† stengler@kph.uni-mainz.de

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In Fig. 1, the layout of MESA is depicted. The core components of the accelerator are two superconducting cryomodules. These cryomodules must be capable of meeting the stringent requirements for beam parameters. Due to the energy-recovering mode and the double-recirculating structure of the accelerator, the cryomodules need to accelerate the fourfold nominal beam current without encountering a beam break-up limit. This is because each cryomodule handles two accelerating and two decelerating beams simultaneously.

Due to the space limitations of the available halls and the requirements for acceleration gradients, it became evident that MESA would need superconducting accelerator modules. At the beginning of the project, in-house development of superconducting components and their operation exceeded the available capacities. Therefore, it was of utmost importance to collaborate with partners from academia and industry to find a solution that would reduce in-house development to a level commensurate with the scope of the project, while training the team in the use of SRF technology.

Through these collaborations, MESA was able to benefit from the expertise and experience of external partners who had already made significant advances in the field of superconductivity technology. This approach allowed the project to focus on integrating existing solutions and adapting them to MESA's specific requirements, thus reducing development time and costs.

TURN-KEY ELEMENTS

Since the Institute for Nuclear Physics already has in-depth experience in the development and operation of normal conducting accelerator components, only those areas of SRF technology that are particularly dependent on turn-key elements were identified:

- Cryomodules
  - Design
  - Production
  - Acceptance and Testing
- Cryogenic Circuit
  - Refrigeration system
  - Piping system

Given the size of the project, it was crucial to ensure a seamless integration between all these aspects not only within the accelerator but also during the Site Acceptance Test (SAT). Specifically, it was essential to ensure a smooth connection between the cryogenic infrastructure and the installation of the cryomodules.

To meet this requirement, it was decided to order all components for testing from a single supplier. This strategic decision aimed to promote a coherent and well-coordinated approach to the testing process. By procuring all the necessary components from a single source, potential compatibility issues and logistical challenges could be minimised. This consolidated procurement strategy allowed for better synchronisation and integration during the installation and testing phases.

Cryomodules

In order to meet both the technical requirements for the cryogenic modules and the requirements resulting of the size of the project, an in-house development was rejected. Instead, the aim was to use the experience gained from large-scale projects and to adapt the core parameters to this experience.

Design In the conception phase, a frequency of 1.3 GHz was chosen because these TESLA/XFEL cavities had already been produced in large series for the European XFEL project [6]. In order to meet both the technical requirements for the cryogenic modules and the size of the project, an in-house development was rejected. Instead, the aim was to use the experience gained from large-scale projects and to adapt the core parameters to this experience. In the conception phase, a frequency of 1.3 GHz was chosen because these TESLA/XFEL cavities had already been produced in large series for the European XFEL project [6]. For the determination of the acceleration gradient, an optimisation was carried out according to the following conditions: The fulfilment of spatial and financial requirements, as well as the minimisation of production iterations and thus manpower requirements. The spatial and financial requirements varied depending on the project. For the MESA project, this optimisation led to the choice of a design with two cryomodules, each containing two cavities that have a consvervative acceleration gradient of 12.5 MV m^{-1}.

With these specifications developed, a global tender was issued, leading to the selection of the ELBE/Rossendorf cryomodule system as the solution for MESA [7].

The advantage of this system was that it had already been used successfully for over ten years in the ELBE accelerator at Helmholtz Zentrum Dresden-Rossendorf (HZDR) [8] and had been used for other accelerators (e.g. ALICE at Daresbury Laboratory) [9].

Since no turnkey system met the exact requirements of MESA, the institute used its capacities to modify them for the specific requirements of the project and to set up a test environment for the acceptance of the modules [10]. This was done through close cooperation with the manufacturer.

Production The production of the cryomodules for MESA covered the period from 2015 to 2019. Of particular importance for the project was that the specification of the operating parameters (E_{Acc} and Q_0) were guaranteed by the manufacturer. This was only possible due to the moderate requirements (E_{Acc} = 12.5 MV m^{-1} with $Q_0 = 1.2 \cdot 10^{10}$ at T = 1.8 K). This enabled the tender requirements to have specified extensive testing procedures implemented, including vertical testing at DESY [11]. These tests not only played a crucial role in verifying the performance and reliability of the cryomodules, but also served to train the MESA team in the use of SRF components.

Overall, the combination of careful monitoring and knowledge transfer enabled the project team to successfully manage the production process, meet quality standards and equip

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their own staff with practical skills and a deeper understanding of the technology, resulting in a smoother SAT. A more in-depth analysis of the production and the SAT can be found in [12] and [13].

Testing The project schedule allowed for a separate horizontal test to be conducted in a dedicated test environment. This test environment offered the advantage that both the cryogenic infrastructure and its operation could be practised before the actual acceptance test of the cryomodules. By conducting this horizontal test, valuable experience could be gained that could be incorporated into the design of the cryogenic infrastructure for the accelerator. This made it possible to optimise and further develop the design by identifying possible weak points or potential for improvement at an early stage.

The experience gained in the vertical tests was incorporated into the construction of the test infrastructure. The construction was carried out in cooperation with the neighbouring Helmholtz Institute Mainz (HIM) [14] as the HIM cryomodule test facility. This consists of a test bunker with test areas for a MESA cryomodule and another multi-purpose test area which was used, among other things, for testing the normal conducting structures of the pre-accelerator [15] and the CH cavities of the Heavy Linear Collider of the FAIR project [16]. The construction of this test infrastructure is a crucial test for the integration of the turn-key SRF components into the in-house developed environments. By setting up the test stand, for example, the interface coordination for the integration of different functional groups (RF, cryogenics, IT, infrastructure, etc.) could be practised.

The SAT was carried out in close cooperation with the manufacturer. All components supplied from a single source (cryogenic distributor valve box, transfer line and cryomodules) were connected together for the first time and connected to the interfaces of the adjacent functional groups. All cavities are within specifications, as it is shown in Fig. 2.

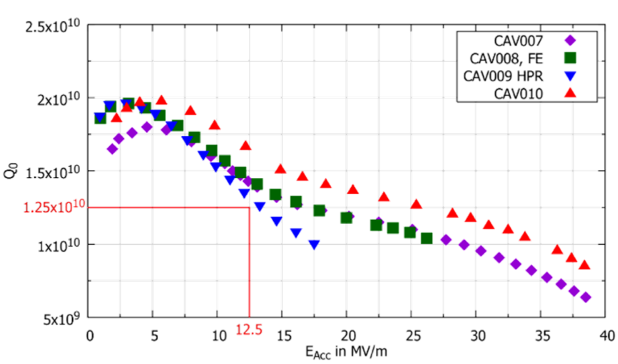

Figure 2: Q over E curve of the vertical test of the MESA cavities. It is shown that all four cavities are within the specification.

Cryogenic Circuit

To ensure that MESA's cryogenic cycle worked effectively, the construction of the HIM cryomodule test facility was crucial to gain the necessary experience. Overcoming challenges such as setting up a helium liquefier, implementing the cooling system and helium recovery were essential for successful operation. The expertise gained facilitated the design and implementation of a reliable cryogenic infrastructure for MESA, ensuring efficient cooling and minimising helium losses.

Refrigeration System The initial helium liquefier was procured in 2010, taking advantage of synergies between the early plans for MESA and experiments conducted on the existing accelerator [17]. The chosen liquefier had a capacity of 140 L h^{-1} and was prepared for future integration with MESA. Close collaboration with the manufacturer enabled necessary upgrades to be implemented, such as ensuring sufficient space in the cold box and preparing for nitrogen pre-cooling.

The helium liquefier was designed to be delivered as a turn-key system since neither the HIM cryomodule test facility nor the MESA infrastructure existed at the time of delivery. It was configured as a standalone system until the HIM cryomodule test facility became operational. Experience was gained through the operation of the liquefier, and during the cryomodule tests, valuable insights were gathered, which helped identify necessary modifications for the cold box. These lessons learned contributed to the optimization of the cryogenic infrastructure for MESA and further enhanced the overall system performance.

Currently, the Helium liquefier is under refurbishment for the MESA modifications.

Piping System The piping system for the HIM cryomodule test facility consists of several components. While the distribution valve box for the cryomodules and the transfer line in between were supplied by the cryomodule manufacturer, the pumping system to generate the 16 mbar is from another manufacturer. The MESA project team was responsible for integrating both control systems into a single control system and connecting them to the cooling system of the Institute of Nuclear Physics. The refrigeration systems are located on the site of the Institute for Nuclear Physics, while the test facility, including the 16 mbar subatmospheric compressor are located at HIM. Both institutes and sites had to be connected by a 200 m long line.

By designing the parameters in collaboration with partners from academia and industry, expertise was developed to adapt the cooling system to MESA's needs and to order the cryogenic infrastructure for MESA. Importance was also placed on sourcing the entire MESA system from a single supplier to minimise potential problems and streamline the integration process.

Seamless integration of the piping system components and successful coordination between the various suppliers and the MESA project team were critical to the smooth operation of the cryomodule test facility. This collaborative approach not only facilitated the achievement of the MESA objectives, but also contributed to the overall efficiency and reliability of the cryogenic infrastructure.

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An overview of the cryogenic infrastructure can be found in [18]. The piping system is shown in Fig. 3.

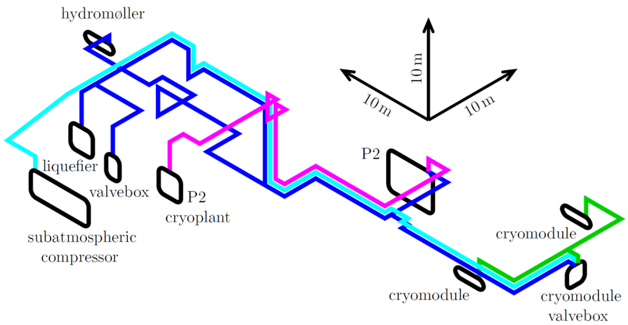

Figure 3: Piping path, dark blue = supply line, green = cryomodule distribution, light blue = 16 mbar string, magenta = P2 target cooling circuit.

CONCLUSION

With the procurement of turnkey core components for the MESA accelerator, the Institute of Nuclear Physics at JGU Mainz has successfully integrated SRF technology within six years. Through close cooperation with partners and manufacturers, not only were turnkey cryogenic modules including the associated cryogenic infrastructure procured, but a wealth of practical knowledge was also gained. As a result, the Mainz site has become an active member of the SRF community. Equipped with a state-of-the-art test infrastructure consisting of a horizontal test stand and an ISO4 clean room, the Mainz site is already making an important contribution to SRF research.

Once the ERL MESA is operational, the community will have access to a small SRF-based accelerator that will not only serve to verify the Standard Model of particle physics, but also play a crucial role in training future generations in SRF technology. This compact accelerator will provide valuable hands-on training opportunities and promote the development of expertise in SRF technology.

Overall, the Institute of Nuclear Physics at JGU Mainz has successfully established itself as a key player in the SRF community through strategic procurement of turnkey components and active collaboration. The integration of SRF technology at the Mainz site not only advances particle physics, but also contributes to the development of a skilled workforce and expertise in SRF technology. The successes achieved in the process provide a solid foundation for future advances and breakthroughs in the field.

By showcasing the successful integration of SRF technology at the Institute for Nuclear Physics at JGU Mainz, we aim to encourage other institutions to embark on similar endeavors, contributing to the overall growth and advancement of the field.

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We also extend our heartfelt thanks to the entire SRF community for their continuous support and collective efforts in advancing the field. The exchange of knowledge, ideas, and experiences has been instrumental in shaping our understanding and pushing the boundaries of SRF technology.

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Lastly, we would like to express our deepest appreciation to the dedicated team members and staff who have worked tirelessly throughout this project. Their commitment, enthusiasm, and hard work have been instrumental in achieving our goals and establishing a thriving SRF research and development facility.

REFERENCES

[1] F. Hug *et al.*, " Status of the MESA ERL Project ", in *Proc. ERL'19*, Berlin, Germany, Sep. 2019, pp. 14–17. doi:10.18429/JACoW-ERL2019-MOCOXBS05

[2] A. Denig, "Recent results from the Mainz Microtron MAMI and an outlook for the future", *AIP Conf. Proc.*, vol. 1735, p. 0200006, 2016. doi:10.1063/1.4949374

[3] D. Becker *et al.*, "The P2 Experiment", *Eur. Phys. J. A*, vol. 54, p. 208, 2018. doi:10.1140/epja/i2018-12611-6

[4] L. Doria, P. Achenbach, M. Christman, A. Denig, and H. Merkel, "Dark Matter at the Intensity Frontier: the new MESA electron accelerator facility", in *Proc. ALPS'19*, Obergurgl, Austria, Apr. 2019. doi:10.48550/arXiv.1908.07921

[5] P. Plattner, F. Hug, and T. Stengler, "Refurbishment of an ELBE-Type Cryomodule for Coated HOM-Antenna Tests for MESA", presented at SRF'23, Grand Rapids, USA, Jun. 2023, paper SUSPB042, this conference.

[6] D. Reschke, "Recent Progress with EU-XFEL", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, pp. 14–23. doi:10.18429/JACoW-SRF2015-MOAA02

[7] F. Schlander, K. Aulenbacher, R.G. Heine, D. Simon, and T. Stengler, "1.3 GHz SRF Cryomodules for the Mainz Energy-recovering Superconducting Accelerator MESA", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 2853–2855. doi:10.18429/JACoW-IPAC2015-WEPMA041

[8] J. Teichert *et al.*, "RF status of superconducting module development suitable for CW operation: ELBE cryostats", *Nucl. Instrum. Methods Phys. Res., Sec. A*, vol. 557, p. 239, 2006. doi:10.1016/j.nima.2005.10.077

[9] P.A. McIntosh *et al.*, "Assembly Preparations for the International ERL Cryomodule at Daresbury Laboratory", in *Proc. SRF'09*, Berlin, Germany, Sep. 2009, paper THPPO098, pp. 864–868.

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB082

[10] T. Stengler *et al.*, "Modified ELBE Type Cryomodules for the Mainz Energy-Recovering Superconducting Accelerator MESA", in *Proc. SRF'15*, Whistler, Canada, Sep. 2015, pp. 1413–1416. doi:10.18429/JACoW-SRF2015-THPB116

[11] T. Stengler, K. Aulenbacher, F. Hug, D. Simon, and T. Kuerzeder, "Cryomodule Fabrication and Modification for High Current Operation at the Mainz Energy Recovering Superconducting Accelerator MESA", in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 297–300. doi:10.18429/JACoW-SRF2017-MOPB101

[12] T. Stengler, K. Aulenbacher, F. Hug, and S.D.W. Thomas, "SRF testing for Mainz Energy Recovering Superconducting Accelerator MESA", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 508–512. doi:10.18429/JACoW-SRF2019-TUP041

[13] T. Stengler, K. Aulenbacher, F. Hug, and D. Simon, "Status of the Cryogenic Infrastructure for MESA", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 539. doi:10.18429/JACoW-SRF2021-WEPFAV004

[14] T. Stengler *et al.*, "Status of the Superconducting Cryomodules and Cryogenic System for the Mainz Energy-recovering Superconducting Accelerator MESA", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 2134–2137. doi:10.18429/JACoW-IPAC2016-WEPMB009

[15] R. G. Heine, "Testing of the Milliampere Booster Prototype Cavity", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2693–2696. doi:10.18429/JACoW-IPAC2021-WEPAB041

[16] M. Miski-Oglu *et al.*, "Progress in SRF CH-Cavities for the HELIAC CW Linac at GSI", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 1206–1212. doi:10.18429/JACoW-SRF2019-FRCAA4

[17] K. Aulenbacher, "Opportunities for parity violating electron scattering experiments at the planned MESA facility", in *Hyperfine Interact.*, vol. 200, pp. 3-7, 2011. doi:10.1007/s10751-011-0269-9

[18] F. Hug *et al.*, "Cryogenic Installations for Module Tests at Mainz", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 997–1002. doi:10.18429/JACoW-SRF2019-THP054