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The Cryogenic System for the Mainz Energy-recovering Superconducting Accelerator (MESA)

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Abstract. The Mainz Energy-recovering Superconducting Accelerator (MESA), under construction at Johannes Gutenberg University Mainz, is a superconducting multi-turn energy recovery linac (ERL) delivering high-intensity, low-energy electron beams for precision tests of the Standard Model. MESA's cryogenic system supports two superconducting radiofrequency (SRF) cryomodules (XFEL/TESLA-type, 1.3 GHz) cooled to 1.8 K with up to 8 g/s helium at 16 mbar, a superconducting solenoid for the P2 experiment at 4 K, and a hydrogen target liquefied by 15 K helium. The components and lines are liquid-nitrogen (LN2) shielded.

Helium and nitrogen are distributed from surface-based liquefier and refrigerator to the accelerator 10 m underground via multiple transfer lines, feeding three distribution valve boxes, a 16 mbar subatmospheric compressor for the 1.8 K system and the recovery system. Upgrades to the existing structure include an enhanced helium liquefier to meet flow demands and impurity control, and a dedicated 15 K refrigerator providing the 4 kW cooling to the P2 hydrogen target.

This paper introduces the MESA accelerator and discusses the design and current status of the MESA cryogenic system, focusing on key components such as the cryomodules, the P2 experiment, valve boxes, transfer lines, and the 16 mbar pumping system.

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1 The Mainz Energy-recovering Superconducting Accelerator (MESA)

1.1 Introduction

Particle accelerators have long been essential tools in fundamental research, significantly contributing to the discoveries summarized in the Standard Model of particle physics.

While the Standard Model remains a robust framework for describing elementary particles and their interactions, several observed phenomena cannot be fully explained within its current formulation. This has motivated an ongoing search for physics beyond the Standard Model. Various hypothetical particles have been proposed to address these discrepancies, but none have been experimentally confirmed to date.

Past experiments have laid a strong foundation, but further progress requires improved experimental precision and intensity. Enhancing these parameters allows researchers to probe subtle effects that may have been hidden within the uncertainties of earlier measurements[1].

The Mainz Energy-Recovering Superconducting Accelerator (MESA), currently under construction at the Institute for Nuclear Physics at Johannes Gutenberg University Mainz, is specifically designed to investigate the Standard Model at low energies and high beam intensities [2]. An overview of the current MESA layout is shown in Fig. 1.

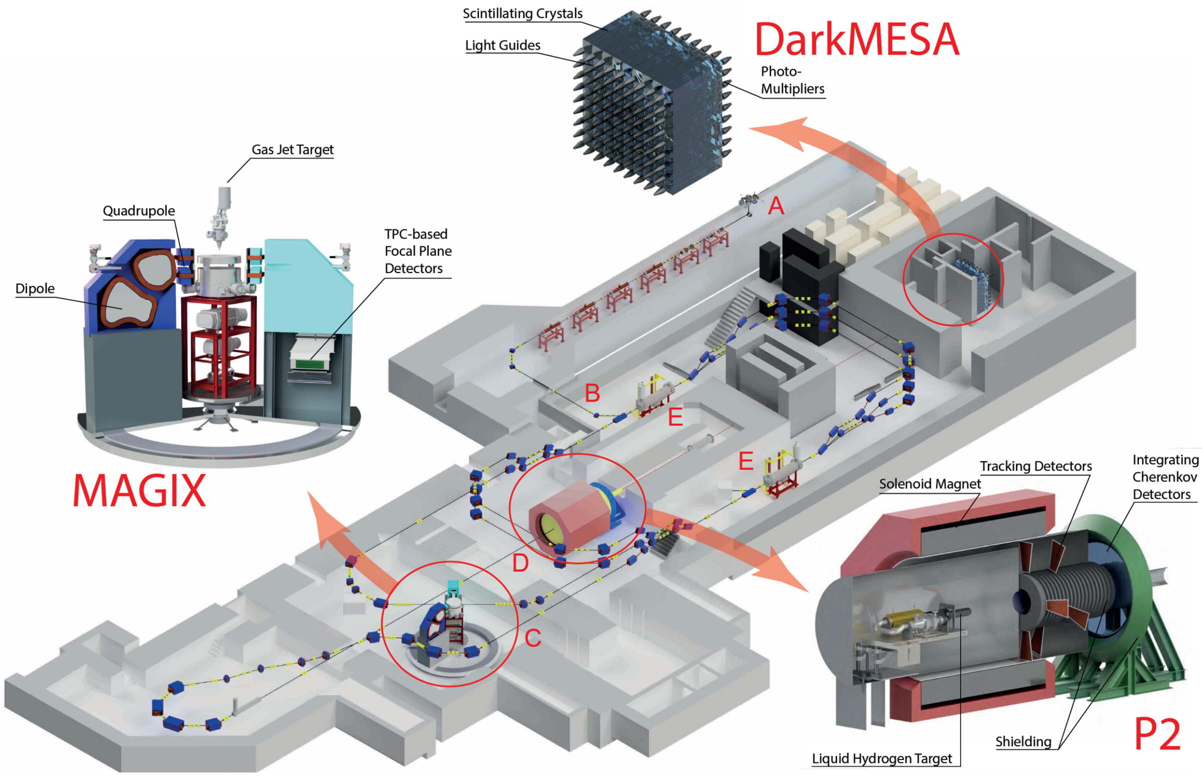

Figure 1: Current design of the Mainz Energy-recovery Superconducting Accelerator (MESA). The injector (A) produces continuous-wave electron beam at 5 MeV and injects them into the main accelerator (B). The two acceleration modules (E), each providing an energy gain of 25 MeV, are traversed multiple times by the electrons before being directed to the experiments MAGIX (C) and P2/DarkMESA (D).

1.2 Design of MESA

MESA is designed as a mulit-turn recirculating linear accelerator, in which the electron beam passes multiple times through the same acceleration structures to achieve progressively higher energies. The beam is separated into different beamlines in the return arcs according to its energy. This configuration reduces the number of required acceleration modules and enables energy recovery, making MESA an efficient energy-recovering linear accelerator (ERL) [2].

The accelerator comprises four functional sections: injection and pre-acceleration (A), the main accelerator (B) containing the cryomodules (E), and two experimental beamlines — MAGIX (C) a spectrometer with a gas jet target, P2 (D) a liquid hydrogen (H_2) target in a solenoid field and DarkMESA a beam dump experiment in conjunction with P2 [1, 3]. Electrons are transported through a vacuum beamline at 1×10^{-9} mbar within a magnetic lattice [4]. The injector LINAC consits of the electron source and accelerating the electron beam to 5 MeV. In the main accelerator section, the beam gains energy through multiple passes in the cryomodules. Depending on experimental needs, the beam is then directed to either of the experiments. Simultaneous operation is not foreseen due to differing beam requirements.

Among the three main experiments planned at MESA—MAGIX, P2, and DarkMESA—only P2 requires cryogenic infrastructure. Consequently, the following sections focus on the cryogenic systems relevant to the P2 beamline and the cryomodules.

A central objective of the P2 experiment is the precise determination of the electroweak mixing angle (Weinberg angle), $\sin^2\theta_W$, at low momentum transfer [1]. Existing measurements in this regime are associated with relatively large uncertainties. Improved precision could reveal deviations from Standard Model predictions and hint at new physics. To achieve the precision in the measurement, the electron beam with an energy of 155 MeV and a beam current of 150 µA will be scattered with a liquid hydrogen target placed within a magnetic field.

Both the hydrogen target and the superconducting solenoid generating the field must be cryogenically cooled, and are thus integrated into the MESA cryogenic system [5].

2 Cryogenic Overview

The MESA cryogenic system supports two ELBE-type superconducting cryomodules operating at 1.8 K and thermally shielded with LN_2. A more detailed description of the cryomodule design and testing is provided in Section 2.1. Additionally, the P2 experiment includes a superconducting solenoid and a liquid hydrogen target. The solenoid operates at 4 K, while the LH_2 target is cooled using 15 K helium gas with a cooling capacity of 4.2 kW. An overview of the nominal LN_2 and LHe consumption rates for 1.8 K operation is provided in Table 1.

Table 1: Cooling Demands for MESA Cryogenic Components

Component	**Cooling Type**	**Temperature**	**Flow Rate**	**Cooling Power**
2 Cryomodules	LHe	1.8 K	$8\,\mathrm{g\,s^{-1}}$	–
	LN_2	77 K	$50\,\mathrm{L\,h^{-1}}$	–
P2 Solenoid	LHe	4 K	$3.7\,\mathrm{g\,s^{-1}}$	–
	LN_2	77 K	$5\,\mathrm{L\,h^{-1}}$	–
P2 LH_2 Target	GHe	15 K	$200\,\mathrm{g\,s^{-1}}$	4.2 kW

A schematic lay-out of the MESA cryogenis system is shown in Fig. 2. A helium liquefier with LHe storage dewar feeds the cryomodules and superconducting solenoid and a 15 K helium refrigerator feeds the liquid hydrogen target. A cryogenic distribution system connects the surface cryoplants to the cryomodules and P2 experiment located in the underground experimental area. The cryogenic distribution system consists of three distribution valve boxes, several multi cryogenic transfer lines and flexible transfer lines. To obtain 2K operation, the system contains further a subatmospheric compressor system and electrical heater. The components are discussed in detail in the following subsections.

2.1 Cryomodules and Cryomodule Valve Box

Each of the two superconducting ELBE-type cryomodules at MESA contains two XFEL-type cavities and is designed for operation at 1.8 K. To reach this temperature, a Joule–Thomson (JT) valve and a heat exchanger are mounted in a dedicated tower above the cavities. This setup enables precise control of cooling in the low-pressure helium environment [6].

Helium vapor from the cryomodules is collected and routed through a gas return line to a subatmospheric pumping system operating down to 16 mbar. A dedicated Cryomodule Valve Box (CM-VB) ensures equal pressure and flow distribution to the cryomodules. The CM-VB was designed with a low design pressure to remain outside the scope of the European Pressure Equipment Directive (PED), simplifying certification but requiring meticulous design of the helium distribution network.

The CM-VB and cryomodules were the first components procured for the MESA cryogenic system, with the order placed in 2015. Initial commissioning—including cooldown and radiofrequency (RF) testing without beam—was conducted at the Helmholtz Institute Mainz between 2016 and 2020. Both cryomodules met all technical specifications during these tests [7].

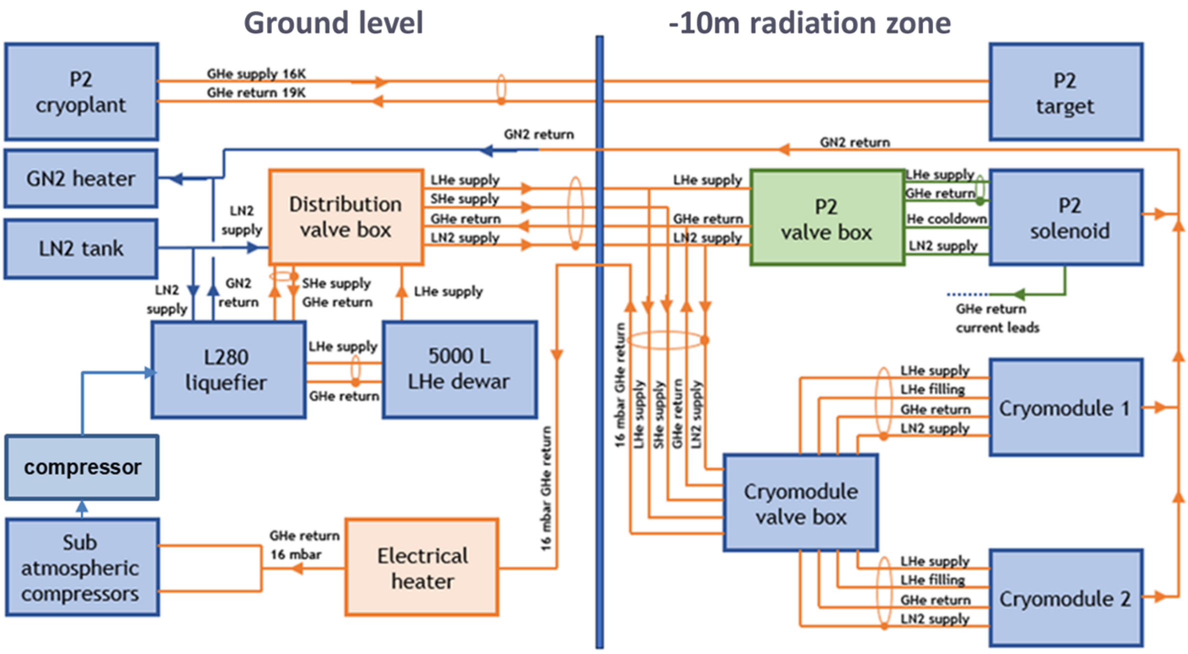

Figure 2: Process Flow Diagram of the cryogenic components of MESA.

Thermal performance measurements at the nominal accelerating gradient revealed total static heat loads of $P_{\text{heat, CM1}} = 27.5\,\text{W}$ and $P_{\text{heat, CM2}} = 34.2\,\text{W}$ for Cryomodules 1 and 2, respectively. These values are well below the specified maximum of 40 W, providing a thermal margin of 22.9 % to accommodate possible future degradation in cavity performance.

2.2 P2: Solenoid and Heat-Exchanger

The P2 experiment at MESA includes two cryogenically cooled components: a superconducting solenoid and LH_2 target system.

The superconducting solenoid is operated at 4 K with liquid helium at a mass flow rate of up to $3.7\,\text{g}\,\text{s}^{-1}$ during cooldown and $\leq 1\,\text{g}\,\text{s}^{-1}$ for operation. To reduce thermal radiation, the solenoid is equipped with a thermal shield actively cooled by liquid nitrogen with a consumption rate of around $5\,\text{L}\,\text{h}^{-1}$. The cryogens are distributed to the solenoid via the P2 Valve Box (P2-VB) that connects to a main supply and return multi transfer line (MTL). One coaxial and two single vacuum insulated flexible transfer lines connect the P2-VB to the P2 solenoid to allow for mechanical decoupling, ease of disconnections and simplified maintenance access.

The LH_2 target is cooled by a gaseous helium heat exchanger operating at 15 K, which is fed by a separate helium refrigerator system. A two-fold (supply and return) multi transfer line connects the LH_2 target to the refrigerator. This circuit is designed to provide up to 4.2 kW of cooling power at a helium mass flow of approximately $200\,\text{g}\,\text{s}^{-1}$. The target design allows stable hydrogen liquefaction under continuous high-current beam operation.

The separation of both cooling loops—one from the main liquefier and the other from the 15 K refrigerator—enables independent control and optimized performance for both the solenoid and the target. Both systems are fully integrated into the common cryogenic distribution network via flexible and coaxial transfer lines.

2.3 Liquefier and Refrigerator

The core of the MESA cryogenic supply system consists of a modified L280 helium liquefier and an additional 15 K refrigerator, both provided by Linde Kryotechnik. The L280, originally procured in 2010, had to be upgraded to support the demands of MESA. A $25\,\text{m}^3$ buffer tank operating at 14 bar is currently installed, with future expansion already planned. The prepared foundation allows for an upgrade to accommodate a tank volume of up to $200\,\text{m}^3$.

The upgrade of the L280 liquefier included several key modifications to adapt the system to the new operational requirements. Liquid nitrogen precooling was integrated to improve liquefication capacity from $140\,\mathrm{L\,h^{-1}}$ to $270\,\mathrm{L\,h^{-1}}$.

To protect the system from potential contamination—particularly from impurities entering through the 16 mbar subatmospheric return lines—a dual 80 K internal adsorber was integrated to prevent the freezing of residual gases.

Additionally, the L280 system supports the extraction of a supercritical helium (SHe) gas stream and is able to ramp the temperature of the helium gas stream for cooldown and warm up. The operational performances of the L280 can be found in Tab. 2. The upgraded L280 liquefier was successfully brought online in 2024, with SHe/mixed-mode operation scheduled for testing within the commissioning phase of the cryogenic system.

Table 2: L280 Liquefier Performance Overview

Operating Mode	Performance
Liquefaction	$270\,\mathrm{L\,h^{-1}} = 9.1\,\mathrm{g\,s^{-1}}$ at 4.4 K, 1.2 bar
Refrigeration	5.5 K, 3 bar, $8\,\mathrm{g\,s^{-1}}$ (net SHe)
Mixed-Mode	$1\,\mathrm{g\,s^{-1}}$ LHe + $<8\,\mathrm{g\,s^{-1}}$ SHe (net)
Helium Throughput	$80\,\mathrm{g\,s^{-1}}$ HD He (typical)

To meet the cooling demands of 4 kW of the P2 experiment's H_2-target heat exchanger, a separate 15 K refrigerator was procured, capable of delivering up to 4.2 kW of cooling power at a flow rate of approximately $200\,\mathrm{g\,s^{-1}}$ of helium gas. The commissioning is ongoing and is expected to be finished within the next months.

Table 3: 15 K Refrigerator Performance Overview

Parameter	Value
Cooling Power	4.2 kW at 15 K
Helium Flow Rate	$200\,\mathrm{g\,s^{-1}}$

2.4 Subatmospheric Compressor and Heater

A key component of the MESA cryogenic infrastructure is the subatmospheric helium return system, which operates at pressures as low as 16 mbar. This subatmospheric compressor is essential to maintaining superfluid helium conditions at 1.8 K within the cryomodules. Helium vapor from the cryomodules is collected in a common manifold and directed to a central compressor located in the surface-level cryoplant.

The subatmospheric compressor designed by Pfeiffer Vacuum comprises two parallel strings, each equipped with four Roots pumps (Okta 6000M, 4000M, 2000M, and 1500GM) and one screw compressor (Cobra NS600). To avoid contamination, all Roots pumps utilize magnetically coupled drives, and the screw compressors are hermetically sealed using canned motors.

The inlet pressure of the compressor can be adjusted within a range of 11 mbar to 36 mbar at a helium flow rate of up to $8\,\mathrm{g\,s^{-1}}$, controlled via a frequency converter connected to the Okta 6000M Roots pumps. This flexibility supports precise system regulation and pressure control.

The complete subatmospheric compressor unit was tested in 2023 and met all performance specifications.

Since the inlet temperature of the subatmospheric compressor is designed for ambient conditions, the returning helium gas must be reheated. Due to spatial and architectural constraints within the existing building, the subatmospheric heater had to be mounted outside, fixed to a wall at an elevated position. First, a passive heater was selected to reduce the power consumption. However, climatic conditions and dimensional limitation restricted the installation to an active electrical heater with a maximum heating power of 15 kW. The subatmospheric heater is part of the distribution system and designed and manufactured by Cryoworld. The heater consists of an immersion flange heater with optimized baffle plate spacing to allow for efficient heating of the 16 mbar GHe. The immersion flange heater is installed in a vacuum insulated vessel that is slightly tilted upwards to minimize the natural convection. The heater power is controlled by solid state relays to heat the GHe to room temperature, measured by a temperature transmitter located at the outlet. All flanges are equipped with a helium guard to avoid pollution of the GHe by air. The manufacturing and installation is ongoing and performance tests are planned within 2025.

2.5 Distribution System

The cryogenic distribution system for MESA is built, installed and delivered by Cryoworld and serves as the interface between the central cryoplant infrastructure located at the surface and the underground located experiments. A 3D view of the cryogenic distribution system within scope of Cryoworld is shown in Fig. 3. It includes a main distribution valve box (DVB) and the P2-VB for the P2 experiment. The DVB is located at the surface and manages the distribution of LHe and LN_2 flows from the cryoplant and LHe storage dewar to the underground equipment. The P2-VB handles the helium and nitrogen supply and controlled cool-down and warm-up to the P2 solenoid.

The distribution system includes several MTLs. The main MTL connects the DVB to the P2-VB and cryomodule VB and contains five process pipes within a single vacuum jacket. The main MTL includes an actively cooled thermal shield connected to the LN2 supply to minimize the heat load to the 4 K process pipes. Additionally, two 4-fold MTLs connect each cryomodule to the cryomodule VB, also including an actively cooled thermal shield. For the P2 experiment, a separate 2-fold MTL connects the 15K refrigerator to the target heat exchanger. In this MTL, the supply line is actively shielded by the return line. A dedicated vacuum insulated GN_2 return line, connecting to the P2 solenoid and the two cryomodules, returns the gaseous nitrogen flow to the surface where it can be safely vented to atmosphere. A summary of the length and performance of the MTLs is given in Table 4. Two electrical cabinets, one located at the surface and one near the P2-VB, include a Siemens PLC and electronics for read-out and control of the sensors, valves and electrical heater.

Table 4: Pressure Drop and Heat Entry into main lines

Component	**L [m]**	**Heat Entry [mW/m]**	**Pressure Drop [mbar]**
MTL main (5-fold)	72	34 / < 1200 (4K/LN2 supply)	111 (SHe) / 19 (LHe)
MTLs to cryomodules (2x)	18	<40 / < 1200 (4K/LN2 supply)	1
MTL P2 cryoplant – target	50	573 / 1257 (supply/return)	48 / 138

3 Design Challenges

The implementation of the MESA cryogenic system presented a number of design challenges, primarily due to the combination of new components with existing infrastructure. The overall system layout could not be fully optimized, as parts of the facility—such as buildings and cable routing—had to be reused. A key constraint was the decision to keep the design pressure of several components, including the cryomodules, helium dewars, and the P2 solenoid, below 0.5 barG to remain outside the scope of the European Pressure Equipment Directive (PED). While this simplifies certification procedures, it necessitated a complex safety analysis for the subatmospheric helium return system, DVB, P2-VB and associated MTLs.

The routing of the cryogenic transfer lines (MTLs) from the surface-level cryoplant to the underground accelerator area required careful consideration. Space constraints, radiation protection requirements, and accessibility issues made the layout particularly challenging. A drawing of the rounting can be found in Fig. 3. To reduce system complexity, multiple cryogenic circuits were consolidated into a single main MTL bundle. The number of pipe bends was minimized to lower pressure losses and thermal load.

Special attention was given to flexibility and serviceability. Coaxial and flexible transfer lines were used between the P2 valve box and the superconducting solenoid to allow for mechanical decoupling, ease of disconnection, and positional adjustments during installation and maintenance. Furthermore, the presence of ionizing radiation in the underground experimental area influenced design decisions regarding material selection, shielding, and component accessibility.

4 Status and Outlook

As of May 2025, significant progress has been made in the installation of the MESA cryogenic distribution system. The cryomodule valve box (CM-VB) and both superconducting cryomodules have been

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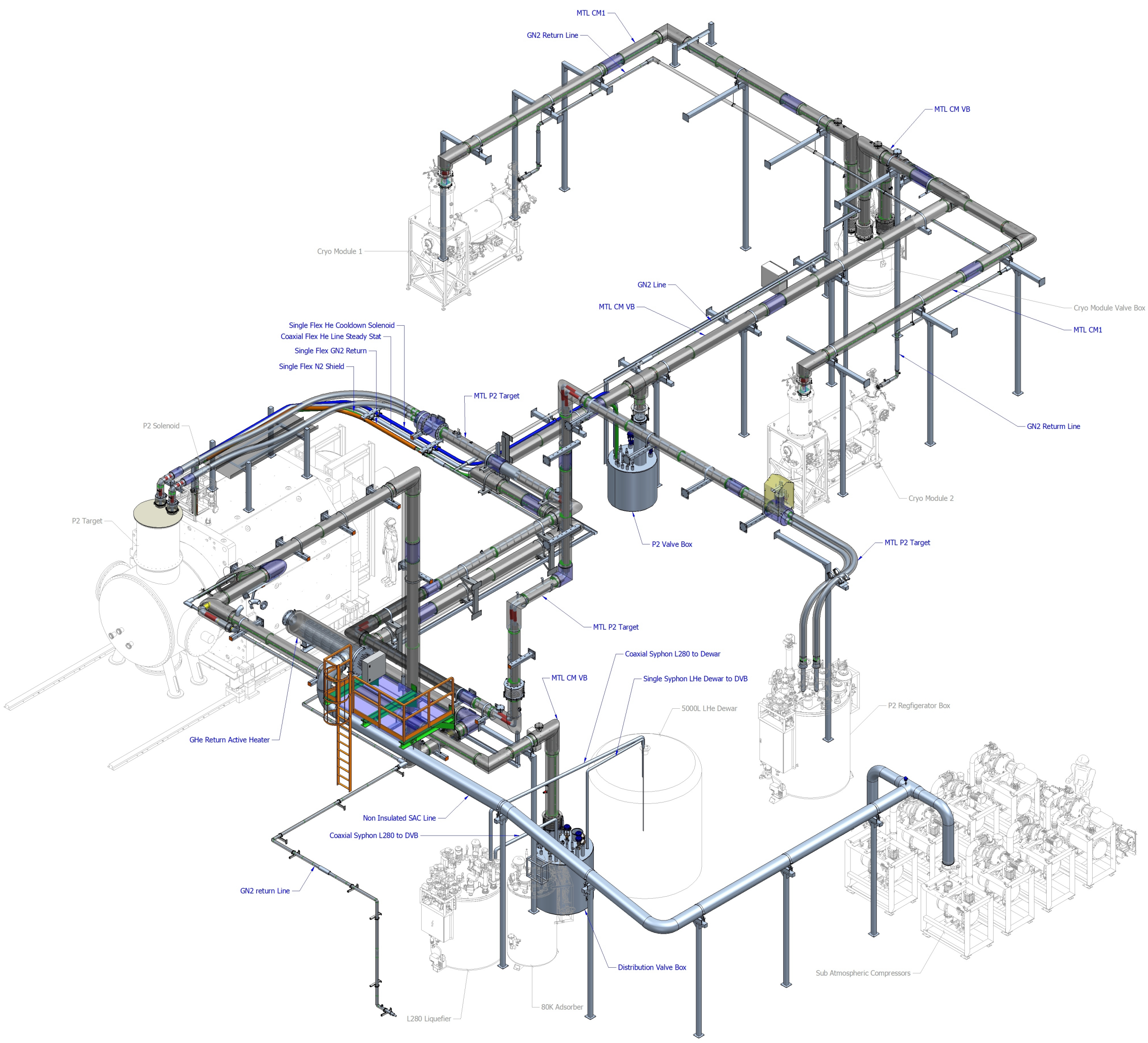

Figure 3: 3D view of MESA's cryogenic components. This geometry had to be chosen due to the constraints imposed by the existing buildings.

positioned within the accelerator hall. The main multi-line transfer line (MTL), the GN_2 return line, and the connections to the CM-VB are fully installed and routed from the surface-level cryoplant to the underground experimental area.

The transfer line to the P2 experiment is also largely in place, with the exception of its initial and final sections. These two sections are manufactured and factory accepted tested and are ready for installation. The installation phase required careful coordination with civil engineering and radiation safety constraints, particularly in the underground zones. The system design allows for modular completion and testing, enabling stepwise integration and early functional verification of key components.

The DVB and required U-tube transfer lines are manufactured, factory acceptance testing is ongoing. Installation of these components and finalization of the main MTL and P2 MTL is planned to start mid-June. Manufacturing of the P2-VB and flexible transfer lines has started, while the vacuum insulated heater vessel is fully designed and material being purchased. Factory acceptance testing of these components is expected beginning of July 2025. The installation work is scheduled for completion by the end of summer 2025, marking a key milestone in preparation for system commissioning and initial cooldown.

5 Conclusion

The cryogenic system for the MESA accelerator at Johannes Gutenberg University Mainz represents a complex integration of new and legacy infrastructure within significant spatial and regulatory constraints. Core components such as the modified L280 liquefier, a dedicated 15 K refrigerator, and a subatmospheric helium return system have been successfully installed and tested. The cryomodules and the cryogenic interfaces for the P2 experiment are in place, and the distribution system is largely completed.

Key design challenges—such as low operating pressures, complex transfer line routing, and radiation-zone compatibility—were addressed through a combination of system consolidation, flexible transfer line technology, and modular valve box architecture. The system has demonstrated its capability to support multiple cooling regimes including superfluid helium, LN_2 shielding, and high-flow 15 K helium gas.

The final installation steps are expected to be completed by the end of summer 2025, followed by the first cooldown and commissioning phase. Lessons learned include the importance of early, system-level planning and the feasibility of implementing advanced cryogenic infrastructure in existing buildings. Operational experience gained during commissioning will inform future upgrades and long-term system optimization.

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References

[1] Becker D et al 2018 The P2 experiment *Eur. Phys. J. A* **54** 208 doi:10.1140/epja/i2018-12611-6

[2] Aulenbacher K 2013 The MESA accelerator *AIP Conf. Proc.* **1563** 5–12 doi:10.1063/1.4829369

[3] Doria L et al 2019 Dark matter at the intensity frontier: the new MESA electron accelerator facility *PoS(ALPS2019)* 022 doi:10.22323/1.360.0022

[4] Simon D 2021 Overall concept for the MESA particle accelerator with special consideration of beam optics and cryogenics (Johannes Gutenberg University Mainz)doi:10.25358/openscience-5809

[5] Stengler T, Aulenbacher K, Hug F and Simon D 2021 Status of the cryogenic infrastructure for MESA *Proc. SRF'21* East Lansing, MI, USA p 539 doi:10.18429/JACoW-SRF2021-WEPFAV004

[6] Stengler T et al 2015 Modified ELBE type cryomodules for the Mainz energy-recovering superconducting accelerator MESA *Proc. SRF'15* Whistler, Canada 1413–1416 doi:10.18429/JACoW-SRF2015-THPB116

[7] Hug F et al 2019 Cryogenic installations for module tests at Mainz *Proc. SRF'19* Dresden, Germany 997–1002 doi:10.18429/JACoW-SRF2019-THP054