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CRYOGENIC INSTALLATIONS FOR MODULE TESTS AT MAINZ*

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Abstract

At Helmholtz Institute Mainz (HIM) a cryomodule test bunker has been set up for testing dressed modules at 2 K. In a first measurement campaign the high power rf tests of two 1.3 GHz cryomodules for the future MESA accelerator have been performed. We will report on the performance of the test setup, the present and upcoming cryogenic installations at the Institute for Nuclear Physics at Mainz (KPH), and in particular on the Helium refrigeration and transport system comprising of a 220 m transport line for liquefied gases.

INTRODUCTION

The future installation of the superconducting MESA accelerator at KPH [1] and the preparatory work at HIM to a CW-operating SRF linac for superheavy element research at GSI [2] have resulted in an increasing demand of liquid Helium (LHe) at both institutes. Therefore, in 2010 a Linde L280 liquefier, yet without liquid nitrogen (LN2) precooling, cryogenic adsorber, and Helium purity monitor, has been installed at KPH. For better efficiency, the liquefier was originally designed (by constructional preparations) to accept 77 K helium from shield cooling or cavity cryostat (additional sidestream input). A considerable amount, up to 66% of the refrigeration energy of 250 kW can be saved in principle [3]. For funding reasons and because of lack of time it was decided to postpone the implementation of such a cold gas return heat exchanger. An LN2 preecooling is already implemented as standard but will be more efficient by replacing the turbines (220 vs 280 l/h) For that, and for installing an additional tandem operating cold adsorber enabling continuous weeks of operation the liquifier needs to be sent to Linde. In 2014 a sub atmospheric compressor

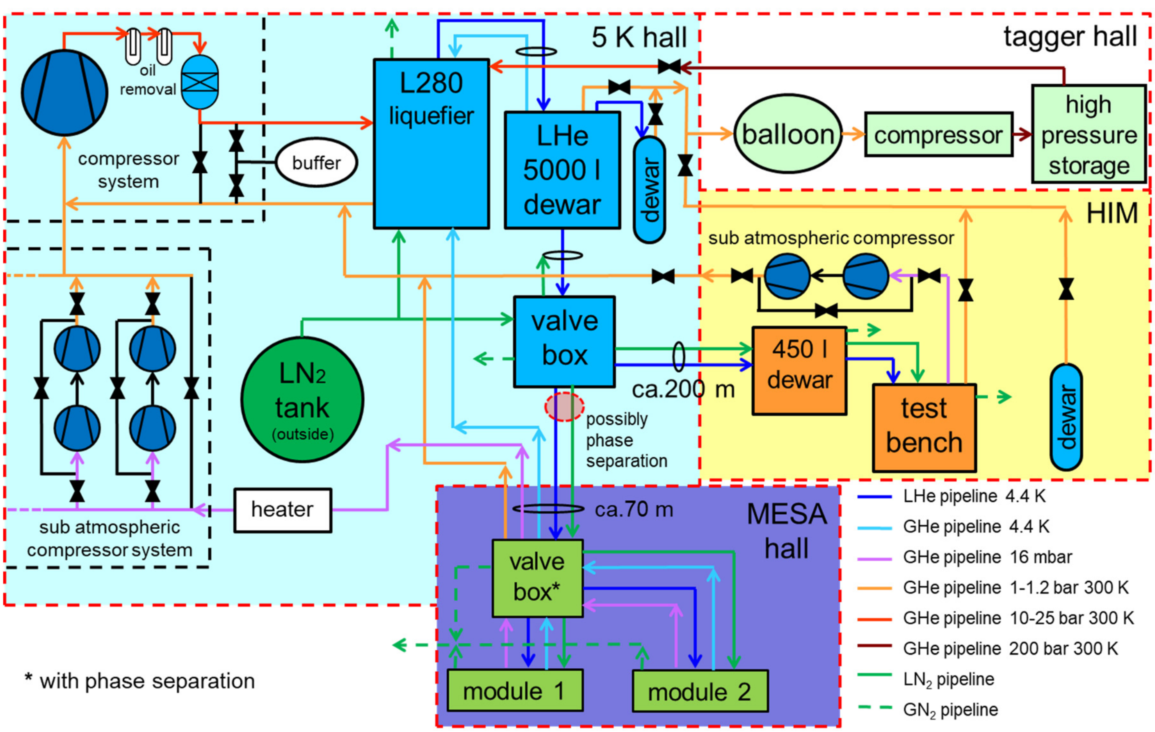

Figure 1: Simplified cryogenics layout of the installations at KPH and HIM. The cryoplant (Linde L280) is located at KPH (5 K hall, green) including a compressor system, a 5000 l dewar for LHe storage, and a valve-box for connecting to the HIM installations. The sub-atmospheric compressors for MESA haven't been installed yet. The Helium recuperation system (balloon, 200 bar compressors, and high pressure storage) is located at the basement of KPH (tagger hall, white). Recently, a 220 m coaxial supply line for LHe and LN2 has been installed to provide cryogenics to the new high power RF test-setup at HIM (orange). In future, a second liquefier and a connection to the MESA hall at KPH (purple) will be added to complete the cryogenic installations and to serve the MESA accelerator and the P2 experiment.

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system for HIM has been ordered and put into operation in 2017. This system is capable to reach a mass flow of >4 g/s at 16 mbar and thus allowing to operate cavities down to 1.8 K at the rf test stand. Finally, in 2016 a 225 m LN2 shielded coaxial cryogenic line has been installed to connect the HIM to the cryoplant at KPH [4]. The flexible line together with the standardized Johnston plugs and the distribution valvebox by now is the backbone of the cryogenic concept of the Mainz cryogenic system. In the next sections we will report on the performance of the different parts of the system and give a lookout to upcoming improvements. Figure 1 gives an overview of the installations.

CRYO PLANT PERFORMANCE

The cryoplant at KPH is operating since 2010 as liquefier serving a 5000 l dewar. From this storage, smaller mobile dewars can be filled and the LHe afterwards can be used for experiments. The evaporating Helium gas is transported into a balloon and compressed into a 200 bar high pressure storage. From this storage the gas can be sent back into the cryoplant using an internal purifier. The Helium recovery system (balloon, compressors) is capable to handle a load of 30 l/s GHe, corresponding to a mass flow of 5.4 g/s. After installation of the cryogenic transport line to HIM in 2016, the cryoplant is still operating in liquefier mode, meaning that all gas from HIM is heated up before sent back to the plant and no energy is recovered using heat exchangers on the cold gas streams from experiments. Furthermore, the return gas is not yet injected into the low pressure cycle of the main compressor of the cryoplant but still through the recovery system and the internal purifier. This is done due to the fact that the coldbox is neither equipped with an internal cold adsorber in front of the turbine cycle nor a gas purity monitoring system so far. Both systems will be added in future, when the plant will be upgraded for full operation of the MESA accelerator. The L280 plant is operated at a nominal pressure of 12.5 bar and reaches a liquefaction rate of 157 l/h reliably (see Fig. 2). During cold tests of the MESA modules, it was found out that smaller liquefaction rates are more convenient in order to match the amount of return gas when operating cryomodules. These smaller rates can be achieved by reducing the inlet pressure of the turbine cycle. Going down to 9.5 bar the liquefaction rate is reduced to 98 l/h (see Fig. 2). Both values have been achieved without precooling of the first heat exchanger with LN2. To run the plant on the nominal liquefaction rate of 280 l/h this LN2 precooling including optimized turbines will be added during the upcoming plant upgrade.

CRYOGENIC TRANSPORT LINE

In 2016, a 225 m coaxial transport line (manufacturer: NEXANS) have been installed to connect the HIM experimental hall to the cryoplant at KPH. This line came along with a valve box connecting to the 5000 l storage. The valve box can be used in future to connect the storage to MESA and MESA experiments as well, switching LHe flow either to MESA or to HIM. The transport line is

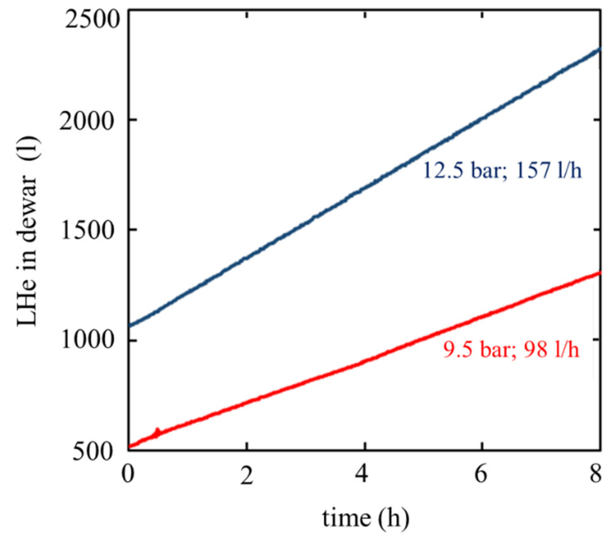

Figure 2: Filling rates of the L280 cryoplant at different inlet pressure for the gas turbines. At 3 bar pressure reduction the liquefaction rate can be reduced by approx. 35%.

shielded with vacuum and through forced flow cooling using LN2. Both sides are equipped with a Johnston type coupler and can easily be connected to any subsequent setup. A great benefit of the transport line is its flexibility. As long as the curvature is not executed at too low bending radius, the bending is reversible and the position of the line can be changed. In the present setup, the end of the cryogenic line is connected to a 450 l dewar for phase separation via a short insulated line from Johnston coupler into the dewar. Since installation, a lot of experiments on the performance of the coaxial line have been carried out. Furthermore, operational data has been collected by using the line for running cryomodules at HIM. More than 100,000 l of LHe have been transported to HIM and successfully been recovered during the last two years. The two main operational experiences regard the LN2 consumption and the efficiency of transporting LHe along the line.

Nitrogen Consumption

It was found out that rather than using a constant forced flow of LN2 with subsequent evaporation of the resuming liquid it is more convenient in terms of LN2 consumption to purge the line once or twice a day for 1.5 hours. The LN2 consumption in this operation mode yields to 500 to 1000 l/day and is within an acceptable limit.

Helium Transport Efficiency

The efficiency of LHe transportation has been measured to be up to 55%, depending on the flow rate, meaning that this fraction of Helium from the storage at KPH ends up as usable liquid in the 450 l phase separator at HIM. The amount of Helium not ending as usable liquid in the dewar is evaporated as flash gas and, after phase separation and being heated up, sent back to the plant. Figure 3 gives an

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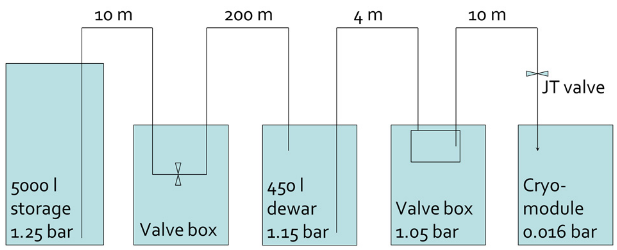

Figure 3: Simplified flow scheme and pressure cascade from 5000 l dewar to the cryomodule.

overview on the Helium transport from the storage to the cryomodule. For discussing the efficiency of the coaxial transport line, the fraction of liquid ending in the 450 l dewar is the key value to look at.

The losses of transportation result from several contributions, first one is the static heat load (on the valve box, the 225 m line and the short connectors at beginning and end). For estimating this part, we run the transport line at a constant flow measuring the temperature at the end just before the short connection into the dewar. By applying a flow, which is just capable to keep the outlet temperature close to Helium boiling temperature (4.25-5 K) but not transporting any liquid anymore, we can measure the losses necessary to keep the line in cold condition. As this condition is applied over night, whenever running one-week test-phases on cryomodules, we collected a lot of data over the 1.5 years of operation resulting in baseline loss of approx. 65 l/h, which comprise of losses from the 225 m line of 30 l/h and losses from the valvebox, necessary for switching Helium flow to different users, of 35 l/h.

Another contribution comes from the needed overpressure and resulting pressure drop of the line into the phase separating dewar. The pressure drop from storage to dewar is necessary to transport the liquid over 225 m distance but results in the presence of an overheated liquid at the end of the line. To lower the temperature down to saturation at the position of the phase separating dewar, energy needs to be extracted from the liquid. This happens by evaporating Helium, therefore the energy amount of energy can be expressed by the latent heat of evaporation and the transported quantity. This contribution is additionally dependent on the pressure difference between LHe storage and dewar as well as the operating pressures of storage and dewar as these quantities affect temperatures and temperature difference of the saturated liquids at both positions. The nominal pressure of the 5000 l storage is 1.25 bar resulting in a saturated Helium temperature of 4.45 K [3]. If the 450 l dewar at HIM is operated at ambient pressure this yields in a temperature difference of 0.2 K. When operating the dewar at an overpressure with respect to ambient as well, like needed to transport the liquid further into a cryomodule, the difference reduces down to 150-100 mbar (see Fig. 3). The quantity of liquid Helium needed to be additionally transported in order to provide the proper latent heat of evaporation has been summed up in Table 1. For calculation, the latent heat of evaporation and the specific heat capacity in the temperature range of 4.25 K to 4.45 K have been approximated by their mean values (C_S = 19 J/mol·K and L = 79.7 J/mol) [5]. These approximations cause an error in the calculated values of less than 10% which is in the same magnitude of the achievable precision of the mass flow measurements.

Table 1: Calculated quantity of additionally evaporated Helium needed per 100 litres filled into the dewar at HIM dependent of pressure and temperature difference between start and end of the cryogenic transport line.

Δp (mbar)	**ΔT (K)**	**Additionally evaporated liquid per 100 l in dewar (l)**
100	0.1	4.7
150	0.15	3.6
200	0.2	2.4

A third and very relevant contribution to transportation losses results from pressure oscillations and turbulent flow in the long cryogenic line. The installation needs to overcome several steps in altitude as well as several horizontal bends. Calculating this contribution can be very complicated as reported in [6-8]. But it can be clearly stated, that pressure fluctuations and turbulences from connectors, valves or bellows can increase the losses significantly. From our observations so far, depending of the pressure difference, different efficiencies of dewar filling can be achieved, while low pressure drops along the 225 m line should be preferred. Nevertheless, too low difference in pressure can stop the flow of liquid completely and needs to be avoided. An optimal difference of ~100 mbar allows proper filling rates at reasonable losses. The evaporation losses for a typical operation mode yield to 150 l/h at a filling rate of the dewar of 160 l/h and a pressure drop of 100 mbar. Therefore, to fill e.g. 160 l/h of LHe into the dewar ~310 l/h need to be extracted from the 5000 l storage resulting in the observed efficiency of the line. Even higher flow rates can be achieved by increasing the pressure drop, but raise the losses at the same time (see Fig. 4).

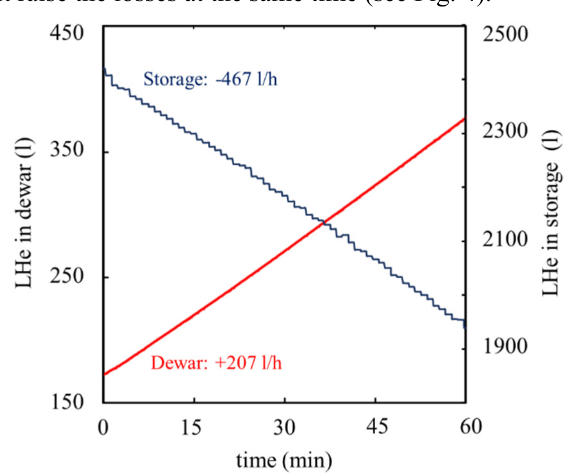

Figure 4: Filling rate of 450 l dewar at HIM compared to the extraction rate from the 5000 l storage at KPH. Filling with over 200 l/h reduces the efficiency of the cryogenic line (44% in the presented case) due to a higher needed pressure drop from storage to dewar. Best operation mode was found out to be 160 l/h at 100 mbar pressure drop with an observed efficiency of more than 50%.

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HIGH POWER RF TEST STAND

In 2017, the high power RF test stand at HIM has been installed and started operation in 2018 with first cool down of the MESA modules. The heavily concrete shielded area allows testing of cryomodules up to 25 MV/m CW. For achieving 1.8 K operating temperature a five-stage subatmospheric compressor system has been added in 2017 allowing a mass flow of >4 g/s at 16 mbar. Figure 5 shows the installations needed for the CW cavity tests. The Helium is provided using the cryogenic line described in the section before. From the 450 l dewar it is sent into a valvebox managing the liquid level and pressure inside the Helium vessel of the cryomodule. The return gas is heated by two devices, one operating at 1 bar and one at 16 mbar before transported to the subatmospheric compressor system or to the recovery system. For performing calorimetric quality factor measurements, a flowmeter has been installed in the 1 bar Helium pipe after the subatmospheric compressors. This meter can measure the complete gasflow coming from the Helium vessel of the cryomodule at a 0.01 l/s precision and therefore, after calibration, can be used to determine static and dynamic losses of the module. For shielding the valvebox and the cryomodule from thermal radiation an 80 K LN2 shield is used. This shield is filled from a 380 l LN2 dewar, which needs to be refilled once a day during operation. The up to 15 kW RF power needed for testing is provided by a 1.3 GHz solid state amplifier [9]. In future, more cavities at different operating frequencies will be tested like e.g. the CH-mode SRF cavities for the CW linac project at GSI. This will require the installation of different power amplifiers.

MESA CRYOMODULE COOLDOWN

First experiments on cryomodules at the the high power rf test stand at HIM have been conducted on two cryomodules built for the MESA accelerator by industry [10,11]. These modules have been cooled down several times and tested up to 12.5 MV/m CW so far. In Fig. 6 the setup of one MESA module inside the test pit can be seen. For testing the modules, a pressure cascade of the Helium system like presented in Fig. 3 is necessary. The typical cooldown of one module to 2 K and all surrounding installations needs approx. 30 hours including an eight hours break during night [12]. When cooling down the module, the cryogenic line described above needs to be put into operation first. The flash gas produced during this process is cold and can be used to pre-cool the cryomodule down to 50 K. At a later stage, liquid Helium from the dewar is mixed to the gas flow ramping down the temperature to 30 K. Below 30 K only liquid Helium from the dewar is used to reach

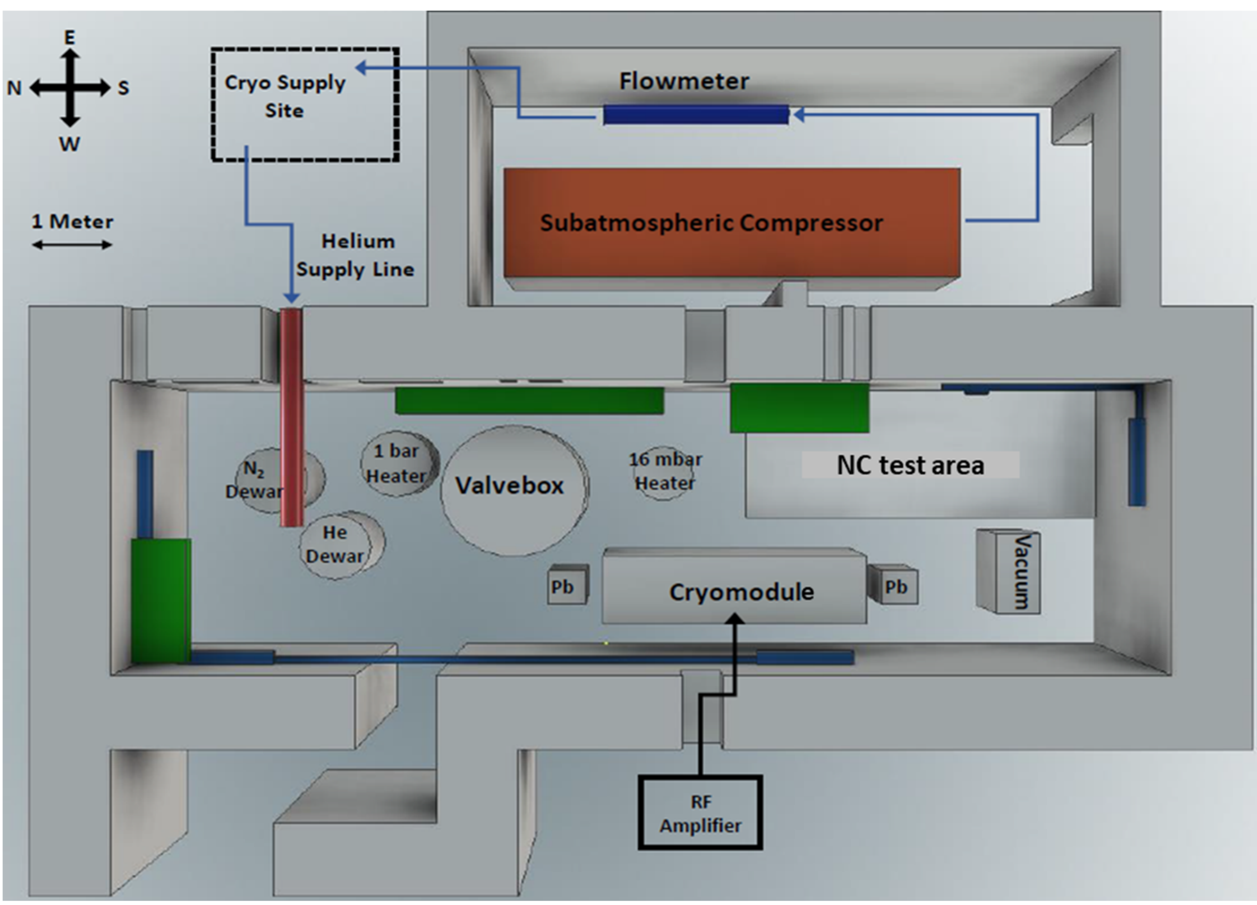

Figure 5: Overview of the high power RF test stand at HIM. It is heavily shielded with concrete walls and has a removable concrete ceiling. Cryomodules can be tested at operating temperatures down to 1.8 K and up to 25 MV/m CW (administrative limit from radiation protection agency). First modules tested here are the ELBE type cryomodules for MESA.

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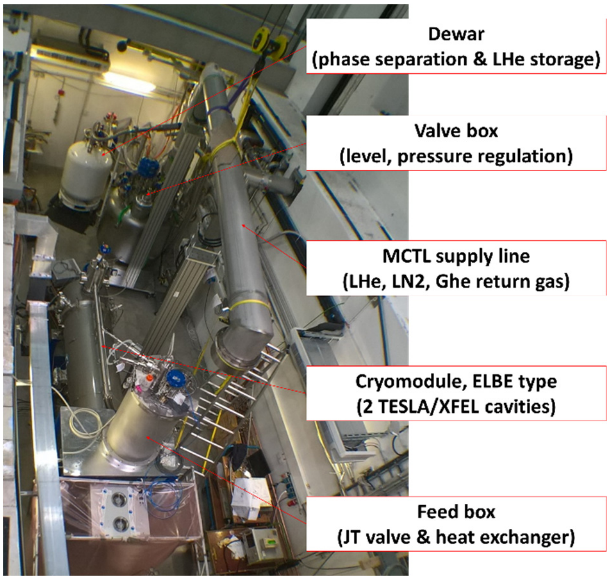

Figure 6: MESA module in test stand during installation (concrete ceiling removed).

4 K at the position of the cavities. At the last step, the sub-atmospheric compressor is used to lower the operation pressure down to 16 mbar and corresponding saturation temperature of 1.8 K. At the same moment the Helium cycle is cooled down, the LN2 cycle of valvebox, feedbox, transfer lines and module are starting to operate as well. Valvebox and transfer lines are cooled by forced flow LN2, the module is cooled by a LN2 reservoir, which can be refilled whenever needed using the forced flow line. In constant operation this refill is done automatic by a simple two-point control loop looking on the level sensor. Figure 7 gives a typical refill pattern of the LN2 reservoir of the module.

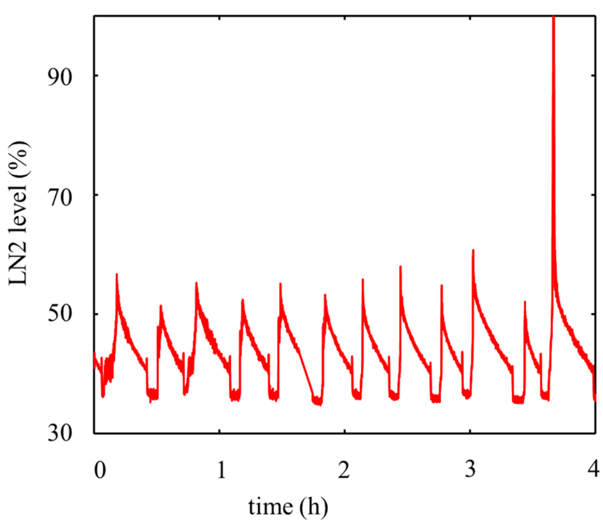

Figure 7: Refill pattern of the cryomodules LN2 shield. From the slopes of the decreasing LN2 level the static heat load on the modules' LN2 shield can be derived.

The LN2 consumption of the complete system (forced flow cooling of valvebox, feedbox, MCTL transport line and module adds up to 250 l/day. From this quantity, the bare module needs 25-50 l/day only. Including refill losses, an operation of the module without feedbox and transfer lines like planned for future high power beam tests at HZB (Berlin) can be managed with less than 100 l/day [13]. The static heat loads at 2 K operation of the two MESA cryomodules have been measured to be 9.0 W and 5.6 W, being both much lower than designed value of <15 W [12].

SUMMARY AND OUTLOOK

A lot of cryogenic infrastructure have been installed and tested successfully at Mainz since 2010. All infrastructure and in particular the 225 m transport line between the participating institutes is working together properly. The next steps will be the completion of the MESA cryomodule tests and the start of SRF testing on CH cavities and long cryomodules for GSI. In addition, major upgrades of the cryogenic system for running the future MESA accelerator are planned in the close future.

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