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Study for cryogenic testing the Super-FRS magnets of FAIR in a new test facility at CERN

J H Derking, A Perin, V Benda and O Pirotte

CERN, Technology Department, Cryogenics Group, Geneva 23, 1211, Switzerland

Email: hendrie.derking@cern.ch

Abstract. The Super-FRS magnets of the international Facility for Antiproton and Ion Research (FAIR) being built at GSI in Germany will be tested at a new cryogenic test facility currently under construction at CERN. During nominal operation the magnets will be cooled with liquid helium to 4.5 K. Over a period of three years in total 57 magnets will be tested of three different types. A study is performed to determine the cryogenic requirements for testing the Super-FRS magnets. The required operational parameters for the cool down, magnet test and warm up phases are determined and the results are discussed in this paper. For pre-cooling the magnets to 90 K with a rate of 1 $K \cdot h^{-1}$, a maximum cooling power of 5.6 kW is required. Cooling down the magnets further to 4.5 K and filling will be performed with LHe within 24 h. For warming up the magnets a maximum heater power of 14 kW is needed. It is concluded that the planned test facility currently under construction at CERN fulfills the cryogenic requirements for testing the Super-FRS magnets.

1. Introduction

A new cryogenic test facility is currently under construction in building 180 at the Meyrin site of CERN for future needs of the laboratory [1]. The facility will be constructed by refurbishing and upgrading the existing infrastructure and will be at first used for the cryogenic testing of the Super-FRS magnets of the international Facility for Antiproton and Ion Research (FAIR) being built at GSI in Germany [2]. The test facility contains three magnet test benches. The main components of the cryogenic system are a helium refrigeration system based on a Sulzer TCF200 cold box, two cool down / warm-up units (CWUs), a 50 m^3 liquid nitrogen (LN_2) tank, a 5 m^3 liquid helium (LHe) dewar, six cryogenic valve boxes, various cryogenic transfer lines and a gaseous helium (GHe) storage and distribution system at room temperature. The layout of the cryogenic system of the test facility is discussed in detail in [1].

A study is performed to determine whether the test facility fulfills the cryogenic requirements for testing the Super-FRS magnets. The results of this study are presented in this paper. The paper starts with summarizing the cryogenic requirements for testing the Super-FRS magnets and describing the proposed test schedule. Then, the required operational parameters for the cool down, warm up and magnet test phases are determined.

2. Cryogenic test requirements for the Super-FRS magnets

The Super-FRS magnets are iron dominated superconducting magnets that will be cooled by a saturated LHe bath at 4.5 K [3, 4]. In total 57 magnet assemblies of three different types will be tested at CERN: dipole, multiplet type 1 and multiplet type 2. The dipole magnets have a cooled coil and the iron yoke is at room temperature. This results in a rather small cold mass of 2’000 kg compared to the total mass

Table 1. Cryogenic characteristics of the Super-FRS magnets.

Type	Quantity	Mass [kg]	Cold mass [kg]	LHe volume [m^3]	Nominal heat load [W]	Thermal shield heat load [W]	Maximum current [A]	Stored energy [MJ]	Pole field [T]
dipole	24	50’000	2’000	0.025	4	35	230	0.5	1.6
multiplet 1	24	70’000	45’000	1.350	30	160	300	2.7	2.5
multiplet 2	9	25’000	20’000	0.900	30	160	300	1.2	2.5

of 50’000 kg. The multiplet 1 magnets are the largest and heaviest magnets with a cold mass of 45’000 kg and a total mass up to 70’000 kg. They are composed of 3 quadrupoles and up to 6 corrector magnets. The multiplet 2 magnets are composed of 2 quadrupoles. They hold a cold mass of 20’000 kg and have a total mass of 25’000 kg. The main cryogenic characteristics of each type are summarized in table 1.

All magnets are located in a vacuum insulated cryostat with an actively cooled thermal shield and have a warm beam pipe through their bore. The design pressure of all magnets is 2 MPa. During the cryogenic testing at CERN, the thermal shield needs to be cooled to a temperature below 90 K. The expected heat load to the thermal shield is maximum 160 W for both multiplet types and 35 W for a dipole. The expected heat load to the cold mass is estimated to be 30 W for a multiplet and 4 W for a dipole in nominal operation. During ramping up and ramping down of the magnet current, an additional dynamic heat load of 35 W is expected. The current leads are actively cooled by a GHe flow of maximum 1.6 $g{\cdot}s^{-1}$ at a magnet current of 300 A taken from the saturated LHe bath.

In the temperature range of 300 K to 90 K, the maximum cool down and warm-up rate has to be limited to 1 $K{\cdot}h^{-1}$ and the maximum allowed temperature difference between the coldest and the warmest point of the magnet cold mass is 50 K.

3. Testing schedule

The test cycle of a Super-FRS magnet can be divided into five phases:

phase 1: Installation and preparation of the magnet at a test bench.
phase 2: Cool down of the magnet to 4.5 K and filling with LHe.
phase 3: Magnet testing at operational conditions.
phase 4: Evaporating the LHe and warming up the magnet to room temperature.
phase 5: Testing the magnet at warm and disconnecting it from the test bench.

The cool down and warm up of the magnet (test phases 2 and 4) are planned to be performed in automatic mode that is also continued outside working hours. The other test phases will only be performed during working hours. For testing the magnet at operating conditions (phase 3) only one measurement setup is available. Therefore, this phase can only be performed at one test bench at a time. Based on a compromise between the technical requirements, reasonable cost investment and an acceptable test schedule, it is decided that the test facility will contain three test benches.

The proposed time schedule for testing a Super-FRS magnet is shown in figure 1. The test schedule requires that at a given time maximum one magnet is in cooling-down phase, another magnet in warm up phase and the third magnet in the preparation phase, the testing phase or the disconnection phase (phase 1, 3 or 5). The test cycle of one Super-FRS magnet will take in total 42 days or 37 working days. Four working days are used for the installation and preparation of the magnet at a test bench. This phase includes evacuating the vacuum space and leak testing. Cooling down and filling the magnet will be performed in 10 days as well as the evaporation of the LHe and the warm up of the magnet. Testing the

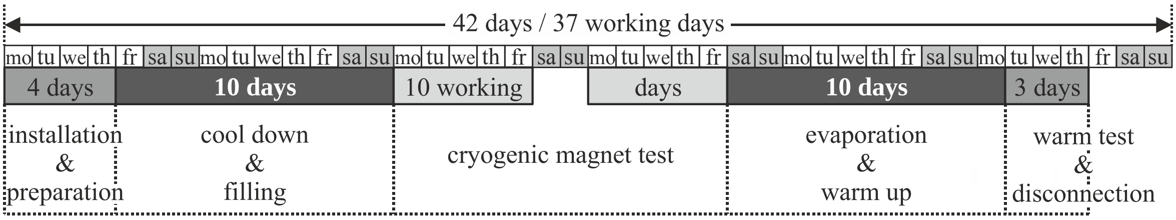

Figure 1. Time schedule for testing a Super-FRS magnet.

magnet at operation conditions will be done in 10 working days. In case of problems during this phase, the tests can be continued outside working hours and during the spare weekend within the testing period. Testing the magnet at warm and disconnecting it from the test bench will take about 3 days. The last 3 days of each period are spare days that can be used in case of unexpected problems.

Taking into account 2 weeks of CERN closure and 4 weeks of annual maintenance, about 46 weeks per year are available for testing the Super-FRS magnets. Each test bench can afford the test of 7 magnets per year. In total the test facility is thus capable in testing 21 Super-FRS magnets per year. Testing all the 57 Super-FRS magnets will take about 3 years.

4. Operational parameters for each mode

A study is performed to determine the required operational parameters for the cryogenic system of the test facility. The successive operation modes for the cryogenic system are defined as:

1. Pre-cooling the magnet from 293 K to 90 K.
2. Cooling down the magnet from 90 K to 4.5 K and filling the the magnet with LHe.
3. Keeping the magnet at operating conditions during the cryogenic testing.
4. Evaporating the LHe and warming up the magnet to 293 K.

Multiplet 1 is the largest magnet in terms of magnet cold mass and thus will require the largest cooling power or heating power. Therefore, the required parameters for the various operation modes for the multiplet 1 are discussed in more detail in the following subsections.

4.1. Pre-cooling phase from 293 K to 90 K

Pre-cooling the Super-FRS magnets from 293 K to 90 K will be done with a GHe flow at a pressure of about 1 MPa delivered by one of the CWUs. LN_2 is used as cooling source in the CWUs, so the minimum temperature of the GHe flow is about 80 K. During the pre-cooling phase, the cold mass and the thermal shield are connected in series and the GHe flow passes via the thermal shield to the magnet cold mass. The maximum cool-down rate of the magnets is limited to 1 $K \cdot h^{-1}$, and the maximum temperature difference between the coldest point (and thus the GHe flow) and the warmest point of the magnet cold mass is 50 K. The maximum GHe flow rate is 50 $g \cdot s^{-1}$ given by the compressor capacity.

The energy (Q_m) that needs to be extracted to cool down a magnet from temperature T_1 to temperature T_2 can be expressed by

$$\Delta Q_m = M_m \int_{T_1}^{T_2} c_m dT_m \tag{1}$$

where M_m is the cold mass, c_m is the specific heat and T_m is magnet temperature. The cooling power (P_{cool}) of a GHe flow with mass-flow rate $(\dot{m}_{GHe})$ increasing in temperature from T_l to T_h can be expressed by

$$P_{cool} = \dot{m}_{GHe} \int_{T_l}^{T_h} c_{p,He} dT_f \tag{2}$$

with $c_{p,He}$ the specific heat at constant pressure of helium and T_f the GHe flow temperature. By using equations (1) and (2), the GHe flow rate required to cool down a magnet with a speed of 1 K·h^{-1} can be determined by

$$\dot{m}_{GHe} = \frac{1}{3600} \frac{\int_{T_l}^{T_l+1} c_m dT_m}{\int_{T_l}^{T_l+50} c_{p,He} dT_f} \tag{3}$$

where the temperature difference in the GHe flow is taken as 50 K.

Figure 2 gives the temperature of the GHe and the magnet, the calculated required cooling power and the required GHe flow rate as a function of time for pre-cooling Multiplet 1 from 293 K to 90 K. In the calculations it is assumed that the magnet cold mass consists fully of iron and that no cooling power is lost (perfect heat exchange between the GHe flow and the magnet cold mass). As shown in figure 2a, the temperature of the GHe flow is 50 K lower than the magnet temperature with a minimum of 80 K determined by the temperature of the LN$_2$ that is used as cooling source. The cool-down time from 293 K to 90 K is 203 h (8.5 days) as constrained by the 1 K·h^{-1} limit. Figure 2b shows that the required cooling power has a maximum value of 5.6 kW at 293 K and decreases to 2.3 kW at a magnet temperature of 90 K due to the decrease in specific heat capacity of the magnet with decreasing temperature. The required GHe flow rate decreases from 21.4 g·s^{-1} at 293 K to 14 g·s^{-1} at 130 K, as shown in figure 2c. Then, it starts to increase steeply to a maximum value of 45 g·s^{-1} due to the decrease in temperature difference between the GHe flow and the magnet.

The amount of LN$_2$ required to cool down a magnet to 90 K depends on the CWU design that for both CWUs is discussed in more detail in [2]. The design of CWU2 is optimized in terms of efficiency. In the ideal case, cooling down Mulitplet 1 with CWU2 from 293 K to 90 K requires 13 m^3 of LN$_2$.

The CWUs installed in the test facility have cooling capacities of 9 kW and 15 kW. The calculations above show that both CWUs have sufficient cooling capacity to pre-cool the Super-FRS magnets to 90 K within the given time span and the given requirements.

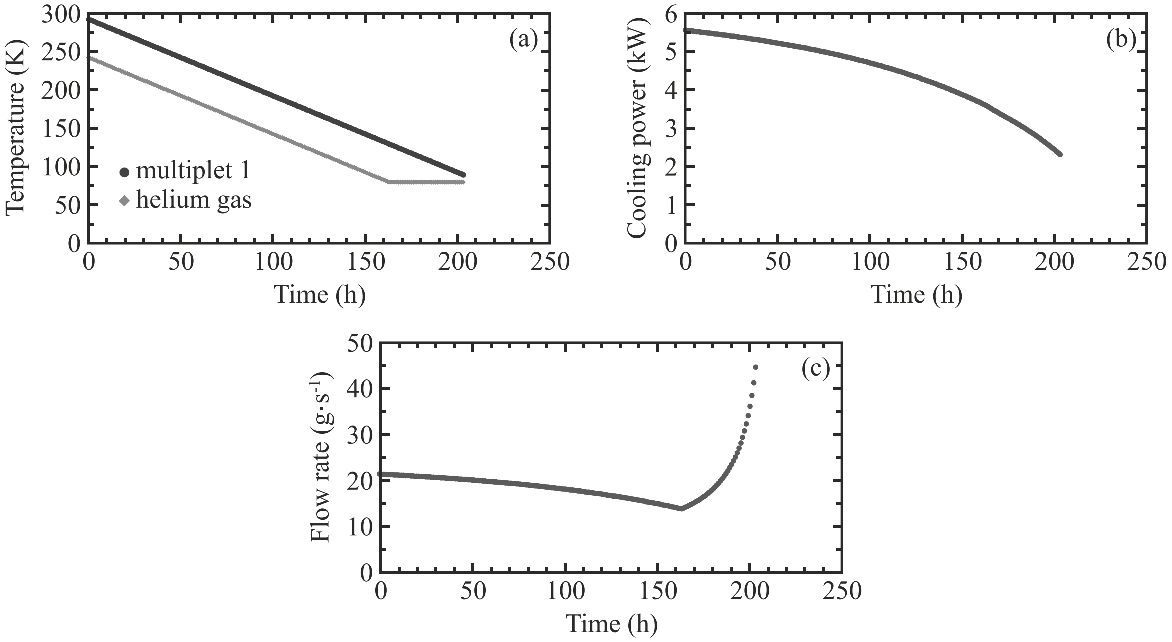

Figure 2. a) Temperature of the GHe flow and multiplet 1, b) required cooling power and c) GHe flow rate versus time for pre-cooling multiplet 1 from 293 K to 90 K.

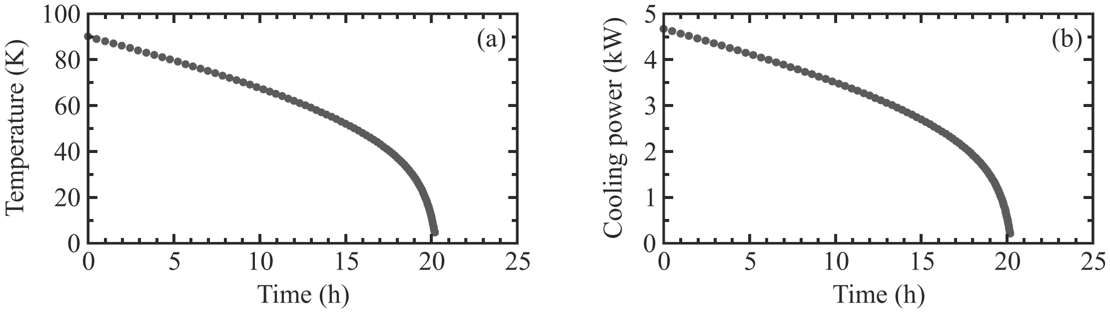

Figure 3. a) Temperature of the magnet cold mass and b) available helium cooling capacity versus time for cooling a multiplet 1 from 90 K to 4.5 K.

4.2. Cooling down from 90 K to 4.5 K and LHe filling

Within the proposed time schedule for testing the Super-FRS magnets, about one day is available to cool down the magnet from 90 K to 4.5 K and to fill it with LHe. For this phase, no limitation on the cool down speed is given. The cool down from 90 K to 4.5 K is done with LHe at about 0.14 MPa. During this phase, the cooling power of the helium (P_{He}) consists of the latent heat (L_{LHe}) plus the available heat capacity in the GHe flow from 4.5 K to the magnet temperature (T_m) and can be expressed by

$$P_{He} = \dot{m}_{He} L_{LHe} + \dot{m}_{He} \int_{4.5}^{T_m} c_{p,He} dT \tag{4}$$

The cryogenic system is capable of filling the magnets with a LHe flow of about 20 g·s^{-1} by taking the LHe from a storage dewar. At this flow rate, multiplet 1 is filled in about 2.5 h, multiplet 2 in about 1.5 h and the dipole in less than 10 minutes.

The cool down of the multiplet 1 from 90 K to 4.5 K needs to be performed in about 20 h. The total heat that needs to be extracted to cool down multiplet 1 from 90 K to 4.5 K is about 241 MJ. By using equation (4) and assuming that all cooling power of the helium is used (no loss), an average LHe flow rate of 10 g·s^{-1} is required to cool down the multiplet 1 from 90 K to 4.5 K in 20 h. The minimum amount of LHe required is 6.2 m^3.

Figure 3 shows the calculated temperature and the helium cooling power versus time for cooling down a multiplet 1 with a LHe flow rate of 10 g·s^{-1}. As shown, the available cooling capacity is maximum 4.6 kW at 90 K. It decreases due to the decrease in magnet temperature. The cool down is performed in about 20 h.

The cryogenic system of the test facility contains a LHe storage dewar with a capacity of 5 m^3 that is fully available for the cool down and filling phase. For filling a multiplet 1 about 1.4 m^3 of LHe is required, so approximately 3.5 m^3 of LHe is available for the cool down phase. In addition, the cold box has a liquefaction capacity of 5.6 g·s^{-1} [2], resulting in a minimum LHe production of 3.4 m^3 in 20 h. Thus, in total 6.9 m^3 of LHe is available for cooling down which is enough to cool a multiplet 1 and cover the losses. This means that the cryogenic system has sufficient capacity to cool down the Super-FRS magnets from 90 K to 4.5 K within the required time.

4.3. Nominal operation during the testing phase

During the test phase, the cryogenic system needs to keep the Super-FRS magnets at operating conditions. The heat load to the cold mass of the multiplet 1 is about 30 W. By using the latent heat of LHe at 0.13 MPa, this corresponds to an evaporation rate of 1.6 g·s^{-1}. The evaporated GHe will be used for actively cooling the current leads and is fully warmed up to room temperature. During ramping up and ramping down of the multiplet current, the additional dynamic heat load is estimated to be 35 W for a period of about 10 minutes. The heat load to the thermal shield is estimated to be maximum 160 W

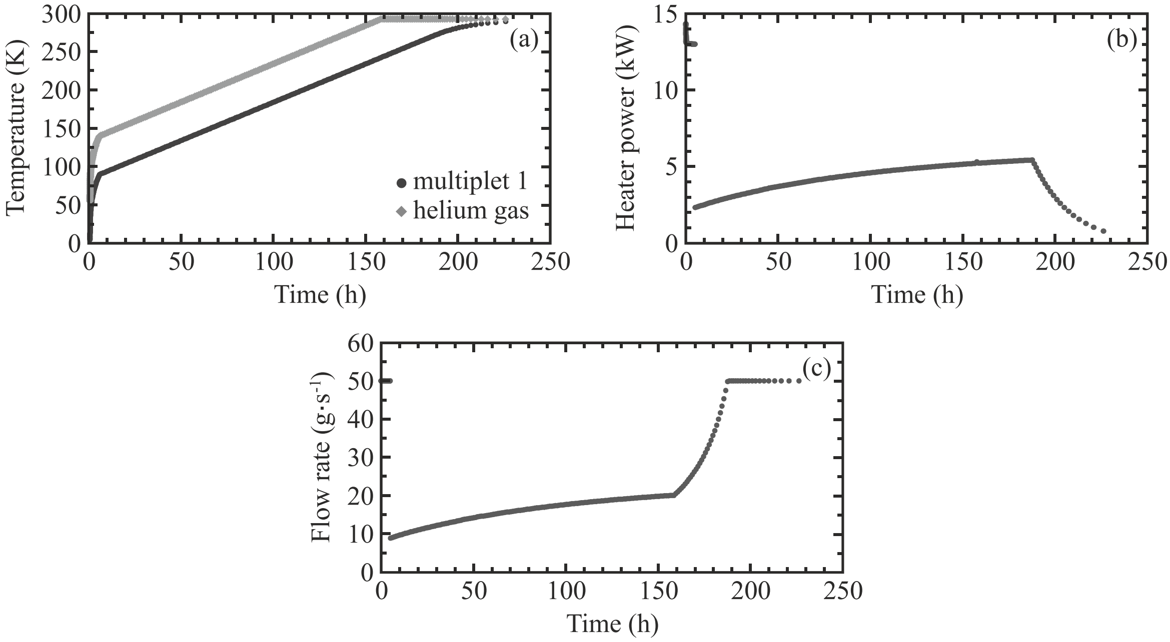

Figure 4. a) Temperature of the GHe flow and multiplet 1, b) calculated GHe flow rate, and c) delivered heater power versus time for warming up multiplet 1.

for the multiplet 1. The static heat load to the 4.5 K circuits of the cryogenic system is estimated to be about 22 W and that to the 60 K thermal shield circuits about 100 W.

At a liquefaction capacity of 1.6 g·s^{-1}, the cold box has an additional refrigeration power of about 1.0 kW available. It also has a cooling power of 1.0 kW at 60 K that can be used for thermal shield cooling. So the cryogenic system has sufficient capacity to keep the Super-FRS magnets at operating conditions during the cryogenic test phase.

4.4. Evaporating the LHe and warming up the magnets

After the cryogenic test phase, the LHe needs to be removed and the magnets need to be warmed up to room temperature. The LHe will be evaporated by an electrical heater with a power of 300 W installed inside the magnet. It can be calculated that this will take about 3 h for the multiplet 1, 2 h for the multiplet 2 and less than 10 minutes for the dipole.

After the LHe is evaporated, the magnets will be warmed up to room temperature with a GHe flow at a pressure of about 1 MPa delivered by one of the CWUs. During the warming-up phase, the cold mass and the thermal shield are again connected in series and the GHe flow passes via the thermal shield to the magnet cold mass. The maximum allowed temperature difference between the GHe flow and the coldest point of the magnet is 50 K. The warm up rate is limited to 1 K·h^{-1} above a magnet cold mass temperature of 90 K. The maximum temperature of the GHe flow is limited to 293 K and its maximum flow rate to 50 g·s^{-1} by the compressor capacity.

Equations (1), (2) and (3) can be used to calculate the required heating power and GHe flow rate. Figure 4 shows the temperature of the GHe flow and the multiplet 1, the calculated required heating power and the required GHe flow rate as a function of time for warming-up multiplet 1 from 5 K to 293 K. The warming up from 5 K to 90 K can be performed at full capacity, so with a GHe flow rate of 50 g·s^{-1}. This results in a maximum required heater power of 14 kW at a magnet temperature of 5 K, as shown in figure 4b. The required heater power decreases due to the change in specific heat capacity of the GHe. The warming up of multiplet 1 to 90 K takes about 5 h.

As shown in figure 4a, the warming up of multiplet 1 from 90 K to 285 K takes about 207 h (8.5 days) and is mostly determined by the 1 K·h^{-1} limit. The GHe flow rate increases from 9 g·s^{-1} at 90 K to 20 g·s^{-1}

at 243 K, as given in figure 4c. Then it increases steeply to its maximum value of 50 $g{\cdot}s^{-1}$ reached at a cold mass temperature of 273 K. The required heating power increases from 2.3 kW at a cold mass temperature of 90 K to 5.4 kW at 273 K. It then decreases steeply. The steep increase in GHe flow rate and decrease in required heating power is caused by the decrease in temperature difference between the GHe flow and the magnet cold mass due to the maximum GHe temperature of 293 K.

Both CWUs have a heating capacity of 15 kW. The calculations above show that both CWUs have sufficient heating capacity to warm-up the Super-FRS magnets to room temperature. However, above a magnet cold mass temperature of 273 K, the warm up will be slower than the requirement of 1 $K{\cdot}h^{-1}$. This is caused by the limited temperature difference available between the GHe flow and the magnet cold mass. An option to increase the warm-up rate is to break the insulation vacuum with dry nitrogen gas to increase the convection.

5. Conclusions

A study is performed to determine the required operational parameters for testing the 57 Super-FRS magnets of the FAIR project in a new magnet test facility that is currently under development at CERN. Over a period of three years in total 57 magnets will be tested of three different types. Testing one magnet will take 42 days and in total 21 magnets can be tested per year.

The results of the study are discussed for the multiplet 1 which is the magnet with the largest cold mass. For pre-cooling a multiplet 1 from 293 K to 90 K at the required rate of 1 $K{\cdot}h^{-1}$, a maximum cooling power of 5.6 kW is required. The pre-cooling phase will take about 8.5 days. For cooling the multiplet 1 from 90 K to 4.5 K with LHe and filling it, a minimum amount of 6.2 m^3 of LHe is required. The test facility is capable of performing this cool down within 24 h as required. Warming up the magnets from 5 K to room temperature is performed with a GHe flow. A maximum heating power of 14 kW is required and on average the heating power does not exceed 5.4 kW. The total warm up will take about 9 days. It is shown that below a magnet cold mass temperature of 273 K, the test facility is capable of warming up the magnets with the required rate of 1 $K{\cdot}h^{-1}$. Above this temperature, the test facility cannot fulfill the cryogenic requirements for the warm up. However, the warm-up rate can be increased by breaking the insulation vacuum with dry gas.

Overall, the paper shows that the cryogenic system of the planned test facility at CERN is able to fulfill the cryogenic requirements for testing the Super-FRS magnets.

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