Progress of the FAIR Cryogenic System

M. Kauschke, H. Kollmus, M. Martinez-Lopez
GSI Helmholtzzentrum für Schwerionenforschung GmbH,
Planckstr. 1
64291 Darmstadt
Germany
M.Kauschke@gsi.de

Abstract. The planning revision of the cryogenic system for the Facility of Antiproton and Ion Research (FAIR, Darmstadt, Germany) resulted in the choice of a single universal plant, which should provide a wide range of cryogenic operation modes, as refrigeration capacity at 4.4K, liquefaction or intermediate temperature levels. The adaptation to the FAIR specific requirements will be done later by adding a second plant. One major demand for the plant is the short term adaptation to variations in the load requirements in the system. An exemplary integration into the overall FAIR system will be shown with the experiments in the Compressed Baryonic Matter (CBM) cave. The CBM cave will house an already existing magnet, HADES, and a new magnet for the CBM experiment, which is still under design. The scheduling of the different operation modes related to the operation of the main consumers as SIS100 or SuperFRS is shown.

1. Introduction
The FAIR accelerator center being built in Darmstadt is one of the largest projects for basic research in physics worldwide. Hundreds of superconductive magnets as well as diverse cryogenic-based detecting systems will require of a complex cryogenic infrastructure which main component will be a unique cryogenic plant able of providing 19kW cooling power at 4.4K equivalent. In order to meet the specific cooling requirements, the cryo plant should adapt to a wide variety of working scenarios which will be analyzed in this article.

In Figure 1 the reduced layout of FAIR and the position of the main consumers is given. The synchrotron with a rigidity of 100 Tm (SIS100) causing heat loads varying between 4 and 10kW@4.4K and the super fragment separator (SuperFRS) with a stable heat loads of 4kW but large liquid helium reservoir cryostats (4.5 t He) are the main consumers of the cryogenic facility[1]. On the other side, smaller experiments as HADES and CBM[2] with comparatively modest con-

Figure 1: Reduced layout of FAIR
sumptions of less than 400W@4.4K need to be served by the same cryo plant. In addition to the static and dynamic heat load requirements during the different experiments, the cryo plant should cover the cooling stages of all the different helium consumers such as for example a period of high liquefaction demand as in the case of LHe filling of the SuperFRS cryostats.

2. Cryogenic users

2.1. SIS100

The magnets for SIS100 are iron dominated magnets with a superconducting coil and an iron yoke close to 4.4K. Details of the magnet design are given in Figure 2. For the cryogenic supply of SIS100 the machine is subdivided into sextants. Each magnet of the sextant –coil, iron and bus bars- form a separate hydraulic chain. All these hydraulic chains are connected by a common supply and return header. Each sextant has 60 parallel channels, 18 dipoles, 28 quadrupoles and 12 for smaller components or the cryogenic infrastructure. In Figure 2 the sketch of a sextant is given.

![Figure 2: Sketch of the hydraulic scheme of a SIS100 sextant showing the dipole (DP) and quadrupole (QD) magnets as well as the heat load sources (q). Each magnet has its own hydraulic connection between supply and return header. For the conditioning of the helium flow a heater at the inlet of each circuit is foreseen. The heat load onto the supply line is compensated by re-coolers within each magnet and by-pass line (BPL) module.](image)

During the experimental program for FAIR the magnetic field at the SIS100 will be ramped in different cycles. Due to eddy currents and hysteresis losses heat will be induced into the coil and the iron yoke. For the design of the cryogenic system, three reference cycles are highlighted to represent the operation of FAIR. The cycles are given in Table 1.

The proton cycle (cycle A) and the RIB cycle (cycle B) represent approximately 90% of the operation time of the accelerator. The third cycle (the triangular cycle C) will introduce the maximum heat load into the system, which will cause the cooling to be limited by the hydraulic characteristics of the sextants as described before. This cycle will be rarely run, but it will allow heavy ion experiments on the edge of the facility’s energy range. The adaptation of the mass flow through the parallel channels is done by adjusting the pressure in the supply header. To guarantee a one-phase helium flow in the supply header, the supply pressure cannot be reduced by more than 0.2 bar above the suction pressure.
Table 1: Reference cycles for the operation of SIS100[3] and the heat generated due to the cycles within the accelerator components[4]

| Cycle A          | Intensity: $2 \times 10^{13}$ | Repetition rate [s] | Heat load |
|------------------|-------------------------------|---------------------|-----------|
| Proton cycle     |                               | 5                   | Dipole [W]    | 1316       |
|                  |                               |                     | Quadrupole [W] | 1022       |
|                  |                               |                     | Total [W]     | 4600       |

| Cycle B          | Intensity: $5 \times 10^{11}$ | Repetition rate [s] | Heat load |
|------------------|-------------------------------|---------------------|-----------|
| RIB cycle U      |                               | 4                   | Dipole [W]    | 1078       |
|                  |                               |                     | Quadrupole [W] | 738        |
|                  |                               |                     | Total [W]     | 4040       |

| Cycle C          | Intensity: $1.2 \times 10^{-11}$ | Repetition rate [s] | Heat load |
|------------------|----------------------------------|---------------------|-----------|
| triangular cycle U |                               | 1.029               | Dipole [W]    | 6998       |
|                  |                               |                     | Quadrupole [W] | 4935       |
|                  |                               |                     | Total [W]     | 13500      |

In Table 2 the heat loads for the different reference cycles and the stored helium inventory is given and two more cases are added. The first case is the one of “no ramping”, where the supply pressure will keep at a value that allows a fast start of ramping. The last case is the “4 K hold” where the supply pressure will be reduced below than 0.2 bar. In this case, the demand of single phase operation in the supply line is given up in order to achieve a smaller heat in-leak into the system. This solution has the drawback that the system will require more time to reach the state of “ready for operation”, as the gas phase in the supply header needs first to be removed.

2.2. SuperFRS
The SuperFRS will consist in superconducting dipoles with warm iron yoke, and cosinus theta style multiplets. These multiplets house several quadru- and multipoles in a common helium bath. More details about the magnets are given in [5] - [7].

The SuperFRS consists of 27 dipoles and 35 multiplets, together with the directly connected experiments, the total cold mass of this cryogenic branch of the FAIR facility sums to 1300t [8].
### Table 2: Stored helium inventory and heat loads in the complete sextants for different cycles

| Stored mass | No ramping Ready for operation | Cycle A | Cycle B | Cycle B | No ramping Low loss hold |
|-------------|-------------------------------|---------|---------|---------|--------------------------|
| High pressure side [kg] | 415 | 415 | 426 | 415 | 209 |
| Low pressure side [kg] | 394 | 394 | 217 | 470 | 251 |
| Total load [W] | 5500 | 6900 | 6346 | 13550 | 2300 |

2.3. Experiments
Within the FAIR facility several superconducting detector magnets are foreseen. One of the largest experimental sites that will be supplied with the beam produced at the SIS100 is the CBM cave. The cave houses two detector magnets: the HADES magnet, which is already in operation, and the CBM, which is currently under design. The CBM cave will be cryogenically connected to the SuperFRS due to the topology of FAIR therefore the installation process has to be scheduled carefully. The existing cooling shield of the HADES magnet must be modified in order to be able to run with the helium at 50K supplied by the cryo plant instead of LN$_2$ as it does currently. This substitution is necessary for safety purposes as the cave is underground and the nitrogen in big concentrations is an oxygen deficiency hazard. In addition, helium will not be activated in this highly radiative environment.

Other superconducting detector magnets are PANDA or HEDgeHOB which are too far away from the main cryogenic infrastructure to be connected in an efficient way, they will be supplied by an independent cryo plant.

3. Refrigerator
In Figure 3 the schematic layout of the cryogenic infrastructure is given. The distances between the main components are still under revision as the pipe routing in the FAIR building planning is still being optimized. For simplicity, CBM will not be mentioned further in the operational analysis performed in this paper. Nevertheless, the distribution box connecting the CBM to the system allows a cooldown of the SuperFRS from the CWU and a simultaneous operation of CBM.

The design of the cryogenic distribution system and feedboxes has followed the process parameters that appear in Table 3.

### Table 3: Process parameters for FAIR

| Supply | 4.6 K, 3 bar | 50K, 18 bar |
|-------------------------------|-----------------|-----------------|
| Return | < 5K, 1.25 bar | 80K, 17 bar | 300 K, 1.1 bar |
| Multi-purpose line | 5-300K, 1.25-17 bar |

In addition, the design of all helium circuits is made for a maximum pressure of 20 bar and each experimental system should be able to be cooled down and warmed up individually, while the rest of the systems are still in operation. In Table 4 heat loads and liquefaction rates are summarized for six different common operational situations. As some experiments have to be supplied by a dedicated cycle for a period of more than 8h, all cases should be covered in a steady state operation of the plant.

The main geometric data of the cryogenic infrastructure are given in Figure 3.
Table 4: Requested refrigeration capacity in different operational case

| Operation                                      | Refrigeration at 4.4 K [kW] | Shield 50-80 K [kW] | Hybrid current leads [g/s] | Resistive current leads [g/s] |
|------------------------------------------------|-----------------------------|---------------------|-----------------------------|------------------------------|
| Operation of SuperFRS/ SIS 100 cycle A         | 14                          | 49                  | 33                          | 17                           |
| Filling of SuperFRS/SIS100 4.4K hold           | 7.4                         | 49                  | 33                          | 66                           |
| Operation of SuperFRS/ SIS 100 no ramping      | 9.7                         | 49                  | 33                          | 17                           |
| SuperFRS                                       | 3.1                         | 25                  |                              | 17                           |
| SIS 100 cycle C                                | 14                          | 25                  | 33                          |                              |
| 80 K hold                                      |                              | 49                  |                              | 11                           |

Figure 3: Schematic layout of the common cryogenic system for FAIR with the main distances

In Figure 4, the 4.4K operation of the full system is presented. For the cool-down process between 100 and 4 K, warm-up and the case of a quench, the return gas will flow back to the refrigerator via the multi-purpose line (MPL), entering in the cold box at different temperature levels. During the 4.4K operation of the refrigerator (CRYO2), different options to adapt to variations in the heat load due to cycling are foreseen:

- next to the refrigerator a 20000l storage can be filled with liquid helium in situations of overcapacity in the liquefaction due to small decreases in load or its helium can be evaporated to increase the liquefaction during small load increases
- heaters within the users immediately replace the heat load
- the valves of the turbines are partly closed (in this case the energy consumption will nearly be at its maximum but the adaptation time to load changes is very short)
- reduction of the compressor flow to adapt to lower loads (in this case the energy consumption will be reduced but it requires longer adaptation time > 1h)
The major cooling capacity is required during the cool-down of the SuperFRS due to its large total cold mass, for this case the Cool-down/Warm-up Unit (CWU) has been foreseen. The removal of 355 GJ from the multiplets is done with liquid nitrogen (which requires the delivery of approximately one truck per day). The CWU will use the LN$_2$ to cool-down the helium which is being re-circulated inside the SuperFRS by a dedicated compressor placed in the common compressor station. The parallel operation of CRYO2 and the CWU is given in Figure 5.

The inlet temperature to the SuperFRS (to fulfill the specific maximum temperature gradient) may be adjusted by the bypass valve around the LN$_2$ sub-cooler.

The warm-up of the SuperFRS is done in two steps. The first step is to evaporate the liquid helium contained at the cryostats. The resulting boil-off will be directed to the main refrigerator, where it can be liquefied and stored in the dewar or it can be compressed into the warm gas storage. Once the temperature of the cryostat rises by the thermal in-leak to a temperature of e.g. 20 K and the pressure has risen to about 4 bar, then starts the second step. In this step the dedicated CWU compressor will be started and the temperature of the helium gas being circulated will be raised to a value of about 40 °C, while the return temperature of the low pressure stream is about 10 °C. The heat for the warm-up of the cryostats essentially comes from the electric motor of the compressor, i.e. no special electric heater is needed for the warm-up. The warm-up is slower than the cool-down, because it is limited by the allowed temperature difference of 30 K in the plate fin heat exchangers.

CRYO2 can be supported by the CWU with an additional helium stream cooled by liquid nitrogen, shown in Figure 6. The stream will be fed into the plant on the middle pressure, via the MPL or through the shield return line. By doing this an increase of the refrigeration power of approximately 20% can be achieved. This cooling scheme is only acceptable for short term usage, as no permanent truck traffic should be generated by the operation of FAIR.
Figure 5: Layout for the cool down of SuperFRS down to 100K, while SIS100 can be operated

Figure 6: Layout for covering peak loads by supporting the Cryo 2 plant by LN₂ in the CWU
4. Conclusions

FAIR will start operation with one cryogenic plant which will provide enough refrigeration power to cover approximately the 90% of experimental scenarios. To provide the refrigeration capacity required during the cooling of the large cold mass of the SuperFRS, a dedicated CWU is foreseen which will be operated with liquid nitrogen.

Further upgrades are being envisaged depending on the final requirements that will brought to attention in the future once the first experience has been gathered. These upgrades could be additional cryo plants in case that changes in the experimental directions of FAIR cause higher heat loads or the substitution of the open-cycle LN$_2$ cooling of the CWU by a closed system as a Turbo-Brayton system.

References

[1] FAIR - Technical design report, GSI, Spring 2008
[2] CBM Collaboration, 2012, Technical Design Report, Superconducting Dipole Magnet
[3] H. Liebermann, D. Ondreka, 2014, SIS100 Cycles, Version 2.4.1
[4] Fast-Ramped Superconducting Magnets for FAIR. Production Status and First Test Results, E. Fischer, P. Schnizer, K. Sugita, J. P. Meier, A. Mierau, A. Bleile, P. Szwangruber, H. Müller, C. Roux, 2015, *IEEE Transactions on applied superconductivity*, VOL. 25, NO. 3
[5] Kauschke M., Xiang Y., Schroeder C. H., 2013, *Cryogenics for FAIR, Proceedings of ICEC 24-ICMC 2012*, 677-680
[6] Müller, H., Leibrock, H., Winkler, M., Schnizer, P., Fischer, E., 2013, Status of the SuperFRS magnet development for FAIR, *Proceedings of IPAC2013*, Shanghai, China, THPME005, p 3519
[7] Müller, H., Leibrock, H., Winkler, M., Schnizer, P., Fischer, E., Quettier, L., Munoz-Garcia, J.-E., Irfu, Serio, L., 2015, Status of the SuperFRS magnet development for FAIR, *Proceedings of IPAC2015*, Richmond, VA, USA, WEPMA019, p 2792
[8] Y. Xiang, M. Kauschke, C. H. Schroeder, H., 2015, Cryogenics for Super-FRS at FAIR, *Proceedings of ICEC 25–ICMC 2014*, 847