Options for a reliable cryogenic supply for the FAIR facility

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Abstract. FAIR, which is currently being built at GSI, will provide particle beams with unprecedented intensity and quality. The facility's diversity makes it unique: ions of all natural elements of the periodic table as well as antiprotons can be accelerated. Hence the accelerators and the experimental infrastructure have to be extremely flexible in the adaptation to various operating schemes. The main accelerator, that will be realized within the starting phase of FAIR, is the SIS100 (SchwerIonenSynchrotron 100 Tm). The superconducting magnets of SIS100 will to be hardly not to fast-ramped for several hours, which causes variations in the 4.5K heat load by factor 4. The larger cold mass and the higher liquid helium inventory is necessary for the Super-FRS (Superconducting FRagment Seperator), which will be supplied from the same cryo plant as SIS100.

1. Introduction
As a result of the overall optimization within the realization of FAIR the two main users of cryogenic refrigeration will be supplied from one cryo plant in the beginning; a later upgrade is foreseen in the infrastructure of the buildings [1].

Several different cycles are defined to provide particles (proton up to U28⁺) in the requested intensity (up to 2 × 10¹¹) towards the different users. In these cycles for the synchrotrons ramping speed and flat top times are defined. For the planning of the experimental schemes and the combination of experiments an investigation on the time required to change between different set-ups has been necessary.

For the realization of durable beam times the cryogenic system has to cover the variations of loads and short time interruptions of the liquid helium supply have to be handled.

2. SIS100
The SIS100 is a fast-ramped synchrotron. The chosen magnets are iron dominated magnets with a superconducting coil, which is cooled in the two-phase regime by throttling the helium continuously along the coil[2]. In some places, the magnetic requirements can be only fulfilled by divergent special magnets, therefore SIS 100 consists 108 dipoles and 81 superconducting quadrupole modules. The supply of these magnets is split into sextants. Each sextant has a cold arc, where the magnets share a common insulating vacuum, and a straight section, where all quadrupole modules are separated by warm beam pipe sections. All magnets are cooled in parallel and supplied from the same supply header. The pressure in this header is adopted to the heat load resulting from the different experimental cycles with different ramping schemes. The pressure in the return line is expected to be nearly constant for all cycles. To achieve an equal and sufficient flow distribution through all cooling...
loops each loop is equipped with a flow restrictor at the entrance. This flow restrictor (capillary tube) has to be chosen individually after testing of each component type [3]. The cooling scheme is shown in figure 1.

![Cooling scheme of a SIS100 sextant](image)

FIGURE 1. Cooling scheme of a SIS100 sextant

In addition, for most components with high individual heat loads in front of the capillary tube a heater is foreseen as an individual control element [4]. The heater will cause an increase of the vapor fraction and therefore the mass flow will be reduced for the same pressure head. Due to the eddy losses in the beam vacuum chamber, the chamber has to be cooled actively to guarantee a temperature below 15 K along the full chamber. As the characteristic of the head load in the vacuum chamber derivates from the one in the magnets and the warm-up the chamber without the magnets, a separate supply line for the vacuum chamber is foreseen.

**Table 1.** The reference cycles for the system design of SIS100. The dynamic loads add to the static loads. The static loads on the 4K-loop are 3450W and 14800 W on the 50-80 K shield loop.

| Cycle 0 | Cycle A | Cycle B | Cycle C |
|---------|---------|---------|---------|
| 4K stand-by | Proton cycle | RIB cycle U^{28+} | triangular cycle U^{28+} |
| Intensity: 2*10^{13} | Intensity: 5*10^{11} | Intensity: 1.3*10^{11} |
| Repetition rate: 5s | Repetition rate: 4s | Repetition rate: 0.991 s |
| Q_{dyne}= 0W | Q_{dyne}= 3880W | Q_{dyne}= 3060W | Q_{dyne}= 11300W |

**Table 2.** The stored mass versus the operating conditions for the 3 process lines in a SIS100 sextant

![Graphs](image)
In figure 2 the time the helium travels along the sextant is given for the different magnet positions. The flow-through time of each magnets sums between 1 to 2 minutes.

![Figure 2. Velocity and integral flow time along one sextant](image.png)

Together with the results from a single magnet behaviour, various process elements have been introduced to the SIS100 sextant to guarantee a safe switching between cycles. For the control of the mass flow through a single magnet each inlet of a magnet cooling loop is equipped with a heater. The surplus of liquid helium will be either boiled-off (short term reaction to sudden loss of the dynamic heat load) or recycled with a pump into the high pressure supply.

Together with the overall analysis for the safe start of cycle C from cycle 0 or A, the supply pressure has to be raised at least 2 h in advance and the surplus compensated by the heaters. Therefore the staggering of the cycles has to be done in such a way, that the loads are only changed slightly and long settling times may be avoided.

The cryo plant will follow the demands by adopting the provided refrigeration power between 40 and 120%. The overcapacity for SIS100 is either provided by a temporary liquid nitrogen support or by the FAIR overall experimental schedule.

3. Super-FRS
The Super-FRS is a 2-stage in-flight separator with several branches. Therefore, magnets with a large acceptance have been required. As the design for the quadrupoles has to be realized by using superconducting coils the dipoles are also designed using superconductors [5, 6]. Each multiplet is equipped with up to 9 pairs of current leads for 250A. For the analyses of the overall reliability of the system the use of an additional “fall-back” compressor was undertaken to provide space and utilities for this component. For this investigation the full version of the Super-FRS has been considered. The characteristic data of the magnets are given in table 3.

| Table 3. Magnets of Super-FRS |
|-----------------------------|
| **amount**  | long | short | dipole |
| **[-]**     | 27   | 7     | 27     |
| **liquid helium volume** [l]| 1600 | 1100  | 50     |
| **[t]**     | 42-52| 15-20 | 1,2    |

The magnet supply is divided into 6 branches, within these branches all magnets have a common supply and return line at 4K and a common warm gas return line for the current leads, the shield cooling loop is not given in this sketch, figure 3, as it does not affect this investigation. The branches
will be connected by branch boxes, which include re-coolers. The liquid inventory of these re-coolers is not considered. The warm piping is connected directly with the compressor station, and guarantee a pressure head that is small enough for the safe operation.

During in interruption of the cryogenic system the full-boil off could be recovered by this warm line, and only the distribution system would increase in pressure up-to the design pressure. But as the design for the warm gas line will be optimised in the case of normal operation, a higher pressure drop between the magnet and the compressor system has to be assumed during the full recovery of the boil-off coming from the magnets. The minimal pressure that may be realized on the magnets is assumed to 1.45 bar. For this minimal pressure and other release pressure the remaining liquid helium level in a long multiplet is calculated and given in figure 4. From these calculations the refilling time of the magnets is calculated and given on the right in figure 4.

With these results the required compressor system for such a scenario is investigated. In figure 5 the comparison for the recovery from all magnets, and only from the multiplets is given.
Figure 5. Dashed lines: The boil-off mass flow for the Super-FRS, coming from the magnets, that has to be handled to keep the system at 1.45 bar. Straight lines: The required refilling time for the magnets (the time for the system itself is not added in this chart as it is independent from the magnet pressure and will be added in every case).

What can be seen is, that the boil-off stream from the dipole leads to an one third higher mass flow in a quite short time in the beginning, but reduces the refilling time just by 10%. Therefore, the recovery compressor would only handle the boil-off from the multiplets.

This investigation allows to follow the idea of a compressor parallel and independent from the compressor system of the cryo plant. As an advantage of the FAIR electrical topology this compressor is even connected to another electrical grit, and could be so full redundant to the other systems. The further weighting has to be done, when the price for such a compressor may be better compared to the unavailability of Super-FRS.

4. Conclusion
For the system design of the FAIR cryo infrastructure options for a higher reliability are shown as technical possible, but the order of operating cycles has to be chosen more sensible than the users have been used to in the normal conducting machines at GSI. Nevertheless the machines will be able to serve all demands of the experiments, but the overall experimental time schedule has to be adopted.

References
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