Local Cryogenics for the SIS100 at FAIR

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Abstract. In the coming years a new international accelerator Facility for Antiproton and Ion Research (FAIR), one of the largest research projects worldwide, will be built close to Darmstadt in Germany. FAIR will provide antiproton and ion beams with unprecedented intensity and quality. One of its major accelerators will be a synchrotron called SIS100 having a circumference of about 1100 meters. The SIS100 tunnel will house a complex cryogenic system supplying up to 20 kW cooling capacity @ 4.5 K to about 300 superconducting fast ramped magnets and other physics equipment. The planned SIS100 local cryogenic system can be principally divided into three sections each fed from a separate Feed Box. Every Feed Box supplies liquid helium for magnet, vacuum chamber, cryo collimator, current lead and bus-bar cooling as well as 50 K helium for the current lead and thermal shield cooling, independently to two sixth of the ring. Each sixth of the ring, so called sextant, consists of a cold arc and a straight warm section. By-pass Lines circumvent the straight warm sections of the sextants, where warm equipment (e.g. normal conducting cavities and magnets) is located. Between the warm equipment, are superconducting magnets located which also need to be supplied from the By-pass Lines with helium and cold electrical connections. The By-pass Lines are Polish in-kind contribution, coordinated by the Jagiellonian University of Krakow and will be designed, manufactured and commissioned by the Wroclaw University of Technology. In this paper the SIS100 local cryogenic system will be described with focus on the By-pass Lines and on magnet cooling including the balancing of differences between dipole and quadrupole circuits and the coping with dynamic loads.

1. Introduction
A new international accelerator Facility for Antiproton and Ion Research (FAIR) will be built close to Darmstadt in Germany [1]. It will provide antiproton and ion beams with unprecedented intensity and quality. The working horse of the facility will be a synchrotron with 100 Tm, the so called SIS100, having a circumference of 1083 m. It consists of 108 deflection magnets (dipoles) and 192 focusing magnet units (quadrupoles). The superconducting magnets, beam vacuum chambers and other physics equipment need to be cooled to liquid helium temperature. Therefore, a complex local cryogenic system is required in order to distribute up to 20 kW cooling power @ 4.5 K (in cooling mode).

2. Local cryogenic system
The SIS100 local cryogenic system is described in [2, 3]. It can be principally divided into three sections each fed from a separate Feed Box, see Figure 1. Each Feed Box supplies liquid helium for
magnet, bus-bar, current lead and vacuum chamber cooling as well as 50 K helium for the current lead and thermal shield cooling to two sextants, i.e. to two sixths of the ring. The purpose of such an infrastructure is to be able to separate the ring into six sextants which can be independently cooled down, warmed up and serviced.

3. Magnet cooling
The helium process pipes integrated in the magnet cryostats are summarized in Table 1. A magnet supply line transfers helium from the Feed Box to the End Box. Its size is chosen to accomplish a negligible pressure drop along the 180 m length of the sextant in order to avoid misdistribution. Magnet coils and bus-bars are arranged in parallel and are connected to the magnet supply line. The same is valid for the vacuum chamber supply line, which is needed for cooling of the beam vacuum chambers and cryo collimators. These two supply lines house an internal tube as heat exchanger to successively sub-cool the helium along the sextant. The helium is send back to the Feed Box via the common return.

The supply lines for beam vacuum chambers and magnet coils are separated since their heat loads and hydraulic behavior strongly differ. The helium mass flow can be adjusted via the pressure in these supply lines. The pressures will be independently controlled to be between 1.45 up to 1.8 bara. The pressure of the common return is defined by the compressors’ suction pressure and the pressure loss. It will be about 1.25 bara.

Figure 1. Cryogenic system of SIS100 at FAIR.
Table 1. SIS100 process pipes and operational conditions.

| Process line                        | Outer $\varnothing$ x thickness in mm | Operating temperature in K | Operating pressure in bara | Design pressure in bara |
|-------------------------------------|--------------------------------------|-----------------------------|---------------------------|-------------------------|
| He supply magnet                    | 54 x 2                               | 4.5                         | 1.8 *                     | 20                      |
| He supply vacuum chamber            | 32 x 2                               | 4.5                         | 1.8 *                     | 20                      |
| He return magnet + vacuum chamber   | 108 x 3                              | 4.3                         | 1.1 *                     | 20                      |
| He supply shield                    | 42.4 x 2                             | 50                          | 18                        | 20                      |
| He return shield                    | 42.4 x 2                             | 80                          | 17                        | 20                      |

*The operation pressure during cool down is up to 18 bara.

3.1. Balancing of differences between dipole and quadrupole circuits
The heat loads can be principally divided into the static and the dynamic part. The dynamic heat load is caused by ramping the electrical current, i.e. the magnetic field. The largest heat load is induced during the so called triangular cycle, where the electrical current is continuously ramped up to 14 kA with a ramp rate of 28 kA/s, i.e. with a ramping frequency of 1 Hz.

The heat loads of the helium cooling circuits are summarized in Table 2. The difference of static heat load for dipoles and quadrupoles can be neglected. However, a strong difference of the dynamic heat load can be seen.

Table 2. Heat loads of the liquid helium cooling circuits of SIS100 dipoles (DPs) and quadrupole (QP) units. The presented heat loads of the dipole are measured at the first of series magnet. The heat loads of the quadrupole unit are estimated. Heat loads of the vacuum chamber are not considered in the table.

| Circuits      | Static load in W | Dynamic load for triangular cycle in W |
|---------------|------------------|---------------------------------------|
| DP circuit    | 2                | 50                                    |
| QP circuit    | 3                | 25... 35                              |

Since the heat load and the hydraulic length of a quadrupole circuit are approximately the half compared to the dipole circuit, hydraulic restrictors need to be applied in the quadrupole cooling circuit. Mechanical balancing valves will not be used. Instead, capillary tubes with an inner diameter of at least 2 mm, to avoid clocking, will balance the helium mass flow passing in parallel through dipole and quadrupole units.

3.2. Coping with dynamic loads
As mentioned, no mechanical valves are planned to adjust the helium mass flow to the strongly varying dynamic loads. Instead, heaters will be applied, acting as hydraulic balancing valves. Two heaters (one for redundancy) will be located at the inlet of each magnet cooling circuit. Their purposes are explained in the following.

1) The machine’s ramping cycles, i.e. the dynamic loads will be changed within extreme short time of some seconds only. These changes are much faster than the reaction time of the refrigerator system. The quickly reacting heaters will simulate the maximum dynamic load of the envisaged ramping cycles. Doing so, the refrigerator system must simply provide a constant cooling power at constant pressure and temperature. Therefore no adaptation to the ramping cycles by the refrigeration system is required and a stable cryogenic operation can be achieved.
2) A common return line filled with too much liquid helium can lead to unstable hydraulic behavior and will be avoided by heating. Such filling with excessive liquid helium would occur before ramping the machine, i.e. having only static heat loads. In Figure 2 the two cases, “static heat load” and “static heat loads plus 14 W heating”, are presented for the dipole. It can be seen, that the void fraction, of the helium entering the common return line, can be increased by heating. The increase of void fraction is significantly amplified, since the helium mass flow is reduced to about 50 % by the larger friction of the gas fraction. The use of local heaters at the inlet of each cooling circuit has a great advantage which needs to be addressed. It is possible to evaporate the returning liquid helium for instance with heaters in the common return or in the Feed Box. However, for the case depicted in Figure 2, the double heating power (29 W instead of 14 W) is needed to achieve the same void fraction with a heater located in the return stream. This is due to the described reduction of the mass flow. Therefore, the use of heaters at the inlet of each cooling circuit can even save operating power of the refrigeration system.

3) The before mentioned effect is of great advantage for the mass flow control. The limited range of mass flow control by regulating the supply pressure can be strongly enlarged by heating. Due to the sensitivity of the helium mass flow to the heating power it is possible to balance the cooling of individual magnets. Temperatures at the coil or at the outlet of the cooling circuit can be used as actuating variables.

Heaters have important advantages compared to mechanical valves in the described application. They are failure safe. In case both heaters fail, this magnet is cooled with a larger mass flow than needed. Further, if the heaters are switched off then no additional pressure drop is created. The heat leak is smaller and there is no danger of thermo acoustic oscillations. Their integration is easy, because they are small, they can be attached at the outside of the process lines and only their electrical wires need to be fed through the cryostat. Last but not least, their price is competitive.

![Figure 2](image-url)

**Figure 2.** T-s diagram for the SIS100 dipole with “static heat load” and “static heat load plus 14 W heating” at the inlet of the cooling circuit. Calculations are performed with the inlet pressure \(p_{in} = 1.6\) bar, a temperature difference at the recooler \(\Delta T_{rec} = 0.2\) K and outlet pressure \(p_{out} = 1.25\) bar. Calculated values for the case “static heat load” are \(x_{out} = 17\) % and mass flow = 2.0 g/s. For the case “static heat load plus 14 W heating” the void fraction \(x_{out} = 92\) % and the mass flow of 1.1 g/s are calculated.
4. Polish in-kind

The whole Polish in-kind contribution is coordinated by the Jagiellonian University of Krakow. The Wroclaw University of Technology (WrUT), having great experience in designing cryogenic components like transfer lines [4], is responsible for the design, manufacturing and commissioning of the contributed cryogenic components like By-pass Lines (BPLs), Feed Boxes, Current Lead Boxes and End Boxes. The first delivery is foreseen for late 2015 and will include the first part of the BPL, which is required for the string test. The string test will be set up to test parts of the cryogenic and magnetic system. After the tests the first BPL part will be installed in SIS100.

4.1. By-pass Line

The already described SIS100 sextants consist of a cold arc and a straight warm section. By-pass Lines circumvent the straight warm sections of the sextants, where warm equipment (e.g. normal conducting cavities and magnets) is located. Between the warm equipment, superconducting magnets are located which also need to be supplied from the By-pass Lines with helium and cold electrical connections, see Figure 3. Each BPL has a length of about 45 m and connects 5 quadrupole doublets.

Figure 3. Sketch (not in scale) of the SIS100 By-pass Lines including Feed Boxes, End Boxes and Current Lead Boxes.
A single BPL houses, similar to the magnets, five helium process pipes and four pairs of superconducting bus-bars used to power the magnets.

The design of the BPLs uses an innovative concept to compensate thermal contractions of the floating cold mass. Its principle is to remove forces induced by internal supports from the BPL cold mass, and to suspend the entire interior on swinging slings, see Figure 4. The free movement of the BPL cold mass significantly reduces the forces to the magnets, and helps to maintain their stable position relative to the beam axis. The vacuum vessel of the bypass line is fully protected against the effects of helium leakage.

Figure 4. Cross section of the SIS100 BPL. Depicted are amongst others the bus-bars and the slings, i.e. the supports of the cold mass.

The set of four bus-bar pairs, supplying the electrical power to the SIS100 magnets have a substantial impact on the design. Due to a considerable total length of the bus-bars, and the individually controlled fast-ramping of the magnets, the presence of cross-talk between bus-bar pairs and parasitic capacities can affect the quality of the magnetic fields and consequently of the beam. The layout of the BPL cross-section is determined by maximizing the distance between the bus-bar pairs. Further a new concept of the bus-bar supports is designed and already electrically tested at cold at GSI.

Currently the first BPL piece, see Figure 5, is approved and the production has started.
Figure 5. First BPL piece being currently in production. This BPL piece will connect the arc termination magnet module with the Feed Box of sextant 5. Figure 5a) depicts the BPL piece from outside and b) depicts the cold mass and the supports.

4.2. Current Lead Box
In order to supply the electrical current of up to 14 kA to four families of superconducting magnets, altogether 8 electrical circuits have to be translated from normal conducting to the super conducting state. For this purpose, gas cooled current leads were developed by GSI and Mark & Wedell. In total 6 current lead boxes, each housing 4 current leads, will be built by WrUT. A detailed specification has been written and the contract between FAIR and WrUT is in preparation.
5. Conclusion

The SIS100 is a fast ramping machine creating a significant dynamic heat load in the cryogenic system. Since the maximum dynamic heat load and the hydraulic length of a quadrupole cooling circuit are approximately the half compared to the dipole circuit, hydraulic restrictors need to be applied in the quadrupole cooling circuit. Capillary tubes with an inner diameter of at least 2 mm will be used.

No mechanical valves are planned to adjust the helium mass flow through the magnets to the strongly varying dynamic loads. Instead, heaters will be applied, acting as hydraulic balancing valves. These heaters will be located at the inlet of each magnet cooling circuit. The quickly reacting heaters will simulate the maximum dynamic load of the envisaged ramping cycles. Doing so, the refrigerator system must simply provide a constant cooling capacity at constant conditions. Further the flooding of the common return with excessive liquid helium and subsequently hydraulic instabilities can be avoided by heating. Moreover, the mass flow passing through the cooling circuits is sensitive to the heating power, which allows for the cooling control of individual magnets. The heaters have important advantages compared to mechanical valves in the described application, for instance failure safety, no additional pressure drop in case of being switched off, small heat in leak, no danger of thermo acoustic oscillations, easy integration and they are inexpensive.

The whole Polish in-kind contribution is coordinated by the Jagiellonian University of Krakow. The Wroclaw University of Technology is responsible for the design, manufacturing and commissioning of the contributed cryogenic components like By-pass Lines, Feed Boxes, Current Lead Boxes and End Boxes. The first delivery is foreseen for late 2015 and will include the first part of the BPL, which is required for the string test. The string test will be set up to test parts of the cryogenic and magnetic system. After the tests the first BPL part will be installed in SIS100.

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