GSI Helmholtzzentrum für Schwerionenforschung GmbH

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Common specification of the cooling system of the superconducting SIS 100 magnets

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Abstract

This document represents the Common Specification for the cooling system of the superconducting SIS100 magnets. The specification regards to all superconducting magnet modules in the arcs and in the straight sections of SIS100.

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1. Purpose and classification of the document

The purpose of this document is to specify the technical requirements of the helium cooling system of the SIS100 magnet modules. Where ever requirements are specified in the General Specifications [1], technical Guidelines or detailed Specifications they are only referenced in this document.
The document regards to the following magnet parts, cooled by forced helium flow:

- superconducting coils
- superconducting bus bars with voltage breakers
- magnet yokes
- common girders in the quadrupole units
- beam vacuum chambers
- cryo catchers
- cryo sorption pumps

Although the components cooled at 50K are listed in the chapters related to the magnet modules, this document is not related to the 50K cryogenic system. The requirements on the thermal radiation shield and on the structures, passively cooled at 50K (e.g. cold-warm transition, thermal anchors of the current leads) are defined in the specification of the cryostats of the magnet modules.

2. Scope of the technical system

2.1. System overview

The SIS100 ring is divided into six independently cooled sectors (Figure 1). Each sector consists of a long arc cryostat and three stand-alone cryostats in the straight parts of a sector. The SIS100 synchrotron has 108 cryogenic dipole modules, 83 cryogenic quadrupole modules and 12 so called “missing dipole” modules.

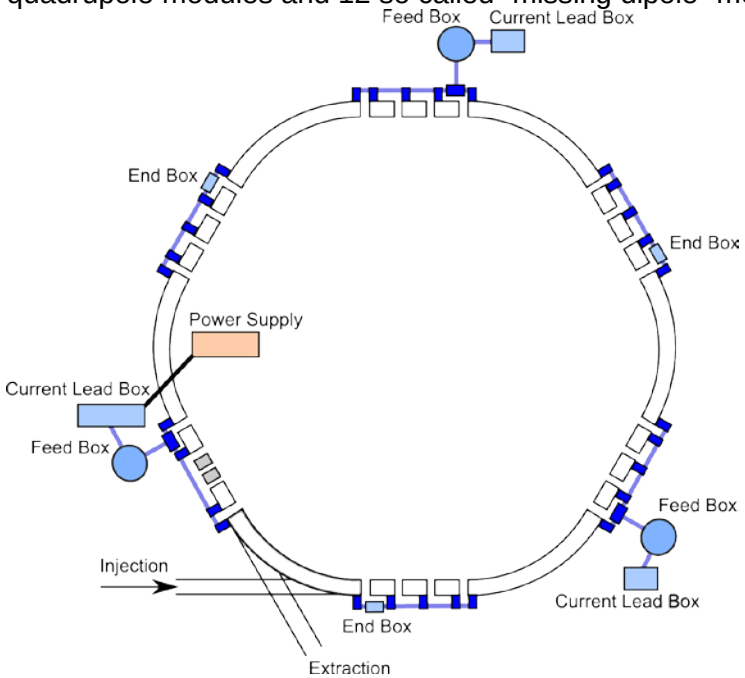


Figure 1 Cooling scheme of the SIS100 ring

Each of six sectors of SIS100 contains 14 cells of the ion optical lattice numbered from 1 to E in hexadecimal system. The straight sections of each sector contain cells 1, 2 and 3 followed by cells 4 ... E in the arc part of the sector. The quadrupole doublet modules are installed in each of 14 cells. As an exception one warm normal conducting quadrupole doublet will be installed in the cell 2 in the extraction sector (Figure 1). Every two dipoles modules will be installed in each arc at 10 places between the cells 4 and E. At the beginning and at the end of each arc (between cells 4 and 5 respective D and E) only one of the dipole modules will be installed. The second one will be replaced by so called "missing" dipole module (section 3.6).
Cooling channels of all magnets in one sector are connected to the common helium supply and return headers (Figure 2, right). The forced helium flow passes the magnet coil and the magnet yoke, connected in series (Figure 2, left).

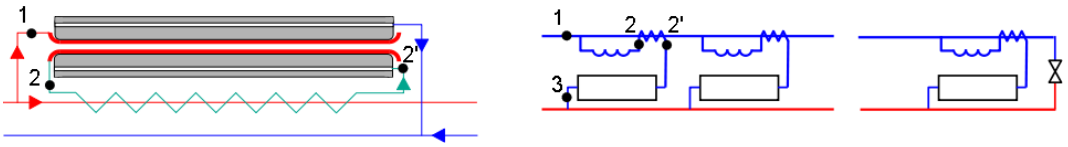


Figure 2: Cooling scheme of a single dipole magnet and of the SIS100 sector

The helium in the supply line and at the coil inlet (Point 1, Figure 2 and Figure 3) is sub-cooled, i.e. it has a temperature below the saturation line at the local pressure.
The helium passes the magnet bus bars and the coil (Points 1 - 2), the recooler cocated in the supply header (2 - 2'), the yoke (2 - 3) and goes to the return header. The aim of the recooler is the avoiding of the appearance of the vapor fraction in the supply line over the whole length of the SIS100 sector. Depending on the heat release in the magnet, the helium may leave the yoke either as two-phase or as vapor at T = 6 - 7 K (Figure 3).

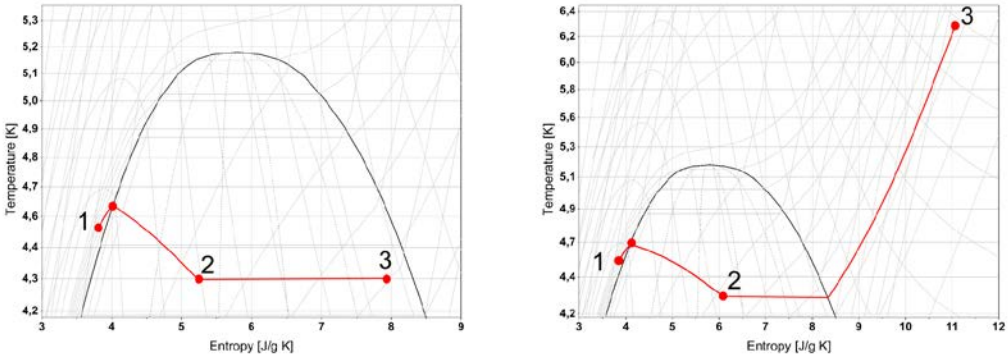


Figure 3: TS diagrams for the heat release in the dipole of 40 W (left) and 70 W (right)

2.2. Limits of the system and environment

The cooling system of each magnet has following interfaces to other systems:

1. The supply and return headers of all dipole and quadrupole modules in the arc cryostat are connected in series. The headers in each module must have the same dimensions and the same positions in the cryostats. The compensation elements on the ends of the supply and return headers in each module shall be able to compensate the production tolerances, misalignment during the

assembling and the movement of the cold mass extremities caused by the thermal contraction.

2. The helium supply and return lines of the quadrupole doublets in the straight sections have to match the corresponding lines in the connection cryostat. The compensation elements installed between the helium lines should be able to compensate the production tolerances, misalignment during the assembling and the movement of the cold mass caused by the thermal contraction.
3. The supply and return headers in each magnet module in the arc cryostat are fixed either to the magnet yoke in dipoles or to the common girders in the quadrupole doublets. The fixtures are done by the combination of fixed and sliding supports in order to compensate the movement of the cold mass caused by the thermal contraction.
4. All components of the cooling systems shall not touch the thermal radiation shield and other parts of the magnet module with the temperatures higher than 4K. An appropriate distance to these parts has to be assured.

3. Construction and design features

3.1. Definitions

1. 4 K in terms of this document means the temperature of the cold mass. The exact value of the temperature may vary between 4.3 K and about 7 K during the normal operation, depending on the operation mode and the position of the component within the cooling channel.
2. 50 K in terms of this document means the temperature of the thermal radiation shield. The exact value of the temperature within 50 K circuit may vary between 50 K and 80 K, depending on the position of the modules in the synchrotron ring.
3. Cold mass in terms of this document is the technical system housed in the cryostat and supposed to be cooled down to 4 K at normal operation.
4. Warm condition in terms of this document means the room temperature.
5. Actively cooled components in terms of this document are technical systems cooled by forced helium flow either at 4 K or at 50 K
6. Passively cooled components in terms of this document are technical systems cooled entirely by thermal conduction either at 4 K or at 50 K
7. A cooling channel or flow channel in terms of this document is an unbranched flow path between the helium supply and return headers of the SIS100 ring.
8. 4 K circuit in this document means all flow channels in one magnet module. Generally magnet modules have more than one cooling channel. The 4 K circuit of the quadrupole doublet module has three parallel flow channels connected to the supply and return headers - two for the cooling of magnets and one for the cooling of the beam vacuum chambers.
9. 50 K circuit in this document means a cooling circuit for the thermal radiation shield and for some passively cooled components like thermal anchors of the magnet support structures, current leads, cold-warm transitions etc.
10. Recooler in terms of this document is a heat exchanger embedded in the helium supply line
11. Current leads in terms of this document are the local current leads of the corrector magnets with a nominal current of about 250 A

12. Cool down and warm up in terms of this document are the operating modes of the SIS100 ring. During these modes the ring is being cooled down / warmed up from the room temperature to 4 K.
13. Normal operation in terms of this document is the operating mode of the SIS100 ring. In this mode the magnets are at 4 K and being ramped. The heat load to the magnets is the sum of the static heat losses and dynamic losses caused by the fast ramped magnetic field.
14. Stand-by in terms of this document is the operating mode of the SIS100 ring at 4 K, but without powering of the magnets. The heat load to the magnets is caused only by the static heat load.
15. Vapor quality x in terms of this document is the vapor mass vraction of the two-phase helium flow.
16. The sizes of the tubes in this document are always given as ØD x W with D the outer diameter of the tube and W the wall thickness in mm.

3.2. Common Specifications, Technical Guidelines and Engineering Drawings

The following technical guidelines are mandatory for the production of the SIS100 magnet cooling system:

1. FAIR General Specifications, F-GS-B-01e [1]
2. FAIR Technical Guideline 2.35e: “Steel Materials for Pressurized Cryogenic Components” [2]
3. Common Specification for Cryostats of Cryogenic Modules in FAIR Accelerators, F-CS-CR-01e [3]
4. Technical Guideline F-TG-K-3.52e: Temperature Sensors for Cryogenic Purposes [4]
5. Technical Guideline F-TG-K-13.5e: Temperature Sensor Installation for Cryogenic Purposes [5]
6. FAIR Technical Guideline 6.11e: Cleaning and Cleanliness of Cryostats and Related Components [6]
7. FAIR Technical Guideline 7.24e: “Pressurized Leak Testing of Cryogenic Tubing” [7]
8. FAIR Technical Guideline 7.23e: “He Leak Testing of Cryogenic Tubing” [8]
9. FAIR Technical Guideline 7.26e: “Flow Rate Test for Cryogenic Processing Pipes” [9]
10. FAIR Technical Guideline 10.16e: Documentation and Certificates for Cryogenic Modules [10]

The magnet modules shall be produced according to the engineering drawings referenced in the Detailed Specification of the magnet module.

3.3. Helium supply and return headers

Each magnet module in the arc section is equipped with three straight tubes, indicated on the Figure 4 as A1, A2 and B. The lines A1 and A2 are the 4 K helium supply headers for the magnets and for the beam vacuum chambers respectively. The line B is the common return line for both supply headers - A1 and A2. C and D are the 50K supply and return lines for the cooling of the thermal radiation shields.. The parameters of each header are given in the Table 1.

Table 1 Helium headers in the arc section

Line	Purpose	Size, mm	Operation pressure*, bar(a)	Design pressure, bar(a)
A1	Supply line for the magnet cooling	Ø54 x 2	1.5 - 2.0	20
A2	Supply line for beam vacuum chambers	Ø32 x 2	1.5 - 2.0	20
B	4K Return line	Ø108 x 3	1.1 - 1.2	20
C	50K supply line	DN40	18	20
D	50K return line	DN40	17	20

*) Pressure values are given for the normal operation. Pressure values at cool down / warm up will be higher

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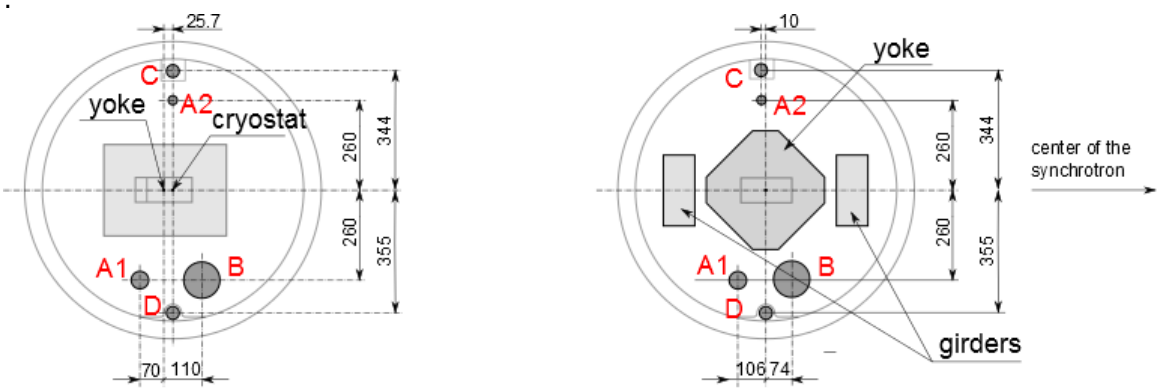


Figure 4: Positions of the helium supply and return headers (view from the beam downstream)

Due to the design pressure of 20 bar all tubing within the magnet modules is the pressure equipment according to the European Pressure Equipment Directive 2014/68/EU. The components (see figure 4) have categories as follows:
- line A1 - no category,
- line A2 - no category,
- line B - category 1,
- line C - no category,
- line D - no category.

All pressure loaded components must be designed, manufactured and tested according to the German AD 2000 pressure vessel code and fulfill the requirements of the Pressure Equipment Directive 2014/68/EU.

All headers shall be manufactured from cold rolled stainless steel tubes. The material has to be chosen according to the Technical Guideline “Steel Materials for Pressurized Cryogenic Components” [2]. The tolerances for the outer diameter and for the wall thickness shall be at least D4/T3 according to ISO 1127.

All helium headers should be covered by 10 layers of MLI (multi-layer Insulation) in order to reduce the heat flux to the helium inventory in case of loss of insulation vacuum.

The headers must be fixed to the cold mass in the middle point of the magnet module by a fixed supports. At both end points of the magnet module the headers must be fixed by sliding supports with respect on the thermal contraction. The fixations of the bearings on the cold mass should be done by bolting to the magnet yoke (dipole modules) or to the common girders (quadrupole doublets).

The positions of the headers relative to the centre of the magnet are given in the Figure 4. The positions are valid for all dipole magnet modules and for the quadrupole modules in the arc sections. The position tolerances in x-y plane for all headers are ±1.0 mm.

For the cold testing of the magnet modules all helium headers shall be equipped with flanges for the Helicoflex® gaskets according to the technical drawings provided by Company.

Additional requirement of the supply headers A1 and A2:

The heat load to the supply headers has to be minimized. Direct coupling of the passively cooled components to the supply headers A1 and A2 is not permitted. Passively cooled components may be coupled either to the cooling channel between the supply and return lines or to the return line B.

3.4. Magnet cooling channels

Following actively cooled components may be a part of the magnet cooling channel:

- Flow restrictor or combined heater/restrictor unit
- Superconducting bus bars and voltage breakers
- Magnet coil
- Recooler
- Cooling tubes in the magnet yoke
- Cooling tubes in the common girder of the quadrupole doublets
- Connection tubes and joints between the components listed above

In order to reduce the eddy current losses caused by a fast ramped magnetic field the cooling tubes in the magnet yokes, coils and superconducting bus bars shall be made of the CuNi alloy CuNi30Mn1Fe.
The materials for all other components of the cooling channel have to be chosen according to the Technical Guideline “Steel materials for pressurized cryogenic components [2].

3.4.1. Flow restrictors

Flow restrictor is the additional flow impedance at the inlet of the flow channel. It is used to reduce the mass flow rate in the cooling channel when the expected vapour quality *x* at the outlet of the cooling channel at normal operation is too low. The flow restrictor will be adjusted and tested by the Company individually for each type of the cooling channel. The adjustment of the flow restrictor shall be checked for each magnet module within the Factory Acceptance Test ans Site Acceptance Tests.

The sizing of the flow restrictors for each type of the quadrupole unit will be defined within the first cold test of every type of the quadrupole unit.

The pressure restrictor is a helically shaped tube with a small inner diameter. The adjustment of the flow rate can be done by the proper choice of the inner diameter following by the adjustment of the tube length. The inner diameter of the tube for the flow restrictor should be not smaller than 2.0 mm. If possible, the tubes with bigger inner diameter should be preferred in order to reduce the risk of blockages by frozen gases like hydrogen or neon. If an small inner diameter < 2 mm cannot be avoided, an additional particle filter shall be installed before the flow restrictor.

3.4.2. Magnet coils

The Nuclotron type superconducting cable is used for the production of the magnet coils. The hydraulic resistance of the cooling channel depends mainly on the inner diameter and of the length of the cooling tube of the Nuclotron cable.

The inner diameters of the cooling tubes are:

- 4.7 mm for the main dipoles and quadrupoles
- 4.0 mm for all corrector magnets

The coil length of each magnet module is specified in the detailed specification of the magnet module and in the set of technical drawings of the module. The approximate values for the coil lengths including superconducting bus bars with voltage breakers are summarized in the Table 2

Table 2 Cable inner diameters and estimated coil lengths of the SIS100 magnets

Magnet type	Inner diameter [mm]	Coil length incl. bus bars [m]
Main dipole	4.7	108
Main quadrupoles	4.7	65
Steerer	4.0	32
Chromaticity sextupole	4.0	18
Multipole corrector	4.0	43

3.4.3. Superconducting bus bars of main dipoles and quadrupoles

Superconducting bus bars for all SIS100 dipoles and quadrupoles are made of the same cable as the magnet coils (see 3.4.2) and have the cooling tubes 5.7 x 0.5 mm with an inner diameter of 4.7 mm. The layout and the length of the bus bars for each magnet module are specified in the detailed specifications of the magnet modules. Bus bars are labelled on the flow schemes as follow:

DPi / DPo	inner / outer dipole bus bars
DFi / DFo	inner / outer bus bars of defocussing quadrupoles
F1i / F1o	inner / outer bus bars of focusing quadrupoles, circuit 1
F2i / F2o	inner / outer bus bars of focusing quadrupoles, circuit 2

3.4.4. Superconducting bus bars of the corrector magnets

Superconducting bus bars of the corrector magnets connect terminal boxes of the magnet coils with local current leads. The tube size is 5.0 x 0.5 (inner diameter 4.0 mm). The helium flow in the bus bars will cool also the terminal boxes of the corrector magnets as well as the cold terminals of the current leads.

3.4.5. Voltage breaker

The voltage breakers (Figure 5) provide electrical insulation of the parts of the cooling channel with different potentials from each other or from the ground. They shall be radiation hard, leak-tight at helium temperatures and have a high electrical resistance. Voltage breakers have the inner diameter of 6 mm.

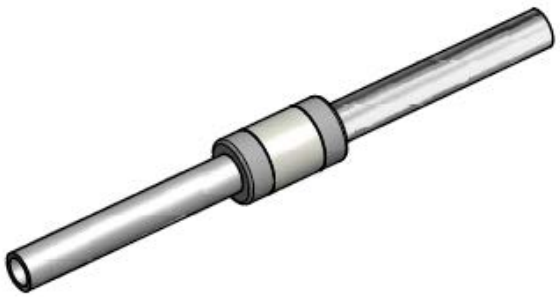


Figure 5: Voltage breakers

There are two types of voltage breakers with different materials of the cooling tubes. For the interconnection between the bus bars the voltage breakers with two cooling tubes made of the CuNi30Mn1Fe alloy shall be applied (Technical drawing F559-013-002; Friatec AG). The voltage breakers with CuNi30Mn1Fe / 1.4571 material combinations are foreseen for the interconnection between the bus bars and the stainless steel cooling tubes at the ground potential (Technical drawing F559-013-004, Friatec AG).

3.4.6. Recooler

Recooler is a heat exchanger embedded in the helium supply headers A1 and A2 (Table 1). It can be designed as a tube-in-tube heat exchanger (Figure 6). Another design may be also proposed by contractor.
The two-phase helium in the inner tube has the temperature of about 4.3 - 4.4 K. At the normal operation the sub-cooled helium from the feed box is delivered to the SIS100 sector at P = 1.5 - 1.8 bar(a) and T~4.4 K, i.e. its temperature is by 0.1 - 0.2 K lower, then the saturation temperature. The temperatures difference between the outer and inner tubes causes the heat transfer from the sub-cooled to the two-phase helium. The aim of the recooler is to remove the heat load to the supply header and to keep the helium in the outer tube in the single phase over the whole length of the SIS100 sector.

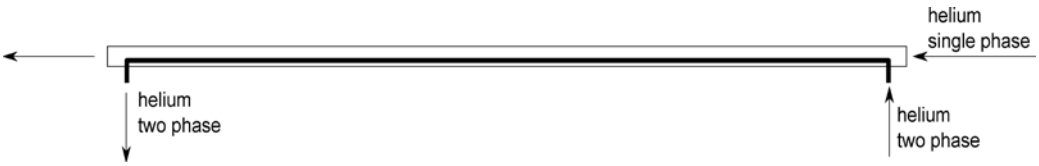


Figure 6: Helium supply line with embedded recooler.

The inner tube of the heat exchanger embedded in the A1 helium header (Figure 6) has a size Ø10 x 1 mm.
The heat exchanger may be of both types - counter-flow or parallel-flow.
The inner part has to be supported within the outer tube at least at one point in the middle in order to reduce vibrations. The distance between supports has to be rated by contractor.

3.4.7. Cooling tubes in the magnet yokes

The diameters of the cooling tubes in the magnet yokes are:

- Ø12 x 1 for the main dipoles and quadrupoles
- At least 6 mm inner diameter for all corrector magnets

The material of the cooling tubes in the magnet yoke is a CuNi alloy with 30% nickel content. The positions of the cooling tubes are presented in the Figure 7 – 8.

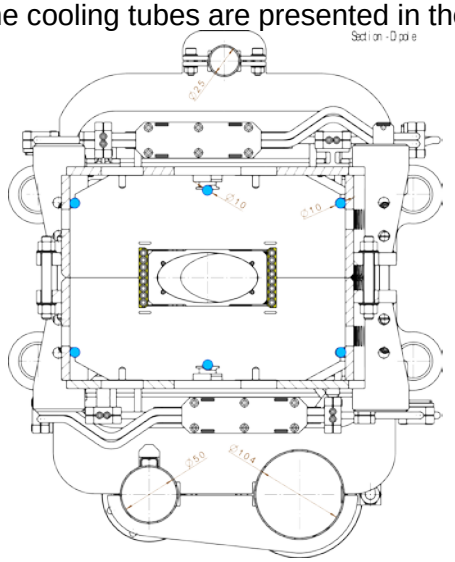


Figure 7: Cooling channels in the dipole yoke (blue circles)

To assure a good thermal contact the cooling tubes shall be pressed on the yoke either by stainless steel brackets (Figure 7, cooling tubes in the corners) or by a spring element. A possible solution for a spring element is presented in the Figure 10.
In order to improve the thermal contact between the cooling tubes and the lamination sheets a thin indium foil may be placed in the gaps between the tubes and the magnet yoke.

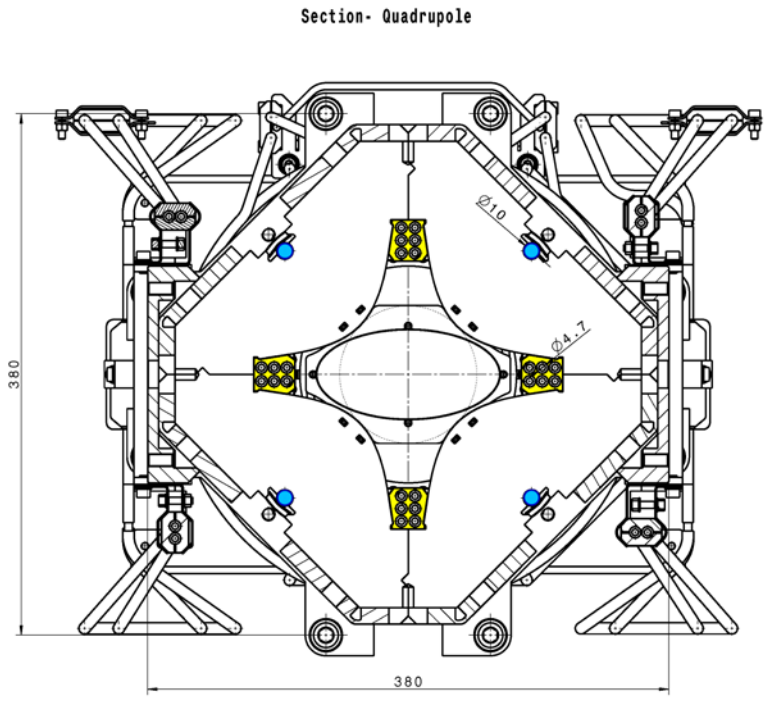


Figure 8: Cooling tubes in the quadrupole yoke (blue circles)

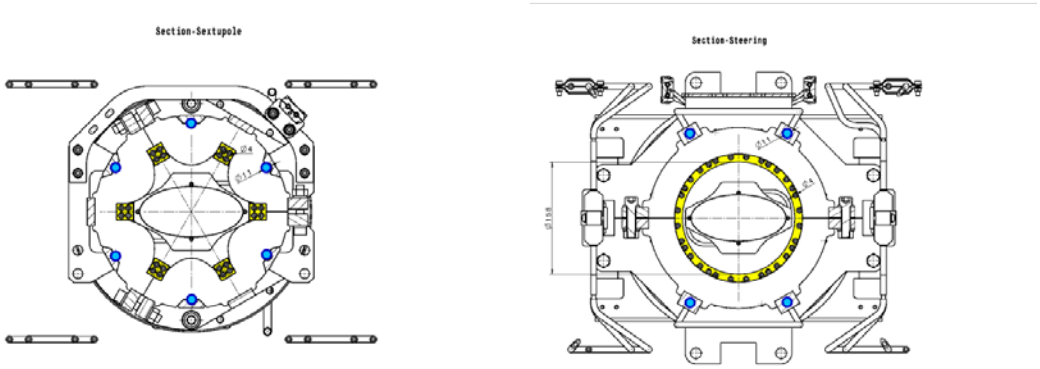


Figure 9: Sextupole (left) and steerer (right). Blue circles denote the cooling tubes in the yokes.

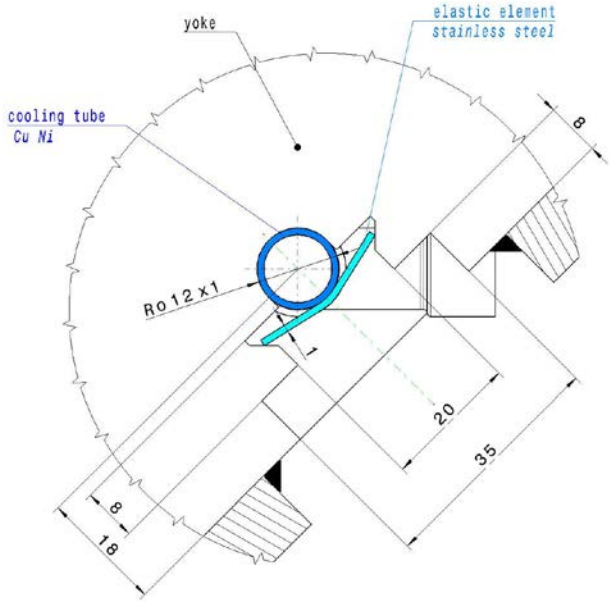


Figure 10: An example for a fixation of the cooling tubes in the yoke of the sextupole magnet.

3.4.8. Cooling tubes in the common girders of the quadrupole doublets

All helium headers and both quadrupole units will be fixed on two common girders cooled by 4K helium flow.
The cooling tubes of the common girders have a square cross-section 12x1.5 and are welded on the common girders. To reduce the danger of different thermal contraction of the inside and outside girders during the cool down and warm up of the magnet module, the helium flow in each cooling channel of the quadrupole doublet shall cool only one part of the girder - upstream or downstream (see Figure 16).

3.4.9. Connection tubes and joints

In order to reduce the pressure losses in the cooling channel, the lengths of all connection tubes shall be minimized. The minimal allowable inner diameter is 4.7 mm. Tubes with bigger inner diameter are preferred. The number of bends and fittings shall be minimized in order to reduce the pressure losses.
The permitted joining processes are TIG welding and brazing. For the prototypes and for the first-of-series modules the Swagelok® fittings are also allowed.
All joining processes have to assure the leak tightness of the helium circuit. The integral leak rate of the overall helium circuit of one magnet module has to be less than $5 \cdot 10^{-8}$ mbar/l/s at al operating conditions including cool-down and operation at temperatures of 4 K.

3.5. Cooling of the beam vacuum chambers

The beam vacuum chambers in the SIS100 ring are cooled by two-phase forced helium flow on the similar way as the magnets.

In every other dipole module the beam vacuum chamber will be connected in series with a cryo sorption pump (see section 3.6).
In a quadrupole doublet modules two beam vacuum chambers will be connected in series. In the quadrupole doublet modules with cryo catcher the cryo catcher chamber will be also connected in series with both beam vacuum chambers (see Figure 16)

Following actively cooled components may be a part of the vacuum chamber cooling channel:

- Flow restrictor
- Recooler
- Cooling tubes of the beam vacuum chamber
- Cooling tubes of the adsorption pumps
- Cooling tubes of the cryocatcher chamber

The materials have to be chosen according to the Technical Guideline “Steel Materials for Pressurized Cryogenic Components” [2] except for the cooling tubes of the beam vacuum chambers (see section 3.5.4).

3.5.1. Flow restrictor

The flow restrictors specified in 3.4.1 is also used in the cooling channel for the beam vacuum chamber. No heaters will be installed before the flow restrictors of the beam vacuum chamber cooling channels.

3.5.2. Recooler

The recooler for cooling channel of the beam vacuum chamber has the same design as for the magnet cooling channels (section 3.4.6).
The inner tube of the heat exchanger has a size Ø6 x 1 mm.

3.5.3. Cooling tubes of the cryo adsorption pump

Cooling tubes of the sorption pump have the size Ø6 x 1 mm.

3.5.4. Cooling tubes of the beam vacuum chamber

Cooling tubes of the dipole and quadrupole beam vacuum chambers have a size ofØ5 x 0.5. They will be made of the special cryogenic stainless steel grade X2CrMnNiMoN19-12-11-1 with very low relative magnetic permeability at cryogenic temperatures. The cooling tubes are specified in the detailed specifications for the dipole and quadrupole beam vacuum chambers.

3.5.5. Cooling tubes of the cryocatcher chamber

The size of the cooling tubes of the cryocatcher chamber is Ø6 x 1: The length of the cooling tube is about 0.6 m. The tube is brazed onto the cooper plating of the cryocatcher chamber as specified in the detailed specification of the cryocatcher module.

3.5.6. Connection tubes and joints

The requirements to the cooling tubes and joints are described in 3.4.9. The minimal permitted inner diameter for the connection tubes in the cooling channel V is 4.0 mm.

3.6. Cooling scheme of the dipole modules

There are two types of the cryogenic dipole modules: electrically connected to the inner dipole bus bar (I – type) and to the outer bus bar (O- type).
The helium flow schemes of both types of dipole modules are presented in the Figure 11 and Figure 12. The 4 K circuit of the dipole module has two parallel cooling channels - one for the magnet and one for the beam vacuum chamber. The inlets in both cooling channels are marked in the Figure 11 as M and V. The inlet to the cooling channel M is equipped with electrical heaters (see section 3.10.2).

Helium in the magnet cooling channel M passes following elements connected in series:

1. Connector to the supply header (header A1, DN50)
2. Voltage breaker (VB), bus bar F2i
3. VB, bus bar QDo
4. VB, bus bar F2o
5. VB, bus bar QDi
6. VB, bus bar F1i
7. VB, bus bar Dpi with magnet coil
8. VB, bus bar F1o
9. VB, bus bar DPo
10. VB, recooler
11. Cooling tubes in the yoke
12. Connector to the return header (header B, DN100).

Helium in the cooling channel V for the vacuum chamber passes following elements:

1. Connector to the supply header (header A2, DN25)
2. Flow restrictor
3. Cooling tubes of the cryo pump (if available)
4. Recooler
5. Cooling tubes of the beam vacuum chamber
6. Connector to the return header (header B, DN100)

The connection tubes of the beam vacuum chamber may be either on the upstream or on the downstream site of the magnet, depending on the position of the dipole module in the SIS100 sector.

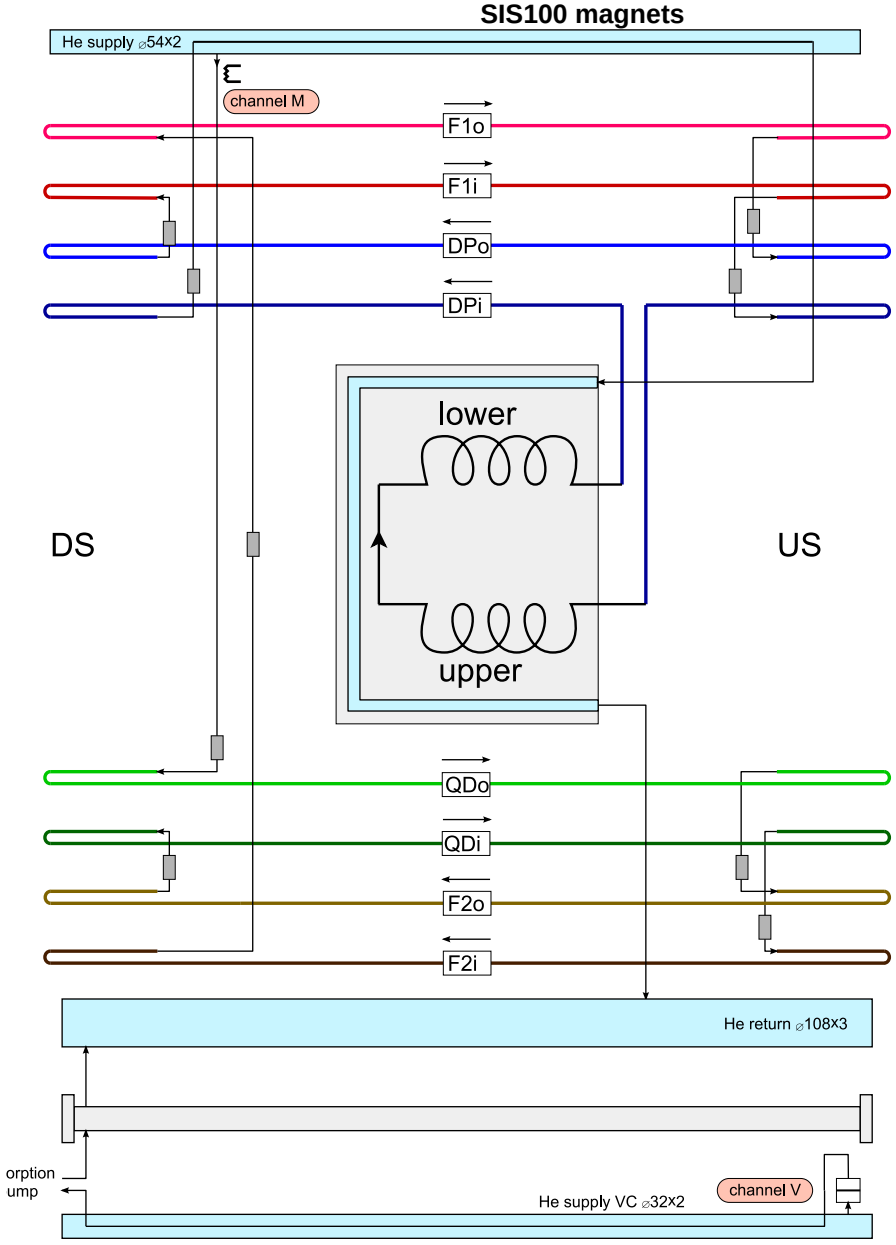


Figure 11: Cooling scheme of the I-type dipole module

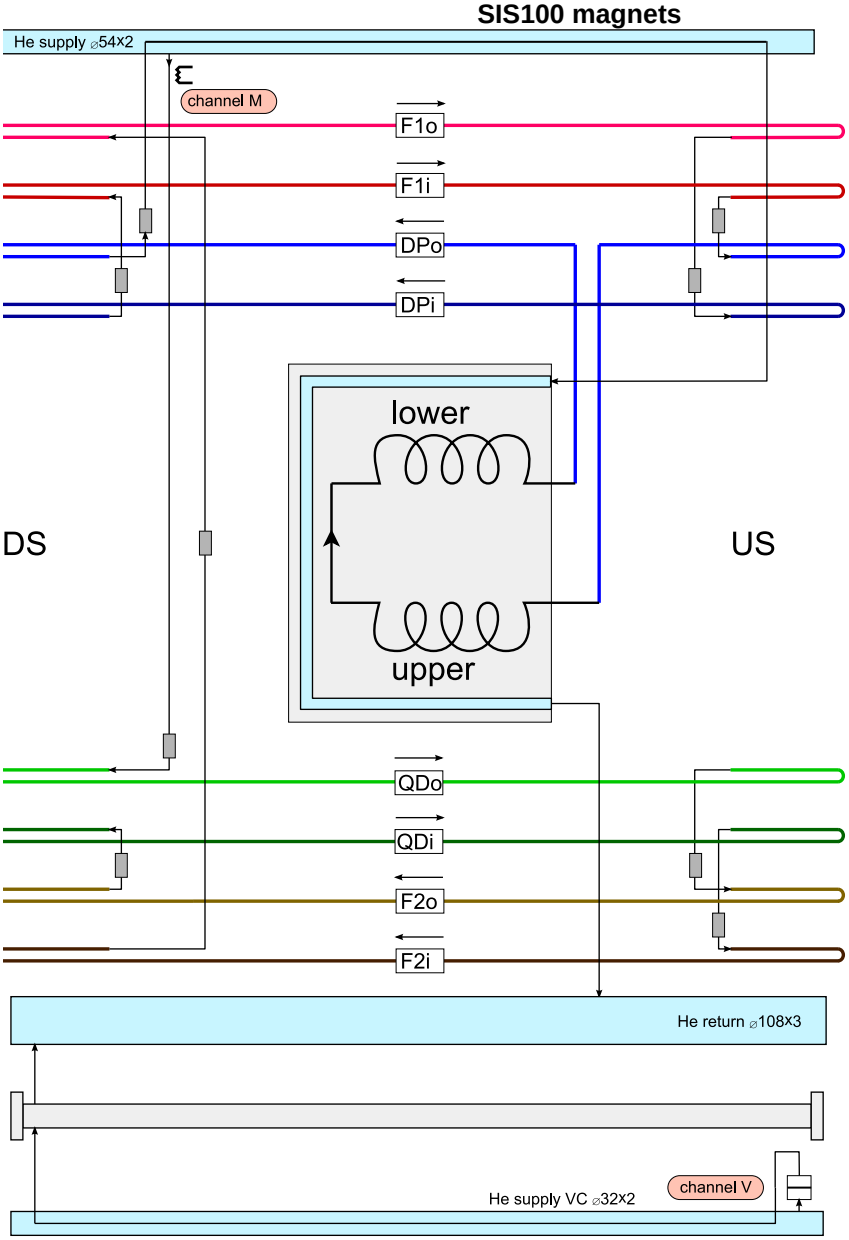


Figure 12: Cooling scheme of the O-type dipole module

3.7. Cooling scheme of the Missing Dipole Modules

The Missing Dipole Modules will replace the regular dipole modules at two places in each arc where no dipole field is required (section 2.1). The Missing Dipole Modules don't contain a superconducting magnet. The only items to be cooled by helium flow at 4 K are the superconducting bus bars and the beam vacuum chamber. 6 of 12 missing dipole modules (one per sector) will be equipped with pressure relief valves between helium headers A2 and B. Figure 13 and Figure 14 shows the flow diagrams of the both versions of the missing dipole module.

Helium in the magnet cooling channel passes following elements connected in series:

1. Connector to the supply header

2. Flow restrictor with heater
3. All bus bars with voltage breakers
4. Recooler
5. Connector to the return header

Elements to be cooled at 50 K by thermal conduction:

- thermal anchors on the support roads

Figure 13 show the helium flow scheme of the missing dipole module with relief valves.

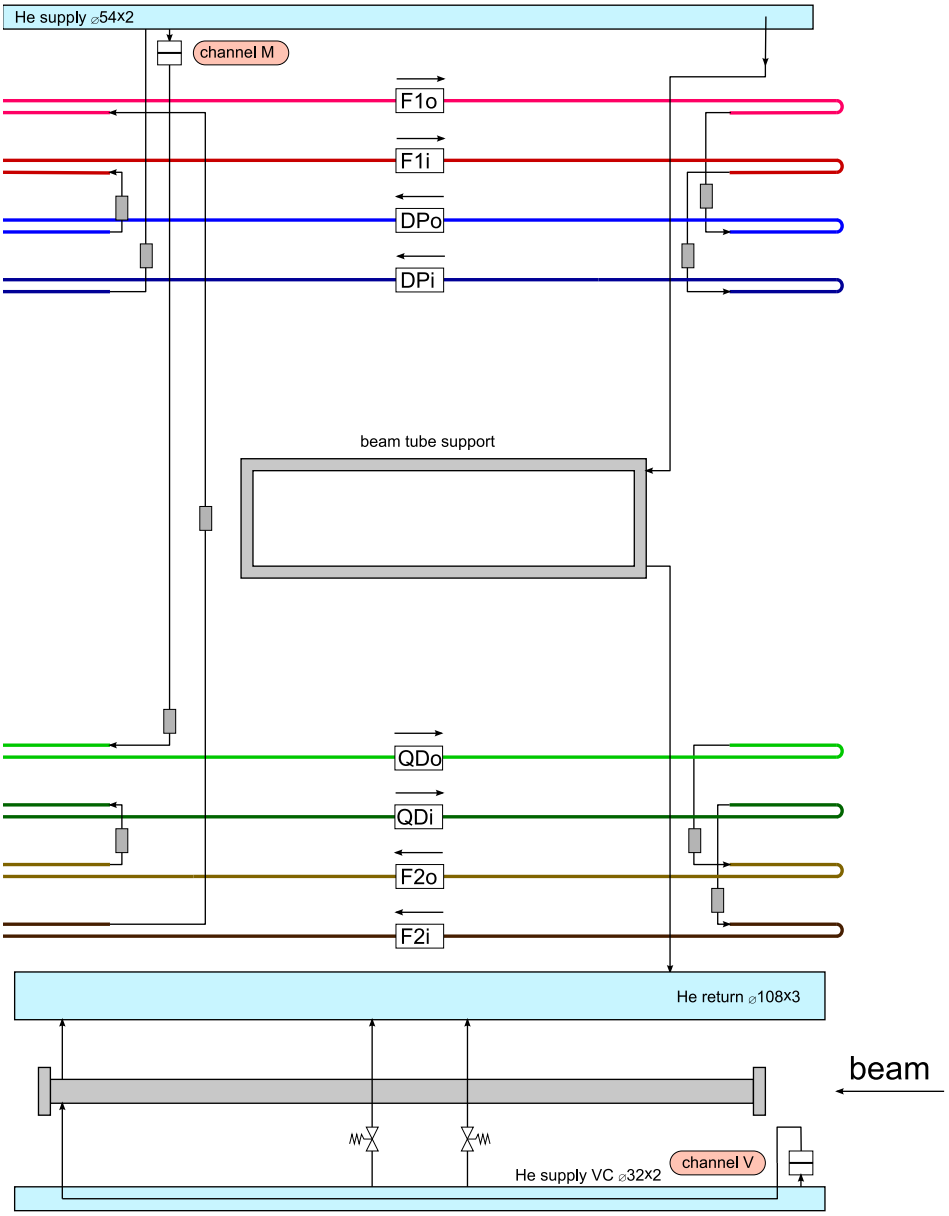


Figure 13: Cooling scheme of the missing dipole modules with pressure relief valves between headers A2 and B.

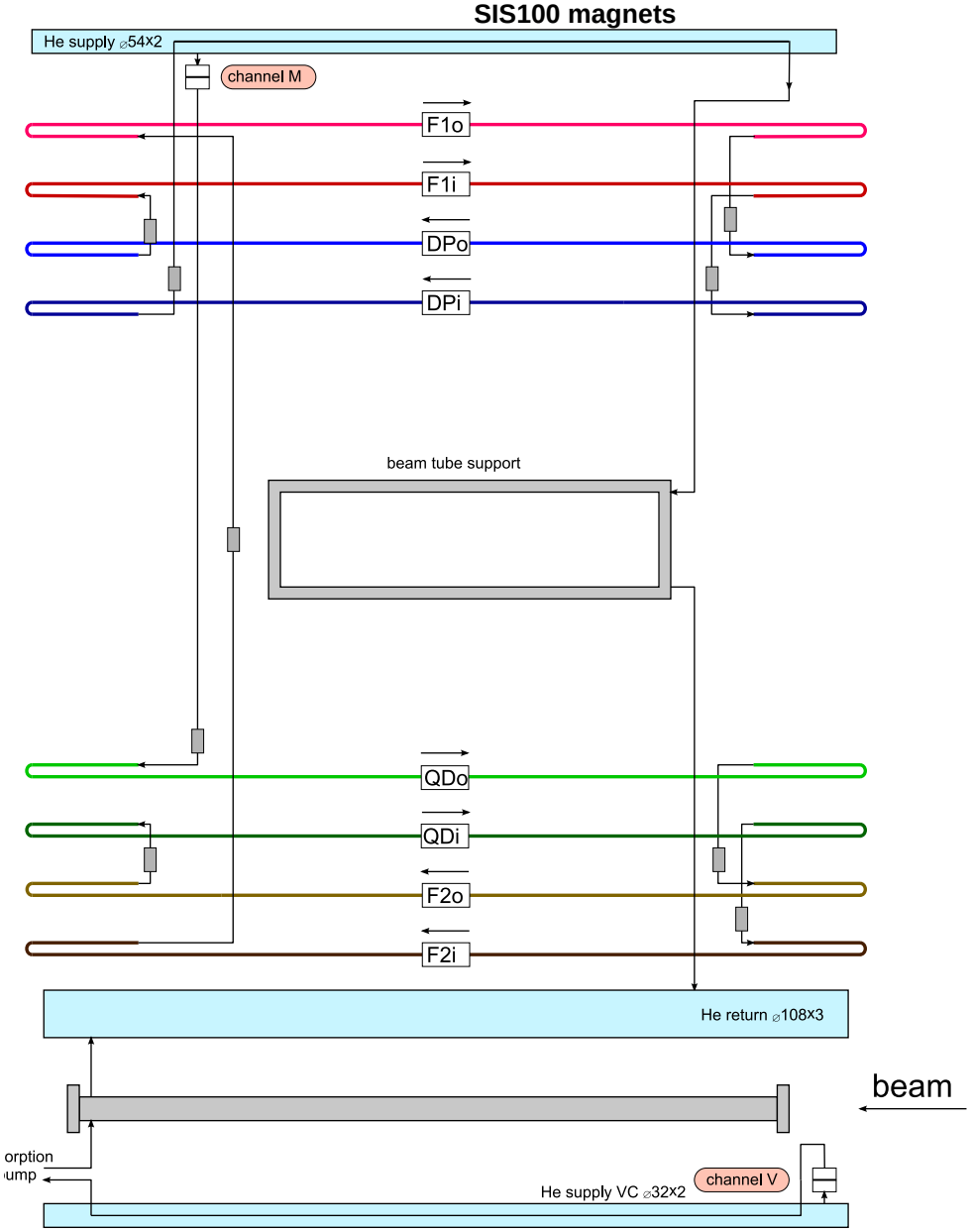


Figure 14: Cooling scheme of the missing dipole modules without pressure relief valves. This version of the missing dipole module has additional connection for the cooling of the sorption pump.

3.8. Cooling scheme of the Quadrupole Doublet Modules in the arc sections of the SIS100 ring

The 4 K cooling circuit of the regular quadrupole modules in the arc cryostats (Figure 17) consists of up to 3 magnet cooling channels M1, M2, M3 and one cooling channel V for the beam vacuum chambers.
There are 5 different types of the regular arc quadrupole modules and 4 different types of the arc termination modules. The components to be actively cooled at 4 K are listed in the Tables 3 - 5.
A complete flow scheme of each type of module in the arc cryostats is specified in the detailed specifications of the regular arc QP modules and of the arc termination

modules. Figure 16 presents a simplified flow scheme of a regular arc quadrupole module with two parallel magnet cooling channels M1 and M2.

Table 3: Regular quadrupole doublet modules in the arc sections of the SIS100

Name	Q-ty	Channel M1 (upstream)	Channel M2 (downstream)	Channel M3	Channel V
1.7B	12	sextupole CV quadrupole DF	steerer quadrupole F1/F2		two beam chambers cryo catcher chamber
2.5	6				
1.6A	12	quadrupole DF	steerer quadrupole F1/F2 sextupole CH		two beam chambers cryo catcher chamber
2.8C	12				
2.9D	12	quadrupole DF	steerer quadrupole F2	γt-quadrupole	two beam chambers cryo catcher chamber

Table 4: Arc termination modules downstream

Name	Q-ty	Channel M1 (upstream)	Channel M2 (downstream)	Channel M3	Channel V
1.E	5	multipole corrector quadrupole DF	steerer quadrupole F1		two beam chambers cryo catcher chamber
1.Ei	1				

Table 5: Arc termination modules upstream

Name	Q-ty	Channel M1	Channel M2	Channel M3	Channel V
2.4	5	quadrupole DF	steerer quadrupole F2	multipole corr.	two beam chambers
2.4x	1				

The inlets to the cooling channels M1, M2 and M3 are equipped with electrical heaters (see section 3.10.2). Two heaters and one flow restrictors are combined in one heater-restrictor unit (Figure 15).

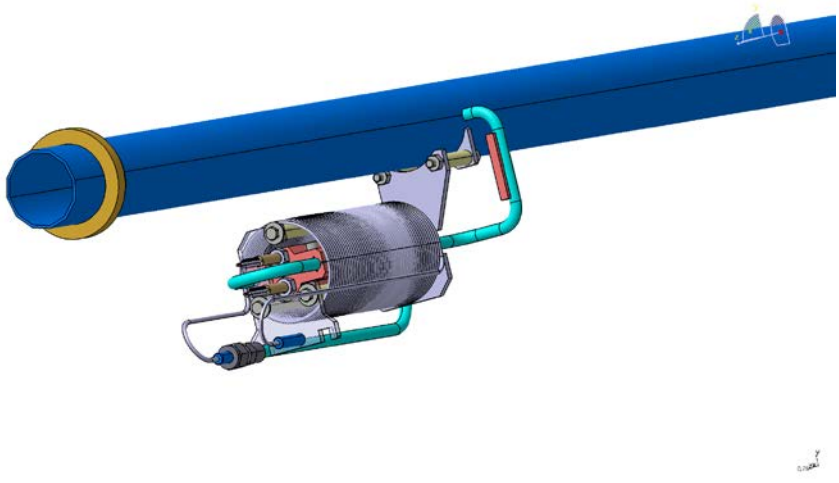


Figure 15: Flow restrictor with heater attached to the supply header of the quadrupole unit.

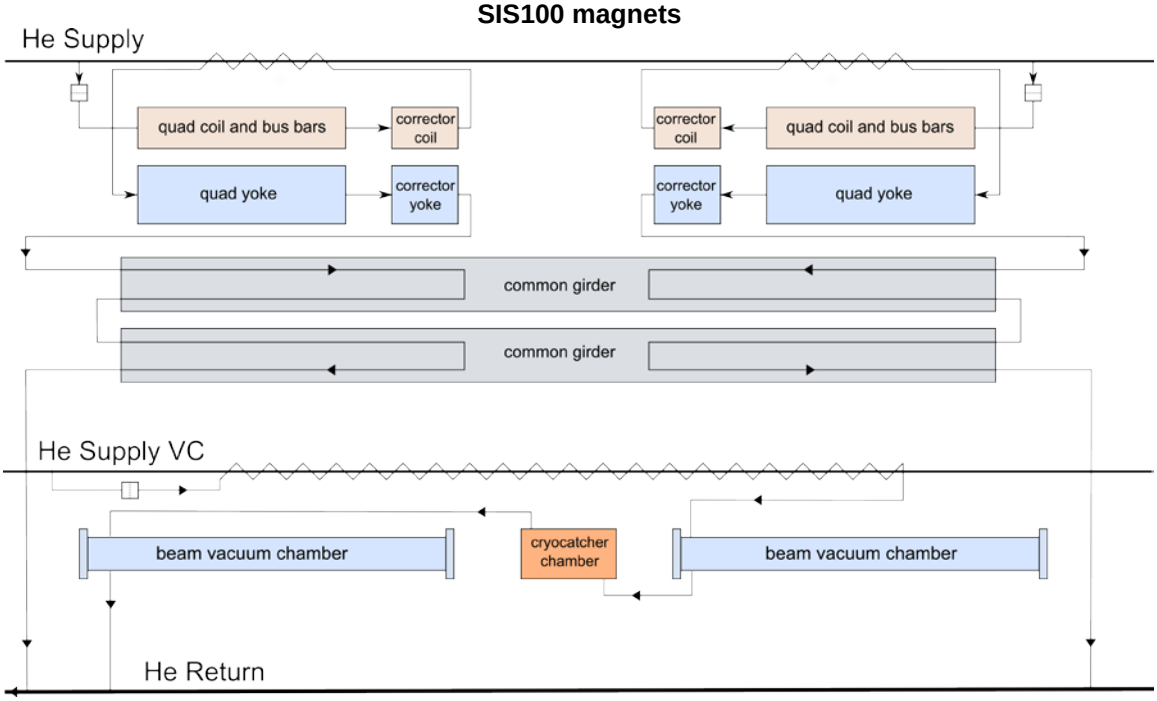


Figure 16: Simplified flow scheme of a quadrupole doublet in the arc cryostats.

Helium in both magnet cooling channels M1 and M2 passes following elements connected in series:

1. Connector to the supply header (line A1, DN50)
2. Flow restrictor (heater-restrictor unit)
3. Coil of the corrector magnet
4. Coil of the quadrupole magnet and bus bars
5. Recooler
6. Yoke of the corrector magnet
7. Yoke of the quadrupole
8. Cooling tubes of the common girders
9. Connector to the supply header (line B, DN100)

The cold terminals of the local current leads are attached to the helium tube between the flow restrictor and the coil of the corrector magnet.

Almost all QP doublets in the arc sections except six upstream arc termination modules (Table 5) have cryo catchers located between two quadrupole units. In these modules the cryocatcher chamber is connected in series with both vacuum chambers (Figure 16). Every other doublet with cryocatcher has a pumping port with cold-warm transition cooled at 50 K.

Helium in the cooling channel for the vacuum chambers passes following elements:

1. Connector to the supply header (line A2, DN25)
2. Flow restrictor
3. Recooler
4. Cooling tubes in the first beam vacuum chamber
5. For modules with cryocatcher: cooling tubes in the cryocatcher chamber
6. Cooling tubes in the second beam vacuum chamber
7. Connector to the return header (line B, DN100)

Some quadrupole doublets include a beam position monitor (BPM). A BPM doesn't require the helium temperature for proper operation. Since the BPM is located in the cold environment, it will become cold. The temperature of the BPM is not specified and may float. No special arrangements for cooling are needed.

Elements to be passively cooled at 50 K:

- thermal anchors of the current leads of the corrector magnets
- thermal anchors of the support roads
- modules with cryocatcher: cryocatcher block
- every other module with cryocatcher: pumping cold-warm transitions
- arc termination modules: cold-warm transitions

The flow scheme shown on Figure 16 is also valid for the downstream arc termination modules (Table 4). The upstream arc termination modules (Table 5) will have a third cooling channel M3 for a multipole corrector magnet. The modules 1.Ei and 2.4x are the arc termination modules for the beam injection and extraction respectively. They will be housed in special Y-cryostats. The complete flow schemes of these modules are specified in the detailed specification of the arc termination modules.

3.9. Cooling scheme of the Quadrupole Doublet Modules in the straight sections of the SIS100 ring

The 4 K cooling circuit of the quadrupole doublets in the straight sections (Figure 17) consists of two magnet cooling channels M1, M2 and one cooling channel V for the beam vacuum chambers. As against to the arc QP modules, the helium supply and return headers are located in the bypass line. The bypass line is connected to the magnet cryostat. The inlets and outlets of the cooling channels M1, M2 and V are connected to the helium headers in the bypass line.
There are two different types of quadrupole doublets in the straight sections (Table 6), however the modules labelled with 's' differs only in the shape of the beam vacuum chamber (star shape chamber) and the bus bars.

Table 6: Modules for the straight sections of SIS100

Type	Quantity	Channel M1 (upstream)	Channel M2 (downstream)	Channel V
1.123	15	DF quadrupole	Steerer F1/F2 quadrupole	two beam chambers sorption pump
1.13s	2			

Figure 17 presents the simplified flow diagram. The complete flow schemes of the modules 1.123 / 1.123s are specified in the detailed specifications of the cooling system of the quadrupole modules for the straight sections of SIS100.

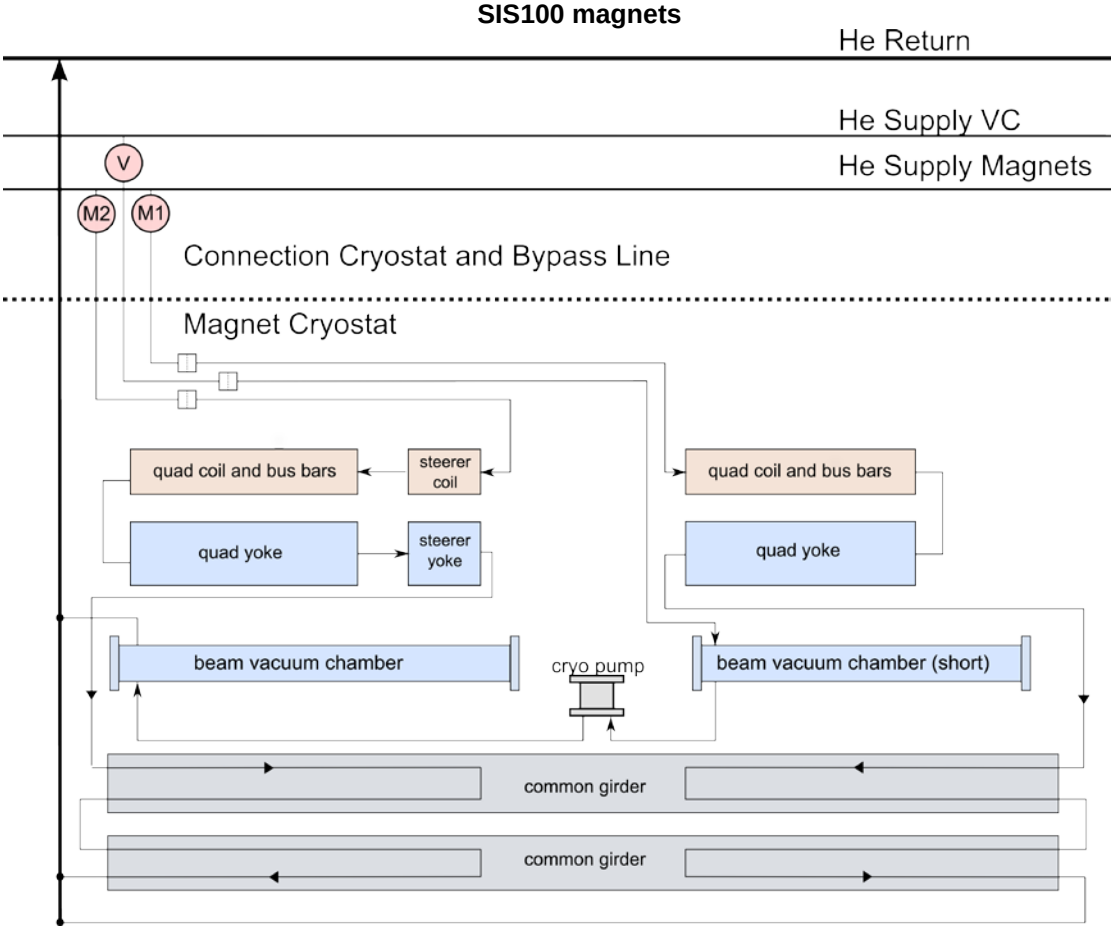


Figure 17: Cooling scheme of the quadrupole doublets in the straight sections

All upstream units in the straight sections include a beam position monitors (BPM). A BPM doesn't require the helium temperature for the proper operation and no special arrangements for cooling are needed.

3.10. Instrumentation

Each magnet module will be equipped with temperature sensors and with heaters according to the instrumentation list of the magnet module.

3.10.1. Temperature sensors

The cooling channels for the cooling of magnets or of the beam vacuum chambers will be equipped with temperature sensors located in vacuum on the helium piping. The types of the temperature sensors and the guidelines for the sensor installation are given in [4], [5].

In the magnet modules the sensors shall be installed at least on the following positions:

1. On the inlet to each cooling channel M or V, just behind the connection to the supply header
2. After each superconducting coil (main dipole, main quadrupole, corrector magnets) on the nearest cooling tube with ground potential

3. On the outlet from the cooling channel, just before the connection to the return header

The last temperature sensor at the outlet from the cooling channel and their cabling shall be duplicated for redundancy.

Cooling system of the pre-series modules will have additional temperature sensors on the helium piping.

Besides, the magnet module may have temperature sensors on the magnet yokes, local current leads, beam vacuum chambers etc. The positions of these sensors are described in the detailed specifications and in the instrumentation lists of the appropriate components. If the components are not included in the delivery of the magnet module (such as beam vacuum chambers), the magnet module shall have a routed cables with connectors for the later installation of the temperature sensors.

The mandatory document for the quantity and the positions of temperature sensors for each magnet module is the instrumentation list included in the detailed specification of the magnet module.

3.10.2. Heaters

Magnet cooling channels in the dipole modules, quadrupole doublet modules and missing dipole modules shall be equipped with electrical heaters located at the inlet to the cooling channel just after the connection to the header A1 (see for example the Figure 11, channel M). The heater cartridges will be installed in the copper plates brazed to the helium line (Figure 18). In the cooling channel with flow restrictors the heater will be integrated in the restrictor assembly (Figure 15).

The cooling channels V for the beam vacuum chambers will have no heaters.

Two independent heater cartridges with integrated thermocouples must be installed in the copper block for redundancy. The type HHP 6.5 mm with article number MIPA22018C (Hotset Heizpatronen und Zubehör GmbH, Lüdenscheid, Germany) or equivalent must be used. The electrical power of the heater is 21 W at 43 V. The heater cartridge will be delivered with 5 m long cables for heater and thermocouple. The cables of the heater and the thermocouple must be twisted and routed separately to the corresponding feedthrough.

The heater cables and the thermocouple cables can be routed together, but must held a distance from other cables and bus bars from at least 2 mm. At a distance from 3.4m (+/-20cm) from the cartridge (cable length) the cable must be thermalized at the thermal shield of the module. The distance from the thermal shield to the electrical feed through should be about 1.25m (+/-25cm). If the cable is shortened more than 30 cm less, the new cable length must be documented in the inspection and test protocol.

By making a high voltage test of a complete module it is necessary to connect all pins of the heater and thermocouple feedthroughs with ground.

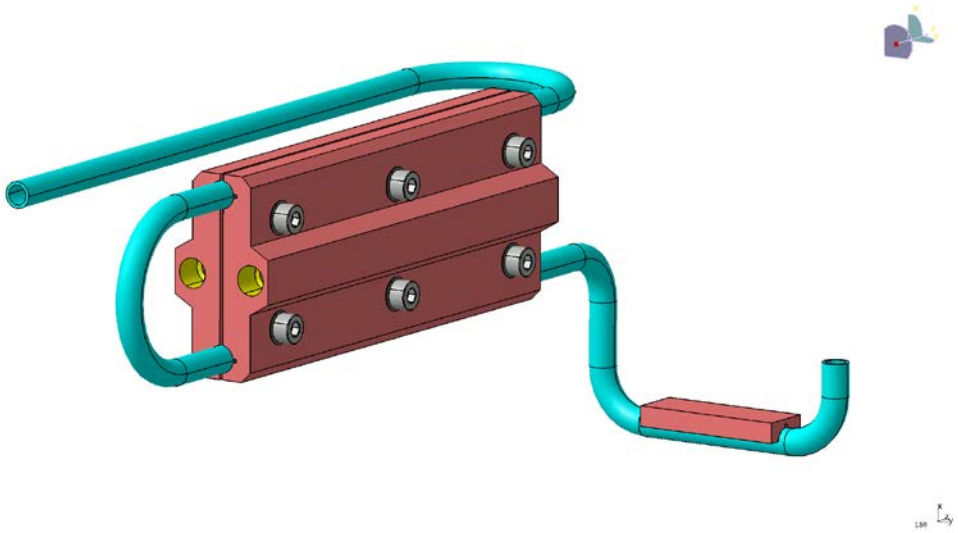


Figure 18: Copper blocks for two heater cartridges.

3.11. Safety Devices

Since the cooling system of each magnet module is pressure equipment in terms of 2014/68/EU, it must at least fulfill the requirements for a device of the category I in terms of 2014/68/EU.
The 4 K and 50 K cooling circuits of all SIS100 magnets don't have their own safety devices. To protect the helium piping from unacceptable overpressure during any possible operation mode, the safety devices will be installed in the feed boxes and in the end boxes of the SIS100 ring (Figure 1).
For the FAT and SAT an adequate safety system has to be included in the testing infrastructure.

Each Missing Dipole Module installed in the middle part of the sector will have two pressure relief valves between the headers A2 and B (Figure 13) to prevent the header A2 from unacceptable overpressure in case of the loss of insulation vacuum. The nominal diameter of each valve shall be at least DN25. The both valves have different response pressure of about 3 and 4 bar(g).

3.12. Production

All tubes used for the manufacturing shall be cleaned according to [6].

The cooling system must be produced according to the pressure vessel codes AD2000, and 2014/68/EU. All tubes and other components of the cooling circuits shall have the material certificates. The welders and brazers shall be certified according to the PED 2014/68/EU.

4. Quality assurance, tests and acceptance

4.1. Quality assurance system of the supplier

The Contractor shall establish and follow an adequate quality assurance system for the production of the cooling system of the magnet modules. The quality assurance system has to be certified according to the German AD2000 pressure vessel code.
All materials used in the construction of the components of the cooling system shall be procured with appropriate material certifications according to the AD2000 code.
Furthermore the Contractor shall establish an adequate procedure for the installation of the temperature sensors on the helium piping. The procedure shall guarantee the correct identification of each thermometer in the final assembly.

4.2. Quality inspection tests performed by Contractor

The contractor shall perform a series of acceptance and performance tests on the cooling system of the completed magnet module in order to demonstrate compliance with this specification before delivery to the principal.
All measuring equipment shall be procured by the Contractor.

The Contractor has to perform the following sequence of the Factory Acceptance Tests:

1. Document compliance according to the Pressure Equipment Directive PED 2014/68/EU. Checking of the welder's, material and equipment certificates required by a AD2000 pressure vessel code

2. Visual inspection.
   The helium headers shall be inspected for the correct orientation, visible damages and deformations. The helium piping has to be free of oil and dust. The clearance of the sliding supports on the helium headers shall be checked.

3. Dimensional inspection.
   Before assembling in the cryostat the positions of helium headers shall be inspected for compliance with drawing dimensions. The inspection report shall contain the actual measured positions of the helium headers on both sides - upstream and downstream.
   For the modules in the arc sections the reference axis is the magnet axis.
   For modules in the straight sections the dimensional inspection refers to the positions of the helium supply and return lines relatively to the connection flange.
   The dimensional inspection of these modules shall be done after assembling in the cryostat.
   Any out-of-tolerance conditions shall be resolved with the principal prior to shipment of the magnet module.

4. Pressure test.
   The entire helium circuit shall be pressurized at testing pressure and tested according to the AD2000 pressure vessel code.

5. Integral leak test.
   The leak test shall be performed on the assembled cold mass according to the FAIR technical guideline "He Leak Testing of Cryogenic Tubing" [8].

6. Flow rate test.
   The flow rate test shall be performed for each magnet cooling channel and for the cooling channel of the beam vacuum chambers according to the FAIR technical guideline “Flow Rate Test for Cryogenic Processing Pipes” [9]. The nominal value and the measured values for all modules in the series have to coincide within a 5%. The nominal flow rates will be fixed for each kind of the cooling channel after the test of the first modules of the series.

7. Test of the instrumentation.
   The electrical integrity of the temperature sensors and heaters shall be tested. The test protocol shall contain the measured resistance of the sensor in the four-wire configuration and the sensor-to-ground resistance. The resistance of the sensor has to match the nominal value at room temperature according to the calibration data. The electrical integrity of the heater power circuit (section 3.10.2) shall be checked.

All results of the acceptance tests of the cooling system shall be included in the Factory Acceptance Test protocol of the magnet module.

4.3. Quality inspection tests performed by Company

Formal acceptance of the cooling system will be performed within the Site Acceptance Test of the completed magnet module and will take place only after successful completion of the Factory Acceptance Tests.

Following tests of the cooling system will be performed:

1. Visual inspection test
2. Test of the instrumentation at room temperature
3. Test of the instrumentation at helium temperature
4. Integral leak test at room temperature
5. Integral leak test at helium temperature
6. Mass flow rate tests at room temperature
7. Mass flow rate tests at helium temperature

The tests at helium temperatures will be performed within the cold testing program of the magnet module.

The integral leak rate of the cold mass will be observed during cooling down and further on during the magnet testing. The integral leak rate during the cooling down, operation at 4 K and warming up has to be below $5 \cdot 10^{-8}$ mbar·l/s.

4.4. Cold testing of the Quadrupole Units and Quadrupole Doublet Modules

Each Quadrupole Unit will be tested at helium temperature before delivering to the Contractor responsible for the integration of the Quadrupole Doubled Modules.

The assembled Quadrupole Doublet Modules will be shipped to the Contractor responsible for the cold testing of the Quadrupole Doublet Modules. The cold testing of the finally assembled cooling circuit will be a part of the Site Acceptance Test of the Quadrupole Doublet Modules. Within the cold testing program the helium mass flow rates and the tightness at helium temperatures will be tested at operation conditions.

5. Documentation

The contractor has to provide the whole set of the technical drawings, CAD data and material certificates specified in the Technical Guideline “Documentation and Certificates for Cryogenic Modules“[10]. The technical drawings and CAD data will be a part of the drawing set of the magnet module.

Beside of that, the contractor has to provide following documentation:

1. The assignment of the temperature sensors installed on the cooling tubes to their calibration data.
2. A list of all hydraulic components for each cooling channel. This list shall be provided as a table either as a text file or as a MS Excel worksheet. In the table all hydraulic elements connected in series within a cooling channel shall be listed. The table shall have following fields for each element:
   - Name of the element (tube, coil, bus bar, elbow, joint etc.)
   - Hydraulic diameter
   - Length of the element

   The table may be compiled using the CAD model “as built”

Attached Documents

I. Related Documentation

[1] FAIR General Specifications, F-GS-B-01e, EDMS Nr. 1365092

[2] Technical Guideline F-TG-K-2.35e: “Steel Materials for Pressurized Cryogenic Components”, EDMS Nr. 1172134

[3] Common Specification for Cryostats of Cryogenic Modules in FAIR Accelerators, F-CS-CR-01e, EDMS Nr. 1174184

[4] Technical Guideline F-TG-K-3.52e: Temperature Sensors for Cryogenic Purposes, EDMS Nr. 1172141

[5] Technical Guideline F-TG-K-13.5e: Temperature Sensor Installation for Cryogenic Purposes, EDMS Nr. 1172858

[6] Technical Guideline F-TG-K-6.11e: Cleaning and Cleanliness of Cryostats and Related Components, EDMS Nr. 1172153

[7] Technical Guideline F-TG-K-7.24e: “Pressurized Leak Testing of Cryogenic Tubing”, EDMS Nr. 1172845

[8] Technical Guideline F-TG-K-7.23e: “He Leak Testing of Cryogenic Tubing”, EDMS Nr. 1172844

[9] Technical Guideline F-TG-K-7.26e: “Flow Rate Test for Cryogenic Processing Pipes”, EDMS Nr. 1172846

[10] Technical Guideline F-TG-K-10.16e: Documentation and Certificates for Cryogenic Modules, EDMS Nr. 1172856