Development of integrated superconducting quadrupole doublet modules for operation in the SIS100 accelerator

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Abstract. The FAIR project (Facility for Antiproton and Ion Research) evolves and builds an international accelerator- and experimental facility for basic research activities in various fields of modern physics. Within the course of this project, integrated quadrupole doublet modules are in development. The quadrupole doublet modules provide a pair of superconducting main quadrupoles (focusing and defocusing), corrector magnets, cryogenic collimators and beam position monitors as integrated sets of ion-optical elements. Furthermore LHe cooled beam pipes and vacuum cold-warm transitions are used as ultra-high vacuum components for beam transportation. Superconducting bus bars are used for 13 kA current supply of the main quadrupole magnets. All components are integrated as one common cold mass into one cryostat. High temperature super conductor local current leads will be applied for the low current supply of corrector magnets. The quadrupole doublet modules will be operated in the SIS100 heavy ion accelerator, the core component of the FAIR project. A first version of a corrector magnet has already been manufactured at the Joint Institute for Nuclear Research (JINR), Russia, and is now ready for testing. The ion-optical lattice structure of SIS100 requires multiple configurations of named components. Eleven different configurations, organized in four categories, provide the required quadrupole doublet module setups. The high integration level of multiple ion-optical, mechanical and cryogenic functions, based on requirements of operation safety, is leading towards a sophisticated mechanical structure and cooling solution, to satisfy the demanding requirements on position preservation during thermal cycling. The mechanical and cryogenic design solutions will be discussed.

1. Introduction to FAIR and the SIS100 - accelerator

The FAIR project builds a new international accelerator facility for fundamental research with antiprotons and heavy ions. The development and procurement of components for FAIR construction is in progress. SIS100, the main accelerator of the research facility [1] is a heavy ion synchrotron with 1084 m in circumference at 12.5 m underground. SIS100 is planned for to reach a magnetic rigidity of 100 Tm. Its basic magnet design concept is derived from the super conducting magnet design of the Nuclotron accelerator, being in operation at JINR since 1993 [2]. The two existing accelerators UNILAC and SIS18 will be employed as pre-accelerators, injecting proton and heavy ion beams into the high energy synchrotron, which produces high intensity and high energy proton and ion beams. SIS100 has a six-fold symmetry with six arc sections and long straight sections, providing space for injection-, extraction- and extended radio frequency acceleration systems. The ion optical lattice of a

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sextant is composed of 14 cells, each of 12.90 m in length. The ion optical lattice of one sextant consists of 10 lattice cells in the arcs, eight with two dipole magnets and one cell with only one dipole magnet at each end of an arc. A straight section shows four lattice cells of a total length of 51.60 m. The components, being of functional effect in the ion optical lattice, are focusing and defocusing quadrupole magnets, sextupole magnets, paired steering magnets, cryo-catchers and beam position monitors. These components are organized in different configurations within multiple types of quadrupole doublet modules.

2. Structure of SIS100 – Quadrupole Doublet Modules
At current state of the art only Nuclotron-type superconducting magnets are fulfilling the demanding requirements in the magnet technology, needed for SIS100 [1]. To master the challenge of realizing fast ramped quadrupole magnets with a ramp rate of 58 (T/m)/s and a maximum quadrupole magnetic field gradient in the magnet center of 27.8 T/m, the fundamental design solutions of the SIS100 quadrupole magnets are the concepts of 2-phase He-cooling, SC quadrupole magnet-, SC cable- and coil, bus bar design and their interconnections. For module integration the mechanical suspension concept of crossed load- and tie rods was taken as the basic approach and was optimized for application as suspension for an integrated cold mass of quadrupole doublets.

2.1. Module classes and configurations
The ion optical lattice of SIS100 requires multiple configurations of quadrupole doublet modules, split in 4 classes and 11 configurations. An overview on classes and configurations is given in [3]. During the running design phase, a reduction of different configurations was achieved by eliminating differences in electrical connections of the quadrupole magnets in the straight sections. A re-design of the bus bars of the straight section modules led to a unification for the modules in the ion optical lattice-cells 1 to 3, now being equipped with one single quadrupole doublet module type only. The differences in current supply of the modules in the ion optical lattice cells 1, compared to 2 and 3 are now solved by a modified electrical scheme for the bypass line, supplying the straight section modules. Formerly, the different current supply schemes of straight section modules were organized in the modules themselves.

2.2. Arc section modules
The arc section modules are mostly unified in design structure of cold mass, cold mass suspension, cooling and cryostat integration. The cold mass (see figure 1) is built from a down-stream located unit which mainly consists of an F2-focusing quadrupole magnet [4] (F1 and F2 means focusing quadrupoles at SIS100 power supply circuit 1 or 2, QD means defocusing quadrupole), a steering magnet [5], a beam position monitor [6], a set of F1 and F2-bus bars, a bus bar for steering magnet supply with a terminal for connection of local current leads. Voltage breakers are installed at dedicated sheet metal supports which also support the main bus bars. The up-stream located unit mainly consists of a defocusing quadrupole magnet, a vertically focusing sextupole magnet [5], a QD-bus bar, a dipole-bus bar, a bus bar with cold terminal for Sextupole magnet current supply and is also equipped with voltage breakers. In between the two units a cryo catcher [7] is located. The He-supply system consists of a LHe-supply line for magnet cooling [8], a LHe-supply line for vacuum chamber cooling, a 2-phase-He return line, a flow restrictor for vacuum chamber supply and other flow restrictors for magnet supply. The cold mass is integrated by a common girder structure and is suspended by a suspension system, composed from crossed load- and tie rods [3].

The fully assembled module (see figure 2) integrates the cold mass by bearing its load rods in suspension domes and retaining additional tension forces of tie-rods in the corresponding lower suspension domes. The full insulation vacuum vessel is supported on foot plates being integral parts of stiffening structures where also fiducial target seats and crane eyelets are fixed to. Floor conveying interfaces are located at the lower side of the vessel. The service port with its closure allows access to the inner components like roughing cold-warm-transition and local current leads. Instrumentation
Flanges for feeding out temperature sensor- and voltage tap signals are attached to the service-port. A further instrumentation flange feeds out the signaling cable of the beam position monitor. Warm cables for power supply of corrector magnets are connected in room temperature connection boxes, mounted on cabling chassis, feeding current to the warm terminals of the local current leads which are covered by protection caps. The interconnection thermal shields with multi-layer insulation are surrounded by telescopic compensation bellow systems for continuity of insulation vacuum in the arc sections of the accelerator. A straight section quadrupole doublet module is protected against inner overpressure ($p_{\text{response}} \leq 0.3 \, \text{bar(gauge)}$) by a simple blanking flange, loosely fixed on blow-off flanges. Operator protection against cold gas blow-off from an activated safety system is realized by a guide tube, surrounding the valve. The insulation vacuum is pumped by a turbo molecular pump, connected to the vessel and the ultra-high vacuum roughing pump, also a turbo molecular pump, is connected to the roughing cold-warm transition which is reaching through the service-port to the cryo-catcher.

**Figure 1.** CAD-Model of the integrated cold mass of a SIS100-quadrupole doublet module of the straight section type 2.5. Explanations: 01 - F2-focusing quadrupole magnet, 02 - steering magnet, 03 - beam position monitor, 04 - F1-bus bar, 05 - F2-bus bar, 06 - local current lead terminal, 07 - defocusing quadrupole magnet, 08 - sextupole magnet, 09 - QD-bus bar, 10 - dipole-bus bar, 11 - local current lead terminal, 12 - cryo catcher, 13 - magnet cooling supply line, 14 - vacuum chamber cooling supply line, 15 - 2-phase return line, 16 - flow restrictor, 17 - common girder, 18 - load-rod, 19 - tie rod, 20 - voltage breaker.

Each quadrupole doublet module is equipped with a service port, providing access to the local current leads. Fast access is required to the high temperature superconducting stacks, being the essential part of the local current leads which are expected to be subject to repair processes. For each corrector magnet circuit, a dedicated set of local current leads is installed. For thermal interception the local current leads are thermally coupled to a heat exchanger (at $50 \, \text{K} < T_{\text{intercept}} < 80 \, \text{K}$) in the shield cooling supply line. The roughing cold-warm transition, for roughing beam pipe vacuum, is also thermally intercepted at shield temperature and is mechanically supported in the service port. All
sensor cabling of the quadrupole doublet module is fed out by instrumentation flanges located at the service port.

![Figure 2](image)

**Figure 2.** CAD-Model of an integrated quadrupole doublet module of the arc section type 2.5. Explanation: 01 - insulation vacuum vessel, 02 and 03 - telescopic compensation bellow systems, 04 - crane eyelets, 05 - blow-off flange, 06 - foot plates, 07 - lower suspension domes, 08 - upper suspension domes, 09 - fiducial target seats, 10 - service port with closure, 11 - Instrumentation flange for temperature sensors, 12 - Instrumentation flange for voltage taps, 13 - beam position monitor flange, 14 - forklift slots, 15 - warm terminals of local current leads, 16 - terminal boxes for corrector magnets, 17 - cabling chassis, 18 and 19 - interconnection thermal shields with multi-layer insulation, 20 - turbo molecular pump (ultra-high vacuum roughing), 21 - turbo molecular pump (insulation vacuum)

2.3. **Straight section modules and arc termination modules**

The cold mass design concept, the cold mass integrated in a common girder and suspended by crossed suspension rods, is the same also for straight section- and arc termination modules. Differing configurations of cryostats distinguishes their integration design. The straight section quadrupole doublet modules are always located in between warm sections of SIS100. Compared to an arc section module, the straight section quadrupole doublet module is terminated by a closure at its up-stream- and down-stream end. Continuous He-lines and bus bars for cooling- and power supply are not available in this module type, thus they are coupled to cryogenic by-pass lines, from where bus bars and He-branch lines are fed-in for module supply. For assembly and installation purposes, dedicated large ports are available, e.g. for orbital welding of tubing and bus bar interconnections.

Dedicated arc termination modules are located at the up-stream- and down-stream ends of 5 out of 6 SIS100-arc sections. Due to the positions of the modules in the ring, their cryostats systems have to sustain large pressure forces in axial direction of approximately 77 kN. Nevertheless, the challenging stability requirements of 50 µm of allowed displacement at the fiducial target seats of the vacuum vessels (cooled down system relative to ventilated system) were aimed for to be fulfilled also for the arc termination modules. By supporting the vacuum vessel against additional supporting brackets, a
maximum axial displacement of $\leq 60 \mu m$ can be achieved for the fiducial target seats. By applying these support brackets, the standard support frames can be used instead of special heavy duty supports and alignment feet, as applied for the special injection- and extraction modules. Within the cryostat end cap, all internal supply of the modules (bus bars, He-supply at 4 K for magnets, vacuum chambers and 50 K – 80 K for thermal shielding) is fed into a cryogenic by-pass line, which is attached to the feed port of an end cap. The end cap is equipped with large cross section openings, to allow installation operations for bus bar interconnection and orbital welding of LHe-supply lines. Forces, introduced by the compensation bellows of pressurized LHe-lines are induced into the support flange of the front lid ($p_{\text{max}} = 18 \text{ bar (absolute)}$, max. nominal diameter of 100 mm).

2.4. Special modules for beam injection and -extraction
For the task of beam injection and -extraction, specialized modules are foreseen at each termination of the arc section in sector 5 of SIS100. Both of these modules incorporate an additional beam line branch, dedicated to the purpose of guiding the incoming, respectively outgoing heavy ion beam into or out of the accelerator. The Injection branch is located in the same horizontal plane as the ring branch of the injection module. It holds two special quadrupole magnets, integrated in a vertically arranged common girder, while the ring branch common girder remains horizontal. Due to a high mechanical integration density, owing to a low slope of 4.22$^\circ$ for the injection beam pipe, the outer girder of the ring branch is a modified and reduced version of the common girder as used in the arc sections. Instead of a suspension system, the injection branch is supported on separated pillars, which allow independent alignment with three linear degrees of freedom and one rotational degree of freedom around the beam axis in the module. Compared to the injection module, the extraction branch in the extraction module, also integrated in a common girder, is located in the same vertical plane as the corresponding ring branch. The extraction branch holds two of the same special quadrupole magnets as the injection branch in the injection module. For mechanical decoupling from the ring branch, the extraction branch is supported by two suspension pillars, each providing three linear degrees of freedom and one rotational degree of freedom around the beam axis. The cryostat systems of the injection and extraction modules are specially designed for stability optimization. Due to the extraordinary cold mass design, the cryostat design is in addition differing from the standard cylindrical geometry. For this, instability must be compensated by greater wall thickness of their vessels and more complex stiffeners. This and the approximately doubled weight of the special cold mass configuration leads to the need for heavy duty support frames and -alignment feet.

3. Mechanical calculation results and cryogenic engineering solution

3.1. Stability of the integrated cold mass and the integrated module
Within the advanced module design phase of the quadrupole doublet modules, the stability behaviour of the cold mass was optimised for the case of the arc section modules. Two quadrupole units, each one combining a quadrupole magnet and a corrector magnet, are assembled in one common girder which integrates the cold mass. This integrated cold mass is suspended in a system of crossed load- an tie-rods (see figure 1). The requirements on allowed position errors of the cold mass of $\Delta x, \Delta y = \pm 125 \mu m$ for the quadrupole magnets, $\Delta x, \Delta y = \pm 175 \mu m$ for corrector magnets[3], is expected to be acceptably met when applying a correction of a predictable offset in cold mass alignment during module assembly. A design calculation, applying the finite element method to simulate the load cases “warm and ventilated system with pre-stressed suspension system” and “operation at 4 K” was performed for an advanced and detailed module design. The calculation was performed for quadrupole units, ideally aligned to each other in a common girder, prior to pre-stressing the suspension system with 10 kN at the up-stream tie-rods and 10.6 kN at the down-stream tie-rods. The different forces are required to minimise total tilt of the cold mass. The diagram in figure 3 compares results of engineering calculations of the two load cases for the vertical magnet positions (evaluation in Y-direction along a reference line in the vertical main plain of the quadrupole magnet). The dashed lines
are representing results for the warm situation. This load case is defined by gravity load and a pre-stressed suspension system at room temperature with no insulation vacuum. The solid lines represent the results for the cold mass in operation at 4 K, also with lateral forces applied. A general offset of the cold mass axes to the cryostat main axes of approximately -0.9 mm is owed to the pre-stress, being applied to the suspension system. Due to pre-stressing, a lowering of the cold mass of -0.9 mm, compared to an unloaded suspension system is a natural result, as long as not pre-compensated by dedicated measures. During cold mass alignment this offset must be pre-compensated by adding the same positive amount of +0.9 mm prior to pre-stressing to the vertical cold mass position to overcome such deviation after pre-stressing. The process of pre-stressing and pre-alignment is planned to be monitored by load cells and a laser-tracker which is aiming on fiducial targets. When the pre-compensation is applied, the remaining differences between warm- and operation condition, as shown in the calculation results, can be practically neglected.

Due to pressurized compensation bellows in the cryogenic supply system have to compensate an angular offset from the adjacent dipole modules of 1.66°, also lateral forces are working at the cold mass suspension system during operation ($F_{\text{lateral}} \approx 22$ N at up-stream- and down-stream end of the cold mass). The resulting lateral offset (-X - direction, in opposite direction of the ring center) of $\leq 10$ µm [3] during beam operation is also negligible.

Results of engineering calculations, on stability of the insulation vacuum vessel are showing that requirements on stability of fiducial target seats are expectable to be met for the quadrupole doublet modules with cylindrical structure (straight section-, arc-termination- and arc-section modules). The maximum deviation of fiducial targets between an unstressed vessel (no insulation vacuum) and a vessel with atmospheric pressure forces applied is approximately 17 µm, which is far below the allowed deviation of 50 µm. For the injection and extraction modules, the maximum displacement is more the 50 µm (~86 µm at injection- and ~160 µm at extraction module), due to the less stable structure of their vessels. By applying more than 4 fiducial target seats, as usual for all other module types, such an error can be compensated by correction calculations during alignment. Additional

![Figure 3](image-url)
optical windows in the injection- and extraction modules allow the observation of fiducial targets, fixed to the cold mass, at operation temperature.

3.2. Cryogenic cooling solution [9]

The basic cooling concept of a SIS100 sector is shown in figure 4. Dipole modules and quadrupole units of one sector are connected in parallel to the common He-supply and -return lines. Helium in the supply line is sub-cooled and has a temperature of about 4.5 K to 4.6 K at a pressure of 1.5 to 1.6 bar (absolute). The Helium is successively cooling magnet bus bars, magnet coils (points 1 and 2) and iron yokes (points 2 and 3). Due to a pressure drop in the magnet coils and bus bars, as well as by static and dynamic heat loads, the Helium in point 2 is in a 2-phase state at $p_2 = p_3 = 1.1$ to 1.2 bar (absolute) and $T_2 = T_3 = 4.3$ K to 4.4 K (subscripts 1, 2 and 3 denote the points in figure 4). The major part of dynamic heat losses is created in the iron yokes, so the Helium in point 3 can be either 2-phase or vapor, depending of the particular operation mode of SIS100. The re-coolers, attached to the supply headers (points 2 and 2’) are transferring heat to the two 2-phase He and keeping it in the single-phase state in the supply header over the full length of a sector. The cooling scheme of the quadrupole doublets is shown in figure 5. A quadrupole doublet module has two parallel flow channels for the cooling of both quadrupole units, denoted in the diagram as M1 and M2.

**Figure 4.** Basic cooling scheme of a SIS100 sector. Explanation: a – restrictor, b – re-cooler, c – cold mass, d – short cut valve

**Figure 5.** Basic cooling scheme of SIS100 quadrupole doublet modules.

Corrector magnets in the quadrupole units are hydraulically connected in series with the main quadrupoles. All corrector magnets have cooling tubes with an inner diameter of 4.0 mm and a length of 15 to 43 m. The He-flux from the outlet of each quadrupole unit is applied also for cooling the common girder in series for best uniformity of temperature distribution over the whole cold mass. Since fast ramped magnetic fields are generating heat losses also in beam vacuum chambers, the
dipole- and quadrupole doublet modules both require dedicated cooling circuits for beam vacuum chambers and cryo-catchers (channel V in figure 5). To adjust the hydraulic resistances of different types of the quadrupole units to each other and also to fit the quadrupole unit flow-resistances to the dipole hydraulic resistance, additional impedances (flow restrictors) are foreseen at the inlets of each cooling channels M1, M2 and V. The sizing of flow restrictors will be tuned for each type of quadrupole unit within the first cold testing cycle of each unit.

4. Conclusion and outlook on production

All fundamental design solutions for the different classes and configurations of SIS100 quadrupole doublet modules are fixed and the finalization of engineering design is in progress. Engineering calculations are showing an uncritical behavior of the cold mass in terms of position stability at operation. The cryogenic cooling concept is well planned and was implemented into the module design. Tuning of flow unit resistances is required for each one of the quadrupole units during their very first cold-run. The production of a first corrector magnet (sextupole magnet) was started already at the FAIR-collaboration partner JINR [9]. Also the planning for the first of series production of quadrupole units for an arc section quadrupole doublet module is running at JINR. An open call for tender for integration of quadrupole doublet modules is in preparation at GSI Helmholtzzentrum für Schwerionenforschung GmbH. All quadrupole units are planned to be produced, cryogenically and magnetically tested at JINR and then being delivered to a dedicated company for integration into quadrupole doublet modules. For final testing of electrical- and cryogenic integrity (e.g. high voltage tests, pressure and leakage tests), the modules will be shipped to a dedicated test facility before being delivered to FAIR for final tunnel installation.

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