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SUPERCONDUCTING MAGNETS FOR SIS100 AT FAIR – STATUS UPDATE

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Abstract

At the Facility for Antiproton and Ion Research in Darmstadt, Germany, fast-cycled superferric magnets will be utilised for ion optics in the main accelerator SIS100. The dipole series is fully produced and tested. Recently, the dipoles have been equipped with cryogenic beam vacuum chambers and are now ready for tunnel installation. Currently ongoing is the procurement of the quadrupole and corrector magnets. To form so-called quadrupole units, quadrupoles are mechanically joined with the corrector magnets. The units are then pairwise equipped with beam chambers and, together with beam position monitors and cryo-collimators, integrated into a common cryostat to form a quadrupole doublet module. For each step, series production and testing has started and the status is presented.
To sample the installation processes of SIS100, study collective effects in a module ensemble, and gain experience in operation, several magnet modules and local cryogenics components are currently aligned at a test facility to model a cell of SIS100 in a string test setup.

SIS100 SUPERCONDUCTING MAGNETS

At the Facility for Antiproton and Ion Research (FAIR), which is currently under construction in Darmstadt, Germany, the heavy ion synchrotron SIS100 will be the main accelerator ring [1, 2]. More than 400 superconducting magnets of various types are required for ion optics [3]. Their design concept, which allows for fast cycling, is deduced from the Nuclotron accelerator [4]. Basic features are NbTi-based low-loss cables operated at around 4.5 K, iron yokes for field shaping of the main magnets and a forced flow of two-phase helium for cooling.

Dipoles

The SIS100 dipoles feature highly-precise curved yokes with window-frame aperture and a length of 3 m [5]. The field reaches 1.9 T at a nominal current of 13.2 kA. The magnets can be ramped at rates up to 4 T/s corresponding to 28 kA/s.

Quadrupole Doublet Modules

The SIS100 ion optical lattice is based on doublet focusing, for which quadrupole pairs are integrated into a common module [6, 7]. In a first step, quadrupole units (QPU) are composed by mechanically joining quadrupole magnets with corrector magnets, specificly chromaticity sextupoles, nested steering dipoles, and multipole correctors. Quadrupole doublets modules (QDM) are composed by pairing two quadrupole units on a girder structure to form a common cold mass, which is equipped with a beam vacuum chamber and integrated into a cryostat.
The magnets are cooled by parallel cooling channels. The quadrupoles are powered in series by a busbar system along SIS100 with up to 10.5 kA while the correctors are powered at low current of up to ±250 A by means of local HTS current leads.
The design of the QDMs also includes beam position monitors (BPMs) and cryo-collimators, which are used to dump charge-exchanged ions on well defined positions between the quadrupoles, for which the lattice was optimised. There are 11 types of QDMs depending on the composition of units and further elements.

PROJECT STATUS

Dipoles

All 110 dipoles for SIS100 are produced and tested in a thorough measurement campaign which was completed in 2021. Excellent testing results for field quality and operational characteristics have been revealed [8, 9].
To reach highest intensities for heavy ion beams with intermediate charge states, a basic requirement for SIS100 are ultra-high vacuum conditions to avoid beam losses by ionization [2, 10]. For this, vacuum chambers cooled by a forced flow of two-phase He are utilised and integrated into the aperture of the dipole yokes. Their inner surface acts as a cryopump when cooled below 15 K. The wall thickness is 0.3 mm to limit heating due to eddy currents induced by the fast ramped magnets. To further increase the pumping capacity especially for H_2 and He, cryo-adsorption pumps (CAP) are foreseen between each dipole pair.
Recently, both the beam chambers have been integrated into the dipoles and the CAPs have been attached to each second dipole (see Fig. 1). The process included welding of the chamber flanges and He piping as well as careful testing of the seams by means of pressurization and leak tightness. With completion in 2022, the full series of dipoles is now ready for installation into the SIS100 tunnel.

Quadrupole Doublet Modules

To assemble the QDMs the constituting elements are supplied from individual manufacturers to the main integrator.

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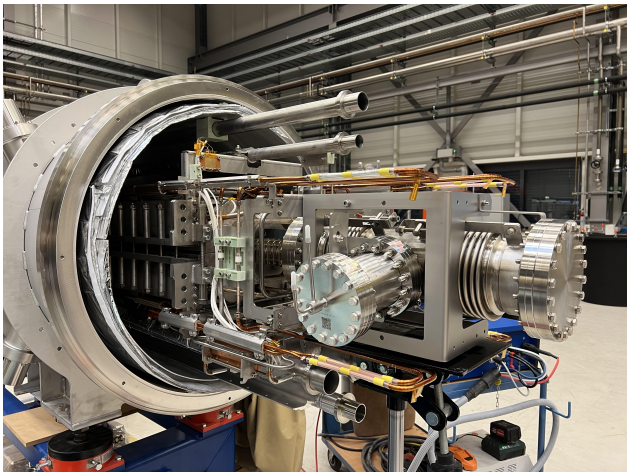

Figure 1: SIS100 superconducting dipole with cryogenic vacuum chamber and cryo-adsorption pump.

Each of the components have passed factory and site acceptance testing before being cleared for integration.

Quadrupole Units The series production of the QPUs has started in 2020. Since then 26 QPUs supplied by JINR, Dubna, have been accepted and delivered to the integrator. Those units comprise chromaticity sextupoles and steering magnets to form the unit types VQD, SF2, and SF1 (see [6]). Prior to delivery, all units have passed a cold testing program at operational temperatures including quench training, electrical integrity, and AC loss measurements. The field quality was reported as within specification defined by iron yokes with machining precision on the level of 50 µm and better [11]. Moreover, the quadrupole magnetic axis was determined with a precision of better than 0.1 mrad and 0.1 mm precision with respect to the yoke. Those data are used as an input parameters for a precise alignment of the quadrupoles at later integration.

Module Integration For the full series of 83 QDMs, the BPMs, cryo-collimators, beam vacuum chambers, and further elements are readily available. Up to now, 13 QDMs of type 2.5 and 1.7B have been fully integrated, see [6] and Fig. 2 with an example.
With an expected learning curve, the integration process of the first 13 modules was accomplished successfully. In this way the mechanical integrity of the complex integration concept was approved for all elements as well as for the interfaces and the piping. For the mounting of the unit pairs on the common girder, spherical joints and shimming plates are used for the precise alignment of the quadrupole magnetic axes to each other. By monitoring the assembly process with laser tracking, it was shown that the alignment can be adjusted on the same level as deviations from the ideal positions are reported. The cryo-collimators are carefully positioned with respect to the beam profile by inserting individually dimensioned spacers depending on the later position of the module in the accelerator ring.

The integration steps are accompanied by a careful factory acceptance testing program for quality assurance before shipment is released. Careful checks comprise mechanical properties, UHV tests at room temperature, pressure tests of the piping, and electrical integrity of the power lines, instrumentation and active elements. The extensive organisational processes and routines required for handling of such a project have been established both on the supplier side as well as at FAIR/GSI.

Module Testing The site acceptance tests (SATs) of the integrated QDMs are currently executed at two testing sites. Five QDMs have been cold tested at the series testing facility at GSI, Darmstadt, which was setup for the SIS100 dipole testing and adapted for QDM testing [9, 12]. Moreover, the THOR facility of INFN, which is located at University of Salerno, was upgraded and adapted for QDM testing as well [1]. The cold testing of a first series QDM has recently been completed while a second testing bench is currently assembled to allow for an increase of the testing rate.
For all cool-downs, the target temperatures could be reached in the expected time span and without mechanical issues. In this way, the cryo-mechanical design concept is basically approved. In particular, first results show that the precise alignment of the unit pairs to each other could be kept at operational temperature. A careful analysis is still ongoing to collect statistical data here.
Regarding the operation of the magnets, the quench behaviour of the quadrupoles shows no de-training at all with respect to the data reported from the SAT of the QPUs even after a long transport from the supplier to the integrator. The sextupoles show excellent quench performance. The steering magnets have been basically approved for operation as well, where currently a thorough analysis is ongoing to map the special characteristics of the nested coils in bipolar ramping modes. During the cold testing of correctors magnets at GSI, the series MID (mutual inductance-based detector) quench electronics was successfully qualified [13]. Generally, the electrical integrity of the modules was found to be sufficient including the local current leads to power the corrector magnets.
The power losses of the modules in AC operation have been confirmed to match the expectations. At a high ramp rate of the SIS100 reference cycle, which was used as the baseline for the dimensioning of the modules, the losses are found to be ≈16 W for the quadrupoles and 5 to 10 W for the correctors. In the further course of the series production, a critical aspect will be the investigation of modules with units comprising two correctors forming the most complex hydraulic system among the modules. Those modules have not yet been produced.
Of fundamental importance for beam operation are the vacuum conditions in the LHe cooled quadrupole chamber system, which is fully CF flanged. After cool down, residual gas densities in the mid to low 10^{-12} mbar range (N_2 room temperature equivalent) were found in static conditions. During magnet ramping with a reference cycle, the chamber wall

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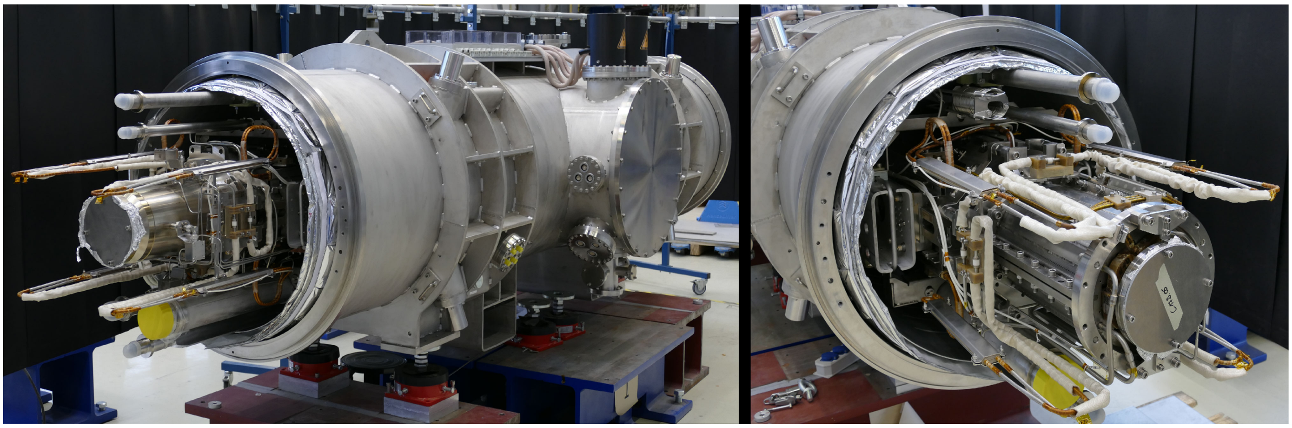

Figure 2: Quadrupole doublet module of type 1.7B, consisting of units of type VQD (vertical chromaticity sextupole, de-focusing quadrupole) and SF1B (steering magnet, focusing quadrupole, beam position monitor). Left: downstream side showing a BPM. Right: upstream side showing a chromaticity sextupole.

temperatures increased partially due to eddy currents from 4.5 K to 6 K, causing a slight pressure rise due to H_2 desorption. Also, a weak but negligible dependence of the cryo-collimator temperature on the ramp cycle has been observed [14]. The cryogenic residual gas atmosphere is dominated almost entirely by hydrogen.

The interconnection integrity and correctness of the BPM assembly are verified by measurements of the full matrix of scattering parameters with use of a network analyser. In addition, time domain reflectometry is used to verify the condition of the BPM cryocables.

OUTLOOK

In order to complete SIS100, both QPU and QDM series have to be completed at high production rates. Unfortunately, the procurement and testing processes of QDMs are significantly hindered by project constraints with respect to the QPU procurement [1]. Major effort is made to re-establish a fluent supply chain.

String Test

In parallel to the procurement processes, a string test is currently in the assembly phase to resemble a SIS100 lattice cell. The setup comprises two dipoles, a QDM, an end cap, an end box and a cryogenic bypass line as well as a standard pumping chamber and a gas inlet system on the room temperature side. In the assembly phase, installation sequences and procedures are developed and validated with a special focus on the interconnection area of the hydraulic system, UHV system, and cryo-magnetic system including its busbars. The corresponding quality assurance processes will be defined and approved for later tunnel installation. In its operational phase, the string will be cooled down to study the interplay between the components in the complex setup in a dedicated testing program (mechanical and electrical integrity, UHV, cryogenics, magnet quench studies, powering and magnet operation).

Tunnel Installation

The civil construction of SIS100 is steadily progressing and the technical infrastructure is being installed. The planning of installation and commissioning processes of the superconducting magnet modules is currently ongoing and the first modules will be installed in the beginning of 2024.

CONCLUSION

The procurement of the SIS100 superconducting dipole modules has been successfully completed including a comprehensive measurement campaign and the integration of the cryogenic beam vacuum chambers, which were procured separately. The modules are available for installation into the SIS100 tunnel.

For the quadrupole doublet modules major progress has been achieved recently. The series production of the quadrupole units and integration of the series of quadrupole doublet modules has been launched successfully. Such processes are accompanied by testing programs for which testing sites have been set up and commissioned both for the quadrupole units as well as for the quadrupole doublet modules. The testing results confirm the principal doublet design and that the production quality required for successful operation of SIS100 is met.

Currently, the progress is delayed due to non-technical reasons. The original production and testing chains have to be re-activated or alternatives established by means of a continuation of quadrupole unit production. The results and experiences from the first successful phase have to set the basis to proceed with the project and increase the module integration rate in order to meet the FAIR timeline.

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