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Cryogenic testing of fast ramping superconducting magnets for the SIS100 synchrotron

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Abstract. The international Facility for Antiproton and Ion Research FAIR is currently under construction at GSI, in Darmstadt, Germany. The core component of FAIR, the superconducting SIS100 synchrotron will operate with a high repetition rate of up to 1 Hz. The SIS100 ring with a circumference of 1083 m contains 108 main dipole magnets with a maximal field of 1.9 T. The ion-optical lattice of SIS100 contains also 166 main quadrupoles and 137 corrector magnets. The quadrupole and corrector magnets are assembled in the quadrupole units that are pair-wise integrated in quadrupole doublet modules. All superconducting magnets will be tested at liquid helium temperature to assure their compliancy with the specification. The main dipole modules are being tested at the magnet test facility at GSI. Cold testing of the quadrupole doublet modules is split in the testing of the quadrupole units at JINR, Russia and in testing of fully assembled quadrupole doublet modules at INFN, Italy. The cold testing program includes dynamic AC loss measurements and hydraulic adjustment of the parallel cooling channels of SIS100 next to the training, magnetic field measurements and other tests. We present the scope of cold testing of different types of magnet modules as well as the test results.

1. Introduction

The superconducting synchrotron SIS100 is the core component of the FAIR accelerator complex which is being built at GSI, Darmstadt, Germany [1]. SIS100 uses fast ramped superconducting magnets designed for the pulsed operation with the ramp up time of 0.5 s. Depending on the operating mode of the synchrotron the main dipole and quadrupole magnets will be cycled with a repetition frequency of up to 1 Hz. Dynamic heat losses caused by fast cycling will reach the values up to 35 W for the dipole magnets and 16 W for quadrupoles [2]. There will be 108 dipoles, 166 quadrupoles and 137 corrector magnets in the SIS100 ring (Table 1). High dynamic heat losses require cooling of coils and yokes with forced flow two-phase helium [3].

Table 1. Superconducting magnets for SIS100 synchrotron

	main dipole	main quad	chrom. sextupole	steerer (hor./vert.)	nested multipole (quad/sext./octup.)
number of magnets	108	166	42	83	12
maximal current, kA	13.2	10.5	0.25	0.25	0.25
ramp time to max, s	0.5	0.5	0.175	0.2	0.175

2. Cryogenic testing of the magnet modules

2.1. Testing strategy

Acceptance tests at cryogenic temperatures are foreseen for each magnet module of SIS100. Generally, the acceptance tests are divided into Factory Acceptance Tests (FAT) at the manufacturer site and Site Acceptance Tests (SAT) which will take place at the dedicated magnet test facilities. The FAT program will be executed at room temperature while the SAT will include both, warm and cold tests.

All dipole prototypes including pre-series dipole are being tested at the Prototype Test Facility (PTF) at GSI. For the series dipoles a new Series Test Facility (STF) was built and put in operation at GSI site in 2016. The new test facility has four test benches for independent testing of up to four dipole modules. Cold testing of quadrupole doublet modules is also possible at STF. However only one pre-series doublet module will be tested at STF. For testing of series doublets a dedicated test facility is being constructed in INFN, Salerno. In general, testing of the quadrupole doublet modules will be split in two parts. All quadrupole magnets with correctors (quadrupole units) will be manufactured and pre-tested in JINR, Dubna. After successfully passed tests the quadrupole units will be pair-wise integrated in the quadrupole doublet modules and the assembled modules will be finally tested at the test facility at INFN.

A standard SAT sequence consists of following steps:

- incoming visual inspection
- tests at room temperature:
    - check of instrumentation (sensors, voltage taps)
    - dimensional inspection
    - high voltage tests
    - measurement of the cold mass position with respect to the cryostat
- mounting on the test bench, pumping and cool down
- tests at helium temperature
    - tests of instrumentation
    - leak tests
    - high voltage tests
    - magnet powering and training
    - magnetic field measurements
    - measurement of heat losses, static and dynamic
    - ramping the 1 Hz cycle and measurement mass flow rates and pressure drop of helium in the cooling channels
- warming up and dismounting from the test bench
- final tests at room temperature (high voltage tests, instrumentation tests)

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2.2. Cryogenic dipole module

SIS100 dipoles are iron-dominated window-frame type magnets with forced flow two-phase helium cooling. The magnet consists of the superconducting coil and helium cooled iron yoke. The coil is made of the inner cooled cable of the Nuclotron type [3], [4]. The cold mass of the dipole magnet is about 2.1 t. More details of the magnet design are given in [5].

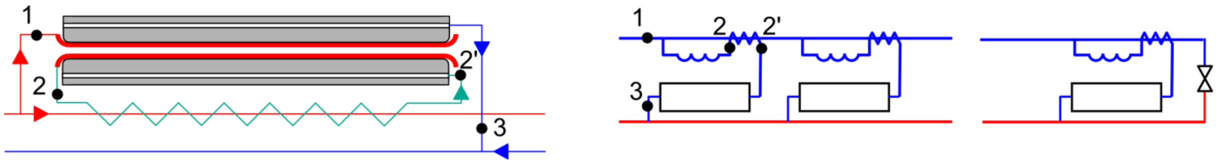

Figure 1. Cooling scheme of the SIS100 dipole (left) and of the SIS100 sector (right).

The cooling concept of SIS100 magnets is presented on Figure 1. All dipole magnets and quadrupole units in one sector are connected in parallel to the helium supply and return lines. The helium in the supply line is sub-cooled and has a temperature of about 4.5 – 4.6 K at P = 1.5 – 1.6 bars. The helium passes through the magnet bus bars and the coil (points 1 - 2) and finally through the iron yoke (points 2 - 3). The subscripts 1, 2 and 3 denote the points on the Figure 1. Due to the pressure drop in the coil and due to the static and dynamic heat load, helium at point 2 is in the two phase state with T = 4.3 - 4.4 K at $P_2 = P_3$ = 1.25 bar. The major part of dynamic heat losses is created in the iron yoke thus the helium at point 3 can be either two phase or vapour, depending on the operation cycle of the SIS100 synchrotron. The heat exchangers attached to the supply header (Points 2 - 2') transfer heat to the two-phase helium flow 2 - 2' and keep helium in the supply header in its single-phase state over the whole length of the SIS100 sector. The hydraulic resistance of the magnet cooling channel is mainly determined by the length of the cable with the inner diameter of 4.7 mm and the total length of 108 m (dipole coil including bus bas).

To adjust the hydraulic resistance of the parallel cooling channels, each magnet module is equipped with flow impedance installed in the helium inlet (point 1 on Figure 1). For the dipole magnet the flow impedance is a 3.5 m long piece of 3.0 x 0.5 mm tube. The impedance reduces the mass flow rate to the desired value. This value is chosen to assure the reliable cooling of the dipole magnet for 1 Hz reference cycle (Figure 2). This synchrotron cycle with the maximal field of 1.9 T will be used for acceleration of U^{28+} ions to 2.7 GeV. It is the most demanding cycle with respect to the dynamic heat load. The ramp rates are 4 T/s and -3.5 T/s for the rising and falling slopes respectively. Measurements on the prototype magnets have shown that the coil outlet temperature T_2 starts to rise causing a quench when the yoke outlet temperature T_3 reaches 8 – 9 K. Taking into account a safety margin the value 5.5 ± 0.5 K has been chosen for the yoke outlet temperature T_3 as the set point for 1 Hz operation (Figure 1) with $\Delta P = P_1 - P_3$ = 0.55 bar.

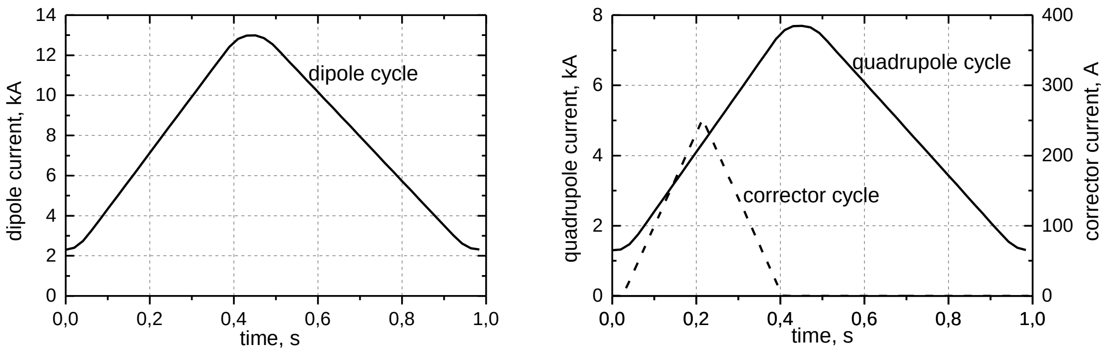

Figure 2. Reference cycles for hydraulic adjustment of the main dipole magnets (left) and the quadrupole units (right)

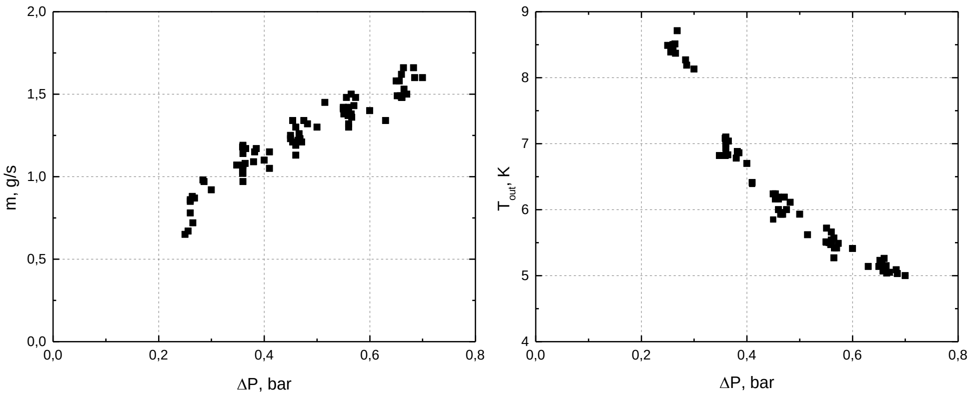

Figure 3. Helium mass flow rates (left plot) and yoke outlet temperatures (right plot) for dipole magnets for 1 Hz reference cycle as function of $\Delta P = P_{in} - P_{out}$. The pressure P_{out} is fixed at 1.14 bar(a). Data for 18 dipole magnets are presented.

The standard test program includes the measurement of dynamic heat losses by V-I method. By this method the voltage on the coil and the magnet current are simultaneously sampled over the whole cycle. Then the dynamic heat load caused by cycling is calculated as the integral of electrical power $P = V \cdot I$. The dynamic losses measured by this method are 34.7 ± 0.3 W (stat.). The estimated systematic error is about 10 % of the measured value.

Another part of the standard test program is the measurement of the yoke outlet temperature at different inlet pressures. The test results are shown on Figure 3. All tested dipole magnets fulfill the specified conditions, 5.5 ± 0.5 K at the yoke outlet at ΔP = 0.55 bar. As mentioned in Section 2.2, the value 5.5 ± 0.5 K was chosen to assure the reliable cooling of the magnet for 1 Hz reference cycle. The temperature measured at the coil outlet (Figure1, point 2) was always at 4.3 – 4.4 K.

Simultaneous measurement of the helium mass flow rate, temperatures and pressures allow calculation of the total heat load, static and dynamic. The total heat load for 1 Hz cycle is 39.5 W with statistical error of 0.4 W. The systematic error is about 4 W and is mainly caused by the accuracy of the mass flow sensor (Coriolis type). Without ramping, the helium at the outlet is in two-phase state and the yoke outlet temperature can't be used for calculation of the heat load. To measure the static heat load the outlet pressure is increased to 2.3 bar and the measurements are performed with super-critical helium. The measured static heat load is 5.1 ± 0.3 W. The difference between the calorimetrically measured total heat load and the static heat load is in good agreement with the dynamic heat load values measured using the V-I method.

2.3. Quadrupole Doublet Modules

Cryogenic tests of SIS100 quadrupole doublet modules [6] are split in two parts, testing of the main quadrupoles with corrector magnets (quadrupole units) and testing of assembled quadrupole doublets.
Manufacturing of main quadrupoles and corrector magnets, assembling them in quadrupole units and testing at helium temperatures will be done by the FAIR in-kind partner JINR, Dubna, Russia. Cryogenic testing of SIS100 quadrupole units is a main part of the Site Acceptance Tests which will be executed at JINR. Cryogenic testing will be performed at the common JINR / FAIR magnet test facility. The standard test sequence for the quadrupole unit is similar to the SAT sequence of dipole module (section 2.2) except for the measurements of the position of the cold mass with respect to the magnet cryostat. Since the quadrupole units do not have their respective cryostats, they are tested in test cryostats which belong to the testing infrastructure. An important step of the test program is the measurement of the position of the magnetic axis of the quadrupoles with respect to the fiducial targets installed on the

quadrupole yoke. These data are required for pair-wise assembling and alignment of units in the quadrupole doublet modules. The cooling conditions will be verified for each quadrupole module in a similar way as for dipole modules. Main quadrupoles and corrector magnets will be simultaneously ramped at 1 Hz (Figure 2, right) and the length of the flow impedance will be adjusted to keep the yoke outlet temperature at 5,5 ± 0.5 K. There are several types of quadrupole units with significantly different hydraulic resistance. In the quadrupole unit the coil of the main quadrupole and the coil of the corrector coil are hydraulically connected in series. Depending on the type of corrector magnet the hydraulic resistances of the units vary in a wide range. Therefore for each new configuration of the unit the length of the capillary tube must be defined and verified by measurements. The criteria for the hydraulic adjustment have been chosen similar to the dipole magnets:

- Quadrupole and corrector magnets are ramped in reference cycle (Figure 2)
- The pressure drop is set to 0.55 bar
- The yoke outlet temperature must match the range between 5 K and 6 K (5.5 ± 0.5 K)

Up to now two pre-series units have been tested [2]. The measured dynamic heat load in reference cycle is 16 W. Series production of quadrupole units at JINR has started and series testing will start in autumn 2019.

After a successfully passed SAT the quadrupole units will be shipped to the contractor Bilfinger Noel GmbH for integration in doublet modules. A quadruple doublet module integrates in one cryostat two quadrupole units, 250 A current leads for corrector magnets, helium cooled beam pipes and other devices. Depending on the type, the doublet modules contain beam position monitors, beam collimators (cryo catchers), cryo sorption pumps for beam vacuum, cold-warm transition and other parts [6]. The test program for quadrupole doublet modules does not include the powering of main quadrupole magnets and focuses on components which were not tested at JINR:

- mechanical interfaces, mechanical integrity and leak tightness at helium temperatures
- electrical integrity of the module, high voltage tests
- tests of instrumentation
- static heat load
- tests of 250 A current leads for corrector magnets (in DC mode only)
- tests of the beam vacuum system
- test of the beam position monitors
- tests of the cryo catchers

After successfully passed SAT the doublet modules will be shipped to GSI for installation in the accelerator tunnel.

2.4. Main current leads

The SIS100 superconducting dipole and quadrupole magnets will be powered through 14 pairs of HTS current leads rated at 14 kA DC. The HTS part of current leads is cooled by helium gas at 50 K. There are in total 38 current leads (19 pairs) including current leads for the STF test facility and spares. All current leads will be tested at STF at GSI. The test program includes leak tests, high voltage insulation tests at 3 kV, ramping 1 Hz dipole reference cycle, 14 kA DC current operation and training ramps up to 17 kA. The helium consumption measured for 1 Hz reference cycle is 0.7 - 0.8 g/s [7]. The current leads can also be operated if the temperature of the HTS stack is increased to 60 K. Currently all current leads have been delivered to GSI for SAT and 17 pairs were successfully tested. Cryogenic testing of remaining two pairs is in preparation.

3. Conclusions

Site Acceptance Tests of SIS100 magnets are executed at three magnet test facilities, at GSI, JINR and INFN. Presently about 50% of dipole magnets are successfully tested. All tested dipoles fulfil the specified values for the magnetic field quality and show a good reproducibility with respect to the hydraulic behaviour and heat load. Two pre-series quadrupole units have been tested at JINR and accepted. Testing of pre-series doublet at GSI and testing of series quadrupole units at JINR is in preparation as well as testing of series doublets at INFN.

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