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Hydraulic adjustment of the two-phase helium forced flow cooled superconducting magnets of the SIS100 heavy ion synchrotron for FAIR

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Abstract. The fast ramped superconducting heavy ion synchrotron SIS100 is the core component of the international FAIR project at GSI in Darmstadt. The magnet system of the SIS100 consists of the superconducting dipoles, quadrupoles and corrector magnets assembled in cryogenic modules. In order to maximize the beam intensity the SIS100 main dipoles will operate up to 1.9 T with 4 T/s with a high repetition rate of up to 1 Hz. The various configurations of parallel cooling circuits must be hydraulically adjusted in respect to their dynamic heat load for a wide spread of operation cycles. We present the results of dynamic heat loss measurements for the different types of magnets as well as the procedure of their hydraulic adjustment.

1. Introduction

The Facility of Proton and Ion Research (FAIR) under construction at GSI [1] will provide high intensity beams of ions and antiprotons for experiments in nuclear, atomic and plasma physics. The operation modes of the FAIR facility will facilitate four experiments simultaneously. The SIS100 synchrotron with magnetic rigidity of 100 T·m is the key component of FAIR. The high repetition rate of SIS100 acceleration cycles up to 1 Hz requires fast-ramped superconducting magnets with high dynamic heat load. The SIS100 dipole and quadrupole magnets as well as the magnets for the NICA project [2] were designed on the basis of the fast-cycling super-ferric magnets for the Nuclotron synchrotron at JINR in Dubna [3]. During an intensive R&D phase the dynamic heat generation caused by fast cycling was considerably reduced in comparison to the original Nuclotron magnets [4]. The losses were experimentally measured on short models and on full size prototypes. Finally, the first-of-series dipole, quadrupole and corrector magnets for SIS100 were built and tested at the cryogenic test facilities at GSI and at JINR. The dynamic heat loads and helium mass flow rates were measured for different operation modes of SIS100. Like for the Nuclotron accelerator the cryogenic cooling scheme of SIS100 and NICA is based on using of the two-phase forced flow helium. All dipole and quadrupole magnets in one sector of the accelerator are connected to one supply and one return header and are cooled in parallel. Due to very different hydraulic resistances of the parallel cooling channels the hydraulic adjustment of each channel is necessary.

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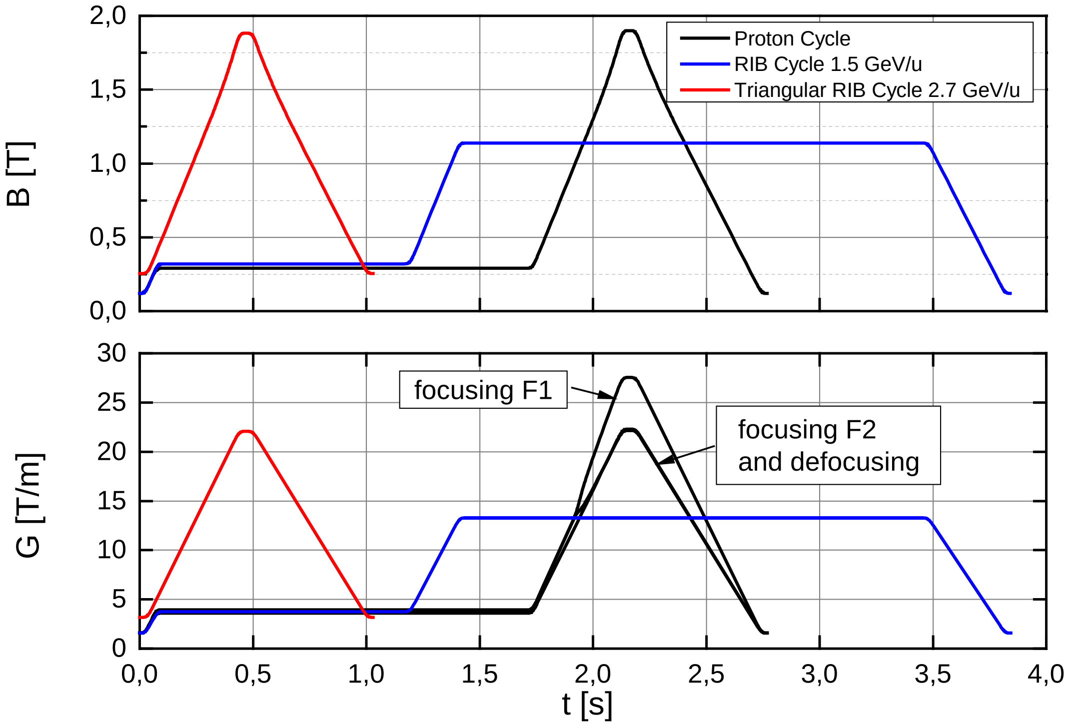

Figure 1. Some examples of the SIS100 operation cycles. The plots show the main dipole field (upper plot) and the field gradients in three families of quadrupole magnets (lower plot) as a function of time. The highest dynamic heat release in the superconducting magnets will be generated in the triangular RIB cycle with 1 Hz repetition rate.

2. SIS100 operating cycles and dynamic heat generation in fast ramped magnets

The operation modes of the SIS100 synchrotron depend on the kind of the ions to be accelerated, the required energy and the extraction type, slow or fast. Some samples of the operation cycles are presented in Figure 1. The upper plot shows some typical time charts for the main dipole field. Each acceleration cycle starts with a beam injection plateau at 0.2 – 0.3 T. The time required for the beam injection and the beam manipulations might vary between 0.01 s for the single-turn injection and 1 – 2 s in case of the multi-turn injection. After the beam injection the dipole field is ramped up to the extraction plateau with the rate of 4 T/s. The level of the extraction plateau depends on the required beam energy and varies between 0.5 T and 1.9 T. The operating current of the dipole magnet at 1.9 T is 13.2 kA. The extraction can take up to several seconds in case of the slow extraction. Then the field is ramped down with the ramp rate of 3.5 T/s and a new acceleration cycle starts. Generally, the SIS100 will serve several experiments concurrently. In this case the sequence of different acceleration cycles will be combined into one super-cycle.

The most demanding operation mode with respect to the dynamic heat generation in the superconducting magnets is the acceleration of U^{28+} ions to 2.7 GeV/u with one-turn injection and fast beam extraction (Triangular RIB Cycle in Figure 1). Due to the extraction field of 1.9 T and the high repetition rate of about 1 Hz this cycle will generate the highest dynamic heat load in dipole magnets.

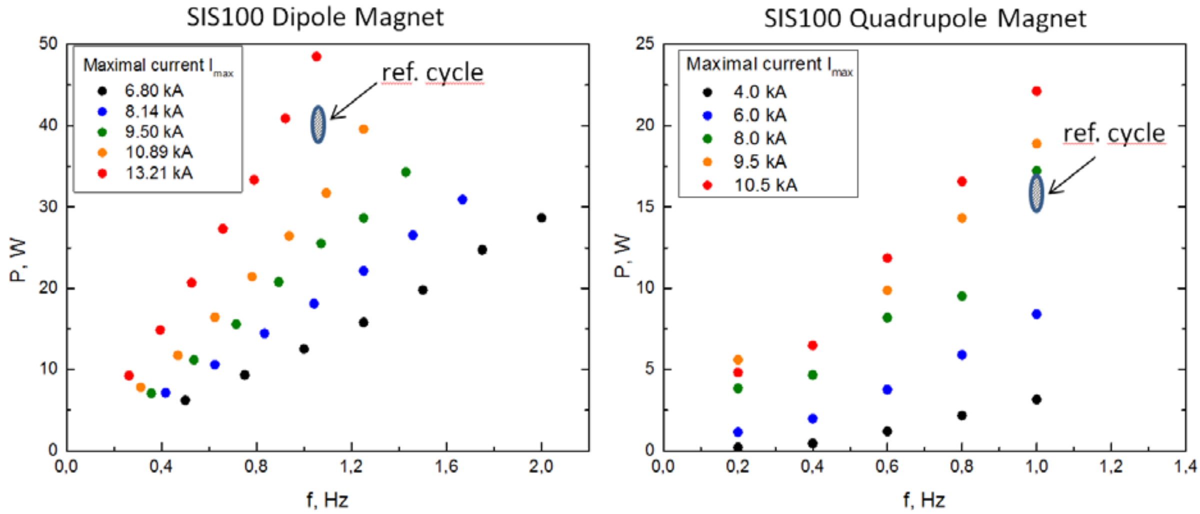

Figure 2. Dynamic heat release (loss matrix) measured on the first-of-series dipole and quadrupole magnets. The dashed areas show the dynamic heat release in the reference cycle.

The time charts for the quadrupole filed gradients are presented in Figure 1, lower plot. There are three independently powered families of quadrupole magnets in SIS100 indicated in Figure 1 as focusing F1, focusing F2 and defocusing quadrupoles. The maximal operating current of the SIS100 quadrupole magnet is 10.5 kA. However this current value will be reached only for the F1 quadrupole family and only in case of acceleration of protons to 29 GeV (see Figure 1, proton cycle). The repetition time of this cycle will be limited to 5 s because of the time required for stochastic cooling of antiprotons in the storage ring. Thus the most demanding operation mode for the quadrupole magnets with respect to the dynamic heat generation is the 1 Hz Triangular RIB Cycle with the maximal current of 7.7 kA in all quadrupole magnets, F1, F2 and defocusing.

The SIS100 dipoles and quadrupoles are iron-dominated magnets. They consist of the iron yokes at helium temperature and of superconducting coils made of hollow inner cooled Nuclotron type cable. The fast cycling generates dynamic heat losses in the iron yokes of the superconducting magnets as well as in the NbTi filaments and in the composite Cu/CuMn matrix. For the continuous triangle current profile the dynamic heat losses depend on the ramp rate $\dot{I} = dI/dt$ and on the minimal and maximal current I_{min} and I_{max}. For $I_{min} = 0$ the cycle repetition rate f is equal to $\dot{I}/2I_{max}$. The dependence of dynamic heat losses on dI/dt and $I_{max}$was investigated at the GSI magnet test facility for the first-of-series dipole magnet [5] and at the JINR magnet test facility for the first-of-series quadrupole [6]. The measured loss matrices are shown on Figure 2. The dashed areas on the plots indicate the losses to be expected in SIS100 Triangular RIB Cycle.

Beside the main dipoles and quadrupoles the superconducting corrector magnets will be installed in SIS100 ring. There are 48 chromaticity sextupole magnets, 84 steering magnets and 12 error compensation multipole correctors. The coils of corrector magnets are made from the Nuclotron type cable with insulated strands [7]. The dynamic heat load of the first-of-series chromaticity sextupole corrector was measured at JINR magnet test facility within the scope of cryogenic testing of the first-of-series quadrupole unit. The maximal dynamic heat generation was 5.9 W for the 3 Hz triangular cycle with $I_{min} = 0\ A$ and $I_{max} = 250\ A$. The corrector magnets are specified for 3 Hz repetition rate and can be operated in bipolar mode between – 250 A and + 250 A. The corrector magnets will be mechanically integrated with main quadrupole magnets in quadrupole units. The cooling circuit of the corrector magnet is connected in series with the quadrupole cooling circuit. Unlike the relatively small heat load the corrector magnets affect the cooling conditions of the quadrupole units because of the

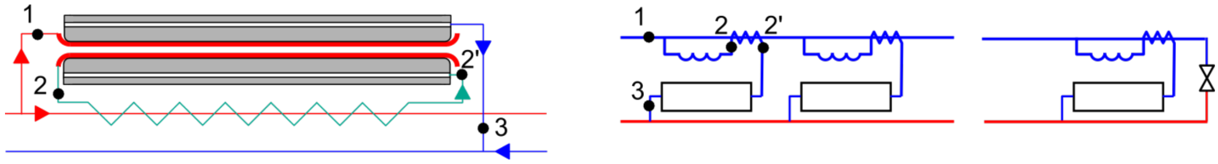

Figure 3. Cooling scheme of the SIS100 magnet (left) and of the SIS100 sector (right). 1 – coil inlet, 2 – coil outlet, 2' – recooler outlet / yoke inlet, 3 – yoke outlet.

additional hydraulic resistance of the corrector coil. On the other hand the operating cycles of corrector magnets have relatively small impact to the total dynamic heat load of the quadrupole unit. The operation cycles of the corrector magnets in SIS100 ring depend on the errors to be compensated and are not well known yet. For the hydraulic adjustment following worst case scenario is chosen: each corrector magnet is cycled once per acceleration cycle from 0 A to 250 A within 0.5 s (Figure 4).

The dipole magnets are tested in their own cryostats. The static heat loads from the ambient due to thermal conduction of the residual gas, trough suspension system and from the thermal radiation shield add about 7 W to the total head load. The cold tests of the quadrupole units are performed in the specially designed testing cryostats. The heat load measured in the testing cryostat is about 5 W. This value includes the heat load caused by the 250A HTS current leads for corrector magnets. After cold testing the quadrupole units will be pairwise-integrated in the quadrupole doublet cryostats. The head load measurements on the first quadrupole doublet module are scheduled for the beginning of 2019.

3. Hydraulic adjustment of the parallel cooling channels of SIS100

All SIS100 magnets are cooled by two-phase helium flow. In each SIS100 sector 18 dipole magnets and 28 quadrupole units are connected to the supply and return headers and form parallel cooling channels (Figure 3). Sub-cooled helium at 1.5 – 1.8 bar from the supply header enter the magnet bus bar in point 1 (Figure 3) and go into the return header with P = 1.25 bar after passing the coil and yoke of the magnet. Thus the pressure difference ΔP between the supply and return headers is variable within the range 0.25 – 0.55 bar. More details about the two-phase cooling of the SIS100 magnets are given in [8].

The main part of the pressure drop incurs in the magnet coils and bus bars with the length of several tenths meter and the inner diameter of 4.7 mm (4.0 mm for corrector coils). In the quadrupole units the coils of the main quadrupoles are connected in series with the corrector coils. There are 7 combinations of the main quadrupole and corrector magnets with highly different hydraulic resistances. To assure the optimal distribution of the helium mass flow rate between the magnets each parallel cooling channel will be hydraulically tuned. The adjustment of the hydraulic resistance will be done by an additional capillary with an inner diameter of 2 mm installed on the inlet into the cooling channel. The relation of the capillary length and the helium mass flow rate was experimentally investigated at GSI [9]. Defining the length of the capillary belongs to the cryogenic testing program of the first-of-series units of each new type.

An important issue is the definition of the adjustment point. Generally, the optimal cooling conditions are given when the two-phase helium leaves the magnet yoke with a mass vapor content x = 1. Since the ΔP is limited to 0.25 – 0.55 bar, the selection of the adjustment point defines the range of the dynamic heat load for which the optimal cooling can be achieved. However a cooling with non-optimal mass flow rate is also possible. Power tests of SIS100 dipole and quadrupole magnets have shown that the magnets can be also reliably operated if the yoke outlet temperature rises up to 7 - 8 K, as long as the temperature at the coil outlet remains at 4.5 K. The ΔP measured of the SIS100 dipole magnet for 1 Hz reference cycle and for x = 1 on the yoke outlet is 0.37 bar. The yoke outlet temperature rises to 5.5 K if the pressure difference falls to 0.23 bar.

To select the adjustment point one has to fix the reference cycle and the temperature of the sub-cooled helium on the coil inlet (point 1 in Figure 3) for all cooling channels. Then the helium length of the capillary can be determined to achieve a desired helium mass flow rate. The triangular RIB cycle

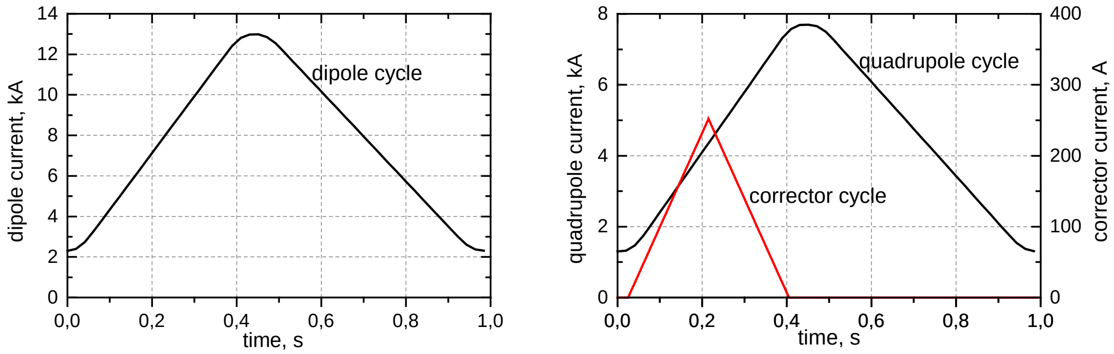

Figure 4. Reference cycles for hydraulic adjustment of the dipole magnets (left) and of the quadrupole units (right). All coils of the corrector magnet will be cycled simultaneously.

with 1 Hz repetition frequency (Figure 1) has been selected as a reference cycle for hydraulic adjustment (Figure 4). This cycle represents the worst case scenario of the SIS100 operation with respect to the dynamic heat generation in the magnets. Thus the capillary length can be chosen with the aim to get a temperature of 5 – 6 K at the yoke outlet.

4. Conclusions

The hydraulic resistances of the parallel cooling channels of the SIS100 magnets will be adjusted by adding additional capillaries with 2 mm inner diameter on the magnet inlets. Each adjusted magnet will be tested at cryogenic conditions. The cold test program will include ramping at reference cycle and checking the yoke outlet temperature at reference pressure difference to verify the optimized helium mass flow rate. The parameters of the reference cycle are derived from the worst case scenario with respect to the dynamic heat generation in the magnets. The length of the capillary will be adapted for each type of the quadrupole units as well as for the dipole magnets in order to assure a reliable operation of SIS100 at high dynamic head load.

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