Investigation of the cooling conditions for the Fast Ramped Superconducting Magnets of the SIS100 Synchrotron

A Bleile\textsuperscript{1}, E Fischer\textsuperscript{1}, H Khodzhibagiy\textsuperscript{2}, A Mireau\textsuperscript{1} and P Schnizer\textsuperscript{1}

\textsuperscript{1} GSI, Germany
\textsuperscript{2} JINR, Russian Federation

E-mail: a.bleile@gsi.de

Abstract. The dynamic losses in fast ramped super ferric magnets will create the main part of the expected heat losses in the superconducting synchrotron SIS100 – the primary accelerator in the Facility for Antiproton and Ion Research (FAIR). The data measured on dipole models at the cryogenic magnet test facility at GSI allow to predict the static and dynamic losses in the superconducting magnets for different operation modes of the SIS100 synchrotron. The calculations of the expected mass flow rates in the cooling channels of the superconducting magnets together with the analysis of the cooling system for different operation modes of the synchrotron will be presented.

1. Introduction
The Facility of Proton and Ion Research (FAIR) will construct as a set of accelerators and storage rings at GSI. The aim of the project is to provide high intensity primary and secondary beams of ions and antiprotons for experiments in nuclear, atomic and plasma physics. The SIS100 synchrotron with a circumference of 1100 meters and a rigidity of 100 Tm will provide the primary beams of different species of ions from protons to uranium and will enable a parallel operation of up to four scientific programs. A big variety of different operation cycles of the SIS100 synchrotron with a repetition rate up to 1 Hz requires fast-ramped superconducting magnets with high dynamic heat release.

The design of the superconducting magnets and of the cooling system of the SIS100 is based on the Nuclotron synchrotron at JINR in Dubna, which was constructed on the basis of the fast-cycling super-ferric magnets \cite{1}. During an intensive R&D phase the magnet field quality, AC losses and long term mechanical stability have been improved and were experimental tested on the short models and on the full size prototypes \cite{2}, \cite{3}.

2. Superconducting magnets for SIS100
2.1. Design aspects
The superferric dipoles and quadrupoles for the SIS100 synchrotron (Figure 1) consists of an iron yoke and a superconducting coil made from the Nuclotron type cable where the superconducting NbTi wires are wrapped around a CuNi tube which acts also as a cooling tube. Both the superconducting coil and the yoke are cooled by two phase helium flow. The inner diameters of the cooling tubes in the coils are 4.7 mm for the main dipoles and quadrupoles and 4.0 mm for the corrector magnets. The
small inner diameter and the big length of the cooling tube (about 108 m for the coil and bus bars of the main dipoles) limit the mass flow rate of the two phase helium up to 1-2 g/s.

Figure 1. Cross sections of super-ferric dipoles and quadrupoles for SIS100

2.2. Cooling scheme

The cooling scheme of the SIS100 dipole magnet is shown on the Figure 2. 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 cools successively the magnet bus bars, the coil (Points 1 -2) and the iron yoke (Points 2 -3). Due to the pressure drop in the coil and bus bars as well as due to the static and dynamic heat load the helium in the Point 2 is in the two phase state at P₂ = P₃ = 1.1 – 1.2 bar and T₂ = T₃ = 4.3 -4.4 K (the subscripts 1,2 and 3 denote the points on the Figure 2). The major part of dynamic heat losses is created in the iron yoke, so the helium in the Point 3 can be either two phase or vapor, depending of the operation mode of the SIS100 synchrotron. All magnets in one sector are connected in parallel (Figure 2, right). The recoolers attached to the supply header (Points 2-2’) transfer the heat to the two phase helium and keep the helium in the supply header in the single phase state over the whole length of the SIS100 sector. The cooling scheme of the quadrupole doublet is shown on the Figure 3. A quadrupole doublet module has two parallel flow channels denoted on the Figure 3 as M1 and M2 for the cooling of both quadrupole units. A unit consists of a quadrupole magnet switched hydraulically in series with a corrector magnet. A corrector magnet can be a steerer, chromaticity sextupole, a multipole corrector or γt-jump quadrupole. All corrector magnets except for the normal conducting γt-jump quadrupoles have the cooling tubes with an inner diameter of 4.0 mm and with the length of 15 – 43 m. The helium flow after each quadrupole unit cools also the common girders – the support structure for the both units.

Since the fast ramped magnetic field generates the heat losses also in the beam vacuum chambers, the dipole and quadrupole magnet modules have a dedicated cooling circuit for the beam vacuum chambers and for the cryo catcher chambers (channel V on the Figure 3).

Figure 2. Cooling scheme of the SIS100 dipole (left) and of the SIS100 sector (right)
3. Cooling conditions for different operation modes of SIS100

The big variety of operating cycles of the SIS100 causes the wide range of the dynamic heat losses. The dynamic losses for dipole magnets have been measured on prototype test facility at GSI and vary from 0 W in the stand-by mode to 70 W in the operating cycle with $B_{\text{max}} = 1.9$ T at repetition rate of 1 Hz (so called triangular cycle). However, this cycle with a one-turn injection is not foreseen for the standard operation of the SIS100. The inner diameter of the cable for the main dipoles and quadrupoles has been optimized for the operation mode with a multi-turn injection which causes the dynamic head load of about 50% of the maximum. In this mode the two phase helium at the output of the main dipoles has a vapor quality $x \approx 0.9$. The estimated values of dynamic losses in the quadrupole magnets are about 35 W. These losses as well as the losses in the corrector magnets will be verified on the first prototype of the quadrupole doublet.

The calculated mass flow rates as well as the conditions on the outputs from the cooling channels are presented in the Table 1 for two cases: 50% and 100% of the maximal dynamic load. The calculations have been performed under following assumption:

- Supply header: $P = 1.6$ bar, $T = 4.5$ K, helium is sub-cooled by 0.2 K
- Return header: $P = 1.2$ bar
- Homogenous model for the two phase flow with the viscosity of the liquid phase ($\eta = \eta_l$)
- Distribution of dynamic losses between coil and yoke: 30% / 70%
- Static losses: 5 W for the dipole modules, 6 W for the quadrupole doublets
- Corrector magnets have a HTS current leads with the heat load $< 0.5$ W/pair at 4.6 K

The calculations show that all configurations of the cooling channels will differ in the helium mass flow rates and in the vapour quality i.e. in the temperature on the output from the cooling channel. At maximal load the helium on the output from the iron yokes of the dipole modules will have a temperature of about 7.3 K. The operation mode with output temperature of the iron yoke of 7-8 K was verified during the cold testing of the dipole prototypes with two-layer coils [4]. The cold tests of the first series dipole with a single layer coil are scheduled to the end of 2013. The losses in the quadrupole units as well as the reliable operation at the maximal load will be verified within the cold
test of the first quadrupole doublet. Especially for the configuration Quadrupole + Steerer + Multipole a dedicated third cooling channel for the multipole corrector may be required because of the long coil of the multipole (43 m cable with inner diameter of 4.0 mm) and thus the low helium mass flow rate.

On the other hand, the mass flow rates through the channels with small hydraulically resistance will be higher than required for the reliable operation, especially at the operation modes with low dynamic losses. Therefore the additional flow impedances (flow restrictors) will be placed on the inputs to the cooling channels M1, M2 and V in the quadrupole modules (Figure 3). The flow restrictors will be sized after the first tests of each type of the quadrupole unit in order to adjust the vapour quality of about 0.9 for all cooling channels at the operation mode with 50% dynamic load.

4. Conclusions
The big variety of operation modes of the SIS100 synchrotron and different configuration of the parallel cooling canals require the adjustment of the hydraulic resistances of all cooling channels to one common level at one of the standard cycles of the SIS100. The adjustment will be done by combination of quadrupole magnets with corrector magnets as well as by additional flow impedances on the inputs to the cooling channels.

References
[1] Baldin A.M. et al. 1995, Superconducting fast cycling magnets of the Nuclotron, *IEEE Trans.of Appl.Supercond.*, Vol.5, pp. 875-877
[2] Fischer E et al., Fast Ramped Superferric Prototype Magnets of the FAIR Project, First Test Results and Design Update, *Proc. of the Particle Accelerator Conference PAC’09*, Vancouver 2009
[3] Fischer E, Khodzhibagian H, Kovalenko A, Schnizer P, Fast Ramped Superferric Prototypes and Conclusions for the Final Design of the SIS100 Main Magnets, *IEEE Trans.of Appl.Supercond.*, Vol.19, pp. 1087-1091, June 2009
[4] Bleile A, Fischer E, Khodzhibagian H, Mierau A, Schnizer P, Measurement of Dynamic Heat Losses in the Fast Ramped Superconducting Magnets for the SIS100 Synchrotron, *Proc. of the 12th International Conference Cryogenics 2012*, pp. 59 – 64, Dresden 2012

Table 1. Mass flow rate and output conditions for different configurations of the cooling channels in one sextant of the SIS100

| Configuration of the cooling channel | number of channels | 50% load m, g/s | 𝑥_{out} | 100% load m, g/s | ℋ_{out}, K |
|------------------------------------|--------------------|----------------|--------|----------------|------------|
| Dipole                             | 18                 | 2.4            | 0.9    | 2.0            | 7.3        |
| Quadrupole                         | 10                 | 2.5            | 0.3    | 2.0            | 4.4*       |
| Quadrupole + Sextupole             | 3                  | 2.6            | 0.6    | 2.3            | 4.7        |
| Quadrupole + Steerer               | 7                  | 2.3            | 0.6    | 2.2            | 4.6        |
| Quadrupole + Steerer + γt-jump quadrupole | 2          | 2.3            | 0.6    | 2.2            | 4.6        |
| Quadrupole + Steerer + Sextupole   | 4                  | 1.9            | 0.9    | 1.7            | 6.5        |
| Quadrupole + Multipole Corrector   | 1                  | 2.0            | 0.8    | 1.8            | 5.7        |
| Quadrupole + Multipole + Steerer   | 1                  | 1.5            | 1.0    | 1.3            | 8.0        |

*) two phase helium, 𝑥 = 0.7