New Design for the SIS100/300 Magnet Cooling

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Abstract—**Two superconducting synchrotrons, SIS100 and SIS300, are planned for the new International Accelerator Facility of Antiprotons and Heavy Ions (FAIR) at GSI, Darmstadt. These accelerator rings, operating at liquid helium temperatures, are placed in one tunnel of 1100 m length. The SIS100 structural superferric dipoles and quadrupoles are based on the Nuclotron-type hollow NbTi composite multi wire cable and cooled in parallel with two-phase helium flows. The peak operating mode for the SIS100 dipoles corresponds to $B_m = 2$ T, dB/dt = 4 T/s, f = 0.58 Hz. Fast-ramped 6 T dipoles (dB/dt = 1 T/s, f = 0.05 Hz) are required for the SIS300 ring. Supercritical helium is used as coolant in the existing concept of the SIS300. We propose two-phase helium cooling also in the SIS300 case. The necessary modifications of the magnet cooling scheme are presented and discussed. General optimization of the SIS100/300 cryogenic system, including helium transfer lines and refrigerator loads for different operating regimes, is considered also. The new design will make it possible to reduce the FAIR project cost.**

Index Terms—**Accelerator, cooling, superconducting magnet, two-phase helium.**

I. INTRODUCTION

THE Gesellschaft fuer Schwerionenforschung mbH (GSI) plans to construct a new accelerator complex, the international Facility for Antiproton and Ion Research (FAIR) [1]. The new accelerator complex will contain two synchrotrons (SIS100 and SIS300), four storage rings and nearly 1 km beam transport lines. It is planned to use superconducting magnets in all these installations. The fast-cycling operating mode of the SIS100 magnets and a fast-ramped operating mode of the SIS300 magnets impose rigid requirements for their cooling system. This limits the reliability of operation on the whole complex in many respects. The Nuclotron synchrotron was constructed on the basis of a fast-cycling superferric magnet [2] and has been successfully operated since 1993 [3], a unique unprecedented machine. The magnets of this synchrotron serve as prototypes for the SIS100 magnet. Fast pulsed magnets with a field strength of 4T and above (similar to the SIS300 magnet) were not yet used for accelerators. This work proposes a new cooling concept for the SIS100/300 magnets.

II. THE SIS100 MAGNET COOLING

The accelerator SIS100 will be constructed of 2T, 4T/s Nuclotron-type superconducting magnets with are feed in parallel by two-phase helium [4, 5]. In the existing concept [6] for the cooling of the SIS100 magnets there are only two strings of the magnets connected to direct and return helium headers similarly to the Nuclotron magnetic system [4]. We suggest dividing the helium feed to the accelerator ring into six segments. It will reduce the number of parallel channels in one string by a factor of three. This will essentially raise the cooling reliability of the magnets and will reduce the diameters of the helium headers. This will result in 54 parallel channels in a segment, and in header diameters of 32 mm for the direct header and 45 mm for the return one.

The accelerator is planned to be used in 5 various super cycles [7]. The parameters of these super cycles are the following: The magnetic field at injection B_{min} is 0.24 T and its ramp rate $dB/d\tau$ is 4 T/s, the magnetic field at extraction B_{max} changes from 0.5 T up to 2 T, the pulses repetition frequency from 0.36 Hz up to 1 Hz. For a dipole magnet with a length of 2.6 m and a aperture of 130mm x 65mm the expected dynamic heat releases in the coil and in the yoke will be 15.5 J/cycle and 29.5 J/cycle, respectively, at "standard" operation cycle with $B_{min} = 0$, $B_{max} = 2$ T, f = 1 Hz and $dB/d\tau = 4$ T/s [8]. For the same cycle a quadrupole lens with a length of 1.0 m and an aperture of 120mm x 63mm will heat release the coil with 7.22 J/cycle and with 9.94 J/cycle the yoke [8]. It is suggested to pack separate elements of a ring in modules within a single cooling channel to minimize the number of parallel channels. Four types of modules are considered in this paper. Module M1 includes: a quadrupole, a pickup and a steerer; 9 such modules are in one segment. Module M2 includes: a quadrupole, a pickup and a multipole, 10 modules of this type are in one segment. Module M3 includes: a quadrupole, a multipole and a collimator, 5 such modules are in one segment. Module M4 includes: a quadrupole, a steerer and a collimator, 6 of them are to be installed in one segment. The heat generated in the multipoles, pickups, collimators, and steerers is estimated based on the experimental data for similar elements of the Nuclotron. The static heat leak is found to 3 W for dipole magnets and 2 W for quadrupole lenses. The total heat releases for the various super cycles is summarized in the Table I for all SIS100 dipole magnets and the various modules.

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Hydraulic calculations were carried out using an iteration method following the procedure described in [9]. Some results of the calculations are presented in Table II.

TABLE I
TOTAL HEAT RELEASES IN THE SIS100 DIPOLES AND MODULES (IN WATT)

Unit	SUPER CYCLE NUMBER				
	1	2	3	4	5
dipole magnet	19.53	18.43	12.53	19.56	15.51
module M 1	12.50	12.08	9.84	12.52	10.97
module M 2	18.80	18.38	16.14	18.82	17.27
module M 3	19.80	19.38	17.14	19.82	18.27
module M 4	13.50	13.08	10.84	13.52	11.97

TABLE II
HYDRAULIC PROPERTIES FOR THE SIS100 DIPOLES AND MODULES

Unit	ΔP (bar)	x_2	x_3	m (g/s)	L (m)
	Super Cycle 1 (jet pump inactive, $x_{3\ average} = 0.874$)				
dipole magnet	0.25	0.352	0.978	1.01	111
module M 1	0.25	0.450	0.836	0.76	161
module M 2	0.25	0.628	0.907	1.05	71.1
module M 3	0.25	0.601	0.912	1.10	67.3
module M 4	0.25	0.424	0.847	0.81	149
	Super Cycle 3 (jet pump operate, $x_{3\ average} = 0.713$)				
dipole magnet	0.20	0.246	0.669	0.96	111
module M 1	0.20	0.425	0.750	0.67	161
module M 2	0.20	0.675	0.919	0.89	71.1
module M 3	0.20	0.647	0.934	0.93	67.3
module M 4	0.20	0.397	0.768	0.72	149

Hydraulic calculations were performed for the modules containing a quadruple, defining the length of the cooling channel for the given diameter of 4 mm and a set of pressure differences. The calculations were based on the following assumptions: The helium temperature at the input $T_1 = 4.4$ K; the pressure at the helium output of the coil $P_2 = 1.1 \cdot 10^5$ Pa; the pressure drop in the iron yoke cooling channel is negligible. The index 1 denotes the input side of the coil, 2 the output of the coil, 3 output of the yoke. The pressure difference is denoted by $\boldsymbol{\Delta P}$; $\boldsymbol{L}$ is the length of the cooling channel, $\boldsymbol{m}$ - the helium mass flow rate, and $\boldsymbol{x}$ - the mass vapor content

$\boldsymbol{\Delta P}$ is regulated by a jet pump (ejector), which allows to smoothly change the mass flow rate of helium through the cooling channels. The pressure difference between the headers is in the range of 0.2 bars to 0.25 bars, as required for cooling the ring elements reliably. It is achieved without the jet pump in all super cycles except for the super cycle 3. With respect to the planned operating time in each super cycle, the average value of the mass flow rate of the cold compressed helium through the ejector will not exceed 1% of the mass flow rate through the last expansion turbine.

The required refrigerator power for cooling the SIS100 in various super cycles was calculated on the basis of the structure of one segment and the data shown in the Table I. It is listed in TABLE III.

TABLE III
REFRIGERATOR LOAD NEEDED TO COOL THE SIS100 (IN WATT)

SUPER CYCLE NUMBER				
1	2	3	4	5
5317 Duration 30 %	5109 Duration 10 %	3999 Duration 10 %	5324 Duration 20 %	4559 Duration 30 %

Considering the duration of each super cycle, the average refrigerator load will not exceed 5600 W for SIS 100 including eddy-current losses of 700 W in the beam pipe.

We suggest placing three refrigerators in regular intervals on the perimeter of the accelerator. Each of them supplies two segments of the SIS100 and the SIS300 accelerators with helium through a liquid helium separator. Each of the three separators is placed in the accelerator tunnel and consists of a liquid helium collector of 500 liters, a heat exchanger-subcooler, and a jet pump. A simplified flow diagram for cooling the SIS100 magnets is given in Fig. 1.

A closed nitrogen cycle is offered for cooling the heat shield. The stream of liquid nitrogen flows from the tank of the condenser located at a surface level down into the tunnel and is split into 2 parts, each of which cools the shield of one segment of the accelerator. Nitrogen vapor from the two segments flows back into the tank and is condensed by a heat exchanger driven with a stream of cold gaseous helium from the refrigerator. The nitrogen circulates in the loop due to the hydrostatic pressure generated by a column of liquid nitrogen. Compared to cooling the heat shield with gaseous helium, the above method will exclude leaks of helium from the shield into the vacuum of the cryostat and will reduce required electric power needed for cooling the shield by approximately 40%. Should all nitrogen in this closed loop leak into the tunnel of the accelerator, the percentage of oxygen in the atmosphere of the tunnel will decrease only by 0.2 %.

After the last expansion turbine the helium flows into the heat exchanger (subcooler) of a separator and passes a separator with the mass flow rate of about 100 g/s. The stream of helium is then divided into two parts and flows into the direct helium header of each segment with a pressure of about 1.4 bar and at temperature of 4.4 K. The cooling channels of 20 dipoles and 30 modules with quadrupoles are connected in parallel to the direct and return helium header of a segment. At the end of a direct header one bypass valve allows the helium to flow into the return header of the segment and another bypass valve in the return header of the next segment. The latter allows supporting the neighbor refrigerator. The header will consist of two parts: the basic header (in the arc cryostats) and a small header (in the cryostat for the straight sections). For one of the two segments small and basic collector lines are connected in parallel, and for the other one in series. In the arc the consumers are connected in parallel whereas in the straight sections they are connected in series. Liquid helium enters the cooling channel from the direct header and successively passes an either coil of a dipole or of a quadrupole, then the subcooler of the direct header. Afterwards it cools the yoke; from there the helium flows back to the separator through the return header. Helium vapor from the separator comes back into the refrigerator with a pressure of about 1.1 bars and at temperature of 4.32 K. During the cooling process described above, the mass vapor content in the two-phase helium flow varies from 0 at the inlet up to approximately 0.9 at the outlet of the cooling channel.

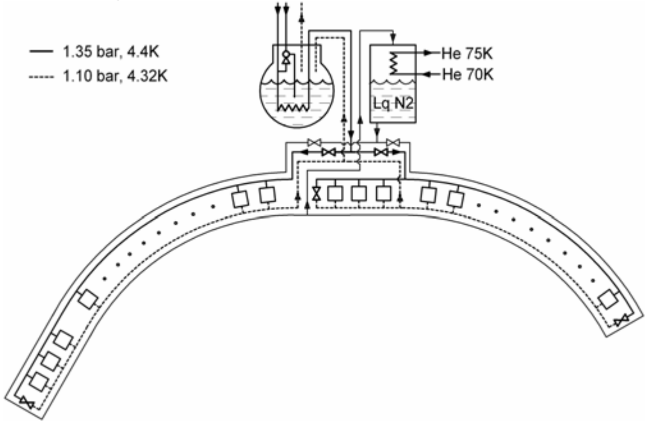

Fig. 1. The simplified scheme of cooling 1/3 part of the SIS100 ring.

III. THE CONCEPT OF SIS300 AND MAGNET COOLING

The existing concept [10] of the SIS300 magnetic system is based on a 6 T, Cos θ-style, fast-ramped magnets of about 2.7 m lengths. A two-layer coil of the magnet, made of Rutherford type cable, is cooled by supercritical helium. We consider possibility to construct the SIS300 magnetic system on the basis of a 4.5 T, Cos θ-style, curved magnet with a single-layer coil made of a high current hollow cable cooled with two-phase helium flow. The idea of such magnets and the progress in their design are presented in [11,12,13]. The main advantages of such approach are, in particular, much higher cooling efficiency, much lower gap field and inductance of the coil. The magnet length should be increased, of course, to about 6.6 m, nevertheless, the ratio between the integral magnetic length and physical length of the dipole will be much better. Moreover, the stored energy in the SIS300 magnets will be much less. The SIS300 quadrupoles magnetic field gradient is approximately 40 T/m and can be fabricated similar to the SIS100 quadrupoles (superferric).

The proposed magnetic system will be lower in cost, manufacturing and operation, and is reliably cooled during fast-ramped operation. The new cooling concept for the SIS300 magnets is completely similar to the cooling concept for the SIS100 magnets. The SIS300 ring also consists on 6 segments. Each of three refrigerators (see Fig.2) cools two segments with two-phase helium flow. 44 parallel channels of helium will then be in one segment (two for each of the12 dipole magnets and on one for each of the 18 module with a lens, the others are intended for by-pass lines). The pressure difference between the helium headers will be in the range from 0.2 bars to 0.25 bars. The expected dynamic heat releases in the SIS300 dipole will be 12.66 W and 0.98 W in the quadruple, calculated for the “standard” operation cycle with B_{min} = 1.42 T, B_{max} = 4.5 T, f= 0.045 Hz and dB/dτ = 0.65 T/s, taking eddy-current losses in the beam pipe into account. Using the duration of each super cycle, the average refrigerator load, generated by SIS 300, will not exceed 1700 W, including static heat leakage, beam monitors and correctors.

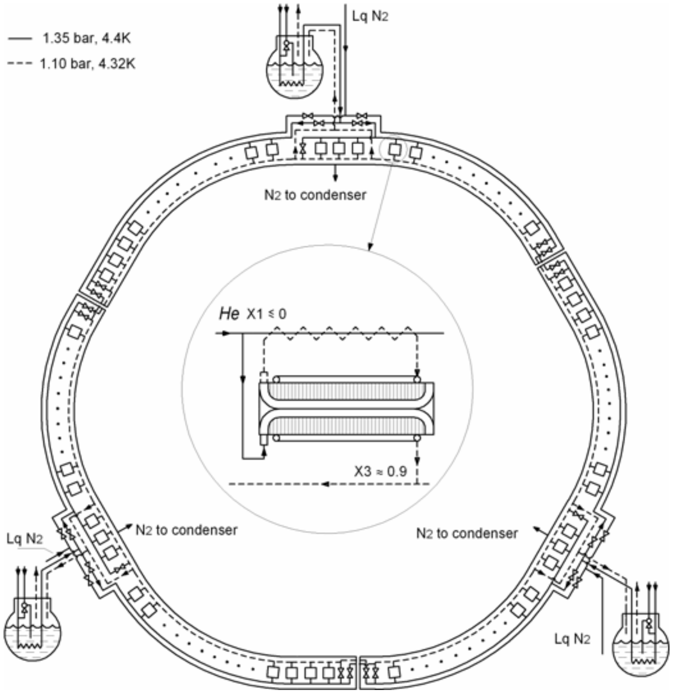

Fig. 2. The SIS300 ring cooling simplified flow diagram

IV. MAIN CHARACTERISTICS OF THE FAIR CRYOGENICS

The following basic principles are suggested for the design of the FAIR cryogenic supply system:

a) A centralized provision of compressed helium with purification and gaseous helium storage systems;

b) Three refrigerators are located above the accelerators tunnel in regular intervals on the circumference;

c) Each refrigerators has to cool two segments of the SIS100 and SIS300 accelerator, and one of them (large refrigerator) provides also cooling power for all other users (beam lines and storage rings);

d) To increase the reliability of cooling and smoothing the peak loads, each refrigerator can support the two others, and the large refrigerator is additional equipped with a vessel for storing liquid helium;

e) The quantity and length of special helium transfer lines should be minimized. The helium supply for the beam lines and storage rings from the large refrigerator can be realized via the helium headers of the100 Tm beam lines;

f) Minimization of the number of current leads and thus minimization of liquid helium consumption.

The estimated average refrigerator load generated by the separate users is listed in the Table IV. The average total equivalent refrigerator load needed to cool the FAIR facilities will be 14840 W at 4.4 K. Considering a capacity reserve of 20 % the required equivalent capacity of the three refrigerators should be 17.8 kW at 4.4 K. Thus two refrigerators with a capacity of 4 kW and a big refrigerator with a capacity of 9.8 kW are necessary for the FAIR cryogenic system.

TABLE IV
REFRIGERATOR LOAD FOR THE FAIR CRYOGENIC SYSTEM

User name	Load at 4.4 K (W)	Load at 70 K kW	Consumption of liquid *He* (g/s)
SIS100	5600	13.1	5.1
SIS300	1700	4.2	8.6
Storage rings	1020	5.5	4.4
Beam lines	730	6.0	15.9
Total	9050	28.8	34.0

The required investment costs, based on information from European suppliers of cryogenic equipment and as estimated for the FAIR cryogenic concept [1] are presented in Table V. The results of the calculation of the FAIR cryogenic system power consumption are given in Table VI.

TABLE V
INVESTMENT COST FOR THE FAIR CRYOGENICS

Nomenclature	Cost (MEuro)
Refrigerators	20.7
Controls	2.07
Warm Lines	0.21
Storage	3.31
Purification	2.07
Helium Inventory	0.41
Miscellaneous	1.03
Distribution Boxes	0.8
Helium Transfer Lines	0.76
Refrigerator's buildings	1.14
SUM	**32.5**

TABLE VI
POWER CONSUMPTION OF THE FAIR CRYOGENIC SYSTEM

Duty	Specific power consumption			Capacity	Power consumption (kW)
	theoretical minimum	efficiency	design		
Refrigerator 4 kW					
4.4 K refrigeration	67.2 (W/W)	27 %	249 (W/W)	2*2920 (W)	1454
70 K refrigeration	3.29 (W/W)	24 %	13.7 (W/W)	2*6920 (W)	190
liquefaction	6780 (J/g)	22 %	30820 (J/g)	2*5.48 (g/s)	338
Refrigerator 9.8 kW					
4.4 K refrigeration	67.2 (W/W)	30 %	224 (W/W)	5020 (W)	1124
70 K refrigeration	3.29 (W/W	25 %	13.2 (W/W)	20721 (W)	274
liquefaction	6780 (J/g)	25 %	27120 (J/g)	30.94 (g/s)	839
SUM					**4219**

V. CONCLUSION

A new approach for the superconducting magnet concept of the SIS100/SIS300 complex of the FAIR project is considered. It was shown that also the SIS300 could be effectively cooled with two-phase helium flow and that a substantial improvement of the general cryogenic concept is possible.

Special attention was directed to define the main principles for the design of the complete magnet cooling system including storage rings and beam transfer lines for efficient operation conditions. The main parameters of the magnet structures and their cooling schemes are given. The heat loads of the substructures and the resulting power consumption of the refrigerators were calculated based on the actual status of the GSI magnet R&D and the planned super cycles. Referring to preliminary cost estimations and the reduced peak field of the chosen SIS300 magnets we expect a significant reduction for the construction as well as for the operational costs of the overall system. The outlined ideas need further investigation with respect to accelerator construction not covered by this paper.

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