RAPIDLY-CYCLING SUPERCONDUCTING ACCELERATOR MAGNETS FOR FAIR AT GSI[#]

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Abstract

The demand for high beam intensities leads to the requirement of rapidly-cycling magnets for synchrotrons. An example is FAIR (Facility for Antiproton and Ion Research) at GSI, which will consist of two superconducting synchrotrons (SIS100 and SIS300) in one tunnel and several storage rings. The high field ramp rate (up to 4 T/s) and the repetition frequency of up to 1 Hz require R&D for the superconducting magnets of these rings. Persistent currents in the superconductor and eddy currents in wire, cable, iron and vacuum chamber reduce the field quality and generate AC losses at cryogenic temperatures. A magnet lifetime of 20 years is desired, resulting in up to $2 \cdot 10^8$ magnet cycles. Therefore, special attention has to be paid to magnet material fatigue problems. R&D work is being done, in collaboration with many institutions. Model dipoles were built and tested. The results of the R&D are reported. Full length dipoles for SIS100 are under construction.

INTRODUCTION

Within an international collaboration it is planned on the GSI site to construct a new accelerator complex FAIR [1], which will provide high intensity primary and secondary beams of ions and antiprotons for experiments in nuclear, atomic and plasma physics. It will consist of 2 synchrotrons in one tunnel, SIS100 (100 Tm rigidity) and SIS300 (300 Tm rigidity) [2], and several storage rings. Figure 1 gives an overview of the facility.

The SIS100 is the heart of the facility. It will accelerate ions and protons at a high repetition rate and either send them to the targets for Radioactive Ion Beam (RIB) or Antiproton Beam production or to the SIS300 for further acceleration to higher energies. The Collector Ring (CR)/ Recycled Experimental Storage Ring (RESR) complex will cool the secondary beams and accumulate the antiprotons. High Energy Storage Ring (HESR) and New Experimental Storage Ring (NESR) are the experimental storage rings for antiprotons and ions, respectively.

In order to reach the required high intensities, the magnets of the synchrotrons have to be rapidly pulsed at a high repetition frequency (AC-operation). The required dipole ramp rate is 4 T/s for SIS100 at about 1 Hz and 1 T/s for SIS300, with a duty cycle of 50%. Parameters of the synchrotrons main magnets are listed in Table 1.

This paper deals only with rapidly-cycling superconducting accelerator magnets needed for FAIR. R&D policy was to restrict the activities at GSI to design and coordination work and to the operation of a test facility for model and prototype magnets. Collaborations were established concentrating at the beginning on dipole R&D and transferring the results to quadrupoles and correctors, afterwards. At the earliest possibility, industry should be involved in the R&D and prototype production.

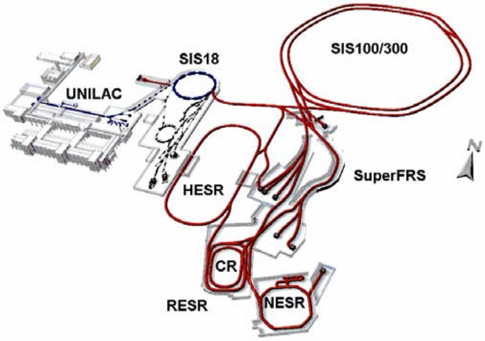

Figure 1: Schematic topology of FAIR.

MAIN R&D TOPICS

In dealing with rapidly-cycling accelerator magnets for the production of high intensity beams, special attention has to be paid to the following items:

Eddy Currents and Persistent Current Effects

Due to the high ramp rate, eddy currents are induced in the conductor (wire, cable), in the iron, in the structural elements and in the beam pipe of the magnet. They create large steady-state AC-losses during continuous operation and impact field quality. Therefore, these currents have to be minimized by appropriate design. Nevertheless, the magnet conductor cooling system has to be designed to carry away these heat loads. Field simulation code was extended to calculate the influence of eddy currents in cable and iron on field quality and AC-losses [3].

Mechanical Structure / Lifetime of the Magnets

The coil and the conductor of a typical SIS100 magnet must survive cool-down and warm-up procedures and about 200 million cycles during their projected lifetime of 20 years. The mechanical structure of the coil must also satisfy these requirements. Material fatigue and crack propagation have to be investigated.

OTHER R&D TOPICS

Iron Selection

The optimum choice of low-carbon steel is important for rapidly-cycling superconducting magnets. The best compromise between high permeability, high saturation flux density and low coercive force has to be found. Permeability and losses for bipolar and unipolar cycles of several steels have been measured at room and cryogenic temperatures [4].

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Table 1: Parameters of the synchrotrons main magnets

	Number of magnets	Usable aperture (mm)	Magnet length (m)	Max. field / Max. gradient	Max. ramp rate
SIS100:					
Dipoles (curved, R= 52.6 m)	108	115 × 60	3.062	1.9 T	4 T/s
Quadrupoles	168	135 × 65	1.3	27.0 T/m	57 T/m/s
SIS300:					
Dipoles (curved, R= 66.7 m)	48 /12	86 (circular)	7.757 / 3.879	4.5 T	1 T/s
Quadrupoles	84	105 (circular)	1.0	45 T/m	10 T/m/s

Quench Protection of the Individual Magnets

The SIS100 dipole string consists of 108 dipoles connected in series with a total stored energy of 4.8 MJ. This magnet string can be protected using 6 dump resistors [5]. By dumping the current (6.5 kA) with a time constant of 175 ms, the hotspot temperature is kept below 300 K. The SIS300 dipole string has 60 dipoles in series with a total stored energy of 49 MJ. Each magnet is equipped with quench heaters and a stack of several, high turn-on-voltage cold diodes. A stack of diffusion type diodes was tested, diodes were irradiated. The current in the string is dumped with resistors with a time constant of 4 s.

Cryogenic System

The 4.2K refrigeration capacity for FAIR is 36 kW. Two refrigeration plants with a common compressor station will provide this capacity, one (Cryo2) is dedicated to the synchrotrons. Its load distribution is given in figure 2. The total heat generated in the synchrotrons is dominated by AC-losses depending on the operational cycle and varying between 100% and 25%, within minutes. The pressure drop must be maintained above a minimal value to avoid instabilities. The unused liquid fraction during low loss operation will be "recycled" by a maintenance-free ejector.

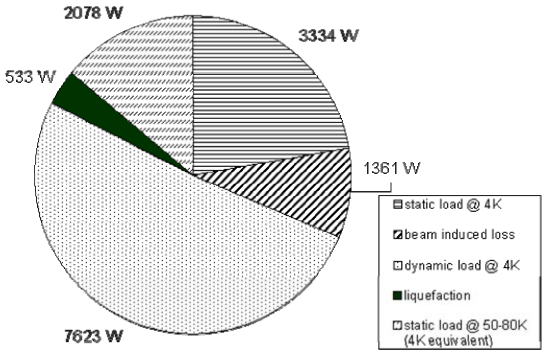

Figure 2: Heat load of the refrigeration plant dedicated to the synchrotrons.

ACCELERATOR MAGNETS

In this chapter the R&D results for the dipoles of the different rings will be described. We chose an existing design with parameters close to our requirements, as a starting point.

SIS100 Dipole

The Nuclotron ring was commissioned at JINR, Dubna in 1993 [6]. It is equipped with iron-dominated magnets with superconducting coils (so-called superferric magnets) [7] and has already reached our main design goal of 4 T/s dipole ramp rate with a repetition rate of 1 Hz [8]. The SIS100 dipole and conductor were designed following the Nuclotron examples. Its cross-section is shown in figure 3. The magnet is of the window-frame type (lamination thickness 0.5 mm). The cold mass comprises coil, iron and beam pipe. The cable has 31 strands wrapped around a Cu-Ni tube and is indirectly cooled by two-phase helium flowing through the tube. This cable (low hydraulic resistance, low friction factor) is especially designed to remove large steady-state AC losses caused by the fast ramp [9]. Field margin of the dipole and temperature margin are 30% along the loadline and 1.6 K respectively.

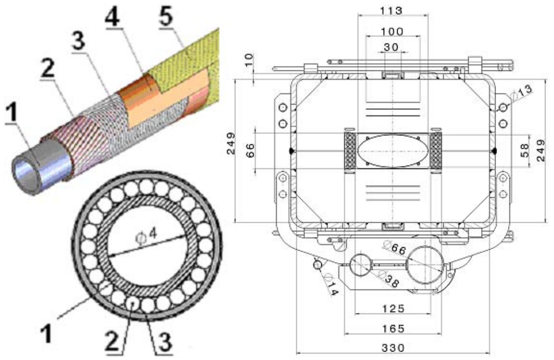

Figure 3: SIS100 dipole with Nuclotron type cable (1-cooling tube, 2 - Superconducting wire, 3 - Nichrome wire, 4 - Kapton tape, 5 – adhesive Kapton tape).

The main R&D goals for the SIS100 prototypes are the reduction of the AC loss heat load at the 4 K level in iron, coil and beam pipe (needs to be cooled for cryogenic pumping!) and the confirmation of the adequacy of the mechanical structure.

Losses

AC losses in yoke and coil were reduced by a factor of 2 during the R&D phase. This was possible by replacing iron end plates by stainless steel end plates, by changing structural elements, and by avoiding eddy currents in the surface of the lamination sheets due to longitudinal field components, by reducing the large raised coil end and by

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slitting the iron end blocks. The losses calculated by ANSYS for the short model magnets are in good agreement with the measured data [10].

Mechanical Structure

A new comb-like G11 structure for the coil was developed. Goal was to position the conductor accurately and to distribute the forces. The coil itself is only slightly pushed against the return yoke. Mockups were built and their mechanical properties measured [11]. The biggest concern is the lifetime of the Cu-Ni-tube. A series of electromagnetic and structural FEM analyses with detailed representation of each conductor were made to identify the parameters required to perform the high-cycle fatigue and fracture mechanics evaluations. The conclusion from the evaluations is that all cooling tubes can withstand the required $2 \cdot 10^8$ operating cycles [12].

Alternatives

A warm-iron, warm-bore superferric magnet (with complicated support of the cold coil against the warm iron) and a resistive magnet were also investigated. Figure 4 compares the resistive and the SIS100 magnets, demonstrating the compact design and material savings of the superferric magnet. It was not surprising that the total investment costs (including power supply, cryogenics, etc.) were comparable, but the lower operating cost greatly favour the superconducting solution [13]. In addition, cryogenic pumping is mandatory to achieve the required vacuum of 10^{-12} mbar.

Figure 4: Comparison of resistive and superferric magnets.

Dipole GSI001 (4T)

When the project preparation phase started the rigidity of the second synchrotron was chosen to be 200 Tm, which required a maximum dipole field of 4 T. On the basis of RHIC Arc Dipole design [14] a model GSI001 was built at BNL [15] (Figure 5). A comprehensive overview of this R&D is given in [16].

We made several modifications to the existing RHIC design to reduce AC losses and improve cooling and mechanical stability: The phenolic spacer around the coil was replaced by a stainless steel collar and holes were laser-cut in the cable insulation at the inner edge of the cable for better cooling. Flux loops creating eddy currents were carefully avoided by using G11 keys, by insulating rods etc. Iron was EBG Stabocor 250-50A with 3.3% silicon, coercivity of 33 A/m. The iron lamination thickness was 0.5 mm. For GSI001, the wire was coated with Stabrite (Sn-4%Ag solder) and the twist pitch reduced from 13 mm to 4 mm with a small current degradation of 4%. Two stainless steel foils 25 µm thick were used as a core between the layers of the cable to reduce the main loss contribution. Rc and Ra were measured to be 60 mOhm and 64 µOhm, respectively [17]. Dynamic wire magnetization was measured as well, delivering the matrix transverse resistivity (incl. magnetoresistance).

Measurements (Losses and Harmonics)

The model magnet GSI001 was tested at BNL in a vertical dewar in pool boiling helium [18] and meanwhile also at the GSI test facility under one-phase supercritical helium conditions. The magnet reached short sample after four quenches, after a thermal cycle it needed one quench. The magnet was operated at GSI for 36 hours under the nominal conditions of (4 T, 1 T/s) without any problems. Losses were measured at BNL with the V-I-method. The losses were also calculated based on the parameters measured on wire, cable and iron [19]. The hysteresis part is in good agreement with the measured data.

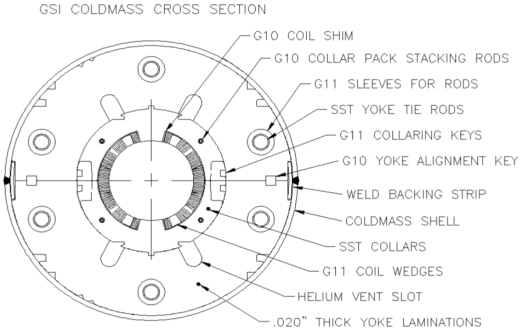

Figure 5 Schematic cross section of GSI001.

The calculated rate dependent losses however are lower than the measured data (Figure 6) despite the corrections for eddy currents in shell and cryostat at higher fields. At GSI losses have been measured calorimetrically and electrically. The calorimetric method gives lower AC loss values than the electrical V-I-method, but the thorough evaluation of the measurement is still under way.

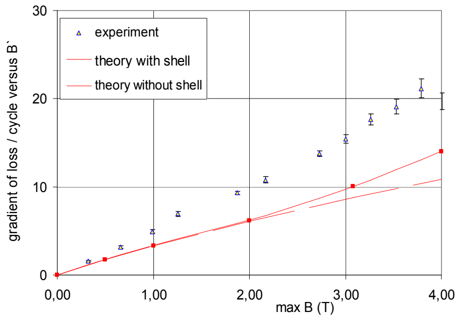

Figure 6: Eddy current losses as a function of maximum field.

Quench current as a function of ramp rate (Figure 7) shows only a small degradation of the quench current in the region of interest (1 T/s), due to moderate AC–heating. This is because of good heat removal, even for supercritical helium cooling. Obviously, current redistribution is possible due to the low adjacent resistance of the cored Rutherford cable.

The harmonic content of the magnet was measured with a stationary coil under DC and 2 T/s conditions. Figure 8 shows the measured sextupole component and the corresponding calculated value by ROXIE and OPERA. 'Mole' measurements are planned at GSI.

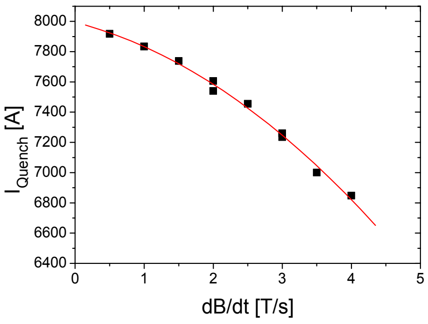

Figure 7: Ramp rate dependent quench current (4.2K).

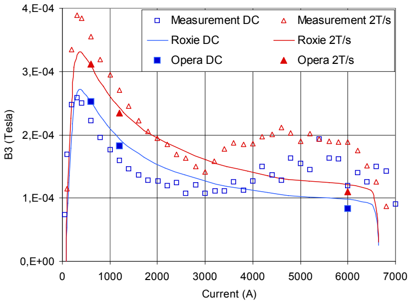

Figure 8: Transient behaviour of the normal sextupole harmonic of GSI001.

SIS300 Dipole (Straight, 6T)

During the R&D phase, it was decided to increase the beam rigidity of the second synchrotron to 300 Tm, i.e. the dipole aperture field to 6 T, and in addition the inner coil diameter to 100 mm. IHEP, Protvino, prepared a Conceptual Design Report on the basis of the UNK dipole [20]. The two-layer coil (based on LHC dipole outer layer cable with stainless steel core) is cooled with supercritical helium, recooled by two-phase helium within the magnet. A collar/iron combination where the iron takes part of the load, was chosen. Besides, the design principles and test results of GSI001 entered the design. Special end design spacers have been developed [21].The tooling design is finished, the model will be ready for testing mid of 2008.

SIS300 Dipole (Curved, 4.5T)

To enlarge acceptance at a minimum field volume, a curved design with a radius of 66.7 m was proposed. The parameters are given in table 2. A first bending test with UNK dipole model demonstrated that such a radius is possible without degradation in critical current and field quality. Technical feasibility studies and cost estimates [22,23] gave 'green light' for further design work by the Italian National Institute of Nuclear Physics (INFN) in the frame of a project called DISCO_RAP (Dipoli SuperCOnduttori RApidamente Pulsati), started in 2006. The geometry of the Rutherford cable for this magnet is the same as that used for the 6 T straight model. Coil winding models with a curved mandrel will be built. A half-length magnet will be ready for testing in 2009.

Table 2: Main characteristics of the 4.5 T curved dipole

central field	4.5 T
effective length	7.757 m
Coil inner Diameter	100 mm
Bending radius	66 2/3 m
Peak field/Central field	1.09
Current	8924 A
Collar thickness	30 mm
AC losses in the windings for a closed cycle 1.5T-4.5 T at 1T/s	20.7 J/m

The coil is mechanically supported only by the collars (in austenitic steel) and the yoke has only a magnetic role. 2D magnetic analyses (Figure 9) show that in operating conditions (at 4.5 K during the energization) the stress in the winding is quite constant around 50 MPa. The stress in the collars is intended to be low to avoid fatigue and crack propagation.

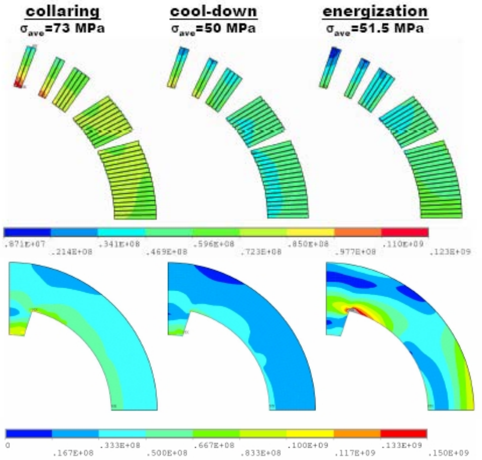

Figure 9: Stress in coil windings and collar after collaring, cooldown and full energization.

SPECIAL R&D

Wire R&D

A pulsed superconducting magnet requires a wire designed to minimize the inherent losses which appear in a high current superconductor operated in an AC regime, namely the hysteretic losses and the filament coupling losses. While the former can be reduced by exploiting smaller NbTi filaments down to 3.5 µm, to be compared, e.g. with the 6 – 7 µm filaments exploited by the LHC lattice magnets, the latter is mainly determined by the resistivity of the interfilamentary matrix at low temperature and the twist pitch. The goal was to produce a RHIC size wire (0.648 mm) with the filament size reduced down to 3.5 µm (which is the lowest possible

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value for a copper matrix without the 'proximity-coupling'-effect). A classical double stack approach (122 x 100 filaments) delivered an effective filament diameter of 4.8 µm due to additional filament magnetization caused by filament distortion. A single stack test was not possible due to stacking problems of the 12240, 1.46 mm wide, mono-cores. Therefore a modified double stack method was used [24].

For larger size wire (0.825 mm) with consequently higher twist pitch the interfilamentary matrix resistivity should be enhanced by two orders of magnitude by means of Cu-0.5 wt% Mn. This alloy has the further advantage of suppressing the proximity effect, which increases the hysteretic losses, having at the same time a better workability and a higher thermal conductivity than other high-resistance Cu alloys, like CuNi. Although some trials were done in the past to manufacture a wire for SSC with the above mentioned characteristics [25], an important R&D effort together with industry is now in progress to manufacture on an industrial scale a wire which fulfils the specific needs of FAIR accelerators [26]. This R&D is also the subject of an INTAS project [27].

Cable R&D

R_a and R_c for the different cables were measured with the "ten stack-method" after the special RHIC curing cycle. A detailed description of the R&D is given in [28]. Measured cable losses agreed well with the losses calculated with the R_a / R_c data mentioned above [29]

Quench energy measurements for samples with different values of R_a were carried out at CERN [30]. Results are shown in figure 10 for heating with quench heaters located at the center of the cable.

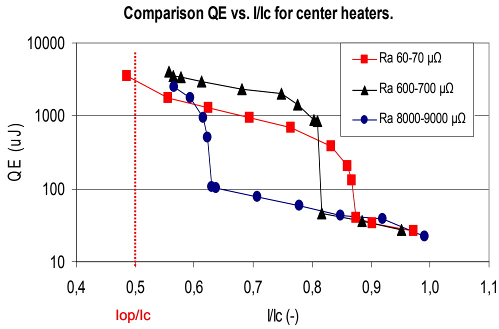

Figure 10: Quench energy data for different values of R_a at 4.3 K and an external field of 6 T (center heaters).

The background field was 6 T corresponding to the maximum field of the IHEP model dipole. From the point of view of stability it is important to stay on the left hand side of the knee. The operation current of the 6 T SIS300 model dipole will be about half the critical current. Therefore a specified value of R_a of 300 µΩ should be no drawback for a stable operation of the magnet.

SUMMARY

Rapidly-cycling magnets are foreseen for the synchrotrons of FAIR. R&D to develop these magnets is going well on the basis of first dipole models. Three full length SIS100 dipoles are under construction. R&D will continue on quadrupoles and correctors.

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REFERENCES

[1] D. Kraemer, this conference
[2] P. Spiller, this conference
[3] B. Auchmann, et al., Proceedings of ICAP, Chamonix, France, 272-276, December 2006.
[4] I. Bogdanov et al., EPAC 04, Zürich,(2004), p. 1741
[5] E. Floch, GSI internal note 9, 2006.
[6] A.D. Kovalenko. EPAC 94, 1994, V. 1, pp.161-164
[7] H.G. Khodzhibagiyan and A.A. Smirnov, Proc. ICIC12, Southampton 1988, 841
[8] A.D. Kovalenko et al, EPAC 04, Zürich, (2004), p. 1735
[9] H.G. Khodzhibagiyan, A.D. Kovalenko, and E. Fischer, IEEE Trans. Appl. Supercond., vol. 14, N2, 2004, pp.1031-1034.
[10] E. Fischer, P. Shcherbakov, R. Kurnyshov, CHATS-06, LBNL, Berkeley, September 5-7, 2006.
[11] G. Moritz et. al, ASC 2006, Seattle
[12] E. Bobrov, GSI Internal Report, October 2006
[13] E. Fischer, „SIS100_costs“, GSI, EMAC II, 2003, Darmstadt
[14] M. Anerella et al., NIM A, 499 (2003) 280.
[15] M.N. Wilson et al., IEEE Trans. Appl. Supercond.12, (2002) 313
[16] A. Ghosh, WAMS Workshop, Archamps, 2004
[17] R. Soika et al., IEEE Trans. Appl. Supercond. 13 (2003) 2380
[18] P. Wanderer et al., Proc. Particle Accelerator Conference, Portland USA, 2003
[19] M.N. Wilson et al., IEEE Trans. Appl. Superconductivity, 14 (2004) 306
[20] A.I. Ageev et al., IEEE Trans. Mag., 28 (1992) 682
[21] Bernhard Auchmann, Stephan Russenschuck, and Nikolai Schwerg, ASC 2006, Seattle, USA
[22] Babcock Noell GmbH, GSI report 2006
[23] Ansaldo Superconduttori S.P.A., report 2006
[24] M. Thoener, European Advanced Superconductor (EAS), private communication
[25] H.C. Kanithi et al., Supercollider 3 (1991) 689
[26] G. Volpini, private communication
[27] GSI INTAS call Ref. Nr. 06-1000012-8865
[28] M.N. Wilson et al., IEEE Trans. Appl Superconductivity, Vol 13, (2003) 704
[29] M.N. Wilson, GSI Report No. 8, 2002
[30] A. Verweij and G. Willering, private communication