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TOWARDS FAST-PULSED SUPERCONDUCTING SYNCHROTRON MAGNETS*

G. Moritz, C. Muehle, GSI, Darmstadt, Germany
M. Anerella, A. Ghosh, W. Sampson, P. Wanderer, E. Willen, BNL, Upton, USA
N. Agapov, H. Khodzhibagiyan, A. Kovalenko, LHE/JINR, Dubna, Russia
W.V. Hassenzahl, AEA, Piedmont, USA
M.N. Wilson, Abingdon, UK

Abstract

The concept for the new GSI accelerator facilities is based on a large synchrotron designed for operation at BR= 200 Tm and with the short cycle-time of about one second to achieve high average beam intensities. Superconducting magnets may reduce considerably investment and operating costs in comparison with conventional magnets. A R&D program was initiated to develop these magnets for a maximum field of 2-4 Tesla and a ramp rate of 4 T/s. In collaboration with JINR (Dubna), the window-frame type Nuclotron dipole, which has been operated with 4 T/s at a maximum field of 2 Tesla, shall be developed to reduce heat losses and to improve the magnetic field quality. Another collaboration with BNL (Brookhaven) was established to develop the one-layer-coil cosθ-type RHIC arc dipole designed for operation at 3.5 Tesla with a rather slow ramp-rate of 0.07 T/s towards the design ramp-rate of 4 T/s. The design concepts for both R&D programs are reported.

1 INTRODUCTION

GSI Darmstadt plans new accelerator facilities [1]. The heart of the proposed accelerator expansion is a dual-ring synchrotron in one tunnel with maximum rigidities of 100 and 200 Tm. This corresponds to maximum dipole fields of 2 and 4 Tesla.

To reach the high average intensities of 10^{12} U^{28+} and $2.5\cdot10^{13}$ protons per second, a short cycling time and thus a high ramp rate of the magnetic field is required—up to 4 T/s for the dipoles. Today, only large storage rings are equipped with superconducting magnets. They operate at a relatively low ramp rate, 0.07 T/s (RHIC) or less. Generally, early attempts to build superconducting magnets for fast-ramped synchrotrons have not been pursued [2]. The exception is the Nuclotron ring at JINR, Dubna. Its superferric dipoles reach ramp rates of 4 T/s [3].

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2 COST COMPARISON

It is not obvious that superconducting magnets are the preferred choice for a fast-pulsed synchrotron. On the investment side they require more technology development and additional costs for the cryogenics. The operating costs are dominated by the losses due to the induced eddy and persistent currents. Thus, before starting the project we had to make a comparison of investment and operating costs comparing a conventional dipole with a superconducting superferric dipole, both designed for an integral field of 5.2 Tm and a ramp rate of up to 4 T/s. Table 1 shows the results for the required 120 dipoles of a 100 Tm rigidity ring.

Table 1: Cost comparison sc vs. resistive dipoles in Million Deutsche Mark.

	Superferric dipoles (2 T/2.6 m)	Resistive dipoles (1.8 T/ 2.9 m)
Power supply	3.7 MDM	14.1 MDM
Dipoles	14.8 MDM	24.0 MDM
Refrigerator (partial)	6.0 MDM	0.0 MDM
Helium distribution	1.8 MDM	0.0 MDM
Total	**26.3 MDM**	**38.1 MDM**

The normal conducting magnet was designed as a hybrid magnet, similar to the main dipole of the existing synchrotron SIS18 at GSI. The basis of the cost estimate for the superconducting magnet was the superferric Nuclotron dipole. The costs assume R&D can reduce the AC-losses in cable and iron by about 2/3. Unfortunately no investment costs are available for this magnet type. Thus, we took the well documented costs for the RHIC Arc dipole magnets [4], scaled them with the integral length and added costs for the shorter length, additional collaring and improved conductor. Finally we assumed that the Nuclo-

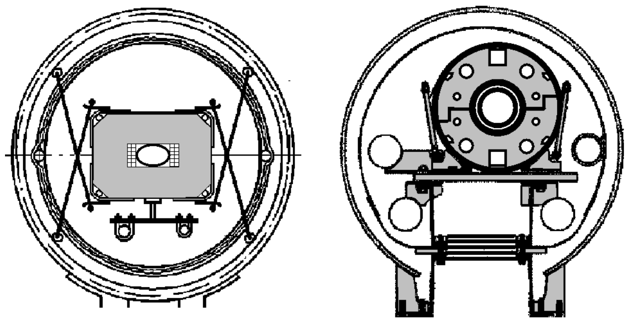
tron magnets are 20% cheaper in production than the RHIC magnets (a rather conservative estimate) and converted the $ into Deutsche Mark by a factor of 1.8. The power supply for the sc magnets is cheaper due the lower stored energy, while we had to add costs, refrigerator and Helium distribution. Costs for quench detection are not included. Vacuum costs may be saved by cryogenic pumping, whereas resistive magnets require a baking system. In any case the superconducting solution has a lower investment cost.
We investigated the operating costs for 2 triangular cycles, up to 1 and to 2 Tesla, each with a ramp rate of 4 T/s (Table 2). The results assume 6000 operating hours per year and a refrigerator factor (electric power / cryogenic power at 4.2 K) of 300. While the costs of the superconducting magnets do not depend very much on the operating field, the costs of the resistive magnets increase with the square of the operating field. The higher the operating field, the more favorable is the situation for the superconducting solution. In case of slow extraction for fixed target experiments the superconducting solution is clearly preferred.

Table 2: Annual Operating costs (MDM)

	Sc. Dipoles	Resistive Dipoles
1 T, 4 T/s	1.9	1.0
2 T, 4 T/s	1.8	4.0

3 TWO MAGNET FAMILIES

As mentioned above, GSI plans a two-ring facility. It has the advantage that the upper high-energy-ring can be used as stretcher ring, while the lower ring represents the work horse for the production of Radioactive Ion Beams and Antiprotons. We decided to equip the rings with different magnet types: The lower one with superferric magnets of the Nuclotron type [5] and the upper one with magnets of the RHIC type [6]. Fig. 1 shows the original dipoles and table 3 their main parameters.



Nuclotron-dipole RHIC-dipole

Figure 1: Cross sections of Nuclotron and RHIC Arc dipole.

This solution has the obvious disadvantage of having two magnet families during R&D and production. But the superferric magnets have many advantages for the low-field, fast-cycling application:
They have lower losses due to the lower maximum field and the structure of the cable. The forced-flow, indirect cooling leads to a simpler cryogenic system and better cooling. The iron-dominated design uses less superconductor leading to smaller magnetization currents. Because of the reduced sensitivity of field quality to conductor position, collars are not needed and the influence of persistent currents is reduced. The design is very cost effective due to its low stored energy and the fact that no special helium containment and bus is needed. The magnets have already reached the design goal; thus the R&D time required is shorter.
Besides, at present we are not sure that we can build a cosθ-magnet (which is well suited for a 4 T application) with a ramp rate of 4 T/s.

Table 3: Dipole Parameters

	Nuclotron dipole	RHIC Arc dipole
Magnet length	1.4 m	9.7 m
Aperture	110 mm x 55 mm	80 mm
Field	1.98 T	3.5 T
Inductance	1.1 mH	28 mH
Number of strands	31	30
Cable type	Hollow tube	Rutherford
Filament diameter	10 μm	6 μm
Copper to superconductor ratio	1.39/1.	2.25/1.
Cable twist pitch	47 mm	74 mm
Strand twist pitch	5 mm	13.5 mm
Cooling method	Two-phase helium	Supercritical helium

4 R&D PROGRAM

4.1 Nuclotron Dipole (Collaboration GSI-JINR)

There are three major R&D goals:

- Improvement of DC field quality (2D/3D)
  We improved the 2D field quality by modifying the iron cross section with iron slots and 'negative shimming'. Three dimensional calculations optimized the field quality by varying the ratio of iron to coil length [7].
- Reduction of losses at 4.2 K
  Following the existing Nuclotron design, we will use insulated laminated iron with 3% Si and a low coercivity of 10 A/m and stainless steel endplates. The Nb-Ti filament diameter will be reduced to 6 μm. We try to reduce the cold mass at 4.2 K by insulating the coil and vacuum chamber from the iron. The coil will form together with the vacuum chamber a compact rigid block, which must be aligned within the iron yoke to minimize the field errors.
  First results are promising and indicate that we can reach our design goal for the AC-losses of 35 W per 2.6 m long magnet, i.e. 13 W/m (4.2 K, 2T, 4 T/s, 1Hz)

- Improvement of mechanical stability
  Better conductor fixation and positioning is under study. We will use 'softer' B-stage epoxy to reduce the number of training quenches.

4.2 RHIC Dipole (Collaboration GSI-BNL)

The challenge here is to ramp this magnet in the range between 1 and 4 T/s. We decided to build five 1 m long model magnets with the same RHIC coil cross sections, but different cables and wires. This approach will use existing tooling, which saves time and money. Before we started building model magnets one of us (MNW) calculated the expected losses and field quality for different cables, varying mainly the adjacent and crossover inter-strand resistance, the twist pitch of the wire and the filament diameter[8]. The most important results were:

- We need a modified Rutherford cable with lower losses than ever achieved in the past. This will require an inner core and heat-treated wire with the shortest twist pitch possible, ≤ 4.0 mm in a 0.65 mm strand.
- Cu wedges have to be replaced by G10-wedges.
- The conductor cooling scheme has to be improved. We have discussed several schemes:
  a) Cooling at the inner edge of the cable is sufficient to remove all the heat generated in the cable because the heat conduction along the copper in the strands is good enough. However, there must be sufficiently good contact to the helium, thus, the insulation has to be opened. The possibilities of porous Kapton, barber pole wrapped Kapton and slit Kapton are under investigation. A potential problem is the danger of electrical shorts.
  b) Inter-turn cooling by the insertion of spacers between the turns.
  c) Cross-flow-cooling as it has been discussed for the SSC Main Ring dipoles [9].
- Additional harmonics are produced by eddy and persistent currents in the coil due to fast operation for several cable types as calculated in [8]. Even in the worst case (cable with highest loss at 4 T/s) the harmonics do not exceed 50 units at a reference radius of 30 mm. With the best cable the harmonics are about 20 units.

The result of these calculations encouraged us to pursue the R&D on the basis of a cosθ-dipole, the magnet type most common and best known among the accelerator magnets.

We plan further modifications: low coercivity, 3% Silicon iron, 1 mm insulated laminations, stainless steel collars.

The following lines show the calculated/measured losses of the magnets at 4.2 K, at present and what we hope to reach after R&D.

Nuclotron-type: SIS-NUC: 2 T, 4T/s , T_c= 1s

Losses [W]	NUC (1.4m)	SIS-NUC(2.6m)	upgrade
Cable	10	18	10
Iron	8 (meas. 37)	15	15
Beam pipe	5	10	5
Total	**23**	**43**	**30**
Measured	**53**		

RHIC-type: SIS-RHIC: 4T, 4 T/s, T_c= 2s

Losses [W]	RHIC (9.5m)	SIS-RHIC (2.6m)	upgrade
Cable	2755	754	118
Iron	145	40	5
Beam pipe	101	28	28
Total	**3001**	**822**	**151**

5 FURTHER R&D

Measurements of the low-loss wires and cables are being made at BNL and the University of Twente. The magnet design codes 'ROXIE' and 'MAFIA' are being extended to include features needed for GSI magnets, especially the contribution from eddy and persistent currents. Staff from the University of Dresden is helping us with the design and construction of the cryogenic facilities for magnet testing and accelerator operation at GSI.

6 SUMMARY

Within the next three years

- We build up at GSI knowledge in croygenics and superconducting magnets
- We will have fast-pulsed model dipoles available as a basis for further project decisions

7 ACKNOWLEDGEMENTS

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