FAST-PULSED SUPERCONDUCTING MAGNETS

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Abstract

Up to now only one synchrotron (Nuclotron at JINR, Dubna) has been equipped with fast-pulsed superconducting magnets. The demand for high beam intensities leads to the requirement of fast-pulsed, periodically cycling magnets for synchrotrons and fast-pulsed magnets for storage rings. An example is FAIR (Facility for Antiproton and Ion Research) at GSI, which will consist of two synchrotrons in one tunnel and several storage rings. The fast field ramp rate and repetition frequency introduce many magnet design problems and constraints in the operation of the accelerator. Persistent currents in the superconductor and eddy currents in wire, cable, iron and vacuum chamber reduce the field quality and generate cryogenic losses. A magnet lifetime of 20 years is anticipated, resulting in up to 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, to reach the requirements mentioned above. Model dipoles were built and tested. The results of the R&D are reported. The advantages of the use of low field, fast pulsed superconducting, compared to resistive, magnets will be discussed.

INTRODUCTION

GSI plans to construct a new accelerator complex, the international "Facility for Antiproton and Ion Research" (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 mainly of 2 synchrotrons, SIS100 (100 Tm rigidity) and SIS300 (300 Tm rigidity), in one tunnel, 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 CR storage ring complex will cool the secondary beams and accumulate the antiprotons. HESR and 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 1T/s for SIS300, with a duty cycle of 50%. All storage rings except the NESR/RESR will be operated as DC rings. The NESR/RESR maximum dipole ramp rate will be 1 T/s, because of the short life time of the decelerated radioactive ions.

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 with institutes having experience with magnets similar to those of FAIR, concentrating at the beginning on dipole R&D and transferring the results to quadrupoles, afterwards. At the earliest possibility, industry should be involved in the R&D.

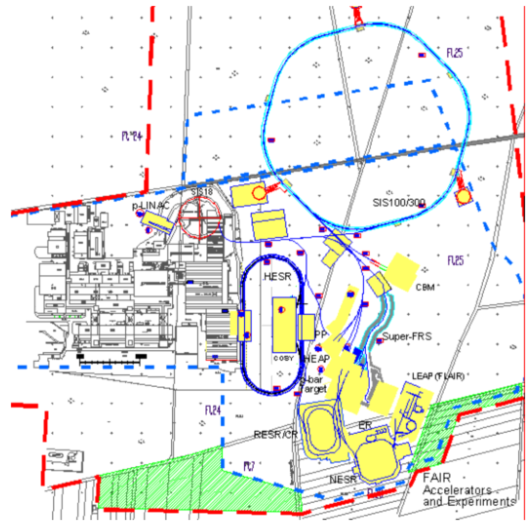

Figure 1: Topology of FAIR.

As SIS100 and SIS300 are to be installed in the same tunnel, their different rigidities lead to different requirements for the magnets, which are compiled in table 1. Consequently, different design approaches are necessary. These are described later on.

Table 1: Main superconducting magnets of the synchrotrons.

	SIS100		SIS300	
Type	Dipole	Quadru-pole	Dipole	Quadru-pole
Number of magnets	108	168	108	156
Aperture (mm)	130×60 (gap height 66)	135×65	86(circ.) (coil ID: 100)	86 (circ.) (coil ID: 100)
Magnet length (m)	2.8	1.1	2.9	0.9
Max. field / Max. gradient	2.1 T	32 T/m	6 T	90 T/m
Max. ramp rate	4T/s	61T/m/s	1T/s	15T/m/s

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R&D TOPICS

Fast cycling of magnets in the Hz-range leads to special problems, which are to be adressed by the R&D. The R&D is directed towards the most critical issues. These are:

- Eddy and persistent currents
- Mechanical structure and lifetime of the magnets.

Further R&D is compiled under other topics.

Eddy and persistent currents

Due to the changing magnetic field, eddy currents are created in the coil, yoke, structural elements, and the beam pipe. These eddy currents affect the field quality and create large steady-state AC losses. First, it is necessary to minimize these effects. Second, good heat removal is necessary, to remove the non-avoidable losses.

The SIS100 main magnet losses are dominated by the dynamic load, which amounts to approximately 75% of the total load. The following magnet parts contribute to the losses:

- Yoke (hysteresis and eddy current loss),
- Structural elements (hysteresis and eddy current loss),
- Beam pipe (eddy current loss),
- strand
  - hysteresis loss ~ filament diameter d → reduce filament size
  - filament coupling loss ~ tp^2/ρ → reduce twist pitch tp, increase matrix resistivity ρ
- cable (Rutherford or similar)
  - strand coupling loss due to adjacent resistance R_a → increase R_a (coating)
  - strand coupling loss due to cross over resistance R_c → increase R_c (cored cable).

Besides reducing the ac losses in the conductor and the cable, one has to provide appropriate cooling and allow for local current redistribution in the cable. All 3 measures together must allow an appropriate temperature margin, under AC operating conditions.

The R&D is therefore directed at development of small filament size wires (2-3µm) and a cored cable.

Mechanical structure and lifetime of the magnets

The fast cycling requirement leads to an enormous number of cycles during the planned lifetime of 20 years. 200 million cycles are expected for SIS100, 1 million cycles for SIS300.

Therefore, the movement of any magnet part during cycling is to be minimized. R&D on material fatigue and crack propagation for critical parts is to be performed.

Other topics

- Magnet quench protection requires special measures because of the high ramp rate, which requires a high charging voltage of the magnet strings. Therefore, stacks of diodes or warm bypass elements are necessary.
- Because the iron yoke of the magnet is at cryogenic temperature, one has to look for a yoke material with the best compromise between a high saturation flux density and low hysteresis losses.
- Since field quality is ramp rate dependent, measurements of the field quality during ramping are needed.

SUPERCONDUCTING MAGNETS FOR SIS 100

These superferric magnets are very similar to those of the Nuclotron ring at JINR, Dubna [2]. The conductor ('Nuclotron-cable') was especially designed to cool large steady-state head loads of rapidly cycling magnets through the use of two phase helium, flowing through a copper-nickel-tube with low hydraulic resistance. The strands, wound around the outside of the tube, are indirectly cooled.

R&D goals are:

- Improvement of DC field quality (2D / 3D)
- Guarantee of long term mechanical stability ($2{\cdot}10^8$ cycles)
- Reduction of eddy / persistent current effects (may affect field quality, losses)

Since these magnets are iron dominated, no influence of the eddy/persistent currents on field quality was observed. However, large cryogenic losses occurred in the original Nuclotron magnets (dipole coil 30%, dipole yoke 70%). The yoke losses consist of hysteresis losses in the iron and eddy current losses in iron and structural support elements of the magnet. Figure 2 shows the reduction of the losses during the R&D phase [3].

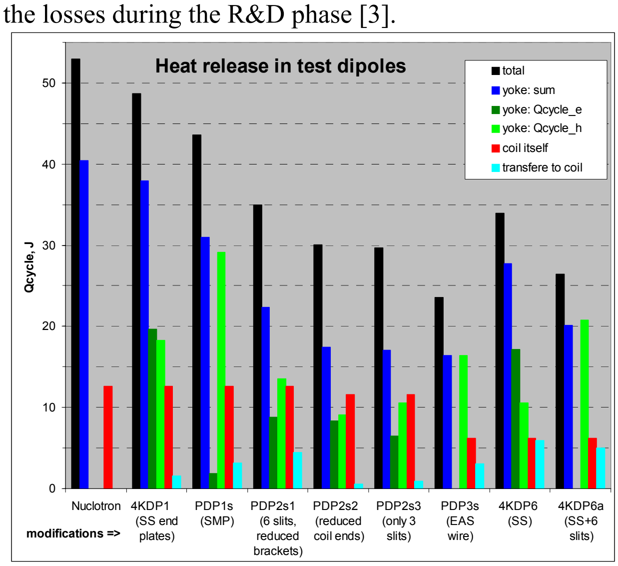

Figure 2: Loss reduction during R&D phase for the triangular cycle 1Hz, 2T.

Detailed investigations were made in order to guarantee the 20 year lifetime of the magnet. The use of a conductor support structure (under development) will reduce the previously existing high point-to point loads between adjacent conductors, due to Lorentz forces, and allow accurate positioning of the conductors (Figure 3) [4].

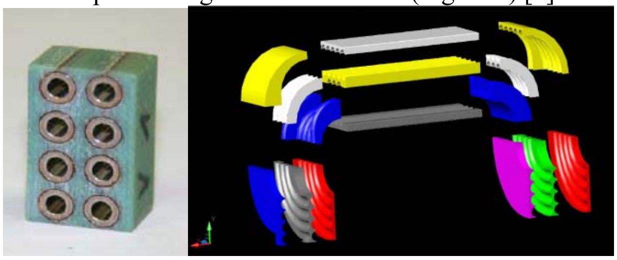

Figure 3: Coil support structure of SIS 100 dipole

Figure 4 shows the lamination cross section of the SIS100 quadrupole. The slits improve field quality and at the same time reduce the eddy currents due to longitudinal field components of the fringe field.

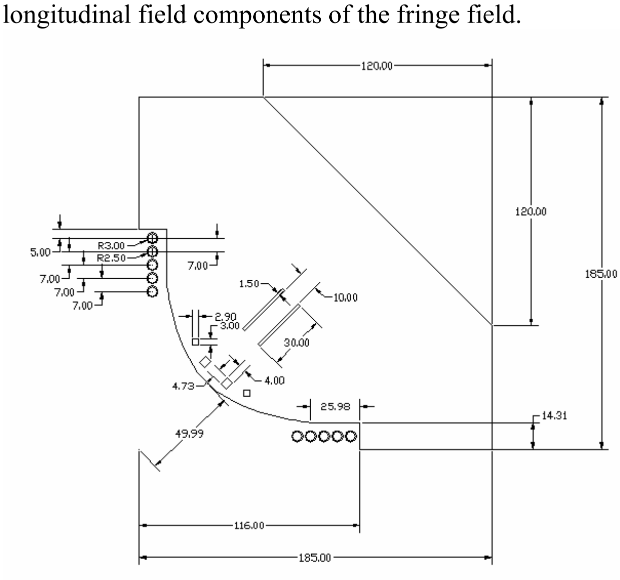

Figure 4: Lamination cross section of SIS100 quadrupole.

The load line in figure 5 demonstrates that these superferric magnets operate at a high saturation level, which is not a problem from the power consumption point of view as it is for a resistive magnet. However, the operating margin is reduced to about 80% of the critical current.

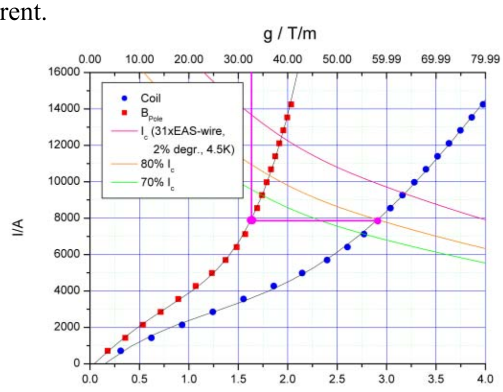

Figure 5: Load line of the SIS100 quadrupole.

Due to the moderate fields of the SIS100 magnets a normal conducting solution is in principle feasible, too. Cost estimations for the dipoles of both solutions were made. Already from the production point of view the superconducting solution is slightly in favour, as the magnets can be more compact. During the 20 years of operation a tremendous amount of energy can be saved (Table 2).

Table 2: Results of the cost estimation for 120 SIS100 dipoles [5]. (* Only the extra costs of the vacuum system and the power supplies for the normal conducting magnets are listed.)

Costs	**sc / k€**	**nc / k€**
Production		
R&D	1690	
Prototype	870	347
Series production	8090	10000
Quench detection	769	
Magnet tests	1548	542
Vacuum system (relative)*		1300
Power supply (relative)*		7940
Compensator unit		5000
Water cooling and air cond.		2350
Cryosystem	12200	
production total	**25167**	**27479**
Operation (20 years)		
Electrical power	4400	24140
Water cooling and air cond.		1553
Operation total	**4400**	**25693**
TOTAL	**29567**	**53172**

SUPERCONDUCTING MAGNETS FOR SIS200/300

Dipole GSI 001

R&D was started at BNL with the construction of a 4T, 1 T/s dipole, called GSI001, built very similarly to the RHIC dipole. It was designed to demonstrate the feasibility of a rapidly cycling cosθ dipole and to investigate related topics such as quench behaviour, AC field quality, and cryogenic losses [6, 7].

Table 3 shows the differences between the RHIC dipole and GSI 001.

Table 3: Parameter of RHIC dipole and GSI 001

	RHIC dipole	RHIC type dipole GSI001
Superconducting wire	NbTi-Cu (1:2.25)	NbTi-Cu (1:2.25)
Filament diameter	6µm	6µm
Twist pitch	13mm	4mm
Coating	no	Stabrite
Cable type	Rutherford without core	Rutherford with 2 x 25µm stain-less steel core

Coil restrain	phenolic spacer	stainless steel collar (G-11CR keys)
Wedges	Cu	G-11CR
Yoke iron	Hc= 145 A/m	Hc= 33 A/m, 3.5% Silicon
Laminations	6.35 mm	0.5 mm, glued

Ramp rate limitation of the quench current:

Figure 6 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. Obviously, current redistribution is possible due to the low adjacent resistance of the cored Rutherford cable.

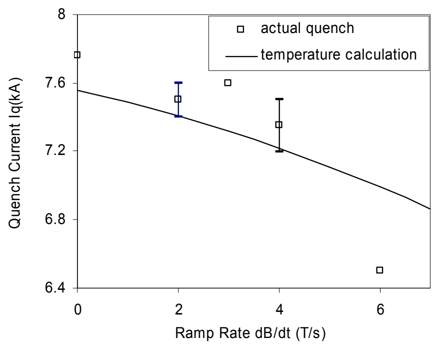

Figure 6: Measured ramp rate dependence of GSI 001.

Cryogenic losses:

Cryogenic losses at the 4K level were measured with the V-I method as a function of the ramp rate and the maximum field during a triangular cycle (Figure 7). The lines show calculated losses, using experimental values of wire and cable resistances, effective filament diameter and iron hysteresis [8]. The hysteresis part is in good agreement, while the measured eddy current contribution (slope) is higher than calculated, especially at higher field levels. Most probably we have here an unknown eddy current contribution.

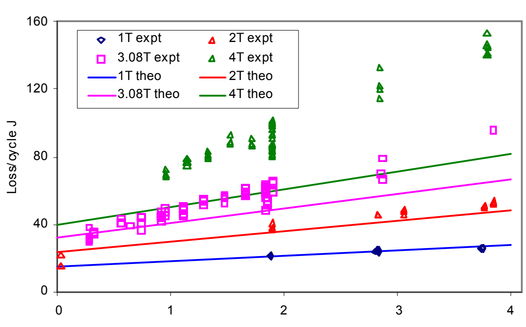

Figure 7: Cryogenic losses of GSI 001 for a triangular cycle

AC field quality:

BNL has developed a stationary harmonic coil system, which allowed a measurement of the field harmonics during the ramp. Figure 8 shows the allowed harmonic b3 (difference between down and up) as a function of the ramp rate up to 4 T/s.

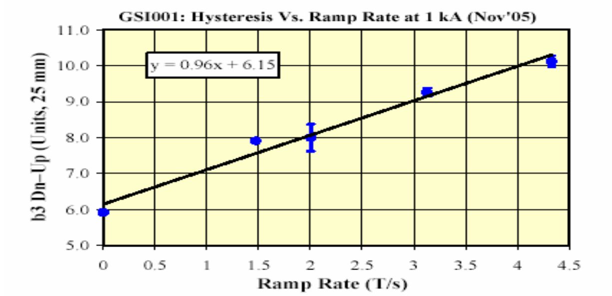

Figure 8: Transient behaviour of the normal sextupole harmonic of GSI 001.

ROXIE and VF Opera 2D code were extended to implement AC effects. Figure 9 shows good agreement between the measured and calculated sextupole component B3 [9].

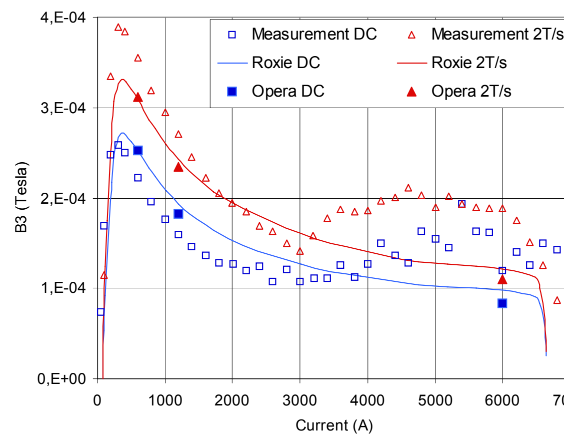

Figure 9: Comparison of measured and calculated b3 at radius of 25 mm.

DC skew terms are small. However, large AC skew terms a2 and a4 were measured, indicating a top-down asymmetry. Simulations are underway to explain this effect.

The magnet GSI 001 will be tested next month in the new test facility at GSI, cooled with forced flow single phase helium.

SIS300 dipole

A conceptual design study was made at IHEP, Protvino based on the design of the UNK dipole.

The main assumptions / results were:

- cooling: one phase supercritical Helium @4.4 K, with internal recooling foreseen
- temperature margin: 1.0 K with the option of lowering the helium temperature
- collared coil supported by iron shell (taking part of the load)
- strand diameter: 0.825 mm
- filament size: 3.5µm
- Rutherford cable: 36 strands with core (LHC dipole outer layer cable dimensions)

- quench protection: magnet not self-protecting, needs heaters

Meanwhile, the technical design (2D/3D magnetic design, FEM mechanical analysis, thermal analysis, quench analysis) is almost finished. Figure 10 shows the 2D coil design and the FEM model for mechanical analysis. The maximum operating temperature of the conductor of the dipole magnet can be deduced (from Figure 11) to be 4.76 K. The minimum critical temperature (at 6T) of the turn closest to the pole is 5.7K. Thus, the temperature margin is about 0.9 K.

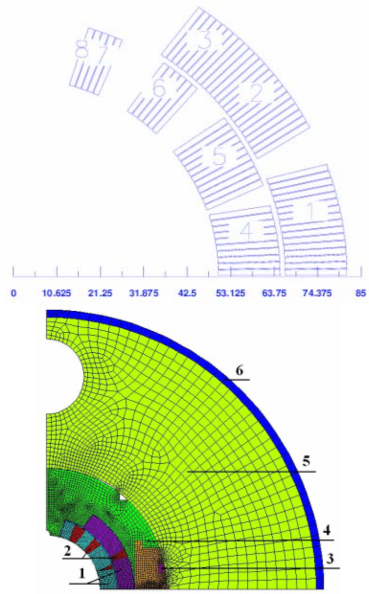

Figure 10: 2D coil design (upper) and FEM model for mechanical analysis of SIS300 dipole (lower). 1-coil, 2-inter-turn spacers (wedges), 3-key, 4-collars, 5-yoke, 6-outer cylinder.

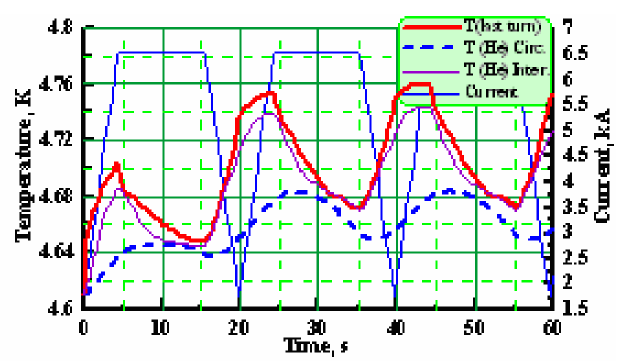

Figure 11: Highest temperature in a magnet of SIS300 dipoles during ramping.

Further work for SIS300 magnets

Dipole:

- tooling design and production
- winding test of a short model coil
- construction and test of model dipoles (cold masses)
- prototype construction and test (project 'Disco-Rap', INFN)

Quadrupole:

- Work packages and milestones have been defined within a project 'SupraPulse' by CEA Saclay.

SUMMARY

Rapidly cycling sc magnets are foreseen for the synchrotrons of FAIR. The R&D to develop these magnets, including low loss conductor, is under way. First dipole models have been built and tested. R&D continues on quadrupoles and full size magnets.

ACKNOWLEDGEMENTS

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REFERENCES

[1] FAIR- Facility for Antiprotons and Ion Research, www.gsi.de

[2] A.M.Baldin, et al. "Superconducting fast cycling magnets of the Nuclotron", IEEE Trans. on Appl. Superconductivity, v.5, 1995, pp.875-877.

[3] Alexander Kovalenko et.al., "New Results on Minimizing AC Power Losses in a Fast Cycling 2T Superferric Dipole with a Cold Yoke", Proceedings of MT19, Genova, Italy, Sep. 2005

[4] EU FP6 'DIRAC secondary Beams', 1st Annual Report, Annex 3: Design report on structural analysis (Deliverable 53 of task 22)

[5] E. Fischer, "Costs study for SIS100 Dipoles", Internal note: MT-INT-EF-2005-002

[6] P. Wanderer et al., "Initial Test of a Fast Ramped Superconducting Model Dipole for GSI's Proposed SIS 200 Accelerator", Proc. 2003 Part. Accel. Conf.

[7] A.K. Ghosh, "Cable Design for Fast Ramped Superconducting Magnets (Cos-θ Design)", WAMS2004, Archamps

[8] M.N. Wilson et al., "Measured and Calculated Losses in Model Dipole for GSI's Heavy Ion Synchrotron," IEEE Trans. Appl. Superconductivity, 14 (2004) 306

[9] G. Moritz et al, "Recent Test Results of the Fast-Pulsed 4 T Cosθ Dipole GSI 001", in Proceedings of the 2005 Particle Accelerator Conference.

[10] I. Bogdanov et al., "Final Report on the Research and Development Contract: Design of 6 T Superconducting Dipoles for the SIS 300", Internal note: MT-INT-Bogdanov-2003-001