FAST RAMPED SUPERFERRIC PROTOTYPE MAGNETS OF THE FAIR PROJECT — FIRST TEST RESULTS AND DESIGN UPDATE*

E. Fischer, A. Mierau, P. Schnizer, C. Schroeder,
A. Bleile, E. Floch, J. Macavei, A. Stafiniak, F. Walter, GSI, Darmstadt, Germany
G. Sikler, W. Gärtner, BNG, Würzburg, Germany

Abstract

The 100 Tm synchrotron SIS 100 is the core component of the international Facility of Antiproton and Ion Research (FAIR) to be built in Darmstadt. An intensive R&D period was conducted to design 3 m long 2 T dipoles providing a stable ramp rate of 4 T/s within an usable aperture of 115mm · 60mm with minimum AC losses, high field quality and good long term operation stability. Three full size dipole - and one quadrupole magnets were built. Recently the first dipole magnet was intensively tested at the GSI cryogenic test facility. We present the measured characteristic parameters: training behaviour, the field quality along the load line for DC operation as well as on the ramp, AC losses, and the cryogenic operation limits. We compare them to the calculated results as well as to the requested design performance. Based on the obtained results we discuss adjustments for the final design.

INTRODUCTION

The SIS 100 synchrotron utilises superconducting magnets providing a field of 2 T (dipole), ramped with a cycle frequency of 1 Hz (4 T/s). The magnets have to be operated at 4.5 K and use the Nuclotron cable (Fig. 1, insert) as its ancestor, the Nuclotron at JINR Dubna [1]. In this cable the superconducting wires are wrapped around a tube which is cooled by a two phase forced helium flow. The magnets create heat when they are ramped due to hysteresis and eddy current effects, which were reduced by a factor of two during previous R&D [2]. Important improvements were also achieved for the magnetic field homogeneity and for the mechanical stability of the coil. The main design issues and operation parameters had been tested on mock-ups and short model magnets [3, 4]. A decisive step toward series production is to scale these results to larger aperture and increased length of the main magnets, required to realize the challenging beam characteristics and to guaranty its stable long time operation performance. In addition the manufacturing technology must be optimised for industrial conditions and the GSI cryogenic test facility had to be prepared and adjusted for the complex measurements on such magnets [5]. The 3D drawing of the BNG dipole is given in Fig. 1. Detailed descriptions of the design and of the manufacturing processes are available in [6, 7].

* This work is supported by the EU FP6 Design Study (contract 515873 - DIRAC secondary beams) and the BMBF

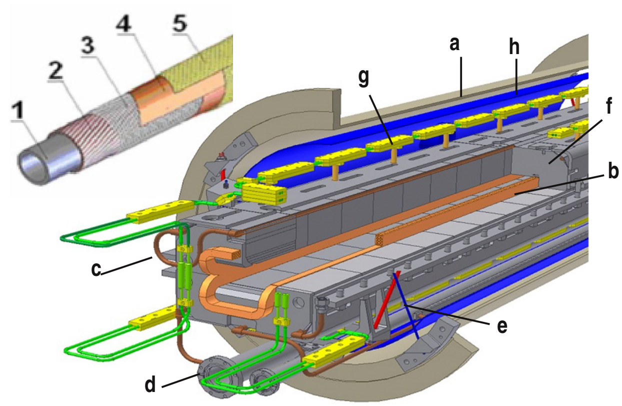

Figure 1: The structure of the Nuclotron cable (top left) and the main features of the magnet design of the first full size dipole. 1 – cooling tube, 2 – superconducting wire (multiflament NbTi/Cu), 3 - Nichrome wire, 4 – Kapton tape, 5 – adhesive Kapton tape, a – cryostat vessel, b – cable and half coil (2 · 4 windings), c – yoke cooling pipes, d – LHe lines, e – suspension rods, f – soft iron yoke, g – bus bars, h – thermal shield

QUENCH TRAINING AND POWER TESTS

The first prototype dipole was delivered by Babcock Noell GmbH and tested at GSI. After cooling down and measuring the virgin load line, quench tests were started. Following the first manual test quench, we furthermore used an automatic ramp sequence: 150 A/s up to 3kA, 75 A/s up to 6kA, 10 A/s up to quench. The first break down of the superconductivity was reached well above the nominal current. (Fig. 2). Already with the forth quench they had occurred near to the high field point within the coils inner layer. Close to these points the short sample limit (ssl) of the cable (i.e. the sum of critical currents of all the sc strands under identical conditions), is very sensitive to the local magnetic field and the temperature distribution inside the coil. Regarding the inaccuracy in local field and temperature values as well as for the sc-wire data we estimate the finally reached quench current to be within 5% of the ssl. Following the quench training, the first power test was started for the highest field level B_{max} = 2.1 T and 4 T/s ramp rate, adjusting the cycle repetition rate up to f = 0.4 Hz (Fig. 2 insert on the right), close to the maximum cooling capability of the two phase helium forced flow, lim-

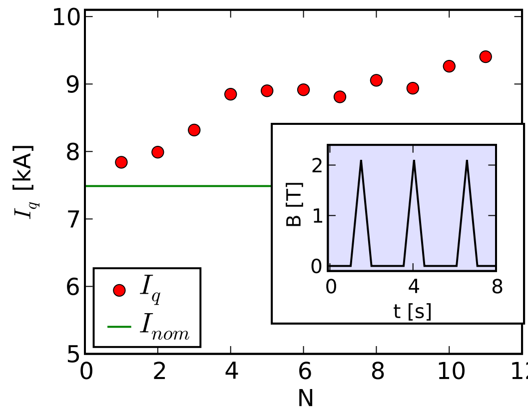

Figure 2: Quench training curve for the first prototype. The insert on the right shows the strongest cycle mode of the magnet continuously tested during one week.

ited by the hydraulic resistance of the coil and the bus bars. Counting all the measurement cycles within two runs, with a thermal cycle in between, up to now the magnet was dynamical ramped for four complete weeks.

MAGNETIC FIELD

For a consistent description of the magnetic field within the elliptic aperture we use elliptic multipoles. Their coordinates are of the type $x = e\cosh\eta\cos\psi$, $y = e\sinh\eta\sin\psi$ with x and y the Cartesian coordinates and η and ψ the elliptic coordinates with $0 \leq \eta \leq \eta_0 < \infty$ and $-\pi \leq \psi \leq \pi$. The field $\mathbf{B} := B_y + iB_x$ can be described within the whole ellipse using

$$\mathbf{B}(\eta,\psi) = \sum_{q=0}^{M} \mathbf{E}_q \cosh[q(\eta + i\psi)]/\cosh(q\eta_0), \quad (1)$$

with $\eta_0 = \tanh^{-1}(b/a)$ the reference ellipse and a and b its half axes [8, 9, 10] (here $a = 45\,mm$ and $b = 17\,mm$). These $\mathbf{E}_q$ can be recalculated to circular multipoles

$$\mathbf{B}(\mathbf{z}) = \mathbf{B}_m \sum_{n=1}^{M} \mathbf{c}_n\,(\mathbf{z}/R_0)^{n-1} \quad (2)$$

using an analytic linear transformation, with $\mathbf{B_m}$ the main field, $\mathbf{z} = x + i\,y$, R_0 the reference radius and $\mathbf{c}_n = b_n + i\,a_n$ the relative higher order multipoles. The b_n's and a_n's are dimensionless constants. In this paper they are given in units i.e. $1\,unit = 100\,ppm$ at a R_0 of $40\,mm$. We chose this free parameter such that the relative allowed harmonics b_n can then be represented as convenient numbers in the order of 1 to 10. Using (2) the field can be interpolated with sufficient accuracy within an ellipse with half axes a, b.

The the transfer function is given in Fig. 3 next to the first allowed harmonic in the centre of the magnet. The measurements agree well with the design values. The detailed analysis of the first magnetic measurements on the

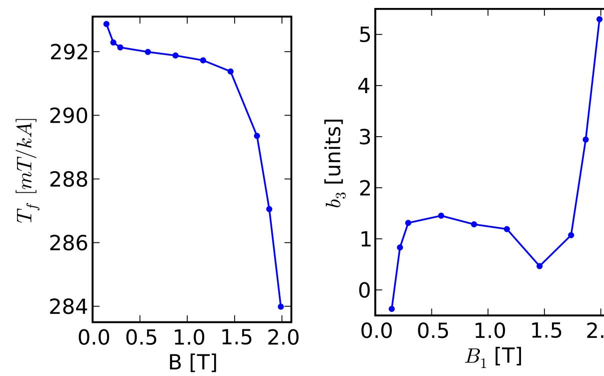

Figure 3: The transfer function of the SIS 100 dipole as well as the sextupole

prototype is presented in [11]. The relaxation constant τ was found to be $30\,\mu s$.

AC LOSSES AND OPERATION LIMITS

The thermal losses at 4 K were measured using both the calorimetric and the V-I method described in [5]. The test cycles of the magnet are defined by $B_{min} = 0$, B_{max}, dB/dt and by the delay t_d between the triangular pulses (Fig. 3). The delay was required for the high loss cycles: Preliminary estimations had shown that this dipole, designed not for a continuous triangular cycle with B_{max} = 2 T and dB/dt = 4 T/s, will operate near its cooling limit for t_d $\approx$ 1s. The corresponding stability limit for the averaged heat load removal (including DC loss) was expected to be found between 35 and 50 W depending on the experimental set cooling conditions, i.e. on the pressure drop Δp and the outlet temperature T_{out} of the helium flow [3]. The most intensive cycles experimentally found to be stable for a fixed ramp rate with increasing B_{max} and - if necessary - t_d are summarised in Table 1.

We found the stability limit slightly below 45 W independent of the set ramp rate, excellently agreeing with the previous estimation taking into account the values chosen for T_{out}. A faster repetition frequency requires to reduce

Table 1: The Maximum Average Power Loss $\bar{P}$ for the Different Operating Cycles with Repetition Frequency f_c

dB/dt $[T/s]$	B_{max} $[T]$	t_d $[s]$	f_c $[Hz]$	$\bar{P}$ $[W]$	T_{out} $[K]$	dP $[mbar]$
1	2.1	0	0.23	30	6.0	640
1.5	2.1	0	0.33	37	7.8	691
2	1.9	0	0.49	43	9.6	735
2.5	2.1	0.8	0.37	41	8.9	740
3	1.9	0.8	0.45	43	9.2	780
3.5	1.9	0.8	0.49	43	9.0	775
4	1.9	1.6	0.37	40	8.4	733
4	2.1	1.5	0.39	40	7.2	406

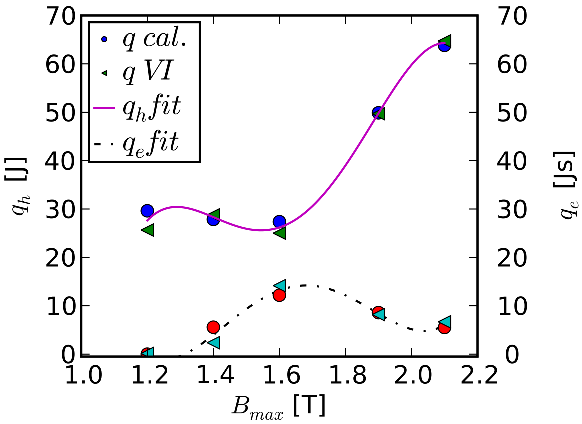

Figure 4: Dependences on B_{max} of the AC loss fit parameters qh and qe obtained from calorimetric and V-I measurements. The lines present the final parameter functions $q_h(B_max)$ and $q_e(B_{max})$ describing the AC loss properties of the magnet according to (3).

the hydraulic resistance of the coil. A optimal design solution for this is the curved single layer dipole as described in [3, 4]. The AC loss data of the dipole for all measured cycles fit well to the usual function

$$P = q_h(B_{max})f + q_e(B_{max})f^2 \qquad (3)$$

assuming that the eddy current relaxation frequency is much higher than the triangular pulse frequency f, correct for the actual packing factor of the iron yoke (99.5%) as shown in [12]. This also means, that the first term in (3) represents the sum of hysteresis loss effects in yoke and coil whereas the second describes the remaining eddy current losses. The fit parameters q_h and q_e are given in Fig. 4. The good agreement between the results of both measurement methods is obvious. So its reasonable to define unique parameter functions $q_h(B_{max})$ and $q_e(B_{max})$ using appropriate functions sets, which allows calculating the loss in the magnet for any arbitrary cycle with sufficient accuracy. The results agree well with the predictions based on short models measurements and on ANSYS calculations taking into account the different iron of the models and the imprecisely known properties of the used isotropic iron M700-100A. The calorimetric measured static head load is about 13 W including 7 W disposed by the anticryostat inserted for magnetic measurements.

Recently a pure triangular ramp with 4 T/s up to 2.1 T was added to the cycle spectrum requested for the SIS 100 dipoles. As shown above the hydraulic resistance of the helium flow limits the average cooling power to 45 W, thus the dipole will not be able to provide a continuous cycling for maximum fields higher than about 1.6 T, see (3) and Fig. 4. The real limit will be significant lower due to statics, beam losses, contributions coming from the vacuum chamber and mainly by the request for a lower outlet temperature $T_{out} \approx 4.5$ K necessary to provide a stable parallel two phase cooling of the magnets within the lattice segments.

CONCLUSION

The first prototype dipole for the SIS100 accelerator was successfully tested at GSI. The magnet showed excellent training as well as power cycling behaviour and will be tested further on. A complete set of AC loss data and the most important magnetic field characteristics were measured and found agreeing well with preliminary estimations. The measured operation limits of the dipole confirm exactly the expected values. The significant features of the magnet design are understood and proven by experiment. The next step toward a final prototype will be constructing and testing a curved dipole with a single layer coil.

REFERENCES

[1] H.G. Khodzhibagiyan and A. Smirnov. "Concept supercon. magnet system for the Nuclotron", ICIC12, Southampton, 1988, pp 841

[2] E. Fischer et al. "Manufacturing of the first full size model of a SIS100 dipole magnet" WAMSDO, May 2008, CERN

[3] E. Fischer, H. Khodzhibagiyan, and A. Kovalenko. "Full size model magnets for the FAIR SIS100 synchrotron" IEEE Trans. Appl. Supercon. June 2008 18:260-63

[4] E . Fischer, H. Khodzhibagiyan, A. Kovalenko, and P. Schnizer, "Fast Ramped Superferric Prototypes and Conclusions for the Final Design of the SIS 100 Main Magnets",ASC08, August 2008, Chicago

[5] A. Stafiniak et al. "Cold testing of rapidly-cycling model magnets for SIS 100 and SIS 300 - methods and results" WAMSDO, May 2008, CERN

[6] G. Sikler et al., "Manufacturing of the first full size model of a SIS100 dipole magnet", WAMSDO, 2008, CERN

[7] G. Sikler et al., "Fabrication of a prototype of a fast cycling superferric dipole magnet", PAC09, May 2009, Vancouver

[8] P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer, "Magnetic field analysis for superferric accelerator magnets using elliptic multipoles and its advantages," IEEE Trans.Appl. Supercon., vol. 18, no. 2, June 2008, pp. 1648-1651.

[9] P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer, "Field representation for elliptic apertures," Gesellschaft für Schwerionenforschung mbH, Planckstrae 1, D-64291 Darmstadt, Tech. Rep., January 2008.

[10] P. Schnizer, B. Schnizer, P. Akishin, and E. Fischer, "Theoretical field analysis for superferric accelerator magnets using plane elliptic or toroidal multipoles and its advantages," EPAC08, June 2008, Genova

[11] E. Fischer et al., "Measured and Calculated Field Properties of the SIS 100 Magnets described using Elliptic and Toroidal Multipoles", PAC09, May 2009, Vancouver

[12] E. Fischer, R. Kurnyshov, P Shcherbakov "Analysis of the Eddy Current Relaxation Time Effects in the FAIR SIS 100 Main Magnets", IEEE Trans. Appl. Supercon., vol. 18, no. 2. , June 2008, 1173 - 1176