FAST-PULSED SC MAGNETS

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Abstract

Up to now, only one synchrotron (Nuclotron at JINR, Dubna) is equipped with fast-pulsed superconducting magnets. The demand for high beam intensities leads to the requirement of fast-pulsed magnets for synchrotrons. An example is the proposed international 'Facility for Antiproton and Ion Research' (FAIR) at GSI, which will consist of two synchrotrons in one tunnel, and several storage rings. The high field ramp rate and repetition frequency introduce many magnet design problems and constraints on 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. Due to the large number of magnet cycles during the lifetime of such a magnet, special attention has to be paid to magnet material fatigue problems. The large charging voltages put some constraints on the use of cold diodes for quench protection. R&D has started at GSI, in collaboration with many institutions, to comply with the constraints 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, (as opposed 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 in one tunnel, SIS 100 (100 Tm rigidity) and SIS300 (300 Tm rigidity), and several storage rings. Figure 1 gives an overview of the facility.

The SIS 100 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 SIS 300 for further acceleration to higher energies. The CR storage ring complex will cool the secondary beams and accumulates 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 SIS 100 at about 1 Hz and 1T/s for SIS 300, 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. The main parameters of the synchrotrons are listed in Table 1.

This paper deals only with fast-pulsed 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.

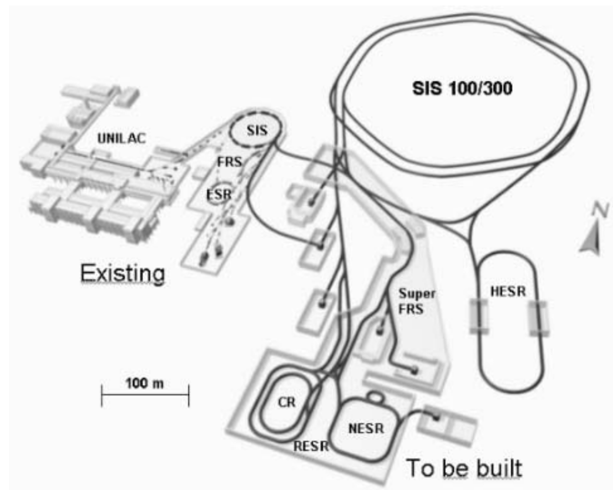

Figure 1: Schematic topology of FAIR.

MAIN R&D TOPICS

In dealing with fast-pulsed 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 fast varying field, eddy currents are induced in the conductor (wire, cable), in the iron and in the structural elements of the magnet. They create large steady-state AC-losses in the case of continuous operation. Besides they affect the 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 [2].

Cryogenic system

The dynamic heat load of the synchrotrons is dominated by AC-losses and for example for SIS 100, varies between 100% and 25%, within minutes. Therefore the helium mass flow will be kept constant, but the unused liquid fraction will be "recycled" either by a liquid helium pump or a maintenance-free ejector.

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Table 1: Magnet Parameters of the synchrotrons.

	Number of magnets	Aperture (mm)	Magnet length (m)	Max. field / Max. gradient	Max. ramp rate
SIS100:					
Dipoles	120	130 × 65	2.6	2 T	4 T/s
Quadrupoles	162	120 × 63	0,6 1.0 0.6	34.2 T/m 36.7 T/m 34.2 T/m	73.4 T/m/s
SIS300:					
Dipoles	120	100 (circular)	2.6	6 T	1 T/s
Quadrupoles	132	100 (circular)	0.6 1.0	93 T/m 89 T/m	15.5 T/m/s 14.8 T/m/s

Quench protection of the individual magnets

The fast-ramped magnets require a high charging voltage, despite their relatively low inductance. Protection with diodes requires a series stack of several, high turn-on-voltage cold diodes,. whereas single diode with lower turn-on-voltage has been used for other accelerator magnets. Though warm bypasses are an alternative, R&D is being initiated on diffusion type diodes.

Mechanical structure / lifetime of the magnets

The coil and the conductor of a typical SIS 100 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, crack propagation etc. have to be investigated.

Cryogenic stability

The high ramp rate increases the probability that a disturbance could lead to a quench. Therefore, the stability margin for such a magnet should be chosen conservatively.

Iron R&D

The optimum choice of low-carbon steel is important for fast-pulsed superconducting magnets. The best compromise between high permeability, high saturation flux density, low coercive force, and high specific resistance has to be found. Permeability and losses for bipolar and unipolar cycles of several steels have been measured at room and cryogenic temperatures [3].

Radiation issues

Radiation deposition, due to primary beam loss, is a major concern in the high intensity synchrotrons and near the targets. It affects the 'hands-on' limit on machine maintenance, the heat load of the cryogenic system, the lifetime of components (coil insulation, cold diodes), and the quench stability of the magnet.

ACCELERATOR MAGNETS

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

SIS 100 dipole

The Nuclotron ring was commissioned at LHE, Dubna in 1993 [4]. It is equipped with iron-dominated magnets with superconducting coils (so-called superferric magnets) [5] and has already reached our main design goal of 4 T/s dipole ramp rate with a repetition rate of 1 Hz [6]. A cross-section of the magnet in the cryostat is shown in Figure 2.

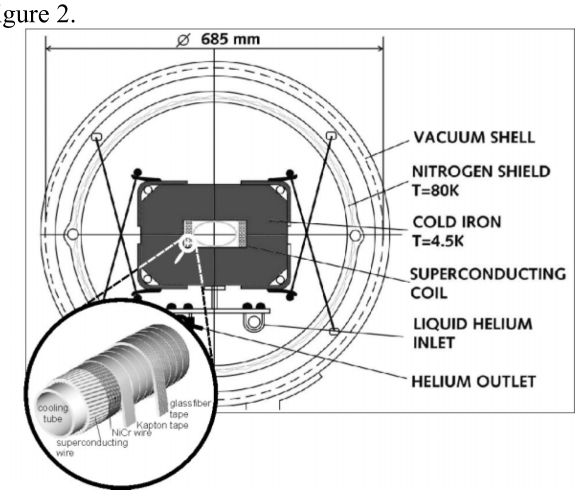

Figure 2: Nuclotron Magnet in its cryostat.

The magnet is of the window-frame type (lamination thickness 0.5 mm). The cold mass comprises coil, iron and beam pipe. A special cable is used: 31 strands are wrapped around a Cu-Ni tube and indirectly cooled by two-phase helium flowing through the tube. This cable (low hydraulic resistance, low friction factor) allows a very effective removal of the steady-state AC losses caused by the fast ramp [7]. Field margin of our current test models and temperature margin are 60% and 1.6K respectively.

The main R&D goals for the SIS-100 prototypes are: 1. reduction of the cryogenic losses at the 4K level in iron, coil and beam pipe, 2. improvement of the 2D and 3D field quality and 3. the confirmation of the adequacy of the mechanical structure.

Losses

At 4K the AC losses of the original Nuclotron dipole amount to 9 W/m (coil) and 29 W/m (yoke) for the standard cycle (4T/s, 2T, 1Hz; no beam pipe). The R&D results obtained up to now on our test magnets lead us to expect a final loss reduction in the SIS100 dipoles to 6 W/m (coil) and 9 W/m (yoke).

In the original dipole the main loss contribution came from the iron. This led to the so-called "80K-option", where the 4K cold mass is confined to only the coil and the iron is operated at 80K [8]. However, R&D showed that we could reduce the loss in the yoke substantially 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 slitting the iron end blocks [5,6]. We verified the end field contribution to the energy loss by measuring the temperature and magnetic flux distribution along the longitudinal axis and by calculating the end field configuration with OPERA 3D [9]. The loss contribution along the magnet axis was also calculated and compared with the measured data [10].

Field quality

The iron lamination cross section was optimized by introducing negative shimming and slots [11]. Figure 3 compares the calculated and measured harmonics for the original dipole and the improved version. Within the measurement accuracy no difference was seen between the results at constant field and the data taken during the ramp. The integral harmonics will be minimized using OPERA 3D varying the coil end geometry and the radial end block chamfering.

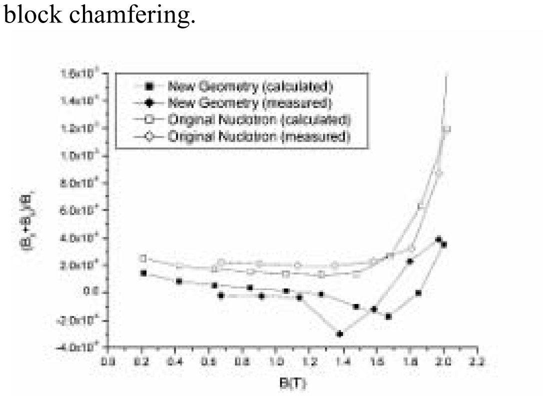

Figure 3: Comparison of calculated and measured field harmonics.

Mechanical structure

The coil of the original Nuclotron dipole is only restrained horizontally by the iron yoke, but has no precompression. Also, the coil structure contains voids between the cables that should be filled, to increase the geometric and mechanical stability. Model coil samples with reinforced internal structure were built. The Young's modulus before and after one million cycles showed no difference. Crack propagation studies of the Cu-Ni material of the tube predict a lifetime of about a billion cycles [12]. A coil mockup pressing the coil against a ceramic inner support by stainless steel strips has been built. The final choice of the coil structure will be evaluated in close collaboration with industry.

Alternatives

We consider the improved Nuclotron type dipole, with the previously mentioned R&D goals achieved as the lowest cost version of possible SIS 100 dipole designs. We also looked at alternatives: a warm-iron, warm-bore H-type dipole with complicated support of the cold coil against the warm iron, was investigated [13] as well as the resistive coil option. Figure 4 shows the different magnet sizes demonstrating the compact design and material savings of the Nuclotron type magnet. Therefore, it was not surprising that the total investment costs (including power supply, cryogenics, etc.) were comparable, but the operating costs were greatly in favour of the superconducting solution [14].

In addition, cryogenic pumping is preferred to achieve the required vacuum of 10^{-12} mbar [15].

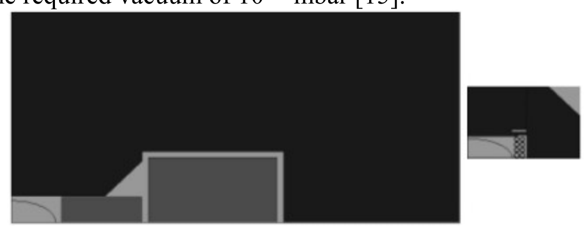

Figure 4: SIS 100 dipole: Comparison of a normal conducting with a superconducting Nuclotron-type version.

Quench protection

Calculation of quench propagation showed that the single dipole is "self-protecting"[16]. 40 of the dipoles will be connected in series. From the MIITS curve, we concluded that we need neither diodes nor warm bypasses to dump the magnet energy of the string safely into a warm dump resistor [17].

Dipole GSI001 (4T)

When the project started the rigidity of the second synchrotron was chosen to be 200 Tm, which required a maximum dipole field of 4T. Therefore, we started R&D in close collaboration with Brookhaven National Laboratory, USA. The RHIC Arc Dipole design [18] with a one layer coil was the basis for a model magnet GSI001 [19] (see Figure 5). A comprehensive overview of this R&D is given in [20].

We made several modifications to the existing RHIC design, however, to reduce AC losses and improve 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. The main effort was to reduce the losses produced by eddy currents in the structure, iron and the cable of the magnet. 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 25µm thick were used as a core between the layers of the cable to reduce the main loss contribution. R_c and R_a were measured to be 60mOhm and 64μOhm, respectively [21]. Dynamic wire magnetization was measured as well [22] delivering the matrix transverse resistivity (incl. magnetoresistance).

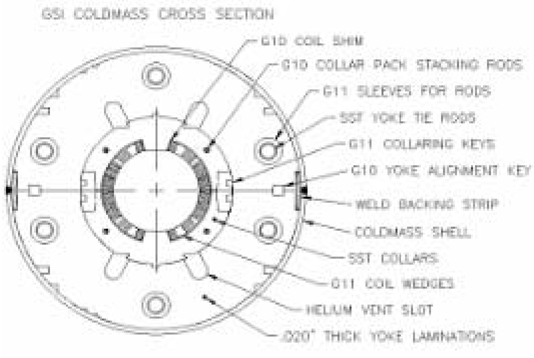

Figure 5 Schematic cross section of GSI001.

Tests

The model magnet GSI001 was tested in a vertical dewar in pool boiling helium [23]. After 4 quenches (slow ramp of 0.05 T/s) the magnet reached short sample critical current, then at 2 T/s, 2 quenches were observed, after that the magnet was continuously operated at 2 T/s for 40 minutes. After a thermal cycle, the magnet was run up to 4 T at a ramp rate of 4 T/s for several cycles. The losses were measured with the V-I-method. The results (in Joules/cycle) are shown in Figure 6 as a function of the ramp rate for different maximum fields. The losses were calculated based on the parameters measured on wire, cable and iron. The hysteresis part is in good agreement with the measured data. In previous calculations, the calculated ramp dependent part also agreed well with experiment [24].

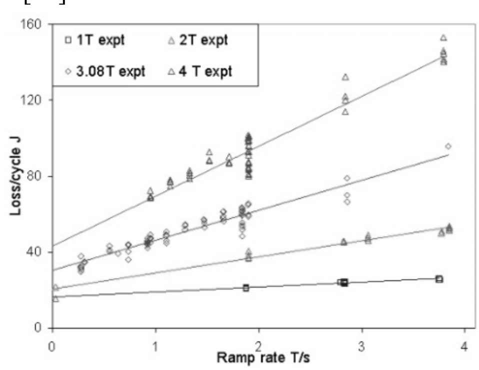

Figure 6: Total magnet losses as a function of the ramp rate.

However, with the wire transverse magnetoresistance included the calculated values are too low at higher fields (Figure 7). One reason could be that we did not include eddy currents contributions in the iron yoke end laminations. 3D end field calculations are in progress to clear this question.

Further measurements are planned: losses in a bipolar cycle, quench current as a function of the ramp rate (RRL), magnetic measurements (harmonics) static and on the ramp, loss measurement of the collared coil alone, and finally a horizontal test of the magnet, with one-phase helium cooling in the new test facility at GSI.

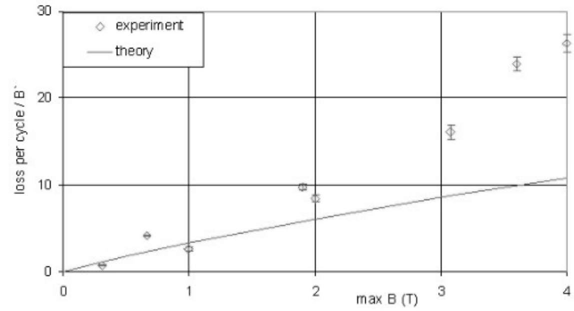

Figure 7: Eddy current losses as a function of maximum field.

SIS 300 dipole (6T)

During the R&D phase, GSI increased the beam rigidity of the second synchrotron to 300 Tm, i.e. the dipole aperture field to 6T, and in addition the inner coil diameter to 100 mm. The UNK dipole data are close to these requirements [25]. The two-layer coil is cooled with one-phase liquid helium, recooled by two-phase helium within the magnet. IHEP, Protvino prepared a Conceptual Design Report, where they investigated different designs. Of course the R&D results of GSI001 had to enter the study.

Choice of mechanical structure

A collar/iron combination where the iron takes part of the load, was chosen [26]. That increases the contribution of the iron to the field and reduces the amount of superconductor. A bending test of the collared coil will answer the question if the dipole will be built straight or with a radius of 50 m.

Choice of cable [27]

To guarantee safe operation of the magnet, a stability temperature margin of 1K at operating field was chosen [28]. To achieve this, we will use a cored cable with 36 strands and an optimized wire diameter of 0.825 mm. The option to lower the helium inlet temperature is technically feasible and now under investigation. Quench calculations showed that the magnet needs heaters, but that the energy can be safely dumped with one dump resistor per 20 magnets and each magnet protected by a stack of 6 cold diodes or by a warm bypass [29].

NESR/RESR dipole

The NESR/RESR dipole is the only storage ring dipole which requires a ramp rate of 1 T/s, to decelerate the short-lived radioactive nuclei. This 1.6T large aperture dipole is planned as a warm-iron, warm-bore superferric H-type dipole with a Nuclotron-type cable [30].

SPECIAL R&D

Wire R&D

The goal was to produce a RHIC size wire (0.648 mm) with the filament size reduced from 6.0 to 3.5 μm (which is the lowest possible value for a copper matrix without the 'proximity-coupling'- effect) in order to reduce the cryogenic losses and to guarantee a good field quality. 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 [31]. A single stack test was not successful due to stacking problems of the 12240, 1.46 mm wide, monocores. European Advanced Superconductors (EAS) therefore used a modified double stack method. A cross section is shown in Figure 8.

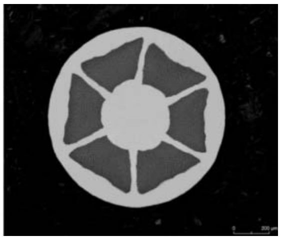

Figure 8 Cross section of the "modified double stack" sc-wire made by EAS.

An alternative approach is the use of Cu-Mn, interfilamentary-matrix wire, with a design such as that developed for the SSC booster [32]. It combines a high matrix resistivity with a low filament diameter.

Cable R&D

Rutherford cored cable development

Several different foils (8 mm wide, typically 25µm thick) for the GSI001 cable production have been tried: Stainless steel, anodized titanium, Cu-.Ni, brass and Kapton. The use of a slotted mandrel avoided perforations. Ra and Rc 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 [33].

CICC development

The work has started within an INTAS collaboration [34] to create a novel CICC cable on the basis of the Nuclotron cable. The idea is to wind the strands around a spiral and then surround it with a round helium tight jacket. That would combine the advantages of a CICC cable (direct helium contact) with the low hydraulic resistance of a Nuclotron cable, necessary for the removal of large AC-losses. Small test coils with both cable types will be built and tested to determine cooling conditions and stability. R&D to increase the engineering current density of the cable has been started as well [35].

Radiation effects due to primary beam loss

We were concerned about the lifetime of the diodes, the organic insulation within the coil, and possible quenches due to primary beam losses in these high-intensity-machines. The SHIELD code calculated the energy dose deposited in, and the neutron flux to, the coil per lost particle for protons and ions [36]. Based on lifetime doses, the allowed primary beam loss per dipole magnet for the quench limit (typically $5*10^{10}$ ions and $5*10^{11}$ protons) and for a lifetime of 10 years (typically 1-5%) was calculated. Heavy ion irradiation experiments are planned to get better values for the life time doses.

CONCLUSIONS

Fast-pulsed magnets are foreseen for the synchrotrons of FAIR. R&D to develop these magnets has started and first dipole models have been produced and tested. R&D will continue on quadrupoles and full size magnets.

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