STATUS OF THE DEVELOPMENT OF THE FAIR SUPERCONDUCTING MAGNETS*

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Abstract

For the planned 'Facility for Antiprotons and Ion Research' (FAIR) a variety of superconducting magnets is foreseen. The synchrotrons SIS100 and SIS300 will use fast-pulsed superferric and superconducting cos (theta) magnets. The storage ring CR and the fragment separator Super-FRS will be equipped with large-scale superferric magnets, while in the storage ring HESR RHIC-type magnets are foreseen. The status of the R&D activities will be presented.

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.

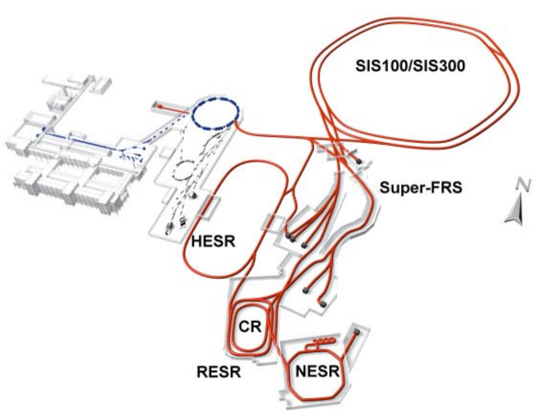

Figure 1: Topology of FAIR.

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 1 T/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.

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.

SUPERCONDUCTING MAGNETS FOR THE SYNCHROTRONS

R&D Topics

Fast cycling of magnets in the Hz-range leads to special problems, which are to be addressed 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, quench protection and choice of yoke material.

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 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 coupling loss) and Rutherford cable or similar cable (strand coupling loss due to adjacent resistance, strand coupling loss due to cross over resistance). 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.

The fast cycling requirement leads to an enormous number of cycles during the planned lifetime of 20 years. $2x10^8$ cycles are expected for SIS100, $1x10^6$ 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.

Magnet quench protection requires special measures because of the high ramp rate, which requires a high

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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.

As SIS100 and SIS300 are to be installed in the same tunnel, their different rigidities lead to different requirements for the magnets. The SIS100 dipoles have 2.1 T peak field and a ramp rate of 4 T/s. The respective values of SIS300 are 6 T and 1 T/s. The gradients of the main quadrupoles are 32 T/m (SIS100) and 90 T/m (SIS300).

Superconducting Magnets for SIS100

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 the improvement of DC field quality (2D/3D), the long term mechanical stability ($2\text{x}10^8$ cycles) and the 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].

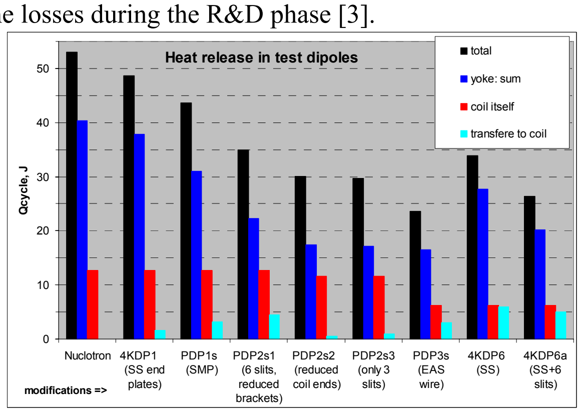

Figure 2: Loss reduction during R&D phase for the triangular cycle 1Hz, 2T.

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 [4].

The same design measures were applied to the quadrupole. Slits in the yoke improve field quality and at the same time reduce the eddy currents due to longitudinal field components of the fringe field.

Superconducting Magnets for SIS300

R&D was started at BNL with the construction of a 4 T, 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 [5, 6].

The comparison of measured and calculated eddy current and hysteresis losses showed good agreement up to 3 T [7].

The ac field quality was measured with a stationary harmonic coil system developed at BNL, which allowed a measurement of the field harmonics during the ramp.

Comparison with AC effects extended versions of ROXIE and VF Opera 2D code showed good agreement between the measured and calculated sextupole component B3 [8].

As the dipole field level was increased to 6 T for having a SIS300 a two layer coil design was necessary. IHEP, Protvino made based on the design of the UNK dipole a conceptual design study [9]. Meanwhile, the technical design (2D/3D magnetic design, FEM mechanical analysis, thermal analysis, quench analysis) is almost finished. It is based on: one phase supercritical Helium @4.4 K with internal recooling, 1.0 K temperature margin, collared coil supported by iron shell, 0.825 mm strand diameter, 3.5 µm filament size, 36 strands Rutherford cable with core (LHC dipole outer layer cable dimensions) and quench protection as the magnet is not self-protecting.

Figure 3 shows the 2D coil design and the FEM model for mechanical analysis. A temperature margin of about 0.9 K was calculated.

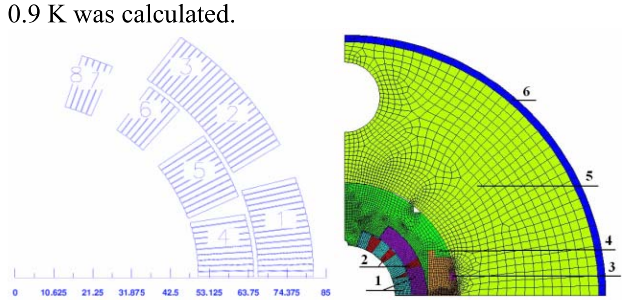

Figure 3: 2D coil design (left) and FEM model for mechanical analysis of SIS300 dipole (right). 1-coil, 2-inter-turn spacers (wedges), 3-key, 4-collars, 5-yoke, 6-outer cylinder.

SUPERCONDUCTING MAGNETS FOR STORAGE RINGS AND SUPER-FRS

Superconducting Magnets for HESR

The magnet system of the HESR is superconducting except for injection equipment, the PANDA chicane and the electron cooler.

The 48 dipole magnets are of cosine theta type with a magnetic length of 1.82 m and follow the RHIC D0 magnet design. The design allows operation with a ramping speed of 0.025 T/s. All 114 quadrupole and 48 sextupole magnets are designed for a magnetic length of 0.5 m [10]. Presently, a study is carried out to investigate the feasibility and costs of curved cosine theta dipole magnets with a bending radius of 13.7 m. This would remove the sagitta influence on the momentum acceptance

Superconducting Magnets for Super-FRS and CR

The 3 first quadrupoles and the first 3 dipoles downstream from the target will be resistive, using a special radiation resistant conductor with metal oxide insulation. All other magnets in the Super-FRS will be superconducting magnets. The requirements of the dipoles for the CR and for the Super-FRS are very similar. It was decided to create a common design for both sections, for synergy reasons. The dipoles will have a warm bore, a warm pole with large apertures (380mm x 140mm) which are required for the large emittance secondary beams. The maximum field will be 1.6 Tesla. Here, saving energy is the most important argument for the use of superferric magnets. The number of turns is high, and consequently the current in the monolith conductor is low, avoiding large cryogenic losses in the leads. Dipoles of this type are installed in the A1900 Fragment-Separator at MSU. A superconducting dipole prototype is presently being developed and will be fabricated in collaboration with the FAIR China Group (FCG).

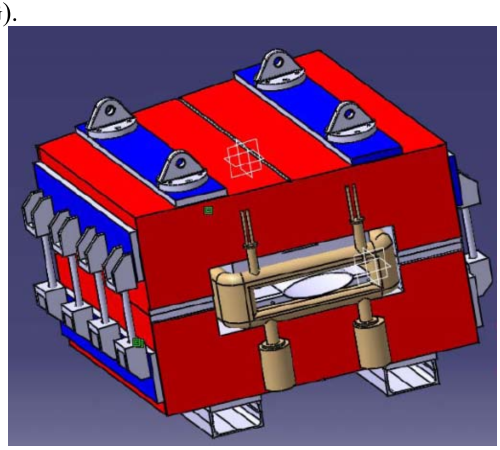

Figure 4: Preliminary design of a CR/Super-FRS dipole, made by the Institute of Modern Physics (IMP), Lanzhou, China.

The high pole tip field, due to high gradient and large aperture, requires the use of a superferric quadrupoles in the Super-FRS. Most of the cold iron quadrupoles are grouped in multiplets, together with sextupoles and embedded octupoles. Similar multiplets for the BigRIPS at RIKEN [11] have already been fabricated on an industrial scale in Japan by Toshiba Corporation [12]. A conceptual design of the Super-FRS multiplet was developed by the Toshiba Corporation, too.

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. The design of large aperture superferric prototype magnets for CR and Super-FRS has started.

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