Status of the Super-Conducting Magnet Design for the HESR at FAIR

R. Eichhorn, F.M. Esser, A. Gussen, S. Martin

Abstract— **The Forschungszentrum Juelich has taken the leadership of a consortium being responsible for the design of the HESR going to be part of the FAIR project at GSI. The HESR is a 50 Tm storage ring for antiprotons using super-conducting magnet technology. On basis of the RHIC Dipole D0 (3.6 T), the magnet design for the HESR has started recently. The principle layout of all magnets, showing the coil arrangement and the expected field quality, calculated with ROXIE will be reported. One key issue will be a very compact layout because of the rather short magnets (being 1.82 m for the dipoles and 0.5 m for the other magnets). Additionally, the need and possible solutions for a bent dipole magnet with a radius of curvature of 13.2 m will be discussed.**

Index Terms—**Superconducting accelerator magnets**

I. INTRODUCTION

The High-Energy Storage Ring (HESR) is one component of the future international facility for antiproton and Ion research (FAIR) currently under design at GSI Darmstadt [1]. It is dedicated to strong interaction studies with antiprotons in the momentum range from 1.5 to 15 GeV/c. An overview of the HESR design work as a whole is given elsewhere [2] in this proceedings, this article will be dedicated to the superconducting magnet system.

Initially, the HESR was designed to be a static accelerator in only a storage ring mode with no dynamic losses in the magnets. During the cost review process of the FAIR facility this has changed towards a synchrotron and storage ring operation. Machine cycle considerations indicated that a slow ramp rate, i.e. some 100 s does not influence the integrated luminosity. Taking this, the dipole ramp was defined to be 25 mT/s (see also tab. 1).

II. 2-D MAGNET DESIGN

The magnet system of the HESR will be one of the major initial investments as it is the case for most circular accelerators. The number of magnets required for the HESR is rather small (48 dipole magnets) compared to other machines, therefore the technical design process was governed by the search of adequate existing magnets and adopting major design features.

A. Dipole Magnets

After a careful inspection of several designs, the most suitable magnet turned out to be the RHIC-D0 magnet[3]. It has a beam pipe aperture of 89 mm, a design field strength of 3.46 T and the original magnet has a length of 2.95 m. To use it for the HESR, this has to be reduced to 1.82 m being not a severe modification. The advantage of adopting this existing magnet layout is clear: The magnet design is highly developed, and as it was made build-to-print, blueprints of all components are available. The magnet has a proven history, all kind of performance data can be found and have been measured and excellent expertise is available.

During the design process, a 4 Tesla option was discussed and studied. As the RHIC dipoles were designed to have a field of 3.46 T this would require major changes in the magnet design. As the circumference of the whole machine would only change by 7 meters, which is roughly 1 % of the ring, the additional required R & D together with the risks seems not to justify these efforts. It was therefore decided to set the design field to amount 3.6 T, which is above the design field of RHIC, but below the reliable proven achievements.

Nevertheless there is still R & D required on the dipole magnets. The HESR lattice foresees a bending angle of 7.5 ° in every dipole, leading to a radius of curvature of 13.9 m. Building and testing a magnet with such small radius of curvature (the RHIC dipoles have 220 m) has not been successful up to now. Therefore, one branch of R&D activity is devoted to the design of a bendable dipole magnet (see below).

TABLE I
PARAMETERS OF THE PROPOSED HESR DIPOLE

Number of Magnets	48
Magnetic length	1.82 m
Beam pipe aperture	89 mm
Coil aperture	100 mm
Maximum field	3.6 T
Minimum field	0.3 T
Ramp rate	25 mT/s
Current at max. field	5000 A
Operating Temperature	4.25 – 4.5 K
Cooling	Forced Flow
Cable	Rutherford 30 Strand RHIC Cable
Sagitta	0 mm
Number of Magnets	48
Magnetic length	1.82 m

Currently it is planned to have a straight magnet with the beam passing on a curved path. This requires an increased field homogeneity and an improved mathematical

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TABLE 2
MULTIPOLE EXPANSION OF THE HESR DIPOLE MAGNET (R_0=35 MM)

b1	10000
b3	0.069
b5	0.098
b7	-1.022
b9	-2.24
b11	-1.34

representation of the end field. Table 1 summarizes the magnet parameters, fig. 1 shows the results of a ROXIE [4] calculation of a 2-D cross section. This single shell design contains 5 coil blocks with a total of 40 turns. The coil aperture is 100 mm and symmetric wedges have been used. At a current of 5000 A a magnetic field of 3.6 T is expected, giving a load line margin to quench of 24 % at 4.1 K operating temperature. Tab. 2 gives the relative multipoles calculated at a reference radius of 35 mm.

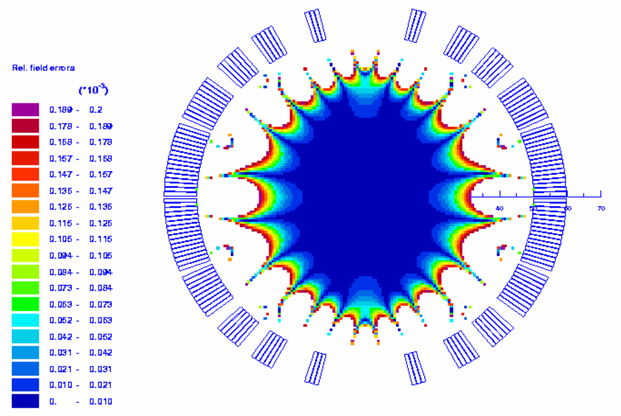


Fig. 1: 2-D field quality computation of the HESR Dipole done with ROXIE[4] assuming idealized iron. The nominal field is 3.6 T

B. Quadrupole Magnets

The beam pipe aperture has been set by beam dynamics calculations, requiring a minimal aperture of 80 mm. Unfortunately there is no RHIC quadrupole or sextupole magnet satisfying this need. Therefore, a new magnetic design is required, but the main features (beside the coil arrangement) will be based on the dipole design.

TABLE 3
MULTIPOLE EXPANSION OF THE HESR QUADRUPOLE MAGNET (R_0=35 MM)

b2	10000
b6	0.001
b10	0.004
b14	-4.69
b18	-1.18

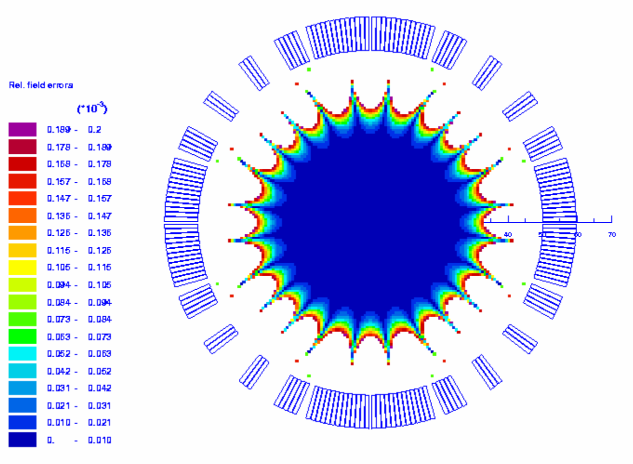


Fig. 2: 2-D field quality computation of the HESR quadrupole with a design gradient of 60 T/m.

As a first step towards the design, the 2-D coil arrangement has been calculated and optimized (see fig. 2 and tab. 3), aiming towards magnets with only small higher order components. The design so far consists of 21 turns arranged in 3 blocks. Again, only symmetric wedges have been used. Operated at 5000 A a gradient of 60 T/m is expected, the load-line margin to quench is 32 % assuming a temperature of 4.1 K.

C. Sextupole Magnets

Demanding beam quality issues force the HESR lattice to provide strong chromaticity correction and manipulation. Therefore, high field sextupoles are necessary which also have to be designed separately. Three coil blocks with a total of 13 turns (see fig. 3) will be used separated by symmetric wedges. The operating current again is 5000 A, leading to a sextupole strength of 460 T/m^2. At an operating temperature of 4.1 K, this should give a margin to quench of more than 40 %. The calculated field components are given in tab. 4.

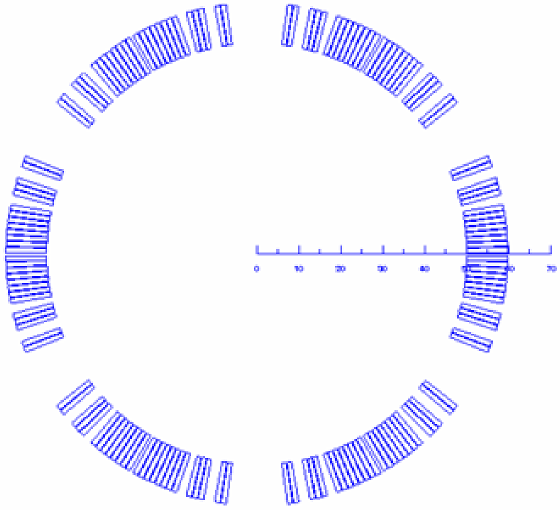


Fig. 3: Coil arrangement for the HESR high field sextupole. The expected field strength is 460 T/m^2.

III. IRON SATURATION EFFECT

As a next step in the design process the effect of the iron

TABLE 4
MULTIPOLE EXPANSION OF THE HESR SEXTUPOLE MAGNET (R_0=35 MM)

b3	10000
b9	-0.141
b15	-0.086

saturation was modeled. Therefore, the iron cross section was parameterized and the field dependant magnetization was simulated. Fig. 4 reports the cross sections and shows the iron property at low field while fig. 5 visualizes the high field situation. The change in the field components according to the change in the driving current is calculated in fig. 6.

Currently it is under investigation, whether this iron cross (RHIC type) section is also suited for the different cryogenic cooling scheme proposed for the HESR (see below). If the existing penetration wholes in the iron can accommodate a two-phase helium pipe (with usually increased diameter), the field dependent behavior of the b’s can be tolerated and thus no modifications in the iron have to be made.

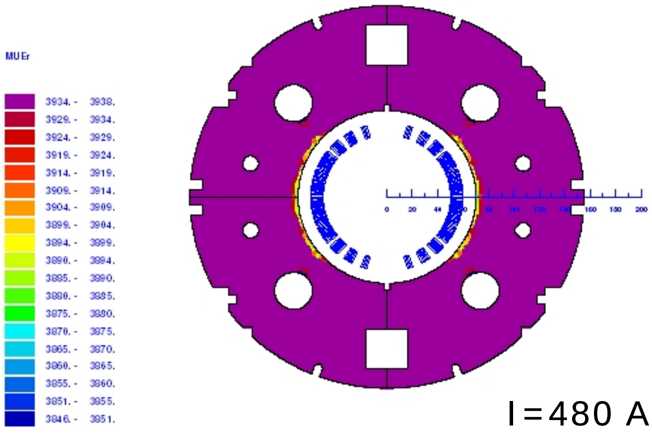


Fig. 4: Magnetic iron suszebility of the HESR dipole magnet at injection field (0.36 T).

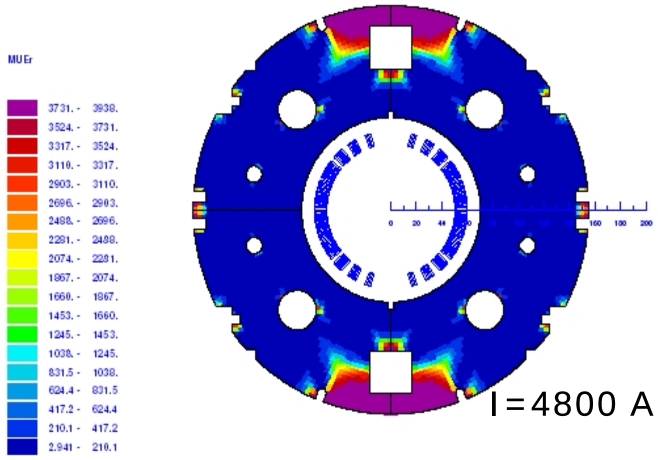


Fig. 5: Magnetic iron suszebility of the HESR dipole magnet at maximum field (3.6 T).

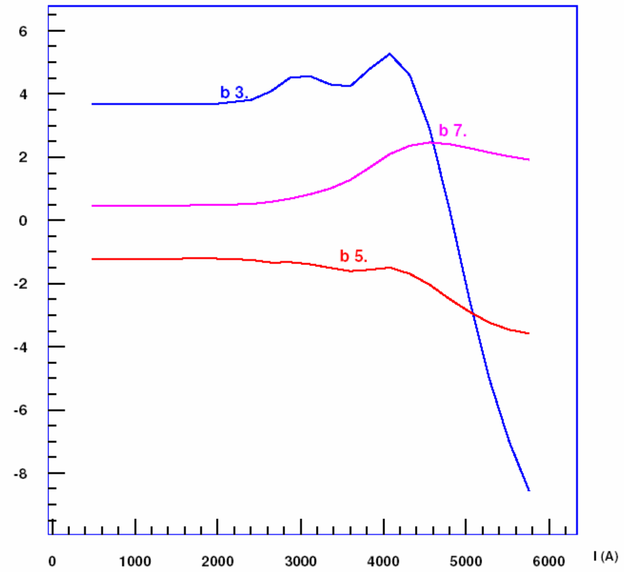


Fig. 6: Evolution of the higher order field components as a function of the driving current. Up to the nominal maximum current of 5000 A the saturation of the iron is well controlled and has only minor impact on the field quality.

IV. CRYOGENIC ASPECTS

Based on the RHIC magnet design [5], the cryogenic features of the HESR cryostats can be estimated quite accurately even in this early stage. The cooling of the magnet coils will be provided by forced flow cooling with supercritical helium. The temperature increase of the helium according to the heat transfer in the magnets should stay below 0.25 K. The maximum temperature reached in a magnet chain thus should be below 4.5 K.

In contrast to the RHIC cryogenic design, the HESR design tries to avoid the use of a cold compressor. This modified scheme was successfully applied at HERA and the TEVATRON. Instead of heaving a large mass flow in the supercritical circuit and only few re-coolers, the magnets themselves act like re-coolers. Thus the cooling of the magnets is provided by a forced flow cooling of supercritical helium, while in the same time atmospheric 4 K helium is evaporated, guaranteeing the constant operating temperature. The 2-phase helium is generated by simply expanding the super-critical helium via a JT-valve, making the layout rather simple. For stability reasons, a pre-cooler adjacent to the first magnet is introduced. Fig. 7 shows a sketch of the proposed concept.

The required cooling of 750 W at 4.5 K is equivalent to approximately 38 g/s of evaporating Helium. Assuming 3 bar pressure for the super-critical helium flow and a temperature of 4.2 K, the liquefaction efficiency of the JT-valve is expected to be above 80%.

To save longitudinal space the HESR will consist of two cryostats only, each featuring a complete 180 degree arc. The cold mass will be segmented to allow easy assembly. The grade of segmentation is currently under investigation. The cryo-module is equipped with a shield cooling at an intermediate temperature of around 50-60 K. This heat shield provides also the cooling for the current leads.

Recently, it was decided to have super-conducting magnets also in the straight sections of the HESR. As theses magnets will be adjacent to ambient components the cryogenics in theses sections have to be designed with special care.

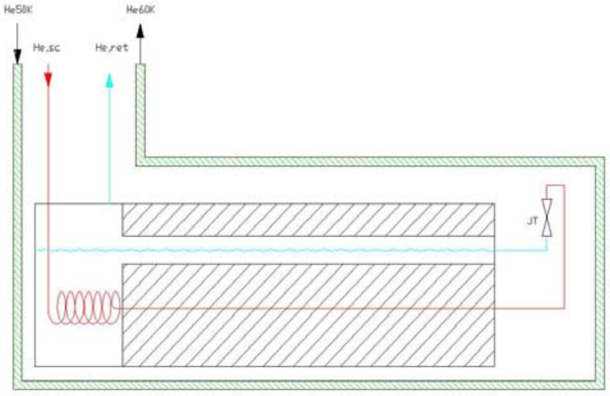


Fig. 8: Sketch of the proposed cryogenic cooling scheme of the HESR magnet chain.

V. INVESTIGATIONS ON ALTERNATIV MAGNET SOLUTIONS

Beside this straight forward approach, some demanding R&D activities have been started:

- As the beam travels on a curved path inside the dipole (which in the current design is straight) leads to certain disadvantages: The effective beam pipe aperture is reduced and the impact of higher order field components is more severe. Curving the magnet according to the beam path curvature (13.9 m) would be advantageous. For this reason several ideas are investigated to estimate the possibility and the perspectives of a highly curved dipole magnet. One possible coil arrangement is shown in fig. 8. The feasibility of this design has to be checked, especially in the magnet end region.

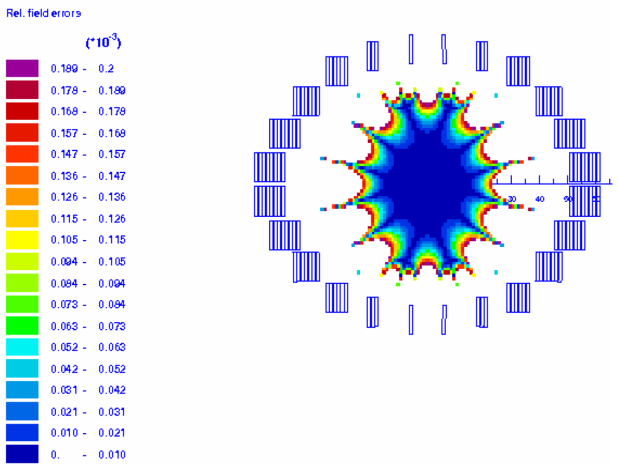
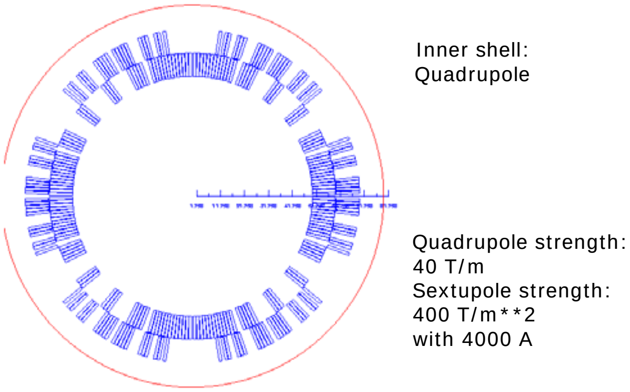


Fig. 8: 2-D field quality computation of an alternative coil arrangement, investigated to design a curved dipole magnet



- The beam dynamics in the HESR request strong sextupole magnets. Currently, a strength of 460 T/m^2 is required which could be reduced dramatically if one is able to place the sextupoles in places of high betatron amplitudes. This leads directly to a combined function magnet (quadrupole/ sextupole magnet). First magnetic field calculations have been performed and are shown in fig. 9- a carefull insight will follow concerning cross talk effects.

VI. STATUS AND OUTLOOK

So far the two dimensional magnetic design has been finished for the arc magnets, the design of the straight section magnets (with increased aperture) is still pending. First simulations on the iron saturation were performed for the dipole magnet. Similar calculations for the quadruple have to follow.

As a next step the end field region has to be designed. First calculations have started recently. The magnet design of the quadrupole and sextupole magnets has to go on including mechanical and cryogenic aspects.

Fig. 9: A combined magnet design (quadrupole/ sextupole).

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