DEVELOPMENT WORK FOR A SHORT, CURVED SUPERCONDUCTING DIPOLE MAGNET FOR THE HESR AT FAIR

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Abstract

Forschungszentrum Jülich has taken the leadership of a consortium responsible for the design of the High-Energy Storage Ring (HESR), which is part of the FAIR project at GSI [1]. Within these activities a design for a short cosine-theta superconducting dipole has been carried out together with industry partners. Its length will be approximately one third of the original HESR dipole, whereas all other design parameter will be the same. The main design criterion is the small bending radius of 15.3 m of the magnet implying that the coil itself has a curved shape. Besides the geometrical design of the cold mass, this paper focuses particularly on the finite element calculations from the assembly through the cool down to the operating temperature of the magnet. First manufacturing tests as well as a report on the achievements so far are presented.

INTRODUCTION

The HESR, a 50 Tm synchrotron/storage ring for strong interaction studies with antiprotons, was first designed as a superconducting accelerator [1], [2] and the development of a curved prototype magnet was a major task. Although there has been a decision to favour an accelerator design based on normal conducting magnets, the once started development was continued up to a fixed milestone.

In order to avoid designing entirely new dipole magnets it was decided to adopt as many features as possible from the successful RHIC D0 design by Brookhaven National Laboratory (BNL) [5]. However, detailed design studies on the available space for HESR showed that magnets with a finite radius of curvature are preferred over straight ones to avoid collisions of the particles with the beam tube and to better exploit the good-field region of the magnets for the particles on their curved paths.

Because of the very short bending radius it is not possible to introduce the curvature while welding the two half-shells under pressure as it has been done before for large bending radii. Therefore, a manufacturing study combined with a detailed design of the cold mass was carried out together with the company Babcock Noell GmbH, Germany. From the realisation of the curvature of the yoke to the wiring design of the bus-bars inside the lead end of the magnet many problems have been solved always keeping in mind to minimize the development work and the production costs.

Field analyses have been carried out in order to assess the effects of curvature on the field homogeneity of the dipole magnets [3]. Also aspects of quench analysis, cryogenics or magnet testing have been studied [4].

SHORT DIPOLE DESIGN

The length of the prototype was reduced to roughly 1 m by retaining all the other design parameters of the original dipole magnet. Only some aspects of the interconnection of the bus-bars were changed to minimise the complexity of the non-lead end. The main parameters of the short prototype magnet are summarized below. A cross section of the prototype is shown in Fig. 1. Fig. 2 gives an impression of the cold mass and the end cover.

Table 1: Features for the short, curved prototype magnet

Feature	**Value**
coil aperture / radius curvature	100 mm / 15.279 m
magnetic / total coil length	1.024 m / 1.240 m
design current	5000 A
max. / min. flux density	3.6 T @5300 A / 0.3 T
max. field variation @r=35 mm	$< 10^{-4}$
ramp rate	25 mT s^{-1}
cable	Rutherford 30 strand
cooling	Forced flow LHe @ 3 bar
inductance	6.2 mH
stored energy @ 5000 A	77.5 kJ
margin to quench	27 %
total mass	approx. 850 kg

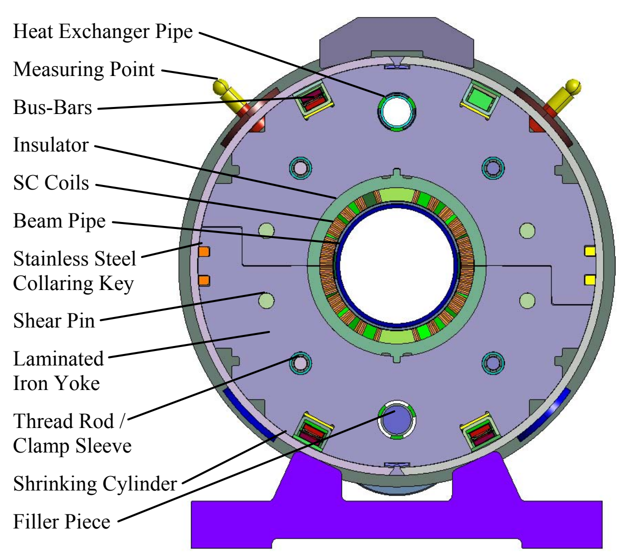

Figure 1: Cross section of the curved superconducting dipole for the HESR@FAIR.

The cosine theta coils are covered with a G11 insulator and then collared with the laminated iron yoke. The heat exchanger pipe is located in the upper part of the yoke, whereas the corresponding opening in the lower yoke is filled with an aluminium rod. Three pairs of bus-bars together with a filling piece are arranged symmetrically at the circumference of the yoke. The laminated yoke consists of 6 mm iron plates, arranged to 210 mm long pieces as sub-units. To realize the curvature of the magnet inside the yoke, two of ten plates are machined on one side to a conical shape (marked yellow in Fig. 2). Four thread rods together with four clamping sleeves per yoke piece ensure a filling factor of the yoke of at least 98% in axial direction.

All the bus-bars are installed in series whereas the bus-bar connections together with the interconnections of the quench diode are located at the lead end. The quench diode is still based on the RHIC design. The non-lead end (not shown) only contains the returns of the bus-bars. The end cover design and the layout of the dipole are shown in Fig. 2.

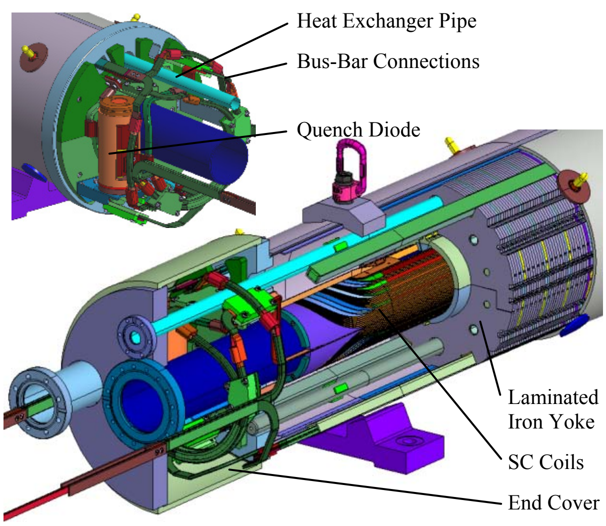

Figure 2: Cross-sectional view of the short dipole and view inside the lead end.

STRUCTURAL ANALYSIS

A mean compressive tangential pre-stress of 60 N/mm² in the coils is the structural objective to allow for safe operation under superconducting conditions. By inserting shims with variable thickness between the upper and lower part of the coils and between the coils and the insulator, the compressive pre-stress in tangential direction after cool-down can be controlled. The development of plastic strains is allowed only during the assembly of the yoke, but not during cool-down and operation.

Stress and Displacement Calculations

The stress and displacement calculations determine the stresses in the components and the differences in geometry of the magnet during the assembly, the cool-down and the operating stage.

Thus, four load steps can be defined:

1. pre stressing after yoke assembly by inserting keys under pressure,
2. pre stressing after half-shell assembly by shrinking due to welding,
3. shrinking during cool-down of the magnet and
4. Lorentz forces inside the coils during operation.

Fig. 3 shows the mean compressive tangential stress in the coil cables after load step 2. The mean value reaches about -82 N/mm², but after cooling down it meets the objective of -60 N/mm² and with Lorentz forces included it stays even below that value (Fig. 4).

Fig. 5 gives an impression of the expected equivalent stress inside the shrinking cylinder after load step 4. The maximum values of about 220 N/mm² are reached in the region of the bus-bar holes of the yoke, the mean tangential pre-stress is about 200 N/mm².

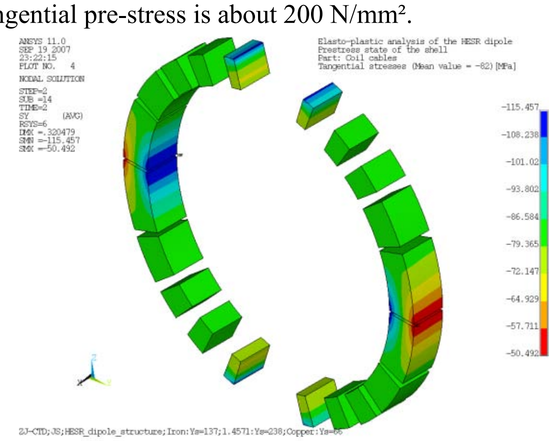

Figure 3: Mean compressive tangential stress in the coil cables after load step 2.

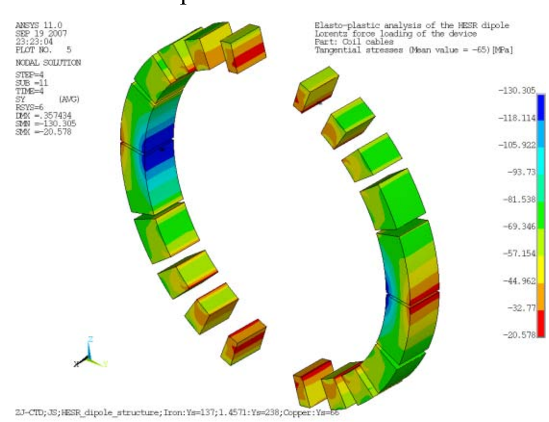

Figure 4: Mean compressive tangential stress in the coil cables after load step 4.

To compare 2D results and 3D results including the curvature, Fig. 6 shows as an example the radial displacement in the yoke after load step 4 with 3D modelling. The difference between horizontal and vertical direction ranges from 130 - 85 µm and from 75 - 30 µm during all the load steps. The comparable difference calculated with a 2D modelling ranges from 120 - 100 µm and from 120 - 80 µm (not shown). For a comparison with the coil cables these values ranges from 110 - 90 µm and from 110 - 70 µm (not shown). The yoke as well as the coils obtain a oval shape.

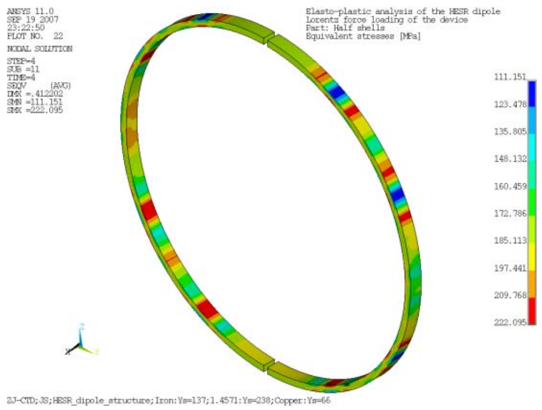

Figure 5: Equivalent stresses in the half-shells (step 4).

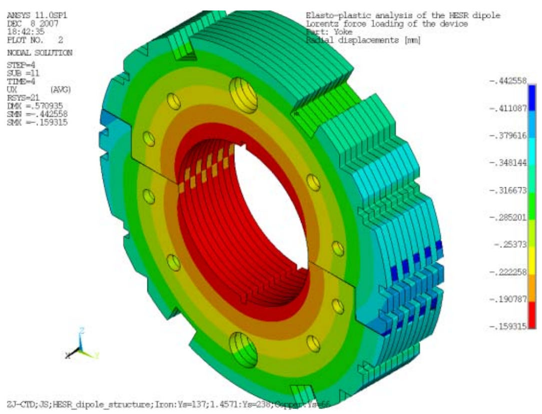

Figure 6: Radial displacement in the yoke after load step 4 with 3D calculation.

Conclusion

The design meets the intended mean compressive tangential pre-stress in the coils of 60 N/mm². Plastic strains develop in the yoke only during assembly while all the other parts of the setup show purely elastic behaviour.

The displacement field leads to an oval shape of the yoke and the coils, which might influence the magnetic behaviour just as well as the gap opening between the lower and upper part of the yoke.

The results of the 2D and 3D calculations follow the same tendency and the quantitative differences are marginal.

MANUFACTURING TESTS

In order to support the theoretical investigations and to get more experience some manufacturing tests were carried out, e.g. some pieces with complex geometry or special material. Fig. 8 shows the manufacture of a half-shell made from a thick stainless steel plate (instead out of bent tubes for a series production) and a spacer element made from a G11 plate (see inset). Both the half-shell and the spacer element displayed the requested geometry and tolerances.

Figure 8: Manufacture of the concave half-shell (shrinking cylinder, AISI 316Ti) and of a spacer element (G11) at Jülich.

CONCLUSION AND OUTLOOK

Based on the RHIC D0 design a new curved dipole magnet was developed. Magnetic field calculation both to optimize the magnetic field and to analyse the influence of the curvature were made. Structural finite element calculations to analyze the pre-stressing during assembly, cooling down and operation state were done with two-dimensional as well as three-dimensional models. In addition some manufacturing tests of some pieces with complex geometry or special material were carried out successfully.

Together with the positive statement from our industry partner concerning manufacturing and assembly of the whole magnet the next step could be prototyping.

According to FAIR project policy a new HESR lattice for normal conducting magnets was developed.

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