Pre-manufacturing design of the superconducting dipole magnet for the CBM detector

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***Abstract*— The CBM detector will research compressed baryon matter on the FAIR facility, GSI, Darmstadt. The superconducting dipole magnet of this detector provides vertical magnetic field with field integral ~ 1 T*m along a beam length of 1 m. The warm bore distance between the dipole coils is 1.44 m. Maximal magnetic field on the superconducting winding is 3.6 T. The stored energy of the magnet is ~ 5 MJ.**

The superconducting coils having 1.34 m of inner diameter will be made of NbTi wire having Cu/SC ratio of 7/1. The SC wire cross-section bare size is 2.02 mm × 3.25 mm. This wire of 30 km of total length in 6 pieces was manufactured by extrusion monolith technique.

The iron yoke having 139 t weight is a part of the CBM magnet. It was manufactured and assembled.

The SC coils were designed according the indirect cooling principle. The superconducting winding is embedded in copper case and will be cooled by 4.5 K helium going through the copper tube attached to the copper case. Two dummy coils were manufactured and tested to choose the epoxy impregnation procedure.

The cooling helium will circulate between the cryostat containing 150 l of LHe and two coils in thermosyphone regime in single loop. The vapor quality at the outlet of the thermosyphone loop is ~ 10%.

The each coil is affected by 3 MN axial force towards the nearest iron yoke. The single cylinder GFRP support strut was designed to withstand this force to have the safety factor > 4 with respect to the ultimate strength and buckling. The GFRP material was chosen and tested.

***Index Terms*— design of the superconducting magnet, indirectly cooled magnet, superconducting dipole magnet for detector, thermosiphon cooling**

I. INTRODUCTION

THE Compressed baryon matter (CBM) detector will play an essential role in the Facility for Antiproton and Ion Research (FAIR) in Darmstadt. The goal of its experiment is to explore the QCD phase diagram in the region of high baryon densities using high-energy nucleus-nucleus collisions that should substantially improve our understanding of the properties of nuclear matter [1]. The FAIR synchrotrons will produce for the CBM experiment the ions with energies from 11 A GeV to 45 A GeV and protons with energies from 29 GeV to 90 GeV.

The superconducting dipole magnet will provide the magnetic field in the silicon tracking system (STS) of the detector [2]. The free aperture of the magnet should be 1.44 m for vertical gap and 3.0 m for horizontal space for the STS placement. The main magnetic field demand for the magnet is to produce 1 T*m field integral along the beam line. The fringe field outside the magnet by the ~ 0.3 m distance should be minimized, below 2 mT at the placement of the Cherenkov detectors. The cryogenic system of the magnet was based on 4.6 K and 50 K gas helium flows supplied by FAIR cryogenic plant that was described in [3].

The paper presents the design of the superconducting dipole magnet developed up to production status. The peculiar items of the magnet are indirectly cooled dipole coils embedded in copper cases. The coils serially connected to the LHe tubes will be cooled by thermosiphon flow at expected heat load of 5 W per coil. The support strut design is based on large single GFRP strut instead of several small ones. The manufactured parts will be also described.

II. MAGNET DESIGN

The main parameters of the magnet are listed in the Table 1.

The view of the dipole magnet is shown on the Fig. 1. It consists of upper and lower coils, the iron yoke, the support and the cryostat. The iron yoke is part of magnet system, and serves as mounting frame for the coils and the cryostat. The support is needed for the alignment purposes: in x-y-z directions and rotation about vertical axis of the magnet.

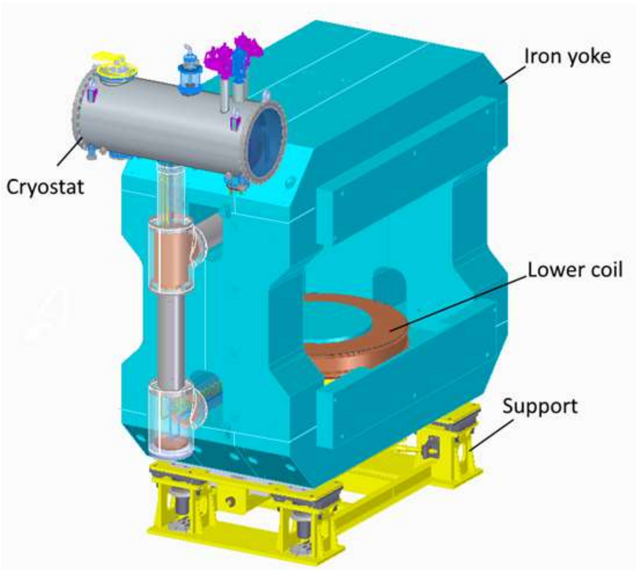

Fig. 1. The general view of the CBM magnet.

This work was done within the contract between the FAIR and BINP started in December 2016.

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TABLE I
MAIN PARAMETERS OF THE MAGNET

Parameters	Values
Inner cold diameter of the winding, mm	1396
Cross section cold sizes of the winding, mm^2	132x157
Number of turns per coil (33 turns per 52 layers)	1716
Operating current Io, A	666
Test current, Io*1.05, A	700
Magnetic field on the coil Bmax, T	3.6
The field integral along the beam line, T*m	1,0
Io/Ic ratio along the load line, %	~50
Cooling helium temperature, K	4.5
Stored energy of the magnet, MJ	5.1
E/M ratio for two windings, kJ/kg	3.1
Iron yoke weight, tons	139

The cross-section of the upper coil is shown on the Fig. 2. The lower coil has identical design. The SC winding will be wound with SC wire made by monolithic technology [4]. The cross-section bare size of the SC wire is 2.02×3.25 mm^2 and the length of one piece is ~ 5.2 km. The insulation of the wire has 0.3 mm total thickness of Kapton and GFRP tapes. The interlayer insulation will be of 0.2 mm thickness made of G-10 sheet. Each winding will be wound of two pieces of the SC wire, so the splicing will be in the middle. The SC winding will be surrounded by the copper case that will serve as winding mandrel, mold and for the thermal stabilization intercepting the external heat in-leaks. The helium cooling tube having inner diameter of 15.3 mm will be soldered to the copper case as seen in Fig. 3. The fixation system of the SC winding includes the eight titanium rods and the large GFRP support strut, Fig. 3. The titanium rods are needed for the assembling purposes mostly while the GFRP strut should withstand ~ 3 MN vertical force attracting the winding to the neighbor horizontal iron blocks. The radiation shields will be made of aluminum and will be covered by multilayer superinsulation. They will be divided on eight electrically insulated parts, as seen in Fig. 4, to decrease values of Lorenz forces induced during quenches.

The coils will be assembled together with the iron yoke blocks of the iron yoke. The wire splicing and tubes connections will be in one assembling place, shown in Fig.5.

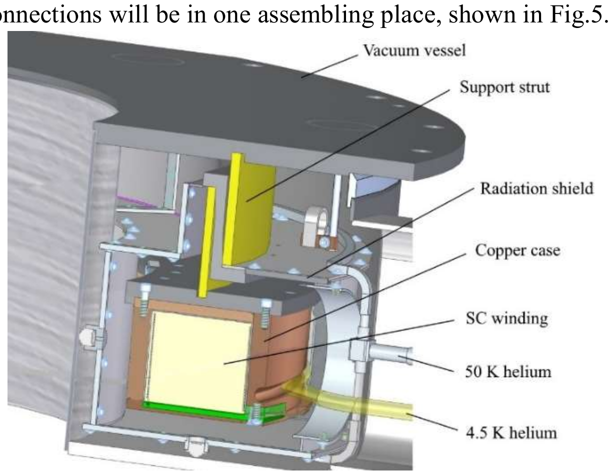

Fig. 2. The cross-section of the upper coil.

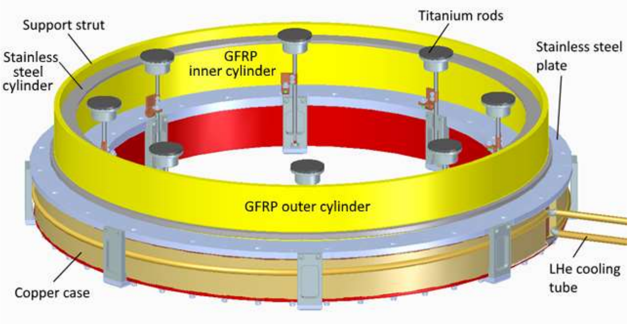

Fig. 3. The upper coil – the view of the SC winding, cooling tube and fixation system. Titanium rods fix the coil during assembling.

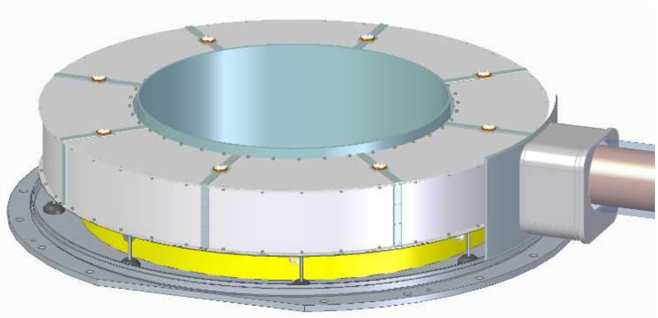

Fig. 4. The lower coil surrounded by the aluminum radiation shield divided in 8 insulated parts.

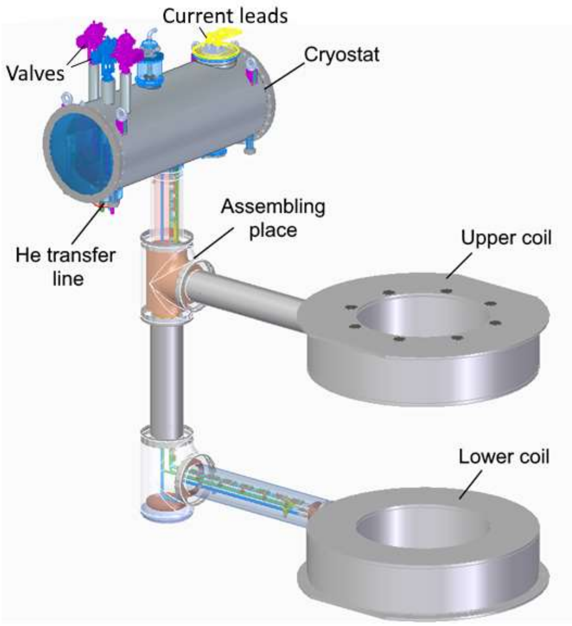

Fig. 5. The separated view of the assembled coils and the cryostat.

The separated view of the coils and the cryostat is shown on the Fig. 5. The assembling place will be disconnected at least two times because the test site will be different to the final one. The helium transfer line will supply the magnet system with helium flows at 4.6 K@ 3 bar and 50 K @ 18 bar. Three cryogenic valves are seen on top of the cryostat which will be used during the cooling stages and ordinary operation. The liquid helium at 4.5 K@ 1.3 bar will be accumulated in the 150 l volume of the cryostat. During ordinary operation the

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coils will be cooled by 4.5 K helium in thermosiphon regime. Most length of the thermosiphon loop is placed horizontally. The thermosiphon cooling system design and analysis requirement was 10% vapor quality and experimental evidence for a similar design is presented in [5].

It is also possible to cool the coils by 4.6 K helium going from the cryogenic plant during some time depending on stability of helium flow parameters [3]. The current leads will involve HTSC inserts using SuperOx 700 A@77 K tape. The 50 K helium flow will cool the current leads, radiation shields, cryogenics valves and other suspension systems.

III. Power Supply and Energy Extraction System

The powering and quench protection system will provide all modes of powering operations and should dissipate the most part of the stored energy on a dump resistor after detection of a quench. The system consists of the power supply, quench detection subsystem and energy extraction subsystem.

Requirements for the quench protection system are:

- The amount of the stored energy to be extracted is up to 5.1 MJ.
- Stored energy should be extracted to the external dump resistor with the value of 1 Ohm. The middle point should be introduced and grounded in order to minimize the voltage between coil and the ground;
- The active elements of the dump resistor should not be hotter than 100° C.
- Quench detection circuit should provide fast detection of the normal phase appearing. The discrimination time should be about 10 ms and the threshold – about 0.1 V (0.1 V corresponds to 6 turns in the normal state).
- For the bus bars the threshold is 0.01 V for quench detection and 500 ms for validation;
- The magnet powering circuit has 2 fast opening switches, at least one, must open within 50 ms of quench detection to force the current through the dump resistor.

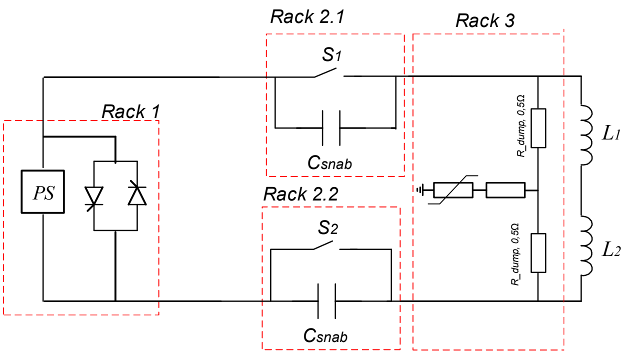

Fig. 6. Powering system of the CBM magnet

IV. Design Calculations

A. Magnetic field calculations

Various magnetic field tasks were calculated using ANSYS codes, Fig. 7. Main results of the magnetic field calculations are listed in the Table 1 and as follows:

- The integrals around the center of the magnet is 1.012 T*m for 666 A.
- The resulting vertical force on one coil with respect to the opposite one is repelling of 3.05 MN value at 700 A current. The horizontal forces of de-centered coil are about 20 kN per 5 mm shift that is not much. Azimuthal variation of the forces values along the coil is below 5%.
- The forces acting on the radiation shields during a quench are below 100 N as the shields were electrically separated into 8 parts, Fig. 4.

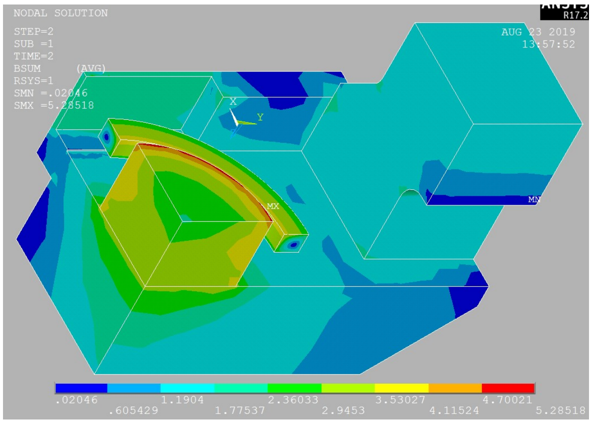

Fig. 7. The field map of absolute value of magnetic field in the 1/8 part of the magnet.

B. Mechanical calculations

The ANSYS FEA was used for the deflection and stress analyses. The strains and stresses were evaluated in the SC winding structure and support strut.

The large support strut will be made of GFRP material. It should withstand the 3 MN of axial load, have minimal displacement, give minimal heat load at 4.5 K and have enough safety factor in buckling analysis. The recommended safety factor for such support should be at least 4 [6]. Some results of stresses and strains calculations are shown in Fig. 8. The benefit of single large GFRP support strut is the uniform distribution of stresses in the SC winding as in the strut itself.

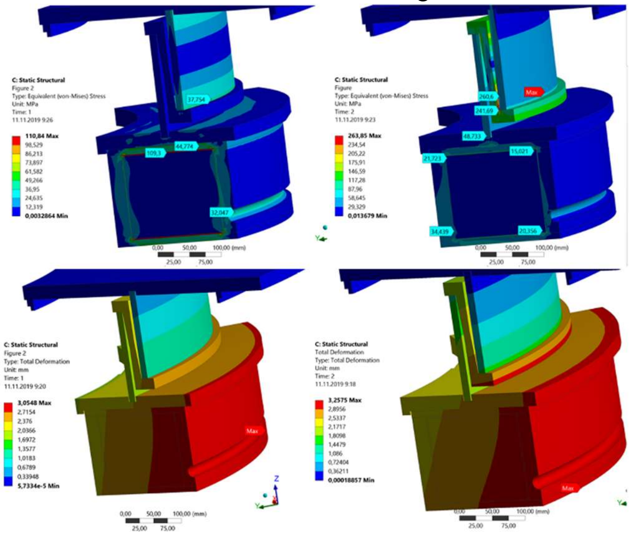

Fig. 8. The von Mises stress after cooling down – a, after Lorenz forces applying. Total deformation after cooling down

– c, d – after Lorenz forces applying.

The buckling analysis gave safety factor of 5.2 value for the chosen material mentioned above.

C. Quench calculations

Although the magnet will be equipped with an external dump resistor, it was demanded that the magnet should be quench protected by passive protecting methods. So, the quench calculations were also aimed the case when the all stored energy would be dissipated in one coil only without the dump resistor. The calculated results of this case are shown in Fig. 9. The eddy current in the copper case has minor effect on the coil current. The 140 K hot spot temperature is considered as acceptable with respect to thermal stresses in the winding. The maximal value of the internal voltage, about 550 V, will be between the coils.

The calculations with 1 Ohm of dump resistor give the 106 K of hot spot temperature and 236 V of voltage between the coils. About 50% of the stored energy will be dissipated in the dump resistor.

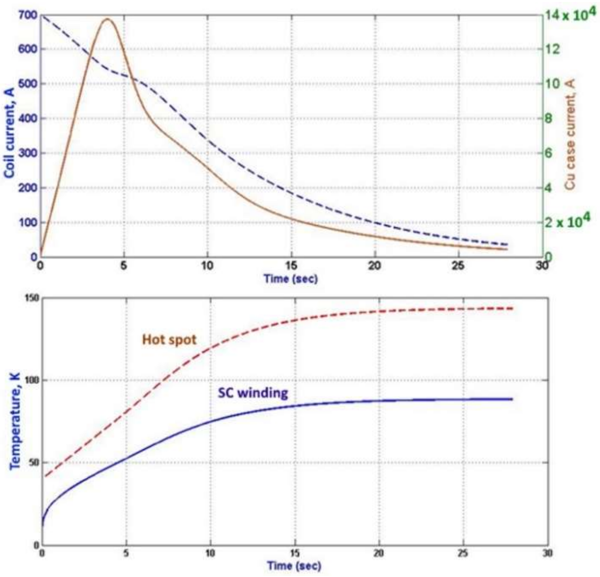

Fig. 9. The results of quench calculations of short-circuited magnet. The current in the copper case is to be compared with 1.14 MA of total current in the winding.

V. Manufacturing Status of the Magnet

By April 2022 the iron yoke was completely manufactured and assembled in the BINP test place, Fig. 10.

The six pieces of SC wire having total length of ~ 32 km were manufactured and wrapped with electrical insulation consisting of 0.1 mm thickness of Kevlar tape and 0.2 thickness of glass cloth tape.

Extensive efforts were done testing the samples from GFRP cylinders of different manufacturers. The ultimate strength, elasticity modulus and thermal conductivity coefficients were measured for small samples. The best material was made of glass roving and glass cloth as reinforcing elements. The glass cloth is important with respect to axial rigidity and stiffness of the strut because it contains axially directed glass strings [7]. The ultimate strength of the chosen GFRP cylinder is 200 MPa. The large GFRP cylinder having inner diameter of 1640 mm and thickness of 12 mm was tested under 1000 tons press to confirm the consistency of the material quality and to see buckling behavior. The test results met all requirements discussed earlier.

Fig. 10. The view of the assembled iron yoke on the test place in BINP.

Two mock-up coils were manufactured to adjust the winding tools and to ensure technology of impregnation by epoxy resin with BN filler of ~ 1 um grain size.

VI. Conclusion

The superconducting dipole magnet was developed until manufacturing stage. Most drawings are finished. The iron yoke is assembled. The features of this magnet are thermosiphon cooling of serially connected two coils, large GFRP support strut and monolith SC wire.

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References

[1] P. Senger, *“The Compressed Baryonic Matter Experiment at FAIR”* JPS Conf. Proc. 022001 (2015).

[2] P. Larionov, *“Overview of the Silicon Tracking System for the CBM experiment”* J. Phys.: Conf. Ser. 2015, 599 012025

[3] A. Bragin *et al., “Development of cryogenic cooling system for the superconducting dipole magnet of the CBM detector”,* Proc. of Conf., 2019, doi: http://dx.doi.org/10.18462/iir.cryo.2019.0034.

[4] Yu.V. Karasev et al. *“The Superconducting NbTi Wire for the CBM Dipole Magnet”*, Journal of Superconductivity and Novel Magnetism 35(4) DOI:10.1007/s10948-022-06143-6

[5] V. Kleymenov *“Mechanical behavior of the FAIR Super-FRS dipole during the cold tests”*, MT28 presentation. Personal discussions.

[6] W.N. Mascarenhas, C.H. Ahrens, A. Ogliari *“Design criteria and safety factors for plastic components design”*, Materials and Design, vol. 25 pp. 257–261, 2004 .

[7] R. Reed, M. Golda *“Cryogenic composite supports: a review of strap and strut properties*” *Cryogenics*, vol. 37, no. 5, pp. 233-250, May 1997