THE DIPOLE MAGNET IRON YOKE DESIGN FOR THE ALICE DIMUON ARM SPECTROMETER

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Abstract

Iron Yoke of about 820 tons for the Dipole Magnet with aluminium water cooled winding has been produced for the DiMuon Arm Spectrometer of ALICE experiment at the LHC. This magnet provides the bending power to measure the momenta of muons. The initial design of the magnet was prepared by JINR. The main feature of this magnet is the huge uncompensated force applied from the neighbouring solenoid magnet L3. The yoke of the magnet was manufactured and preliminary assembled in Russia in Tver region at SMZ manufacturing company and transported to CERN. The results of electromagnetic forces calculations and deflected mode analysis are presented. Design, following up of the yoke production and the main features of the technology process are discussed.

Key-words: Electromagnetic Forces, Magnetic Core, Iron Yoke, Spectrometry, Magnetic Field Calculations.

1. Introduction

A large conventional Dipole Magnet (DM) is required for the DiMuon Arm Spectrometer of ALICE experiment at the LHC. It provides the bending power to measure muons momenta. Design work has been performed at JINR (Dubna) and at CERN. A general description of the design of the magnet and current status of the work are presented in [1] - [4]. An important component part of the DM is 820 tons iron yoke. The general view of the iron yoke preliminary assembled in horizontal position is shown at fig.1.

2. Iron yoke design description

The general concept of the DM is based on a window frame return yoke, fabricated from low carbon steel sheets. The flat vertical poles follow the defined acceptance angle of 9 degrees. The excitation coils are of saddle type. The coils are wound from hollow aluminium conductor and cooled by circulating de-mineralized water. The main flux direction in the gap is horizontal and perpendicular to the LHC beam axis. The DM will work in a cyclic regime over a period of ten years - the full number of operation cycles will be about 4000. The general view of the iron yoke is shown at fig.2.

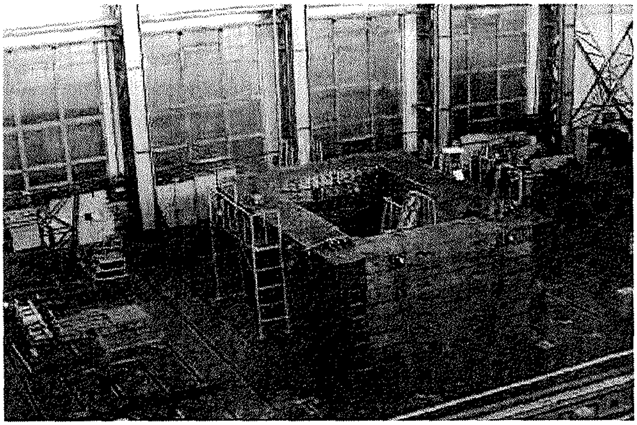

Figure 1: Yoke of the ALICE DM assembled in horizontal position

The DM iron yoke is of mountable-and-dismountable type. It's mass is about 820 tons, the height - 9022 mm, the width - 6896 mm, the length - 3120 mm. The iron yoke consists of four blocks: bottom and top blocks and two uprights, which produce a trapeze form aperture $\pm 9^o$ (2972 mm minimum width), 6090 mm in height. A block consists of seven modules each, which have been rigidly connected by means of bolt flanges and a tie rods system. The modules has mass within 26-30 tons. These steel modules initially have been prepared for other purposes, but have never been used. Each module consists of about 15 metal plates 30 mm in thickness connected with each other by welding trough drilled holes $\oslash$40 mm with pitch 800 mm as on a chess-board. The material of the iron plates is a low carbon steel - Steel 10 (GOST 1577-93). Content of carbon according to the Russian standard is 0.07 - 0.14%. The flanges are welded by arc welding at the extremities of all bottom and vertical beams to provide mutual fixation of the beams. At the beam extremities for fixation of the vertical and top beams there are additional special slots for inserts, supplied with threaded holes. The surfaces of the beams have been machined to provide the precise dimensions and to minimize the gaps between the the beams. To provide the bending resistance of the beams under action of attractive forces in L3 direction the metal palates 30×400 mm have been welded to the vertical beams to create a "box" profile. The vertical beams have the rests (50×400 mm in cross section) on the bottom and top beams to resists attractive forces between pole beams. There are vertical, 40 mm plates on the bottom beams extremities which are used to fixate the yoke to the foundation.

For securing of the base requirements special design decisions have been accepted as follows:

- The first assembly of the yoke is to be in horizontal position;
- The geometrical reproducibility of the aperture within 3mm is to be provided by shim polishing in the vertical/horizontal beams connections;
- Mutual fixation of the beams by dowel pins ($\oslash 40 \times 150$ mm Steel 45) is to be done

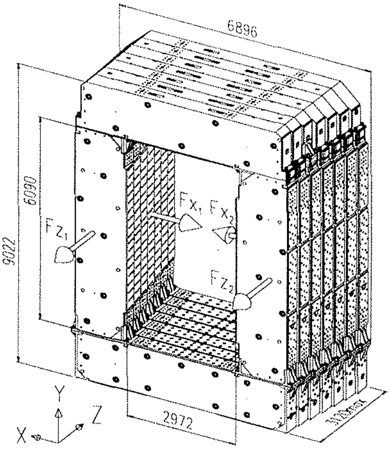

Figure 2: General view of the iron yoke

at the first horizontal assembly. All subsequent assemblies have to be done without additional mutual adjustment of the beams and correction of the shims;

- Space position of the DM aperture is adjusted by means of shims between the foundation surface and the seat surface of the magnet.

The horizontal and vertical beams have been tightened by means of tie rods and bolts M36 (steel 40X). The layers of the magnet have been tightened by tie rods M72 (high-strength steel 40HN2MA) through ⌀87 mm holes. The nuts M72 at the ends of the tie rods have been embedded into the side beams 1 and 7. Standard nuts (steel 40X) have been mounted in couples at the downstream side of the yoke and SUPERBOLT High Strength Tensioners CY-M72×6/W (steel 4340HT)hawe been used at the upstream side. These special nuts have been used to lighten the tightening process of the nuts up to 190 tons. Additionally, after final assembly of the yoke at the operation position, the vertical beams in couples and horizontal beams in couples, are to be welded by arc welding at the outer surface of the yoke.

The DM will be installed on a concrete foundation with a metal plate embedded in the foundation surface, which can be aligned before assembly of the yoke and serves as a geometrical reference. The finally assembled yoke will be fixed there by means of arc welding of brackets to the bottom beams and to the above-mentioned steel plates.

Several assemblies of the DM yoke have been planned. The construction concept takes this into account. The first "horizontal" assembly of the yoke has been necessary in order to verify and correct the geometry and to establish all reference surfaces and locate the reference and alignment dowels. The assemblies of the DM in the underground area at the experimental hall UX25 will be carried out at temporary position to validate the assembly procedure, followed by the final assembly of the magnet at the operation position.

3. Calculations of magnetic forces

Vector Fields TOSCA Version 8.7 code has been applied for the ALICE dipole magnet field/forces calculations. The calculations of magnetic forces have been undertaken to estimate mechanical stability of the yoke for different options of the magnetic circuit configuration:

- Preliminary assembly of the magnet - Detached Dipole Magnet,
- The entire magnet system geometry including L3 Magnet, Dipole Magnet and Muon Filter (Entire model),
- An option of the entire geometry when L3 Magnet switched off ("L3 off"),
- An option of the entire geometry when Dipole Magnet switched off ("DM off").

The whole region has no symmetry planes because:

- the field induced by the solenoid of the L3 Magnet is symmetrical with respect to the z-y plane, while the field induced by the Dipole Magnet winding is anti-symmetrical with respect to the same plane;
- the geometrical centre of the Dipole Magnet is shifted by 0.3 m in y-direction relative the central axe of the L3 Magnet.

Electromagnetic forces applied to the yoke elements have been analyzed in conformity with requirements of OPERA-3D Reference Manual. The results of magnetic forces calculations can be seen in table1.

Table 1: Components of the forces applied to the Dipole Magnet parts at operational conditions

	F_x, kN	F_y, kN	F_z, kN
Yoke	140	47	-1368
Coils	-53	9	628
Sum	87	57	-740

4. Strength analysis

ANSYS 5.3 code has been used to perform structural finite element analysis of the yoke [5]. Additionally, all ANSYS calculations have been controlled by theory of elasticity simplified calculation procedures. The results of these simplified calculations have been used for estimation of safety margin of the constructive elements strength. Comparison of the results shows that the stresses obtained by ANSYS calculations are lower than results of simplified procedures of theory of elasticity. This means there is an addition to the safety margin of the yoke.

Volumetrical electromagnetic forces, gravity, thermal and seismic loads have been considered in the calculations. The immediate proximity of the DM and L3 solenoid exerts a very sufficient influence on the force interaction of the magnets - the attractive force of 1370 kN is applied to the DM. The forces, which are applied to the yoke vertical beams are unsymmetrical ones, because of unsymmetrical character of the magnetic field. For example unequal forces 767 kN and 632 kN are applied to the vertical beams. These beams which serve as magnet poles are attracting to each other by force of 4700 kN. In vertical direction the beams are pressed by force of 11500 kN, which is applied to the flange connections of the horizontal and vertical beams. The electromagnetic loads, applied to the coil parts and thermal loads, caused by temperature drop across the coil width are transmitted from the coils to the yoke beams in some fixation points with the help of the coil supports. Seismic load calculations have been fulfilled in accordance with Code project [6], which is based on [7].

The mechanical loads applied to the yoke will be different in operation regimes, as follows:

1. **Normal operational regime.** The yoke is loaded by the electromagnetic forces of nominal value (the currents in L3 and Dipole Magnets are 100% of the operational values). Temperature drop across the coil width is 30K.
2. **Violation of normal operation regime.** This regime corresponds to overloading of the yoke by the electromagnetic forces of 110% of nominal value and by temperature drop 40 K.
3. **Emergency regime.** In the emergency regime the dipole magnet is loaded by the forces of the normal operational regime and by seismic load simultaneously.
4. **Test regime.** The loads are in conformity with the detached dipole magnet is tested without L3 magnet.

Design criteria and the yoke loading regimes have been established according to Russian National standards [8, 9]. Initial coefficient value of friction between neighbouring beam surfaces without special machining, is to be $f_0 = 0.25$. Reliability index required the calculated value of friction coefficient to be equal to $f = 0.12$. Frictional forces between the beams, which correspond to this friction coefficient, are not sufficient to transmit shear loads between the beams. Cylindrical pins and welded connections have been used to transfer the shear loads between the beams. Vertical beams have been reinforced with side steel plates to increase the rigidity and strength for the shear loads (fig.3)

Design model of a beam includes a rectangle box, which is created by side steel plates, joined by weld seams and flexible filler (steel plates), which is not rigid for shear. This filler has been represented as a solid anisotropic material to decrease the number of finite elements in the calculations. Equivalent shear modulus of the metal plates, joined by the local weld seams, is 240 MPa according to ANSYS calculations. It has appeared that the compressive forces are not distributed for yhe whole volume of the material, and are concentrated in the areas bordering to the tie rods. In the uncompressed areas the modulus of elasticity for tension has been accepted to be $E = 0$ MPa. In the same areas the modulus of elasticity for compression has been accepted to be $E = 200$ GPa. The shear moduli between metal plates in these areas are $G = 240$ GPa. In other areas the material characteristics are equivalent the characteristics of the steel $E = 200$ GPa, $E = 77$ GPa.

In case of the normal operational regime violation, the effecting loads are increased 1.1 times. According to the standards, the permissible stresses are to be increased by

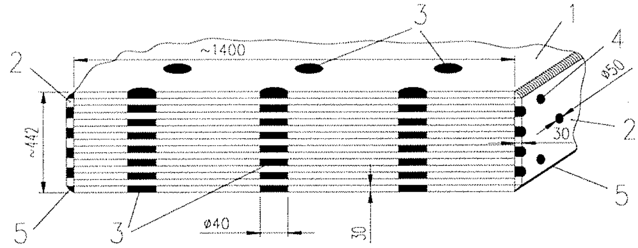

Figure 3: Cross section of a beam: 1 - Beam plates, 2 - Outside plates, 3 - Inner weld points, 4 - Weld points on the side plates, 5 - Weld seams

20%. This means that in the case of the normal operational regime violation the safety margins will not be less than those under the normal conditions. In the emergency regime the permissible stresses are to be increased by 40%. In spite the additional seismic load, the yoke will keep the stability in emergency regime.

Strength Analysis of the iron yoke

Upon analysis of calculated eigenfrequencies of the yoke, we concluded that in Z direction the yoke has a sufficient part of shear deformation, which is created by insignificant shear rigidity of the anisotropic beam filler. Maximal sag of the yoke is about 1.7 mm in L3 direction in the normal operation regime. At that the gaps up to 0.8 mm may appear between the vertical beams in different parts of the yoke. The main cause of the displacement is the week pin contact joints between the beams. The sags of the vertical beams inside of the aperture (x-direction) are within 0.04 - 0.16 mm. According to calculations maximal stresses in the yoke units do not exceed acceptable levels. Strength of yoke is sufficient in the normal operational conditions and in the case of the normal regime violation. To estimate the actual reserve of the constructive elements strength the relative coefficient of strength reserve η was considered in the calculations. It is equal the ratio of permissible stress $[\sigma]$ and actual stress σ:

$$\eta = \frac{[\sigma]}{\sigma}$$

It is appeared that for all yoke units $\eta > 1.0$, namely:

for pin joints between the beams $\eta = 2 - 2.5$;

for bolts M42 connections between horizontal and vertical beams $\eta = 1.9$;

for weld connections including the local weld points between steel plates of the beams, brackets weld seams and the outside weld seams between the vertical beams and between horizontal beams $\eta = 1.3 - 4.0$;

for frictional force in the joints between the vertical walls and the bottom beams and between the bottom beams $\eta = 1.2 - 1.5$;

for tie rod nuts barrels :

- bearing strain of bottom washer $\eta = 1.39$,

- the barrel bottom bearing strain $\eta = 1.02$,
- the barrel bottom shear $\eta = 1.5$,
- bearing strain of the beam sheets under the barrel $\eta = 1.5$,
- barrel wall $\eta = 2$;

Tie rods prestressed by 90% of the full load. If the normal operational regime is violated, the relative safety margins are

- thread $\eta = 1.1$,
- groove $\eta = 1.02$.

Brackets in the joints of the vertical and bottom beams

- washer bearing strain $\eta = 1.7$
- plate bending strength $\eta = 1.06$
- weld joints strength $\eta = 1.8$

The analysis of yoke fixation units to the foundation treats a case of emergency loading, i.e. loading generated by electromagnetic forces under the normal operation regime and by seismic forces simultaneously. Strength of the yoke attachment to the foundation is sufficient to withstand the case of combined loading of the normal regime and an earthquake. Safety margin for the welded units including fixation units of the face sides of the yoke, units of the beams B1 - B7 is $\eta = 1.3 - 2.9$.

5. QA

Integrated approach to quality maintenance in the process of the yoke production has been based on State and Branch standards, currently in force in RF, as well as on SMZ quality regulations. Besides the producer elaborated and coordinated with JINR the program "Program of quality maintenance in the process of the yoke construction" which included:

- Control of technology compliance of the units and assembly units production; certification of the machinery and the personal;
- Input control of the material documentation. Input control of the physical and chemical properties of the materials by testing laboratory of SMZ (chemical contents, strength properties);
- Functional inspection and final control of geometrical characteristics of the units, assembly units and test assembly of the yoke by the Quality Division personal;
- Acceptance of the critical units of the yoke by the JINR representative according to elaborated by JINR test manual.

Control of geometrical characteristics of the fastening elements has been exercised not only in the machine shops, but in the SMZ testing laboratory. Control protocols have been provided. Strength properties of the critical units have been controlled for the witness samples after heat treatment process, or for samples prepared from ready made units. In the process of the yoke production JINR designers executed follow up of the project.

6. Results of tests and measurements

Strength of the load-carrying weld seams of the yoke beams, as well as strength of the screwed holes, used for lifting has been verified by strengthening tests, according to test manual prepared by JINR. An acceptance board has fulfilled the tests with SMZ and JINR representatives. The test results have been fixed in the test protocol.

Control assembly of the yoke bottom part and the yoke in horizontal position has been fulfilled by the producer to verify the assembly procedure and to control the geometrical sizes. Assembly in horizontal position has been stipulated by the lack of assembly area at the factory with bearing capacity above $80t/m^2$. The specific load for the horizontal assembly is about $25t/m^2$, which is acceptable for the bearing capacity of the assembly floor $25t/m^2$.

The assembly area has been aligned relative horizon by metal strips to within 2 mm. The sag of the foundation has been controlled along the perimeter of the yoke after placing of every four beams yoke layer with precision of 0.1 mm.

Assembly of the bottom part in vertical position has been provided by means of technology tie rods, which are identical to the tie rods, used for the vertical assembly in CERN and to Super Nuts of P&S Tensioning Systems Ltd. Tightening of the Super Nuts has been done according to the manual [9]. The tie rods tightening has been increased stepwise (10, 30, 50, 75 and 100 % of rated force). The elongation of the tie rods, the gaps between the beams and the thickness of the 7 beam package (in several cross-sections) as well as space position and geometrical characteristics of the mating surfaces of the beams have been controlled in the tightening process. The elongations of both controlled tie rods amount to 5 and 7.1 mm. It corresponds to calculated value of 7.2 mm as a whole. After tightening of the tie rods all bottom part dimensions have corresponded to the targeted dimensions.

Assembly of the iron yoke in horizontal position has been fulfilled layerwise - bottom and upper beams and two vertical beams create one layer. The tightening of the beams has been done with the set of technology tie rods, spacer tubes and Super Nuts. The mutual positions of the beams of a layer and the mutual positions of the beams in the neighbouring layers have been controlled with space templates to within 0.5 mm. The positions of the beams of a layer have been corrected by means of compensate gaskets between mating surfaces of the vertical and the horizontal beams. Mutual positions of the beams in the neighbouring layers after tightening have been fixed by means of dowel pins.

According to the measurements, the foundation sags have been near the calculated ones, after assembly of every layer (fig.4)

Simultaneously, the mutual space positions of the beams have been measured and fixed in the certificate for future assembly in vertical position. The gaps at the interfaces between the vertical and horizontal beams, as well as gaps between neighbouring layer beams, have been monitored. Changes of the gaps as the new layers have been added and tie rods and bolts have been tightened, have not exceeded 0.2 mm. Actual gaps have not exceeded 0.5 mm instead of planned gaps up to 2 mm.

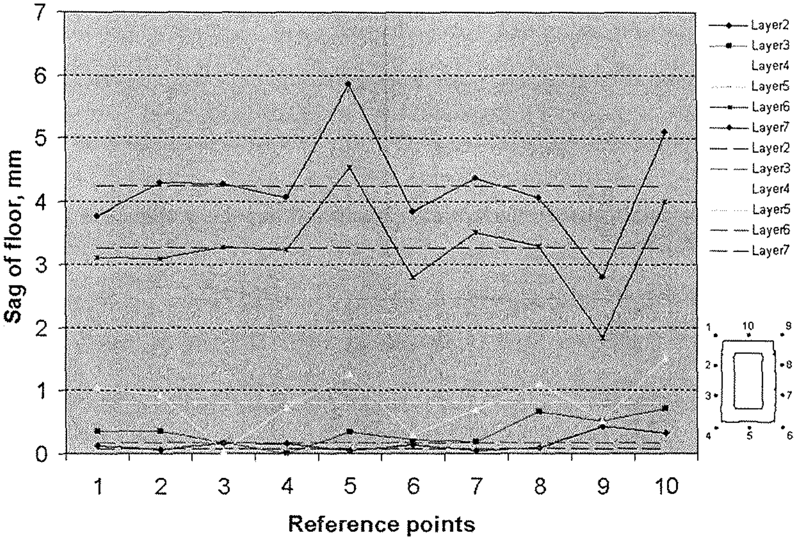

Figure 4: Evaluation of the foundation sag

7. Conclusion

- Design of the iron yoke of the dipole magnet of ALICE spectrometer is intended to withstand the huge uncompensated attractive force of about 1370 kN applied in direction of the neighbouring solenoid magnet L3.
- The iron yoke of the magnet has been manufactured, preliminary assembled in horizontal position by SMZ (Savelovo, Moscow region) and transported in disassembled condition to CERN, Geneva in accordance with collaboration agreement between JINR and CERN.
- Special design measures and high quality of machining of the yoke critical parts guarantee a very high level of geometrical shape reproducibility at the subsequent vertical assemblies.

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