The Dipole Magnet Design for the ALICE DiMuon Arm Spectrometer

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***Abstract*—An essential part of the DiMuon Arm Spectrometer of the ALICE experiment is a conventional Dipole Magnet (DM) of about 890 tons, which provides the bending power to measure the momenta of muons. The JINR engineering design of the DM, technical characteristics and description of the proposed manufacturing procedure are presented. The proposed coil fabrication technique is based on winding of flat pancakes, which are subsequently bent on cylindrical mandrels. The pancakes are then stacked and cured with prepreg insulation. The method is demonstrated on hand of the prototype II, which consists of a pancake made with full-size aluminum conductor. Some details of electromagnetic and mechanical calculations are described. The results of measuring of mechanical and electrical characteristics of materials related to the coil composite structure are discussed.**

***Index Terms*—Electromagnetic forces, magnetic cores, spectrometry, windings.**

I. INTRODUCTION

A LARGE Dipole Magnet (DM) is required for the DiMuon Arm Spectrometer of ALICE experiment at the LHC. It provides the bending power to measure the momenta of muons. In March 1997 the decision was taken by the ALICE Collaboration to build a resistive DM. Since then the design work has been pursued at JINR (Dubna) and at CERN. A general description of the design of the magnet and current status of the work is presented in [1]–[3].

II. MAIN CHARACTERISTICS OF THE DM

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°. The excitation coils are of saddle type. The coils are wound from single cut hollow aluminum conductor. The main flux direction in the gap is horizontal and perpendicular to the LHC beam axis. The coils of the magnet are cooled by circulating demineralized water. The coils are designed to have a maximum temperature rise in the cooling water of up to 30 °C. The DM will work in a cyclic regime over a period of 10 years—the full number of operation cycles will be about 4000. The main parameters of the magnet are listed in Table I.

The general view of the magnet is shown in Fig. 1.

III. DM CONCEPT

The DM iron yoke consists of four parts: bottom and top blocks and two uprights. The parts consist of seven modules each, which are rigidly connected by means of bolt flanges and tie rods system. It has been planned that the yoke will be manufactured from ready made steel modules, prepared for other purposes but never used before. Each module consists of 15 metal plates 30 mm in thickness connected with each other by welding trough drilled holes. The material of the iron plates is a low carbon steel—Steel 10. Content of carbon according to the Russian standard is 0.07–0.14%.

The DM winding consists of two identical cylindrical saddle shape coils covered by eight clamps, enveloping the coils via rubber gasket and joined one to another by assembly plates. Each coil includes 12 shaped pancakes glued together and enveloped by ground wall insulation. The winding is installed in the iron yoke. Coils are fixed at bottom and top beams. Conductor material for the coils is hollow extruded aluminum conductor of Verchnyaya Salda Metallurgical Production Association, Russia, AD0 of 99.5% purity (max. electric resistance at $20\ ^\circ\mathrm{C} < 2.95 \times 10^{-8}$ Ohm × m).

Coil insulation system includes turn-to-turn, pancake-to-pancake and ground wall insulation (correspondingly $1^{+0.1}$ mm, $1^{+0.1}$ mm, 5^{+1} mm overall thickness after curing). The material for the insulation was chosen “B-stage” system—prepreg PST-206 of NPO “Stekloplastic,” Russia. The prepreg consists of a glass cloth (E3-100, 0.1-mm thick) and an epoxy compound EDP-1 (mixture of epoxy resins ED-8 and ED-20) as a bonding material. The mass part of bonding material in prepreg is 34 ± 3%. The lifetime of PST-206 is 3 months at temperatures ≤ 25 °C and 4 months at temperatures ≤ 8 °C. The curing regime of the prepreg stipulates a continuous temperature increase up to 150 °C during 100–200 min, temperature holding for 180 min and specific pressure—2–3 Bar.

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. Several assemblies of the DM are planned. The construction concept takes this into account. The first assembly of the DM will be necessary for the iron yoke only, in order to verify and correct the geometry and to establish all reference surfaces and locate the reference and alignment dowels.

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TABLE I
THE MAIN PARAMETERS OF THE DM

1. Magnetic field		
1.1. Maximum flux density on the magnet axis	T	0.7
1.2. Average Field Integral (z=0 – 14.4 m, Θ = 0^0 – 9^0)	Tm	3.0
1.3. Stray fields in 3 m from the dipole magnet	T	<0.03
2. Electrical parameters		
3.1. Amp-turns total RMS	MA	1.968
3.2. Operation current	kA	5.856
3.3. Inductance (without L3 and MF)	H	1.0
3.4. Power consumption	MW	3.46
3. Winding		
4.1Conductor weight	ton	37.44
4.2. Turn-to-turn Insulation thickness	mm	1
4.3. Inter-pancake insulation thickness	mm	2
4.4. Ground insulation thickness	mm	5
4.5. Number of pancakes in a coil		12
4.6. Number of turns per a pancake		14
4.7. Number of turns per winding		168
4. Conductor		
5.1. Conductor cross section	mm^2	50.5 x 50.5
5.2. Channel diameter	mm	26
5.3. Radius of edges	mm	3
5. Cooling		
6.1. Cooling water flow rate	l/s	29.8
6.2. Cooling water pressure drop	Bar	10.9
6.3. Water temperature rise, (max)	^{0}C	30
6. Magnet yoke		
6.1. Length of the iron yoke	Mm	3115
6.2. Minimum/maximum distance between poles	Mm	2948/3924
6.3. Window height	Mm	6090
6.4. Yoke weight	Ton	820
7. Overall dimensions of the magnet		
7.1. Length	Mm	5091
7.2. Width	Mm	7120
7.3. Height	Mm	9000

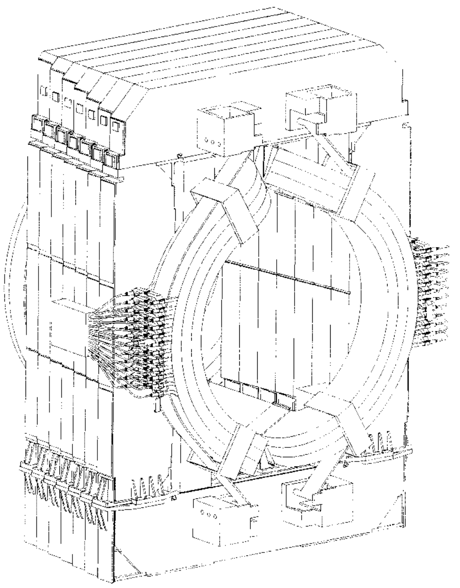

Fig. 1. The general view of the DM.

Assembly of the magnet will start after individual testing of the coils and of the assembled yoke. The first assembly of the DM will be carried out in SXL surface building in order to validate the assembly procedure in the underground area. Rubber gaskets will be inserted between coil surfaces and clamps to distribute the pressure on the surface of the coil, to take up surface irregularities and to allow thermal expansion. The final assembly of the magnet will take place at the experimental hall UX25.

IV. CALCULATIONS OF MAGNET FIELD AND FORCES

The complete magnet circuit of ALICE, including L3 solenoid, the DM and the muon filter (MF) has been modeled in order to predict the bending field integral, the saturation effects in the steel parts and forces applied to the parts of the magnet.

The magnetic field calculations have been performed using the code Opera3D 7.0 (TOSCA). The total number of the hexahedral first order elements was 124 780 and the total number of nodes was 129 258. The maximum flux density at the central axis of the DM has been found to be 0.7 T. Calculations of the dependence of the field integral from the average current density shows that saturation effect in the DM yoke for the operational value of the current density can be neglected. For the definition of the DM bending strength, an analysis of the integrals $\int B_x\, dl$ has been performed. The integration lines begin in the origin of the coordinate system and are located inside the 9° conical aperture. The average value of the field integrals along straight lines inside the 9° conical aperture are equal to $3.04^{+0.27}_{-0.09}$ Am. The absolute values of the magnetic field flux density around the DM does not exceed the level of 0.025 T at a distance of 3.0 m from the yoke in the planes of the coil head parts. The DM is attracted into the direction of the neighboring L3 Magnet by a force of $F_z = -2060$ kN (the attractive force for the Iron Yoke is -2162 kN and the repulsive force for the winding is $+103$ kN).

V. STRESS STRAIN CALCULATIONS OF THE DM STRUCTURAL PARTS DUE TO STATIC, MAGNETIC, SEISMIC, AND TEMPERATURE INDUCED STRESSES

The linear finite-element (FE) model of the magnet and all calculations have been made in the FE program "ANSYS 5.3." The electromagnet loads are applied as nodal forces, obtained from the corresponding force. The temperature loads have been applied to the coil as a temperature gradient of 30 °C.

The stress analysis shows that the average linear shear strength of initial weld joints between metal sheets is 0.19 MN/m. The average linear friction forces, because of studs tightening forces, is 0.2 MN/m. These linear efforts are not enough to prevent the mutual displacements of the metal sheets under the action of the electromagnetic attractive force which produces a linear load between metal sheets of 0.78 MN/m. Therefore all beams are reinforced by welding on the perimeter additional metal plates to create of a rigid primary "case" structure. After final assembly of the DM in the underground area all horizontal beams of the basis and the vertical beams are welded among them. The DM weight of 890 t is not enough to prevent DM from turning over under the action of electromagnet attractive force of 2060 kN. Fixation is realized by welding the iron yoke to the metal foundation.

The local analysis of the coil shows, that the maximum primary tension (20.5 MPa) and the primary plus the secondary stresses (36 MPa) are within the allowable values for the aluminum conductor material AD0. The maximum value of the normal stress in the glue connection between the metal conductor and the insulation is 2.5 MPa, which is less than the allowable value of 4.5 MPa. The shear stress does not exceed 7.8 MPa and it is less than the allowable stress of 9.5 MPa. The normal, 0.9 MPa, and shear, 6 MPa, stresses in the ground insulation also satisfy the strength criteria. The maximum in-plane membrane stress in both conductor insulation and ground insulation is 12 MPa (the allowable value is 140 MPa) and the maximum shear stress is 6.7 MPa (the allowable value is 35 MPa).

All resulting stresses in the construction do not exceed their allowable values calculated in accordance with accepted design criteria [4].

The action of accidental conditions has been analyzed. The coils have been overheated by 10 degrees and the whole structure has been overloaded by 10 percent of electromagnetic forces. The finite element analysis for this case shows that the maximum stresses in the coil conductor and both conductor and ground insulation are still within the allowable limit.

The modal and seismic spectral analyzes for the considered FE model have been provided. The eigenvalues and seismic responses by three directions have been obtained and analyzed. Assuming that the accidental condition effects of overheating and overloading by ponderomotive forces can be considered separately from the seismic accident effect, additional stresses in all construction elements at seismic accidents are not significant and do not lead to strength criteria violations.

VI. Coil Manufacturing Concept

The JINR coil manufacturing concept implies winding of the flat rectangle pancake and shaping it on a cylindrical **7 09 621 6 56 64** fixture. The machine application of the conductor turn insulation, forming trapeze cross-section and cleaning of the conductor surface by metal brushes are carried out during the winding of flat pancakes. After the shaping process the turn-to-turn insulation is pressed and cured by electrical heating of the conductor. The cured pancake has undergone dimension and electrical tests and has been wrapped by interlayer prepreg insulation. After that it is placed and adjusted on the surface of the assembly fixture [Fig. 2(a)]. Then pancake is uniformly clamped to the fixture surface by hold-down tools (pressing beams and pressing jacks), from the top [Fig. 2(b)]. The pressure value is kept for at least 1 h for epoxy resin free relaxation. After that the part of hold-down tools (except pressing jacks on the sides of the pancakes) are removed and second insulated pancake is placed from above [Fig. 2(c)]. Both pancakes are clamped by pressing beams starting from the top of the fixture [Fig. 2(d)]. The pressing jacks on the first pancake sides continue to fix pancake sides to the assembly fixture surface. At the last moment pressure jacks on the lower pancake are removed and transferred to the upper section. The spring back shift (this shift is caused by the residual stresses in the conductor after bending) of the lower pancake sides is prevented by the adhesiveness of surfaces covered by raw prepreg for several minutes during the replacement process. According to the tests, separation effort for the uncured insulation layer and metal surface makes 0.3 $\div$ 0.4 MPa for compression pressure of 0.2 MPa and for compression time $\geq$2 hours. Following this, the procedure sequentially repeats for the following pancakes. After final assembling of all pancakes the coil is wrapped with ground insulation and pressed. The final operation is the prepreg insulation curing.

VII. R&D and Tests

Considerable prototype and test activities have been undertaken during the preparation of the design documentation. Extensive testing of the mechanical and electric characteristics of conductor and insulation material has been carried out.

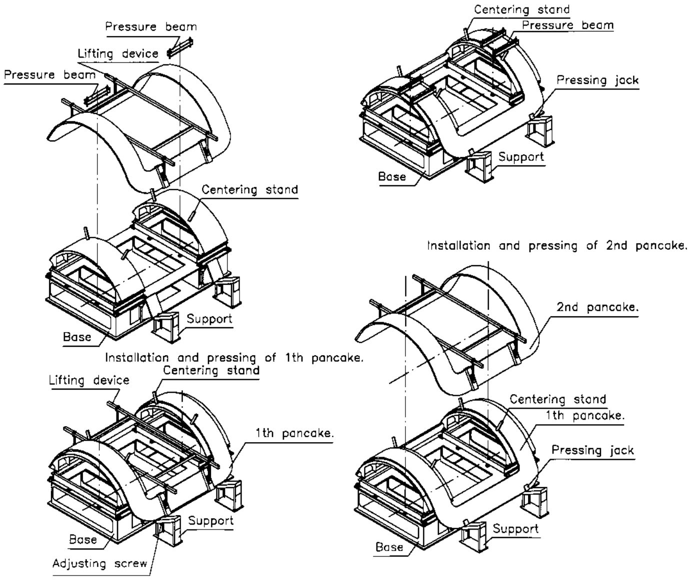

Fig. 2. Assembly procedure of the coil.

One of the critical problems of the coil production is the removal of residual stresses in the aluminum conductor after shaping of a pancake. It is considered that it will be done by conductor heating during the prepreg insulation polymerization process. Some experiments on analysis of relaxation process for aluminum material of the conductor AD0 have been made at temperatures of 150 °C. Main decrease of the stress takes place during the first 2 h at the temperature relaxation process. Stress reduction at 150 °C after 2 h has been 42.5%. The yield stress and ultimate strength of the aluminum at 150 °C have been reduced, respectively, from 63 MPa down to 58 MPa and from 110 MPa down to 87 MPa.

Four combined samples which modeled turn-to-turn and pancake-to-pancake insulation have been prepared to study the mechanical characteristics of the composite material of the coil (Fig. 3). These samples were used for disruption and shear tests of the glued connection between conductor and insulation, thermocycling test.

After testing of samples and prototypes it has been found that insulation works for strain, together with conductor metal only within elasticity limit of the conductor. After the tensile strength test there was no residual elongation of the insulation material. The value of insulation shear modulus is ($G \approx 2\div3$ GPa). Face stresses (end effect) subside at a distance of $\sim$180 $\div$ 200 mm from the edge of the prototype. The correctness of prototype length choice for thermocycling is confirmed ($l \approx 1200$ **mm**). Destructive stresses (lower limits) in disruption test in terms of short-time reliability taking into account the variation for quality adhesion are $\sigma_{ds} = 10$ MPa and $\tau = 21$ MPa. Destructive stresses with account of fatigue at cycle work of material make $\boldsymbol{\sigma}_{dscyc} = \mathbf{4.5\ MP}$ and $\boldsymbol{\tau}_{cyc} = \mathbf{9.5\ MPa}$.

The aim of thermocycle tests has been to check the insulation strength under temperature loads. From the calculations the maximum shear stress in the three bar prototype, which has been used for thermocycle test, is $\tau \approx 16$ MPa and the maximum shear stress in the winding is $\boldsymbol{\tau}_{\max} \approx \mathbf{7.8}$ **MPa**. According to the scale model-prototype relationship the full number of the DM operation cycles corresponds to 100 of prototype cycles. During the tests indications of the displacement sensor, which controls mutual displacements of the glued bars end parts, correspond to the calculated value. Displacement value during tests did not increase. During prototype inspection after tests no damage to insulation has been found. Additionally after the tests four samples $l = 48 \div 55$ mm have been cut from one of the sample faces for insulation disruption tests. Only for the side sample the value $\boldsymbol{\sigma}_{ds} = \mathbf{11.8}$ **MP** has been 12% less than for all other samples. Last tests shows that there was no sufficient decrease of the glue connection strength after the thermocycle tests.

During 1999–2000 JINR has produced a full-scale prototype pancake (Prototype II) with reduced number of turns and reduced length. The aim of the prototyping work has been the development of a simplified model of a coil pancake of the ALICE DM which is very close to a real pancake for the development of design and manufacturing technology. This winding has been produced with 12-m-long bars of high purity aluminum conductor. In order to obtain a single conductor length 69 m the pieces have been welded together before winding the flat layer. The conductor has then been insulated with prepreg fiber glass tape. Flat pancake of Prototype II consisted of five turns. Prototype facilities have been used to wind, to insulate and to shape the saddle type pancake. The finished pancake (Fig. 4.) has been subjected to dimensional checks and electrical tests. Electrical tests demonstrated that the prototype pancake satisfies the accepted criteria.

VIII. CONCLUSION

JINR continues in a collaboration agreement with CERN to develop the magnet yoke and the coil support structures. The design of the yoke has been terminated and the manufacturing has started in Russian industry.

The feasibility of constructing large aluminum conductor coils with the proposed technology was shown by the production of the Prototype II model pancake.

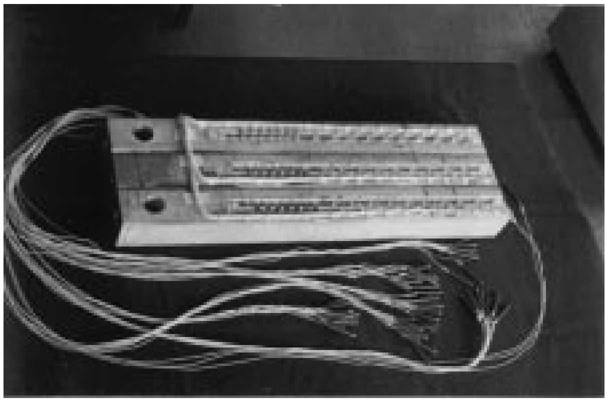

Fig. 3. Three bars sample prepared for strain measurements.

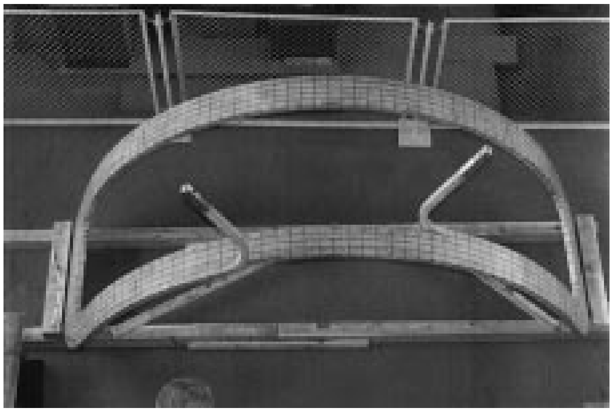

Fig. 4. The model pancake Prototype II, prepared for electric tests.

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