Design and Status of the Dipole Spectrometer Magnet for the ALICE Experiment

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A large Dipole Magnet is required for the Muon Arm spectrometer of the ALICE experiment in the future LHC.
The absence of constraints of symmetry and homogeneity of the magnetic field has lead to a design dominated by economical and feasibility considerations.
In March 1997 the decision was taken to build a resistive dipole magnet for the muon spectrometer of the ALICE experiment. Since then design work has been pursued in JINR/Russia and at CERN. While a common concept has been adopted for the construction of the steel core, two different proposals have been made for the manufacturing technology of the excitation coils. In both cases, however, the conductor material will be Aluminum. The general concept of the dipole magnet 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 degree. The excitation coils are of saddle type. The coils are wound from large hollow Aluminum profiles. They are cooled by pressurized demineralized water. The coil ends are located to both sides of the magnet yoke and determine the overall length of the magnet. The main flux direction in the gap is horizontal and perpendicular to the LHC beam axis.
Both coil concepts and the underlying manufacturing technology are compared and the present status of the development of the magnet is described.

I. INTRODUCTION

The dipole magnet is a major part of the ALICE muon spectrometer and provides the bending power to measure the momenta of muons. The aperture and field integral are determined by the requirements on mass resolution and angular acceptance.
Different proposals for the muon magnet have been evaluated. The ALICE Collaboration chose a resistive dipole magnet at the meeting in March 1997 and a Preliminary Design Report [1] for the magnet was presented in March 1998.
The magnet will be placed directly adjacent to the L3 solenoid magnet, which is already installed and used at present for one of the LEP experiments. The dipole will be installed on a movable platform in order to be rolled back to allow intervention on the muon front absorber.
In addition, the magnet will serve as a support for the muon absorber and beam shielding.
The magnet will be powered by a dc power supply. The coil will be water-cooled with demineralized water.
The concept of the magnet is based on a window frame return yoke that is fabricated from low carbon steel sheets. The general layout of the magnet is shown in Fig. 1. The main parameters for the version with continuously wound coils are given in Table 1.

Table 1. Main Characteristics of the Magnet

Parameter	Value	Unit
Max Flux density	0.67	T
Bending Strength	3.00	Tm
Avg. Gap width	3.30	m
Ampereturns	1.85	MA
Operating Current	6.42	kA
Coil Voltage	572	V
Power	3.67	MW
Inductance	0.70	H
Diff. Pressure	14.3	bar
Diff. Temperature	30	°C
Total weight	835	tonnes
Overall Dimensions (H x W x L)	8.6 x 6.6 x 5.0	m x m x m

The flat vertical poles follow the required acceptance angle of 9 degrees. The excitation coils are of saddle type. Two concepts for a conventional coil, have been proposed [2] [3]. In both cases they are wound from hollow aluminum conductor of large cross-section. The coil ends are located to both sides of the magnet yoke and determine the length of the magnet. The main flux direction in the gap is horizontal and perpendicular to the magnet length axis.

II. MAGNET CORE.

The steel yoke of the magnet has to provide a flux return path for the magnetic field in the fiducial volume. The dimensions of the core parts have been chosen for specified steel characteristics in order to minimize the leakage flux. During operation at nominal field the level of flux density in the steel parts will be close to the saturation value. The absence of constraints on the field quality resulted in a design focused on low material and manufacturing cost.
The return yoke has, consequently, been designed as window frame type with horizontal bottom and top beams

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Manuscript received September 25, 1999
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of trapezoidal shape. The poles are formed by the vertical rectangular side walls.
The proposed construction is based on existing steel stacks, which are available from a former magnet project that has been abandoned. The iron yoke is made of modules of about 45 cm thickness. Each module consists of 3 cm thick plates joined under pressure and welded through previously machined holes.
The modules will have to be cut to the required dimensions. The top and bottom parts will be assembled from seven modules each. The sidewalls are oriented in an angle of 9 degree with respect to the length axis of the magnet and consist of seven modules each.

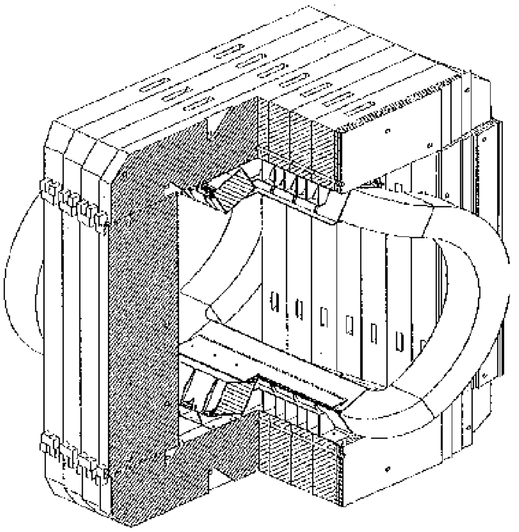

Figure 1 Dipole Magnet assembly

III. EXCITATION WINDINGS

A. *Description of the coil parameters*

The excitation windings consist of two mirror symmetrical saddle-shape coils. A coil is constructed from 12 pancakes with 12 turns each. The cross-section of the winding is rectangular. The longitudinal parts of the coil are parallel to each other. The coil ends have a half-cylindrical shape. The bends of the coil lie in one plane and transit smoothly into the cylindrical part of the coil ends. The coils will be wound from hollow conductor extruded from 99.5% purity aluminum.
The thermal expansion of the coil will be of the order of 4 to 5 mm during magnet operation. Therefore, the coil will slightly move along the longitudinal supports. The saddle parts of the coil will be clamped to the pole ends with the help of ribs and intermediate rubber sheets.
The electrical connections will be located on the outer perimeter of the coil ends. The connection between adjacent layers will consist of welded plain Aluminum bars of large cross-section.
The water inlets will be connected to the water collectors via manifolds and rubber pipes.

B. *Coil manufacturing methods*

1) Continuous winding concept

The conductor can be extruded, as a single cut for the length needed to wind one coil layer. Internal welds in the coils can consequently be avoided.
A heat treatment at 150 degree C is considered to be sufficient to relieve strain and stresses in the conductor which appear during the winding process.
The steps of the coil manufacturing process are described in the following.

1. Flat pancake

   Each coil layer, corresponding to a cooling circuit, is wound flat on a mandrel. The facility for winding the flat layer includes the winding machine, the payoff, the device for aligning, the tension device, the cleaning unit, the taping unit, and the device for passing the conductor. The winding procedure is carried out with constant tension to maintain the mechanical properties and homogeneity while bending the sections. The conductor will be aligned and straightened simultaneously by applying some tension. The insulation is applied before the bending of the conductor during the winding process. The jig for winding the flat racetrack coil is placed on the turntable of the winding machine.

2. Saddle shaping

   In the semi-cylindrical parts of the winding, the bending radius of each layer is greater than 2 m and leads to a very small deformation (1.25 %) of the conductor cross-section. Consequently, the previously wrapped conductor insulation should not be degraded when bending one coil layer to the 3-dimensional shape.
   Bending the flat layer is carried out on a cylindrical fixture, see Fig. 2. After the bending process, the dimensions of the external perimeter of the layer are corrected with clamps. During the shaping process of a layer, the cylindrical surface of the fixture will be the reference for the inner cylindrical surfaces of each layer. Massive clamps along the straight parts of the coils will be used to bend the layer to the desired geometry immediately after the winding. Half-cylindrical plates will confine the layers after bending.

3. Coil assembly

   The pancakes are stacked with pre-preg interlayer insulation. It is assumed that 1 mm thickness will be sufficient for compensating the inaccuracy of the layer manufacturing. The coil dimensions will be referenced to the innermost cylindrical surface and to the inner perimeter of the complete pancake stack.

All layers of one coil are kept under compression to control the outside dimensions during polymerization at 160 degree C.

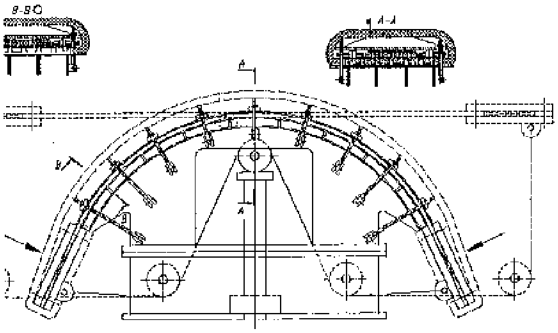

Figure 2 Coil shaping concept

2) *Welded construction*

This construction method relies on a good control of the welding process for aluminum profiles. It is believed that this can be obtained with orbital welding machines. In a previous version for excitation coils with a conical shape, which followed closely the required aperture, this method has been introduced and described in detail [4]. For the present cylindrical geometry of the coils the manufacturing process can be further simplified.

A half turn is formed from a straight Aluminum bar of adequate length. This requires unit lengths of approximately 12 m. A single bending angle of 90 degrees is sufficient to form the coil pancakes.

Four bending operations are necessary per half turn to bend the conductor at each coil end upwards, i.e. out of the coil plane, and then inwards, i.e. towards the length axis of the coil.

The construction from half turn modules results not only in shorter conductor length to be handled but also reduces the tooling set drastically. Since the conductor has a square cross-section the bending radii required for the inward bends are included in those necessary for the upward bends. Therefore, only 12 tools are required for all bends. The described bending procedure allows in principle to execute all bending operations horizontally. For the inward bends this requires, however, to turn the work piece in the vertical direction.

1. Bending sequence

(a) The straight conductor bar has been cut to length of one half turn, cleaned and degreased

(b) The "Upward" bends can now be executed, either by displacing the tool to the opposite side after the 1st bend or by turning the work piece by 180 degrees.

(c) To execute the "Inward" bends it will be necessary to either turn the work piece in the vertical direction and perform horizontal bending operations or to make vertical 90 degree bends.

It is obvious from the number of radii with respect to the number of bends that an important rationalization can be obtained by producing identical bends in series on different work pieces. This will reduce the number of tool fitting operations to at most twice the number of radii, i.e. 24.

2. Pancake Assembly

Each turn will be assembled by welding of two half turns as shown in Fig. 3. 264 internal welds will, therefore, be necessary to build one coil. In addition 22 welds are required for the water and electrical terminal connections. Each half turn in a pancake has a different total length to obtain the necessary change in pitch by one conductor width.

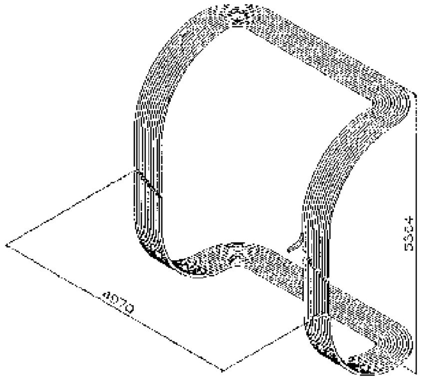

Figure 3 Pancake assembly

In order to provide sufficient clearance for the welding operation the last turn will be spread apart from the previous turns by an adequate tool. Bending tools must be dimensioned to obtain the space between turns which is necessary for the insulation material. It might therefore be considered to apply the conductor insulation immediately after the assembly of a turn in order to control the dimensions continuously.

3. Insulation Method

The conductor insulation can be wrapped after completion of each turn or after assembly of a complete pancake. The bending radii are chosen large enough to allow the use of an automatic wrapping machine. The clearance between turns needed for the passage of the machine can be easily obtained with adequate jigs. The insulated pancake will then form a geometrically well defined structure inside given tolerances.

Depending on the insulation material used, different steps have to be envisaged. In case of classic vacuum impregnation, the introduction of the epoxy resin will follow after the assembly of a complete coil inside a mould. This procedure is, however, technically rather complex due to the 3 dimensional shape of the coils. Pumping of the resin over more than two meter height would be required.

The use of an insulation method with pre-impregnated glass fiber wrapping seems, therefore, to be more attractive. The coil fabrication method is clearly suited for this procedure since the complete winding can be assembled prior to insulation.

4. Coil Assembly

The assembly of a coil is a straightforward operation. It requires the stacking of the previously assembled and insulated pancakes. Once the turns have been wound and welded to form the number of pancakes required for a coil, the conductor and coil insulation can be applied even within short time margins required by the potting time for the pre-preg insulation material.

The stacking follows the Russian doll procedure with the innermost pancake well supported in a stacking fixture and the coil ends facing downwards. The orientation is proposed to avoid mechanical stress during the assembly when the coil ends are not supported. In addition, the assembly fixture can also be used as handling and transportation jig.

5. Coil Insulation

Different methods can be envisaged to apply and cure the thermosetting resin once the ground insulation has been wrapped. In principle the building of a vacuum tight cover around the coil should not raise technical problems. However, the coil dimensions need to be controlled by a reasonably precise mould. The curing of the resin could be envisaged by circulating hot demineralized water in the conductor cooling ducts.

C. Power dissipation and cooling requirements

The direct water cooling of the conductors will remove the major part of the generated heat in the excitation windings. The residual dissipated heat will be intercepted by water cooled heat exchangers in form of aluminum shields, which will be installed to protect the detector chambers in the magnet.

Additional cooling will be provided for the busbar system between the power converter, which will be located above ground at a distance of about 110 m from the dipole magnet.

IV. MAGNET ASSEMBLY

Several successive assemblies of the magnet are planned. The construction concept takes this into account. Once the first assembly of the yoke has been successfully terminated, subsequent re-assemblies will not require realignment of the sub-units. The machined faces at the external sides of the horizontal parts which are used as references for the mating faces between horizontal beams and uprights will also serve as support areas for the moving base.

Consequently, an alignment of the base should be sufficient for the position of the magnet.

Tension rods will be used to consolidate the horizontal beams and the uprights. Adequately positioned dowel pins will guarantee the alignment between sub-units. The mechanical assembly of horizontal and vertical yoke parts has to take the geometry of the yoke into account. To guarantee a precise match at the junction between these items, flanges will be welded at the extremities of the sub-units and machined simultaneously with the mating surfaces. The mechanical connection will then be achieved with tension bolts between flanges.

V. CONCLUSIONS

Both manufacturing methods are considered to be feasible. The winding of continuous pancakes looks attractive since internal welds can be avoided. At the present state this method requires still a considerable amount of validation and testing but it is hoped to gain a reduction in cost with respect to the welded coils. In comparison to the welded construction it can, however, be noticed that a substantially heavier and more complex tooling will be required. The wrapping of the conductor insulation before winding will allow to use existing equipment but might require repair after bending.

The welded construction method has already successfully been applied. It should be emphasized that an irreproachable quality can be obtained with state of the art welding equipment. In addition, contrary to the previous method, repair of faulty sections will be possible during all stages of the coil construction without important material loss. In addition, dimensional tolerances can be controlled and corrected during the assembly of each turn.

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