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**A Shaped Solenoid for Muon Spectroscopy
at High-Energy Hadron Colliders**

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Abstract:

The conceptual design of a large solenoid is described. It is optimized for precision muon spectroscopy for experiments at future hadron colliders, providing polar-angle coverage from 6(10) to (170) 174 degrees. The design uses mass-produced industrial components with the aim of reducing construction costs.

1. Introduction

At the future hadron colliders (the Large hadron Collider (LHC) and the Superconducting Super Collider (SSC)) most physics topics will require the identification and momentum measurement of leptons. The identification of electrons – using transition radiation or 'preshower' techniques – inevitably requires 'tracking', which has to function at luminosities near $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The momentum measurement of electrons may, however, benefit from the potentially excellent resolution of calorimeters. Muons, on the other hand, when identified as penetrating charged particles behind a calorimeter, are practically inert to the associated particle flux and event topology. This ease of identification is counterbalanced, to some extent, by the difficulty of achieving 'good' momentum resolution for the range of interesting momenta of $\sim 10 \text{ GeV}/c$ to $\sim 2 \text{ TeV}/c$.

This challenge of good muon spectroscopy can be addressed in several ways. Iron toroids, magnetized to $\sim 1.8 \text{ T}$, provide a robust method without taxing to the utmost the requirements of tracking methods [1]. The achievable momentum resolution is multiple scattering limited up to very high momenta (typically $500 \text{ GeV}/c$) and is given by $\sigma/p \approx 0.4B[\text{T}] \cdot \sqrt{L} [\text{Fe(m)}]$. Alternatively, tracking in air fields, as pioneered by the L3 Collaboration [2] offers the attractive possibility of high-precision momentum analysis over a wide range of muon momenta. Superconductive magnet systems have also been considered [3,4].

In this note, we report on work on the 'shaped solenoid' carried out within the framework of the 'CERN LHC Magnet Study Group' [4]. This group had the task of analysing a number of potential muon spectroscopy magnets, which could be used in LHC experiments. The study concentrated on the evaluation of the engineering feasibility of such magnets.

In Section 2, we briefly mention the origins of this concept, discuss the basic design parameters and indicate the possible momentum resolution [5]. Section 3 provides an account of the engineering solution developed which allowed a rather reliable cost estimate to be made. In Section 4 we give a brief discussion on the possible muon-tracking system and the integration of other experimental apparatus.

2. The Shaped Solenoidal Magnet

The following specifications were the starting point for the design study:

rapidity coverage:	$ \eta \leq 2.5$
integral $\langle BL^2 \rangle$ for tracking:	$\sim 10 \text{ Tm}^2$.

Here η denotes the pseudorapidity of the muons, related to their polar angle θ through the relation $\eta = -\ln \tan \theta/2$.

The concept discussed here already has a long history. Approximately 15 years ago, the 'Open Axial Field Magnet' was constructed for the Axial Field spectrometer at the CERN Intersecting Storage Rings [6] and extrapolated to several novel magnet configurations for colliders [7]. More recently, the 'Shaped Solenoid' was adapted to the supercollider requirements [8].

The potentially excellent performance motivated us to carry out the design study, which is described in this note. In particular, we wanted to explore ways to realize such a magnet using relatively simple highly automatized fabrication procedures (e.g. for the coil) and industrial standard components to reduce construction time and cost. We deliberately chose a solution with a warm aluminium coil to remain within the scope of 'conventional' technologies [5].

For the following design study, a solenoidal field of $B = 0.5$ T, with an inner winding diameter of 18 m and a length of about 25 m, was considered. The solenoidal field is terminated at both ends by end-caps. The calculations of the field maps were done with the CERN computer library program POISSON, which solves the Poisson equation for two-dimensional problems or for problems of axial rotational symmetry.

In order to improve the bending power of the axial field for particles at small production angles (pseudorapidity $\eta = 2$ to 2.5) two solutions for the field shaping were studied:

- i) a passive shaping of the field by adding to the end-caps a 'nose' insert covering the polar angle of $6-10^\circ$;
- ii) a passive and active shaping by adding to the nose discrete iron disks, which are provided with toroidal coils producing an azimuthal field.

Figures 1a and 1b show schematically, in an axial cut, a quarter section of the solenoidal detector magnet with its coils, the iron of the end-cap, and the return yoke. Two smaller coils are attached to the end-cap in order to extend the solenoidal field as far as possible in the axial direction. They could also be used for active field shaping by increasing their current density. Figure 1a displays the magnetic flux lines for a protruding nose insert, whereas the flux lines with the toroidal insert are shown in Fig. 1b. This version allows the η -coverage to be extended to $|\eta| \leq 3$, albeit at the price of reduced momentum resolution below $p \leq 500$ GeV/c owing to multiple scattering.

The potential momentum resolution achievable with this magnet is shown in Fig. 2 for the 'nose' variant. The following assumptions were made for the calculation:

- the position of the collision vertex is known in the plane transverse to the beams with $\sigma_{x,y} = 200 \mu\text{m}$. Note that the vertex distribution itself has $\sigma_{x,y} \sim 20 \mu\text{m}$.
- The muons traverse a 'barrel' calorimeter which has a total thickness of $110 X_0$; the 'end-cap' calorimeters were assumed to have a thickness of $\sim 120 X_0$; this thickness is considered in the multiple scattering analysis linking the muon track measured behind the calorimeter with the collision vertex.
- The tracking volume extends from $r = 450 \text{ cm}$ to $r = 880 \text{ cm}$ in the barrel region; in the very forward region it extends from $Z = 700 \text{ cm}$ to $Z = 1200 \text{ cm}$ (see also Fig. 3).
- Three chamber planes with equal spacing between chambers provide the sagitta measurement; the effective resolution is $\sigma = 50 \mu\text{m}$ per plane. The thickness t of each chamber plane is assumed to be $t = 0.1 X_0$.
- The magnetic field of Fig. 1a is used.

The results are shown in Fig. 2 as a function of muon momentum and rapidity. As an example, we indicate the momentum resolution for 1 TeV/c muons at different rapidities:

$$\begin{aligned}
 0 < |\eta| < 1.3: & \quad \Delta p/p \text{ between } 10 \text{ and } 12\%, \\
 1.3 < |\eta| < 1.7: & \quad \Delta p/p \text{ between } 12 \text{ and } 13\% \\
 1.7 < |\eta| < 2.5: & \quad \Delta p/p \text{ between } 13 \text{ and } 14\%.
 \end{aligned}$$

For the version with the integrated forward toroids, Fig. 1b, the following statement can be made about the expected momentum resolution:

$$\begin{aligned}
 0 < |\eta| < 2: & \quad \text{comparable to the 'nose' version} \\
 2 < |\eta| < 3: & \quad \Delta p/p \sim 0.15 \text{ for } p \leq .5 \text{ TeV}/c \\
 & \quad \Delta p/p \sim 0.2 \cdot p [\text{TeV}/c] \text{ for } p \geq 0.5 \text{ TeV}/c.
 \end{aligned}$$

The detailed choice between these two versions would be based on physics arguments, which influence the trade-off between momentum resolution and rapidity acceptance.

3. Engineering Considerations for the Shaped Solenoid

3.1 General considerations

Because of the large size and weight of this magnet, its technical design took into consideration only warm windings and a very simple iron yoke for the flux return. This led to the idea of the 'magnetic cavern'.

In all design stages, cost reductions were the guiding principle; this applied for the material as well as for the production and mounting of the magnet components. Standard industrial

products were to be used, preferably requiring only little machining. The weight and size of detector components were to be such that they could be transported with rather conventional means. Two cranes of 250 t loading capacity each were foreseen in the surface assembly hall, to be used in synchronization to handle loads up to 500 t either on the surface or for lowering to the underground area. These cranes are permanent installations, which would also allow intervention on the detector at any time during its functioning.

A study of the civil-engineering costs indicated that it would be more economical to construct one large access shaft of 33 m diameter, centred above the underground detector, rather than two smaller shafts at each end of the detector. Such a central access shaft would, furthermore, considerably facilitate the mounting of the detector.

3.2 Description of the Solenoid Detector

Figures 3, 4 and 5 show a cross-section at the interaction point through the cylindrical part of the solenoid detector, a vertical cut through the whole detector along the beam axis, and a view of the end-caps, respectively. The following sub-section describes the magnet components in some detail. The basic parameters are given in Table 1.

3.3 Iron Return Yoke

The iron return yoke, as shown in the cross-section view of Fig. 3, is made of long iron blocks. These blocks are produced for lamination purposes (they are called 'Bramme' in most of the European steel industry). The price of these iron blocks prior to any lamination or other treatment is quite low. These iron slabs of low-carbon steel, e.g. St 34 or St 37, are cast at the factory in a continuous process and cut in situ to the length $L = (9 + \Delta)$ m, where Δ has to be determined for safe machining of the ends. The cross-section of the slabs can be varied within some limits; we have assumed their maximum dimensions (height x width) to be equal to 27 x 165 cm². The variation of the dimensions during the production process is rather small and not critical for the arrangement. After cutting to length, the slabs still have a temperature close to 800°C. Adequate flatness of the slabs can be achieved by piling up 15 to 20 hot slabs on an even surface during the cooling-down period.

Two rows of 9 m long slabs, one behind the other, are used for the return yoke of the detector. The blocks are placed mainly at the bottom and along the two side walls of the barrel part. During the assembly work, the blocks will be fixed together with a minimal patch welding. This is important for the side walls for secure stacking above the centre line. The iron slabs at the sides will, to a large extent, be embedded in the concrete work, hence the name '*magnetic cavern*'. We note that the magnetic forces acting on the return yoke are longitudinal only and therefore do not tend to detach the iron slabs from the concrete walls. The left and right lower corner of the iron structure are kept free (see Fig. 4). This provides permanent access to the water and power distribution of the solenoid without moving the end-caps.

Table 1: List of basic parameters

<i>Magnetized volume:</i>		
$V = 5600 \text{ m}^3$ (diam. = 18 m, length = 22 m) $B = 0.5 \text{ T}$ $nI = 10^7 \text{ A turns}$ $W = 700 \text{ MJ}$		
<i>Al-solenoid:</i>		
$n = 400 \text{ turns}$ $I = 25000 \text{ A}$ $P = 12 \text{ MW}$ (6 x 2 MW) $R_{\text{inside}} = 9 \text{ m}$ conductor cross-section / turn = $100 \times 4.5 \text{ cm}^2$		
<i>Weight:</i>		
iron:		
barrel		12 000 t
2 end-caps (including nose)		10 000 t
Al-solenoid		
extruded conductor		2500 t
<i>Water cooling of solenoid:</i>		
total water flow ($\Delta T = 20^\circ\text{C}$)		144 l/s
pressure drop per 17 turns		6.5 bar

3.4 End Caps

The solenoid is closed by end-caps which take up the flux of the solenoid and direct it to the iron return yoke (Fig. 5). In order to keep the size and weight of individual sections reasonable, each end-cap is assembled from 24 azimuthal sectors of cast iron weighing 160 or 220 t per slice. Two possible solutions were considered for these sectors:

- i) the whole slice is cast as one solid block;
- ii) one sector consists of a cast caisson open at the outer side of the end-cap; it is filled with a separate, solid iron block; the caisson and the filling blocks each have about half the weight of one slice.

Cost would be the decisive factor for the choice between these solutions. Figure 6 shows some details of an individual cast end-cap slice; only one empty caisson of the second solution is shown. Interconnecting faces have to be machined and neighbouring slices will be screwed together. The side of the slice facing the internal volume can support the two smaller coils.

The end-caps completely cover the area of the return yoke which must support most of the magnetic forces. Each end-cap is attracted by the magnetic field with a force of about 10000 t. In the 'caisson solution', this force will deflect the end-caps at the centre by about 2 cm; the deflection is smaller if the solid blocks are used. The upper six slices of the end-cap are outside the return-yoke area. Therefore, the magnetic flux reaching them is transmitted to the adjacent slices which are in contact with the return yoke. For that reason slices with less iron on their outside edge could be envisaged. The attractive forces are retained by long struts (i.e. tubes of 400 to 500 mm diameter) arranged in an axial direction and equally spaced (see Figs. 3 and 4).

Each end-cap is mounted on a support structure which permits axial displacement allowing access to and mounting of the detector components inside the magnetized volume. Fig. 4 shows one end-cap moved to the 'garage' position. Furthermore, it shows the two previously mentioned possibilities for field shaping and the two additional smaller coils attached to each end-cap. For this purpose, the central part of the end-cap carries either a solid nose protruding into the field or a cone with azimuthally magnetized iron disks. The nose or cone could also carry the forward part of the electromagnetic and hadronic calorimeter weighing about 500 t; it is surrounded by muon chambers. It should be noted that the complete detector is off-centred with respect to the access shaft by about 2 m in the beam direction. This configuration allows full access to the central detector and calorimeter with the end-cap in its garage position.

3.5 Solenoid Coils

The winding of the solenoid will be subdivided into a number of equal coils with the exception of the four smaller coils attached to the end-caps, as indicated in Fig. 4. The coils should be equally spaced in order to permit the passage of the mechanical elements supporting the central calorimeter and the track chambers. Each one will be formed by placing in parallel a number of extruded, water-cooled, hollow Al conductors, as indicated in Fig. 7. These conductors can be obtained from industry at rather low unit cost, in lengths sufficient for the construction of individual coils. Therefore, no intermediate welding is required on the conductor.

A single coil would consist of 17 turns, each turn comprising 20 conductors. The individual conductors have a length of about 1000 m. Owing to the special form of the cross-section, they can be 'clipped' onto one another by swaging them, as indicated in the figure. This avoids welding, which would cause deformation. Neighbouring turns will be insulated by clipping insulator ribbons to each individual conductor during the winding process. The 17 turns

will be clamped together to form one coil. The ends will be connected to the electrical current supply and to a water manifold allowing water circulation in each single conductor.

The winding of the solenoid, with a total of about 400 turns, will consist of 24 coils. Four coils in series will be connected to one power supply of 2 MW. With this arrangement and with a symmetric grounding of the power supplies, the requirements for the electrical insulations are quite modest, $\Delta U \approx \pm 40$ V only. Therefore, the insulation can be done in a rather simple way.

Figure 8 shows a top view of a possible coil-winding facility. The horizontal turning table is located in the main assembly hall and can be served by the two 250 t cranes; the 20 spools with about 1000 m of individual conductor each (≈ 6 t) could be stored in an auxiliary side hall of light construction.

Having finished the winding of one coil, the turns will be clamped together and the coil will then be transported horizontally to another support to prepare the ends and to mount the water manifolds and the electrical connections. Thus the turning table is free for the winding of the next coil.

Each single coil, mounted in the vertical position in the detector, has to be fixed laterally for safe operation. This can be done by special clamps fixed to the iron side walls of the magnetic cavern. If the solenoid is not energized, each coil will sag by approximately 1 cm under its own weight, assuming a good mechanical link between individual conductors. It would be easy to reduce this sagging substantially by the lateral fixations.

3.6 Support Arches and Mounting of the Central Electromagnetic and Hadronic Calorimeter

Figures 3 and 4 show 6 individual arches of large I-beam cross-sections situated above the side walls of the iron return yoke. They are intended to suspend the central part of the detector, including the inner detector and the heavy electromagnetic and hadronic calorimeter and also to support the 10 struts mentioned above, foreseen to discharge the magnetic forces acting on the upper part of the end-caps.

3.7 Cost considerations

In order to find low-cost solutions for the detector layout, industry was contacted in the very early design stage. The price quotations from industry for the material are therefore necessarily based on very preliminary drawings and specifications, and only a small number of firms were contacted. Many detector components have to be assembled and produced on site because of their large dimensions and weight.

The following indicative costs can be given:

· <i>barrel</i>	
cast Fe—slabs (Bramme) + transport	0.6 CHF/kg
· <i>end-caps</i>	
cast Fe (caissons including machining)	4.5 CHF/kg
cast Fe (solid blocks including transport)	1.5 CHF/kg
or as a mean price for the end-cap iron	3.0 CHF/kg
· <i>solenoid</i>	
extruded conductor profile, Al 99.5%	6.0 CHF/kg
Production of the solenoid (estimate)	3.0 CHF/kg

With the above restrictions, this gives the following indicative costs:

· barrel: 12 000 t	7.2 MSF
· end-caps: 2 x 5000 t (mean price 3.0 SF/kg)	30 MSF
· solenoid: 2500 t @ 9 SF/kg (production incl.)	22.5 MSF

To these costs, it is necessary to add those for buildings, cranes, handling tools, power supplies and controls, cooling, safety, and the cost for mounting the components in the underground cavern.

4. Conclusions

We have presented a design study for a large solenoid intended for high-quality muon spectroscopy at future hadron colliders (LHC and SSC). The use of industrial components permits a relatively advantageous price. We believe that such an approach would also be of interest for similar magnets at other accelerator facilities.

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Figure captions:

- Fig. 1a Conceptual layout of the shaped solenoid. The version shown provides polar angle coverage from $9.8^\circ < \theta < 171.2^\circ$ (pseudorapidity $2.5 > \eta > -2.5$). Also shown are the magnetic flux lines which show clearly the effect of the 'shaping' due to the conical pole shape.
- Fig. 1b Shaped solenoid with forward toroids, which extend the magnetic field coverage to $|\eta| < 3$.
- Fig. 2 Calculated momentum resolution as a function of momentum in two regions of pseudorapidity.
- Fig. 3 Longitudinal cross-section through the shaped solenoid. The end-cap on the right side is the 'forward toroid' version; on the left side the 'shaped-cone' version is shown. Four arches support the central detector. Also indicated are the dimensions of the experimental hall. A central shaft, 33 m in diameter, provides access for the installation. Longitudinal extensions allow sufficient withdrawal of the end-caps for detector maintenance and a possible replacement of the central detector.
- Fig. 4 Cross-sections through the cylindrical part of the shaped solenoid. The cylindrical part of the coil and the iron return yoke with partial azimuthal coverage are shown. The return yoke is constructed from unmachined iron blocks, of approximately $9 \times 1.7 \times 0.3 \text{ m}^3$ dimensions ('bramme').
- Fig. 5 Schematic view of the end-caps. A modular construction is shown using modules with two different outer radii.
- Fig. 6 Perspective view of the end-cap caissons.
- Fig. 7 Cross-section through an Al coil showing the form of the extruded conductor. Also shown is the form of the plastic insulator, applied to the coil during the winding process.
- Fig. 8 Schematic view of the coil-winding facility. Each of the 20 small Al conductor coils supplies $\sim 1000 \text{ m}$ of conductor.

Fig.1a

Fig.1b

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6

Fig. 7

Fig. 8