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**GUIDELINES FOR A SUPERCOLLIDER EXPERIMENT:
THE MAGNETIC SYSTEM**

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ABSTRACT

We try to give some general guidelines for optimizing the magnetic system of a general-purpose detector with a high-momentum resolution for muons at a supercollider experiment. Solenoidal and toroidal schemes are investigated, with the possibility of using calorimeter material as the coil.

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1. INTRODUCTION

With the highest luminosity of the proposed Large Hadron Collider (LHC) and Superconducting Super Collider (SSC), the muon channels will be the most clear, if not the only ones, that can be studied. The experimental problem is that the μ momentum needs to be measured with a precision of the order of 1% at 1 TeV/ c in order to reconstruct parent masses with a signal sufficiently high not to be flooded by the huge combinatorial background. An example of this situation is the Higgs search in the 4μ channel in $H^0 \rightarrow Z^0 Z^0 \rightarrow 4\mu$. A Monte Carlo simulation shows that a 10% uncertainty on the μ momentum would be sufficient to rule out the signal [1].

This means that the classical way of measuring the μ momentum by its bending in the iron used to return the field of the central spectrometer is not practicable, since it gives a precision on the momentum of not better than $0.22/\sqrt{L}$ (L = length of the path in the spectrometer, normally a few metres), because of the multiple scattering in the iron, independent of the value of the momentum. To avoid this multiple scattering the μ must be bent in free space in a magnetic field B and on a sufficiently long path L : the magnet used to produce B must enclose the μ spectrometer and cover a wide solid angle. This means that the geometrical dimensions of the magnet tend to be enormous and also, if L is more effective than B to minimize the measurement error, that a compromise with B must be obtained since the μ momentum resolution has a $(BL^2)^{-1}$ dependence.

2. A SOLENOID-BASED EXPERIMENT

When we assume the straightforward solution of a solenoidal magnet with a warm coil, there exists an optimal path length L_{opt} which, for a given electric power P supplied to the magnet coil, minimizes the weight of the magnetic system (coil + iron yoke to close the magnetic circuit). Naturally, in the final project of an experiment based on such a magnet, L_{opt} must be balanced with the cost and complexity of the μ detector, with the dimensions of the experimental hall, etc.

To give a definite basis to our reasoning we assume a solenoidal aluminium coil enclosed in an iron yoke that returns the magnetic field (iron barrel) and makes it uniform inside the coil (iron end-caps).

For quantitative evaluations, a set of hypotheses must be assumed (a) on the coil itself ($\Delta\Omega$ covered, space in the coil for cooling) and (b) on the μ detector (distance of its useful volume from the coil, alignment, multiple scattering and measurement precisions, minimum radius of its useful volume). However, the hypotheses on the rest

of the detectors (i.e. the calorimeters to filter the μ 's and the vertex detectors) are irrelevant to the argument.

We derive the values for both (a) and (b) from the case of the L3 experiment [2] at the Large Electron-Positron storage ring (LEP), which is the example of a set-up best suiting our problem:

- (a.1) The conductor is aluminium and the magnetic-field induction in the iron is assumed to be 1.8 T.
- (a.2) Because of cooling and the structure of the supporting system, the radial encumbrance (or geometrical thickness ΔR) of the coil is twice the conductor thickness ($t = \eta \times \Delta R$, $\eta = 0.5$).
- (a.3) The length L_μ of the μ detector is twice its external radius R_e in order to cover zenith angles from 45° to 135° .
- (b.1) The last point in the μ trajectory is measured at a radius R_e , 0.5 m smaller than the radius R of the useful magnetic field volume, $R_e = R - 0.5$ m. Along the beam axis the μ detector is supposed to be efficient over a length L_μ , 0.8 m shorter than the length L_b of the useful magnetic volume, $L_\mu = L_b - 0.8$ m. These are the assumptions illustrated in fig. 1.
- (b.2) The first point in the μ trajectory is measured at a distance $R_i = 3.0$ m from the beam axis (compared with $R_i = 2.52$ m for L3). The systematic error on the sagitta S is assumed to be $30 \mu\text{m}$, the multiple scattering error $3.8 \mu\text{m}$ at $p = 500$ GeV, and the μ is supposed to be measured in a set of detectors with a precision of $150 \mu\text{m}$ per point, giving a global measurement precision of $48 \mu\text{m}$ at $p = 500$ GeV. In order to measure the dimuon mass with a precision of 1.29% at 1 TeV (that is the precision obtained by L3 for a dimuon mass of 100 GeV), the corresponding sagitta is $S_{500} = 2.62$ mm (the index '500' indicates the momentum in GeV of one of the two μ 's in a symmetric dimuon of 1 TeV).

We will assume S_{500} as a reference parameter for our evaluations. Given the sagitta S and the total electric power P , the weights of the coil and of the corresponding iron can be deduced as a function of the external radius R_e of the μ detector from the simple relations relating the sagitta and the electric power to the magnetic field B :

$$S = (0.3/8) \times [(R_e - R_i)^2 \times B/p] , \quad (1)$$

where $B = \mu_0 \times I/L_b$ (I = total current), and

$$P = \rho_{Al} \times 2\pi \times (R_e + 0.5 + \Delta R/2) \times I^2 / (L_\mu \times \eta \times \Delta R), \quad (2)$$

where ρ_{Al} is the conductivity of aluminium. The thickness ($t = \eta \times \Delta R$) of the solenoid

determines the outer dimensions and the weight of the coil and defines the magnetic field volume; these are input to evaluate the weight of the iron yoke.

The results, parametrizing the ratio between the sagitta S and the reference value $S_{500} = 2.62$ mm, are reported in fig. 2, evaluated for an electric power $P = 12$ MW spent on the coil. As shown in fig. 2, for each obtainable precision in the momentum measurement (expressed by the S/S_{500} parameter), there exists an optimal external radius R_e^{opt} of the μ detector for which the total weight of the iron is a minimum. However, the trend of the aluminium coil weight with R_e is monotonic; added to the iron weight it would give a minimum total weight (coil + iron yoke) at a R_e^{opt} slightly (a few %) higher, but of little meaning given the different prices of the two components.

In the whole energy range the values of the current density in the aluminium coil are very low, i.e. between 0.4 and 1.5 A/mm², so that the encumbrance foreseen for the cooling in the above hypothesis (a.2) is more than sufficient. The values of the magnetic field range from 0.1 to 0.7 T. The minimum iron weight deduced from fig. 2 strongly depends (nearly linearly) on the obtainable precision.

Allowing a 10% (20%) increase of the iron weight the optimal external radius R_e^{opt} diminishes for more than 20% (25%), as shown in fig. 3; this is an important point for calculating the dimensions of an experimental project, weighing up the magnet price against the μ detector price and complexity.

The dependence of the weight of the coil and of the iron yoke on R_e for $S = S_{500}$ is reported in fig. 4, allowing the inner radius R_i to vary by ± 0.5 m around the 3.0 m value assumed in the above evaluations. It turns out that the weight and R_e^{opt} variations with R_i are of secondary importance: a drastic reduction of the ‘vertex + calorimeter’ external radius from 2.7 m (corresponding to $R_i = 3.0$ m) to 2.2 m (corresponding to $R_i = 2.5$ m) results in an 11% reduction in the iron weight and less than 7% in R_e^{opt} .

3. POSSIBLE USE OF THE CALORIMETER MATERIAL FOR THE MAGNETIC SYSTEM

In the solenoid case discussed above, the elements of the magnet (coil + iron yoke) are not used as part of the detectors, unlike what happens in the ‘classical scheme’ where the absorbing material of the calorimeter (normally iron) is used to return the magnetic flux. Could this absorbing material be used in a different way, e.g. for carrying electric current to produce a magnetic field in the volume of the μ detector? Obviously the iron of the ‘classical scheme’ should be replaced by copper, suitable to conduct electric current and also better than the iron as an absorber in a calorimeter.

Two schemes can be foreseen: the current would flow in circles around the beam axis, producing a solenoidal field that starts inside the calorimeter and closes outside, mainly in the μ detector volume (fig. 5); or the current would flow parallel to the beam axis, producing a magnetic field only outside the calorimeter, whose lines are circles centred on the beam axis (toroidal field, see fig. 6). In the following two sections these two possible scenarios will be discussed, assuming for the calorimeter design the following set of hypotheses. Only the absorbing material of the external part of the calorimeter, the so-called 'tail catcher', will carry the electric current; this part is assumed to extend from 2.7 m down to 1.4 m distance from the beam axis and to have a 10 m length in order to cover up to 30° in zenith: this is the calorimeter (outer section) shown in fig. 1. The detector is assumed to occupy a quarter of the corresponding cross-section, while the cross-section devoted to the cooling is assumed to be negligible, provided that the electric current density is kept to less than 2 A/mm^2 . The ratio between the copper cross-section and the total geometrical cross-section is indeed $\eta_c = 0.75$. The innermost part of the calorimeter is not involved in order to preserve the complete freedom of using the best materials and techniques to maximize the energy resolution. The power spent in the whole magnetic system will still be assumed to be $P = 12 \text{ MW}$.

3.1 Possible use of the calorimeter material for the solenoidal system

The coil and iron weights are calculated now solving the above relations for the whole magnetic system (solenoidal coil + calorimeter + iron yoke), allowing the current density in the calorimeter to vary from 0 to 2 A/mm^2 in the copper. The results (fig. 7) are not much different from the previous ones reported in fig. 2.

Two important remarks must be made concerning this scheme.

Firstly, the use of the outer part of the calorimeter as a solenoid, even if it does not help in the magnetic system for the μ spectrometer, can produce a very high field in the interaction region, from which a vertex detector could largely profit.

Secondly, given the smaller dimensions of the calorimeter compared with those of the μ spectrometer, the 'vertex + calorimeter' part could be enclosed in a superconducting coil which, besides contributing to the field in the μ detector, would assure a high field in the vertex region; obviously its radial encumbrance should be considered in the optimization of the whole system.

3.2 Possible use of the calorimeter material for the toroidal system

To compare this second scheme with the previous one, the geometry of the μ detector must be redrawn (fig. 8) in order to match the different trends of the momentum resolution in the toroidal field (see fig. 9).

The magnetic system consists now of the outer part of the calorimeter and of a conductor that closes the current circuit and also defines the magnetic field volume where the μ detector operates (see fig. 8). No iron is present to return the field, as it closes on itself in circular lines. Its strength weakens as $1/R$ with the distance R from the beam axis, and formula (1) for the sagitta modifies to:

$$S = [0.015 \times I \times R_i \times (y - 1 - \ln y)]/p \quad [y = R_e/R_i] . \quad (3)$$

To preserve the analytical quality of the field, the shape of the conductor closing the current circuit should approach, as much as possible, that of a cylinder. An important parameter determining the strength of the field and the electric consumption is the ratio r_s of the total cross-section of this conductor to the cross-section of the conductor in the calorimeter. Assuming that this conductor will be made of aluminium, the above equations (2) and (3) solved for its thickness give the weights reported in fig. 10 as a function of R_e , the parameter r_s , and the obtainable momentum resolution expressed as S/S_{500} .

The R_e values for $r_s = 2$ and $r_s = 3$ are compared in fig. 11 with those of the 'minimum iron weight' aluminium solenoid of fig. 3, as a function of S/S_{500} . For $S/S_{500} \leq 1$ the radial dimensions of the μ detector in this toroidal scheme are significantly smaller than those in the solenoidal one; this advantage adds to the shorter L_b required by the toroidal scheme. It must be noted that increasing r_s the total electric resistance of the coil decreases, allowing R_e to decrease; however, this trend is effective up to $r_s = 3-3.5$, and decreases afterwards at the expense of a sharp increase in the conductor weight.

It must finally be noted that in the case of the solenoid an extra weight must be considered for the structure supporting the calorimeter at the centre of the μ detector; in the case of the toroidal scheme a suitable design could enable the aluminium conductor to be self-supporting, and perhaps to support the calorimeter as well.

A substantial reduction of the dimensions of the μ detector, at the price of a large increase in weight of the current conductor can be achieved by using copper for this conductor, given its better conductivity. The final comparison for $S/S_{500} = 1$ can be summed up in table 1.

Finally, fig. 12 shows how the dimensions of the μ detector and the weight of the aluminium conductor vary with the absorbed electric power.

REFERENCES

- [1] M. Chen et al., Proc. Workshop on Experiments, Detectors and Experimental Areas for the Supercollider, Berkeley, 1987 (World Scientific, Singapore, 1988), p. 95.
- [2] B. Adeva et al. (L3 Collaboration), Nucl. Instrum. Methods **A289** (1990) 35.

Table 1

Comparison of dimensions and weights for different magnetic configurations

Magnet	R_e (m)	L_m (m)	Material	Weight (t)
Toroid ($r_s=1$)	15.2	24.3	Cu	5,876
Toroid ($r_s=2$)	14.3	23.9	Al	3,331
Toroid ($r_s=2$)	12.5	20.0	Cu	9,536
Toroid ($r_s=3$)	12.8	20.5	Al	4,447
Toroid ($r_s=3$)	11.5	18.4	Cu	13,119
Solenoid	13.4	26.8	Al	2,542
			+ Fe	33,275

Figure captions

- Fig. 1: Assumptions for the μ detector.
- Fig. 2: Solenoid: weight of the Al coil (broken lines) and of the Fe (full lines) for different values of the sagitta S .
- Fig. 3: External radius of the μ detector for 'minimum', 'minimum + 10%', and 'minimum + 20%' Fe weight, as a function of the sagitta S .
- Fig. 4: Solenoid: weight variation for different minimum radii of the μ detector.
- Fig. 5: The 'partially compensated' solenoidal scheme.
- Fig. 6: The toroidal scheme.
- Fig. 7: The minimum iron weight as a function of current, using the calorimeter material for the solenoidal system.
- Fig. 8: Assumption for the μ detector using the calorimeter material for the toroidal system.
- Fig. 9: Toroidal field map in the μ detector using the calorimeter material.
- Fig. 10: The weight of the Al conductor as a function of external radius of the μ detector.
- Fig. 11: The external radius of the μ detection volume as a function of the sagitta for different values of r_s .
- Fig. 12: The μ detector dimensions as a function of the weight of the Al conductor for different values of the electric power. *

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12