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THE CHOICE OF SPECTROMETER MAGNETS FOR LEP

by

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Abstract

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Many experiments at LEP will require matching spectrometer magnets. In this report, guidelines are established for providing a starting point in the iterative process of choosing the best device for a particular detector. Magnets are compared in terms of their resolving power based on measurements of sagitta. This approach draws attention to the importance of detector size, and also helps to define the preferred areas of application of normal and superconducting technology. Although most emphasis is placed on the solenoid, toroids and dipoles are also discussed.

1. Introduction

Experiments at LEP will require matching spectrometer magnets for charged particle recognition and momentum measurements. The choice of a suitable magnet for each experiment is an iterative process bounded by requirements of complementarity to the other elements of the detector, and by limits of technical feasibility. The purpose of this report is to assemble some guidelines to help to start the process.

Different types of magnets for central detectors can be compared in terms of momentum resolution obtainable from measurements of sagitta, which is usually a more realistic parameter than magnetic bending power. When considering the choice of a magnet, it is important not to demand of the device more resolution than necessary. The cost and complication of magnets increase more than linearly with increasing power of resolution, and the money and effort could sometimes be more effectively spent on improving the detailed adaptation of the magnet to the experiment, or on other elements of the detector. In the context of LEP, it is therefore useful to recall the following:

- i) The expected spectrum of charged particles coming from an interaction, as predicted by the fragmentation model [1], is strongly skewed towards the lower energies (Fig. 1).
- ii) When a magnet is used in combination with a hadron calorimeter ($\Delta E/E \propto 1/\sqrt{E}$), the momentum resolution of the detector as a whole improves slower than improvements in magnet resolution (Fig. 2).
- iii) In the case of a solenoid of radius R [m] producing field B [T], charged particles having momentum $p < 0.3 BR/\pi$ GeV/c will spiral within the track detector. Absorbant radial vanes in the track detector do not provide a solution to this problem [2]. To illustrate the confusion which this effect may lead to, the track pattern produced by a typical simulated event in the jet detector discussed at Les Houches [3] is shown in Fig. 3.
- iv) Multiple scattering in the beam pipe and the track detector sets a natural limit to the possible momentum resolution.

2. Magnets for a central detector

2.1 Solenoids

Under this heading, we consider the class of magnets producing a cylindrically symmetrical field, the axis of which coincides with that of the colliding beams.

2.1.1 The momentum resolution of a solenoid. The sagitta s [m] of the trajectory of a charged particle carrying momentum p [GeV/c], emanating at zenithal angle $\theta = 90^\circ$ from the interaction on the axis of a solenoid of radius R [m] producing a magnetic field B [T] is given approximately by $s = 0.0375 BR^2/p$. In a realistic case, where a certain distance (0.2 m) must be subtracted from the path length along which measurements can be made in order to accommodate the beam pipe and detector edges, the effective sagitta is:

$$s = 0.0375 B (R - 0.2)^2 / p \quad [\text{m}] .$$

Assuming that the accuracy of the track detector (combined individual measurement precision and number of points) is such as to provide an estimate of S with a precision of 100 μm , this gives an expected momentum resolution:

$$\frac{\Delta p}{p} \simeq \frac{\Delta S}{S} \simeq \frac{0.2668 p}{B(R - 0.2)^2} \% .$$

The sensitivity of momentum resolution defined in this way, to variations in B and R is illustrated in Fig. 4. It should be noted that no assumption is made concerning the vertex, and that at zenithal angles $\theta < 90^\circ$, for a solenoid of constant field and radius, the potential resolution of the magnet improves by a factor of about $\sin \theta$.

2.1.2 Solid angle coverage. If the total length of the solenoid is L [m], the fraction of the solid angle covered is $2 L / \sqrt{4R^2 + L^2}$, centred about the plane of maximum transverse angle. For the purposes of comparison, solenoids with $L = 2R$, i.e. covering down to $\theta = 45^\circ$, will be considered. In fact, by suitable shaping of the coil, it should be possible in certain cases (see below) to increase the solid angle analyzed from 70 % ($135^\circ > \theta > 45^\circ$) to 90 % ($154^\circ > \theta > 26^\circ$) of 4π without substantially increasing L .

2.1.3 Normal and superconducting coils. Independent studies [4,5] comparing the integrated cost of normal and superconducting spectrometer magnets indicate that, where the choice exists, the breakeven point occurs for an equivalent power dissipation (P) of 2 to 3 MW in a room-temperature coil. Initially, the SC coil and its associated cryogenics take longer to build and cost from one to four times that of an equivalent normal version, so time, manpower and cost scheduling of the experiment also influence the choice.

The mass of conductor required for a normal solenoid with an efficient flux return yoke is given by $M \simeq 2(RLB)^2/P$ tonne for aluminium, and twice that amount for copper. The physical thickness of the winding, including insulation and cooling, is about $9.5 M/LR$ cm for aluminium ($\div 3.3$ for copper). The interdependence of momentum resolution and coil mass, radius and thickness for $L = 2R$ and $P = 2$ MW is shown in Fig. 5. It can be seen that for $\Delta p/p$ (100 μ , 10 GeV/c) $\leq 1\%$, a superconducting magnet is probably necessary, regardless of transparency, and that if an equivalent momentum resolution of $\leq 2\%$ is required together with a coil transparency corresponding to ≤ 0.5 radiation lengths of material, then the winding should also be superconducting.

2.1.4 Thin superconducting coils. Thin-wall superconducting solenoids are in use, or planned for, at most storage ring machines [6, 7, 8, 9]. Applying the techniques so successfully used for the CELLO magnet [10], estimates have been made [11] of safe achievable field as a function of total wall thickness in radiation lengths and coil radius. This information has been used to plot curves of best obtainable momentum resolution as a function of coil radius for various wall thicknesses (see Fig. 6).

2.1.5 Thin aluminium coils. The momentum resolution which can be obtained from thin aluminium coils of several average thicknesses is also shown for comparison in Fig. 6. These coils are only competitive with thin SC magnets on the grounds of obtainable momentum resolution for an equivalent thickness of less than 0.25 r.l. In addition, however, the simplicity of the thin room-temperature coils is such that the increase by a factor of about 2.5 for a coil of thickness 0.5 r.l. (1.5 for a coil of 0.35 r.l.) in obtainable $\Delta p/p$, compared with using a superconducting coil, may in certain cases be justified.

2.1.6 Shaped coils. The coil of a solenoid may be shaped to reduce the effective wall thickness traversed by particles coming from the interaction at $\theta < 60^\circ$. An example is shown in Fig. 7. This magnet provides almost constant momentum resolution down to $\theta > 30^\circ$, an effective coil thickness of less than 1.2 times the thickness at $\theta = 90^\circ$ over the whole accepted solid angle, and a shorter total length. Such an arrangement looks particularly interesting for an experiment using a hadron calorimeter which incorporates the flux return yoke in a suitably laminated form. Shaping the coil in this way also gives rise to a more favourable field pattern than would be obtained from a uniform cylindrical solenoid.

This type of geometry would appear to be more easily applicable to room-temperature than thin superconducting coils. Hybrid coils could also be considered.

2.1.7 Open magnets. In the Axial Field Spectrometer [12], the field in the magnet (sketched in Fig. 8) is shaped and no coil material is present in the range $130^\circ < \theta < 40^\circ$. Such a device is, in fact, dipole with hollow conical poles, the axis of which is coincident with the colliding beam trajectories. Acceptance and access are decided advantages of this geometry, but solid angle necessarily shaded by the poles and coils ($40^\circ < \theta < 15^\circ$) is a drawback. The orientation of the flux in the poles is such as to preclude their use for calorimetry (other than sampling).

2.1.8 Very large coils. Interesting momentum resolution would appear to be available in a very large, relatively low field solenoid.

We note that the handling of such coils can cause problems, and although the transport of complete coils of up to 3 m in diameter, and narrow coil sections of up to 5 m in diameter, is feasible, it would be preferable to assemble larger coils on site. A technique presently at the idea stage [13], which might be worth considering for a 6 to 9 m diameter coil would be to wind a flexible liquid helium transfer line containing a superconducting cable directly onto a frame erected in the experimental hall. Whereas large cryostats are difficult to make, the technology already exists [14] for making flexible transfer line in as long a length as required. The transfer line would form the cryostat

for the SC winding, assembled simultaneously. Taking full advantage of its flexible nature, the coil could be transported from the factory on drum(s) of 2 m in diameter. Shaping of the magnet would be easy, as would eventual reshaping of the coil to suit subsequent experimental geometries. Normal conductor magnets, which are also seen to be competitive for large radii, could conceivably take the form of self-supporting structures built up from bolt-together modules.

2.1.9 Flux return yokes. The comparison of the different types of solenoid has been made assuming that magnetic flux is guided from one end of the coil to the other through an external unsaturated steel yoke. The flux return yoke serves to reduce the required number of ampère-turns, and to shield the area surrounding the solenoid from stray field. The minimum mass of steel required for this purpose can be expressed approximately as $17 BR^2 (L+0.65BR+R)$ tonne; for small, open magnets, the effective mass of steel may approach ten times this. For a laminated steel yoke integrated into a mixed material (e.g. steel/uranium) hadron calorimeter, estimates of the mass of steel required can be plotted in terms of $\Delta p/p$ as shown in Fig. 9. Laminating the yoke increases the cost of fabrication, but this is offset by a reduction in the cost of the calorimeter, where the structural qualities, and the low cost/mass ratio of steel are appreciated. Where possible, the plane of the sheets should coincide with the flux lines; at the poles, as illustrated in the example of Fig. 7, this cannot be the case, and the field will be reduced in proportion to the increase of reluctance. Such effects must be calculated on a magnet to magnet basis, and the calorimeter, magnet yoke and coil should be optimized together.

2.1.10 Compensation. The effect of a solenoid field on the circulating beams is to provide some focusing and to excite coupling between horizontal and vertical betatron oscillations. The focusing effect is weak and can be compensated, if necessary, by making some small changes to the machine quadrupole settings; coupling will be compensated using skew quadrupoles, which are also built into the machine structure for adjustment of the emittance ratio [15]. A skew quadrupole scheme is currently used to correct coupling due to solenoids at the CERN-ISR. For solenoidal spectrometer magnets, it should not, therefore, be necessary to install any correcting elements in the interaction regions.

2.2 Toroids

In theory, the toroidal magnet possesses a certain number of attractive qualities. There is no field at the axis, and therefore no need for compensation; there is no iron yoke; and charged particles produced on the axis are deflected in only one plane. In fact, in the comparison between toroids and solenoids, these features carry less weight now than they did some years ago. Solenoids can be compensated using skew quadrupoles; the iron yoke is useful for calorimetry; and existing software can be used to unravel the 3-D trajectories on ever-cheapening computer time. With this new set of ground rules, the major drawback of the toroid - the fact that particles must traverse the inner winding before entering the analyzing field - looms larger than ever. Some interest remains, nevertheless, and it is instructive to quantify the momentum resolution obtainable using similar criteria to those applied to the solenoid.

2.2.1 The momentum resolution of a toroid. Assuming that the sagitta of the trajectory of a charged particle travelling radially through a toroidal field confined between inner and outer radii R_i and R_o [m], and of strength B_i [T] at R_i , corrected for a dead space of 10 cm between the inner radius and the first measurement, can be obtained with a precision of 100 μ , $\Delta p/p$ can be plotted against R_o for various values of B_i and R_o/R_i . For a given B_i , best resolution is obtained when $R_o/R_i \simeq 3.5$, and the curves shown in Fig. 10 apply to this case. These curves also include the improvement in precision obtained when θ is measured between beam pipe and inner conductor, as would usually be the case.

2.2.2 Continuous inner winding. For shadow-less coverage of the azimuth, the inner winding must be uniformly distributed on a cylinder: plots of $\Delta p/p$ against R_o for different thicknesses of this winding, are given in Fig. 11. For the 2 MW aluminium version, it has been assumed that 1 MW is dissipated in the inner winding, allowing another 1 MW for a longer, but thicker, return conductor; the thickness of the thin superconducting version includes a support tube to take the external magnetic pressure, and cryostat walls, etc.

A glance at recorded/total multiplicity of charged hadrons, with various thicknesses of coil (Fig. 12) would suggest that if any useful information is to be extracted from track detector measurement of momentum using the toroidal field, then 0.1 r.l. should be considered a maximum thickness. This implies that for hadron physics, a very thin aluminium coil must be chosen, and that the thicker continuous coils would be more suitable for a spectrometer in which the coil is preceded by, or used as, an absorber (e.g. a muon pair experiment). A thin aluminium toroid with suitable chambers before and after the inner winding is seen to provide similar momentum resolution to a solenoid occupying the same volume.

2.2.3 Lumped coils. Lumped coils are essentially thick, shading part of the azimuth and giving rise to an additional source of background. The optimum number of coils for such a device is eight, and in order to have reasonable acceptance ($>70\%$ of ϕ), the inside radius should be about 1 m. Though the local forces are greater, the mechanical problems associated with this geometry are easier to solve, and the device could be manufactured in transportable modules. To maximize clear acceptance, the coils could be supported from a rigid external frame using a system of rods in tension [16].

Possibly, the most interesting superconducting toroid would be one which combined the modular technique with a pseudo-continuous inner winding. By spreading out the conductor, the field shape is improved, and the peak levels of field and force at the conductor are reduced. Azimuthal acceptance (through an equivalent wall thickness of 1.5 to 2 radiation lengths) could also be increased to about 85 %.

The practical regions of application of thin normal, normal and superconducting toroids in terms of resolution and radius are shown in Fig. 13.

2.3 Dipoles

The strength of dipole spectrometer magnets for LEP is limited by the level of perturbation caused to beam orbits and dispersion, the synchrotron radiation produced, and the increase in background in the interaction region due to the deflection of low energy particles, which

would normally accompany the beam right through the region, into the beam pipe. This last limitation seems at present to be the most stringent. Spectra of the energy of particles arriving in the intersection, and which are expected to produce background, and of those which are susceptible to doing so [17], are compared in Fig. 14. It is estimated that an integrated dipole field of 0.5 Tm at the crossing point, compensated with opposite dipole fields of half the strength, 3 m away on either side, would increase the expected 'natural' background over the central 5 m of the interaction region by 50 %. Vertically oriented bending strengths of this magnitude do not noticeably perturb machine operation, and the resulting synchrotron radiation is of the same order of magnitude as that already expected from beam-beam effects (1 kW), highly collimated within the beam pipe. If such conditions can be tolerated, an arrangement of the type sketched in Fig. 15 would complement the traditional solenoid-based central detector in an interesting way. Magnetic analysis is provided over 85 % of 4π , independent of θ and symmetrical about the horizontal median plane, and the set-up suggests itself for studies of θ -dependent phenomena, asymmetries, etc.

3. Magnets for downstream detectors

Dipoles are preferred, and the compensating magnets for the central dipole described above have been drawn in Fig. 15 as typical of the kind of device which would be designed to cover small angles up to $\theta = 350$ mrad. When used with a solenoid, or with the central dipole off, it would be necessary to add two small compensating dipoles in order to confine the bump in the horizontal closed orbit to the interaction region (see Fig. 16.ii)). It may also be desirable to use these additional compensators to correct the position of the interaction in the central dipole. This is illustrated in Fig. 16.i) and iii).

If, against all expectations, such dipoles should cause an intolerable increase in background, or if very much larger bending power should be required, attention should be paid to the choice of either a toroid or a belt-buckle magnet. Possible versions of these magnets are described in [5]. A superconducting flux exclusion tube could also be used to shield the beams from a strong dipole field, but its thickness would have to be taken into account.

4. Conclusion

The experience gained through the first and second generation of experiments at storage rings provides us with a sound base of knowledge for defining rational architecture for the third generation (i.e. the first generation at LEP). The correct matching of magnet to spectrometer is one of the domains in which spectacular progress has already been made, and to use ill-conceived or ill-fitting magnets will become an increasingly important handicap in the competitive environment of high energy physics experiments. It should also be remembered that although it is frequently the heaviest and most impressive-looking single item of an experiment, the magnet seldom costs more than 15 % of the total.

Some of the magnets suggested here would require a thorough feasibility study, possibly including prototype work, before manufacture could be started. It is not too early to start such work if we are to be ready when LEP is first turned on.

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References and Notes

1. Fields, R.D., Feynman, R.P., Nucl. Phys. B136, 1 (1978).
2. Taylor, T.M., ECFA-LEP Working Group, SSG13/5 (1979).
3. Winter, K., CERN 79-01, 93 (1979).
4. Morpurgo, M., Reported in CERN-DIR/EN/80-1 (1980).
5. Taylor, T.M., ECFA-LEP Working Group SSG13/6 (1979).
6. Morpurgo, M., Cryogenics 17, 89 (1977).
7. Eberhard, P., Green, M.A., Michael, W.B., Taylor, J.D., Wenzel, W.A., IEEE Trans. MAG-13, 78 (1977).
8. Genevey, P., Le Bars, J., Proc. 6th Int. Conf. on Magnet Technology (MT-6), 1033 (1977).

9. Smith, R.P., Niemann, R.C., Catania, F., IEEE Trans. MAG-15, 111 (1979).
10. Desportes, H., Le Bars, J., Mayaux, G., Proc. ICEC-7 (1979).
11. The superconductor considered is multifilamentary NbTi in a minimal copper matrix, soldered to high purity aluminium stabilizing material of just sufficient cross-section for safe operation.
12. Experiment R807, CERN, ISRC/76-36/P95 (1976).
13. Lebrun, P., Private communication.
14. Blessing, H., Laeger, H., Lebrun, P., Rohner, P., Schippl, K.D., to be published in Proc. ICEC-8 (1980).
15. Guignard, G., in CERN/ISR-LEP/79.33, 53 (1979).
16. Taylor, T.M., Proc. 1978 ISABELLE Summer Workshop, 249 (1978).
17. Smith, A., LEP note 164 (1979) and private communication.

Figure Captions

- Fig. 1 : Predicted differential and integral spectrum of charged hadrons produced at a LEP crossing point is strongly skewed towards the lower energies.
- Fig. 2 : The momentum resolution of a magnetic spectrometer combined with a hadron calorimeter. We note that increasing the field by a factor of two does not improve aggregate resolution by as great a factor.
- Fig. 3 : A typical event as seen by the Jet Detector discussed at Les Houches. The solenoid, of radius 1.8 m, produces a field of 1.5 T.
- Fig. 4 : The momentum resolution obtainable in a solenoid, as a function of the radius and field of the magnet. The curves apply to a 10 GeV particle, the sagitta of whose trajectory is measured with a precision of 100 μm .
- Fig. 5 : The interdependence of coil mass, thickness and achievable momentum resolution when using a normal conducting solenoid consuming 2 MW.
- Fig. 6 : Momentum resolution as a function of coil radius and thickness for normal (2 MW) and superconducting solenoids of length $L = 2R$.
- Fig. 7 : A suggested thin aluminium coil, shaped to reduce wall thickness while maintaining good resolution down to $\theta = 30^\circ$.
- Fig. 8 : Schematic drawing of the Open Axial Field Magnet used in experiment R807 at the CERN-ISR.
- Fig. 9 : Resolution obtainable from a solenoid expressed roughly as a function of various total masses of steel, assuming that the steel is diluted with a non-magnetic material to form a 1.5 m thick calorimeter structure.

Fig. 10 : The momentum resolution obtainable in a toroid, expressed as a function of outer radius (R_O) and various fields (B_i) at the inner radius (R_i). We assume $R_O = 3.5 R_i$ and that the sagitta measurement is supplemented by a measurement of θ before the particle enters the inner wall. The curve in the insert indicates the corrections to be made for the other ratios of R_O/R_i . If the measurement of θ previous to the field is not possible, $\Delta p/p$ increases by a factor of ~ 1.35 .

Fig. 11 : Resolution versus outer radius for various thicknesses of a uniformly distributed, 2 MW aluminium coil, and SC coils.

Fig. 12 : The effect of various wall thicknesses on the recorded multiplicity of charged hadrons. The example concerns a toroid covering $150^\circ > \theta > 30^\circ$, with 5° shadows at the extremities to simulate the (necessarily thick) coil returns. The computation was made by H. Grote using the fragmentation model [1], with 500 events.

Fig. 13 : Zones of application of normal and superconducting windings, in terms of $\Delta p/p$ and R_O .

Fig. 14 : Histograms of particles per bunch per 10 GeV interval which stop in the ± 10 m interaction region to produce background ("natural background"), and of degraded particles which normally pass through.

Fig. 15 : A suggested combination of central and downstream low-field dipole magnets. The total power consumption of all three magnets would be less than 0.5 MW.

Fig. 16 : Horizontal beam deflections through an interaction region equipped with dipole analyzing magnets: i) as shown in Fig. 15, ii) with no central dipole, and iii) also as in Fig. 15 but with additional small dipole compensators as used in ii).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

$B = 0,45 \text{ T}$
 $P = 1,3 \text{ MW}$
 $M = 1,6 \text{ t (Al)}$
 (with diluted iron
 yoke / calorimeter)

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Figure 14

Figure 15

Figure 16