DETECTOR MAGNET MEASUREMENTS

D. Newton
Dept. of Physics and Chemistry, University of Lancaster, UK

Abstract
The many differences between detector magnets and accelerator magnets are emphasized, especially the large magnetic volumes and stored energies. External measuring machines are described, as used for mapping the rather open magnets of the 1960s and 1970s. For the almost closed magnets of modern detectors an internal machine is described. The required precision is discussed. Methods for checking the field map are presented, with actual results from one detector.

1. DETECTOR MAGNETS AND ACCELERATOR MAGNETS

The magnetic measurements of detector magnets and accelerator magnets have a few similarities and many differences. The similarities are that the order of magnitude of the fields have up to now been similar, usually between 1 and 2 Tesla, so that the traditional techniques of search coils, Hall probes, NMR probes are suitable for both. Iron yokes have usually been involved, with consequent saturation effects at full field, and the well-known hysteresis effects.

The differences stem from the use of the magnets; in accelerator magnets particles of well-defined momentum pass all the way through, but in detector magnets particles of unknown momentum ranging over a factor of 1000 (e.g. from 0.1 GeV/c to 100 GeV/c, and either sign of charge) may have any trajectory, as shown in Fig. 1.

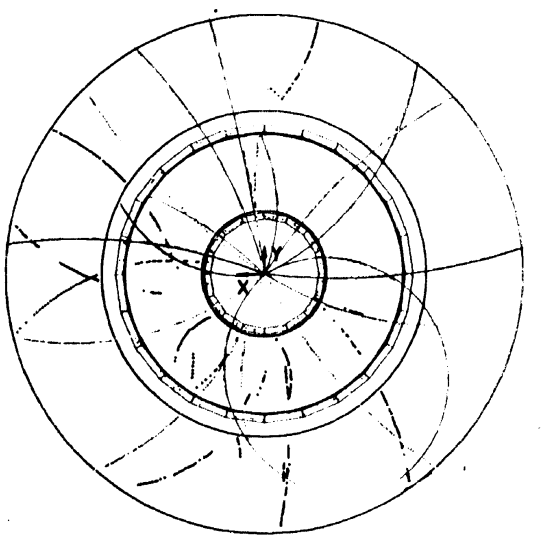

Fig. 1 Tracks of various momenta in a typical detector

The trajectory is detected at sampling points, or continuously in a bubble chamber, and the momentum calculated. If the field were uniform and the trajectory a helix, this would be simple. Over large volumes the attainable fields are not uniform, hence the need for a detailed field map. Then the measured trajectory, even though not a helix, allows the momentum to be determined. The procedure for doing so is far from obvious, and much effort has been devoted to various software techniques[1].

Each detector magnet is unique; the degree of non-uniformity has no precedent. Twenty or thirty years ago this could bring some nasty surprises, but nowadays computer design codes for magnets are very good. Perhaps most important, there is only one opportunity to make the magnetic measurements. Between the engineers assembling and commissioning the magnet, and the physicists filling it with detectors, there will be a few days allowed for the magnetic measurements. Clearly a suitable measuring machine must be ready for this opportunity and must work without breakdown throughout a carefully prepared schedule.

2. STORED ENERGIES AND POLE-TIP FORCES

It is worth drawing attention here to some of the consequences of the very large volumes of magnetic field, in essentially air, of these detector magnets. This contrasts sharply with accelerator magnets. It also shows a spectacular, perhaps frightening, trend over the past few decades and towards the future.

The stored energy density is

$$\frac{1}{2}\mathbf{B}\cdot\mathbf{H} = \frac{B^2}{2\mu\mu_0} \quad (1)$$

$$= 0.4\times 10^6 B^2 \text{ for air} \quad (2)$$

Joule per m^3, and negligible for the iron because the permeability μ has a value of several thousand [2].

At a typical field of $B = 1.6$ T this gives a stored energy of one megajoule (MJ) per m^3. In bubble chambers of the 1960s the magnetic volumes were under one m^3. In the 1970s bubble chambers, and the increasingly popular counter experiments, had magnetic volumes of several (1 to 3) m^3. In the 1980s detectors at fixed target machines became less popular than those at storage rings ISR, $\bar{p}p$, and Petra, and some of these had magnetic volumes of order 10 m^3. Now in the 1990s we have at LEP and HERA some huge solenoid detectors like Aleph, Delphi, H1 which have magnetic volumes of order 100 m^3, and the giant L3 with magnetic volume of order 1000 m^3. The stored energies in these magnetic fields is of order 100 MJ.

It should be noted that a stored energy density of one MJ per m^3 in air but negligible in iron implies a pressure of one million Newtons per m^2 pushing the pole tips together (at the typical field of $B = 1.6$ T, and varying as B^2 for other fields). This is a pressure of ten atmospheres, or ten tons per square foot ! It so happens for the magnet shapes used over the past 30 years that the fields and areas of pole tips have been such as to result in a force pushing the pole-tips together approximately equal to the weight of the magnet in each case. Thus the forces have grown from tens of tons, through hundreds of tons, and are now thousands of tons. For example in the H1 magnet the distance between the pole tips decreases by several millimeters when the magnet is turned on, an important fact when mounting a measuring machine for field mapping, or when mounting precision tracking devices for physics.

3. DETECTOR MAGNETS AND EXTERNAL MEASURING MACHINES

Detectors of the 1960s were chiefly bubble chambers or counter experiments, the latter consisting of scintillation counters on their own or triggering optical spark chambers, and both involving magnets for momentum determination.

A typical bubble chamber of the 1960s was the 150 cm x 50 cm x 50 cm hydrogen chamber used at CERN. The beam traversed the 150 cm length of the chamber, passing between the two coils and through holes in the surrounding iron yoke. The cameras viewed along the axis of the coils and thus along the magnetic field direction. Their depth of field was the full 50 cm depth of the liquid hydrogen. Thus the volume over which tracks could be detected, and over which the magnetic field map was required, was almost all of 150 cm x 50 cm x 50 cm. The field was approximately 1.3 T and was mapped with Hall probes, done of course before the liquid hydrogen chamber was introduced into the magnet.

In the 1960s and 1970s the most common type of detector magnet for counter experiments at the fixed target accelerators was like that shown schematically in Fig. 2. The pole-tips were rectangular and horizontal, typically 0.75 m apart, producing a field of between 1 and 2 T over a volume of 1 to 3 m^3. A detailed description of such a magnet is given by Barber et al [3].

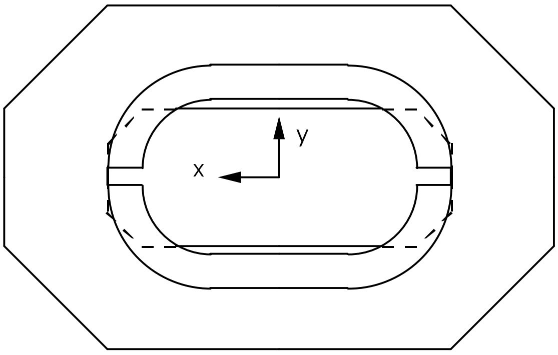

Fig. 2 Front view of a typical detector magnet for counter experiments

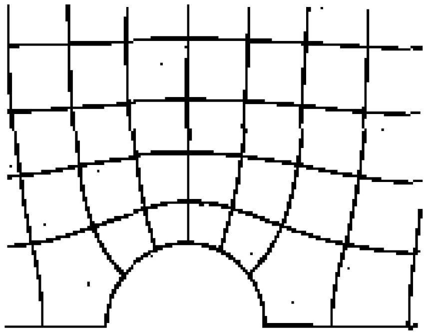

Fig. 3 Local distortion of the field produced by a half-cylinder hump on the lower pole-tip

The most common type of measuring machine had a set of small probes, search coils or Hall plates, on a long aluminium arm supported from a modified lathe bed. There would often be three mutually perpendicular probes to measure the three components of the field. With the coordinate system shown in Fig. 2 the long arm would be parallel to the z axis. The lathe bed would stand outside the magnet with the greatest extent of travel, the length of the lathe bed, parallel to the z axis. One stepping motor would allow a long scan in z, typically in steps of 2 cm. Readout was from the probes while stationary between steps. Other stepping motors on the x and y motions of the lathe bed would allow a full three dimensional scan, often taking several hours. An NMR measurement at the magnet centre would give absolute normalization.

Frequently the travel in z was insufficient to go right through the magnet. In such cases the measuring machine had to be taken round to the other side of the magnet, with resulting problems in relating the two scans to each other. A method for dealing with this was as follows. Before moving the machine an extra scan would be done from the first side. For this extra scan a small iron strip would be fixed onto the lower pole-tip. The shape of the iron strip was not important. It produced a local disturbance to the field shape just above the lower pole tip. Figure 3 shows the effect of a half-cylinder strip, the lines in the diagram being the equipotentials and field lines.

Clearly the scan over the strip would show a symmetric peak in the main component of the field and an anti-symmetric curve for the minor component, thus recording accurately the position of the strip in the coordinate system of the measuring machine. Then the machine would be moved to the other side of the magnet, and another scan made over the strip. Finally the strip would be removed and the proper magnetic measurements continued.

Several detector magnets had circular pole tips protruding through circular coils. The Omega Spectrometer at CERN is typical in this respect (but untypical for the 1970s in having superconducting coils). The natural coordinate system would seem to be the axis of symmetry as z axis, radius r from the z axis, and azimuthal angle φ. One might expect a measuring machine to scan in these z and r and φ coordinates. I cannot remember any such machine. The machines actually used were of the type already described, small probes on a long arm driven by a stepping motor system standing outside the magnet and giving scans on an x,y,z coordinate system. The large size of the Omega Spectrometer meant that the complete field map was a combination of two field maps made with the measuring machine on opposite sides of the magnet, and the technique described above used for relating the two field maps.

4. SOLENOID MAGNETS AND AN INTERNAL MEASURING MACHINE

The rising popularity of storage ring accelerators in the 1980s was accompanied by the development of the " 4• detector ". This is one in which the interaction point of the colliding beams is more or less at the centre of the detector. Secondary particles from the interaction are detected whatever their direction or momentum or charge, or at least very nearly so. Such detectors are almost completely closed; the only access when operating is through the small holes left for the accelerator beams. Solenoidal magnetic fields have become most popular, usually created by a cylindrical superconducting coil producing a field between 1 and 2 T. Figure 4 shows the typical arrangement with the axis of symmetry horizontal to coincide with the axis of the colliding accelerator beams. Surrounding the coil is the barrel part of the iron return yoke. At the ends are the end-caps which complete the iron return yoke and act as pole-tips. Each end-cap has a central hole for the accelerator beams.

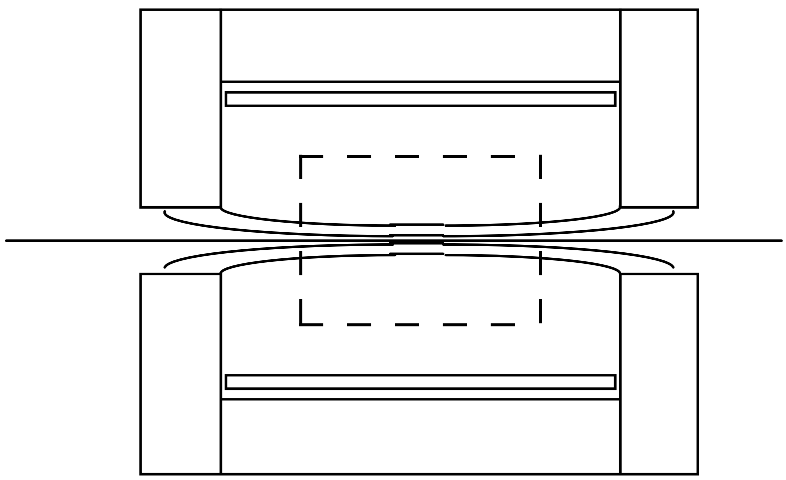

Fig. 4 Typical solenoid detector showing axis, coil, barrel and end-cap iron yoke

4.1 Internal measuring machine

Clearly for such a detector the magnetic field map must be made by a machine inside the almost closed volume. The small holes in the end-caps are sufficient for feeding in mechanical shafts from external stepping motors, and bringing out the readout signals, but the main movement of the arms carrying the probes must be done inside.

Towards the end of the 1980s three such detectors planned (in Europe) were Aleph and Delphi for LEP and H1 for HERA. It happened that the dimensions of the magnetic region were similar. CERN arranged for the construction at MPI, Munich, of the measuring machine shown in Fig 5. This machine was used for magnetic measurements of these three detectors. It was also used for mapping the central part of the L3 magnetic volume and, with some modification, for Opal at CERN and for Zeus at HERA.

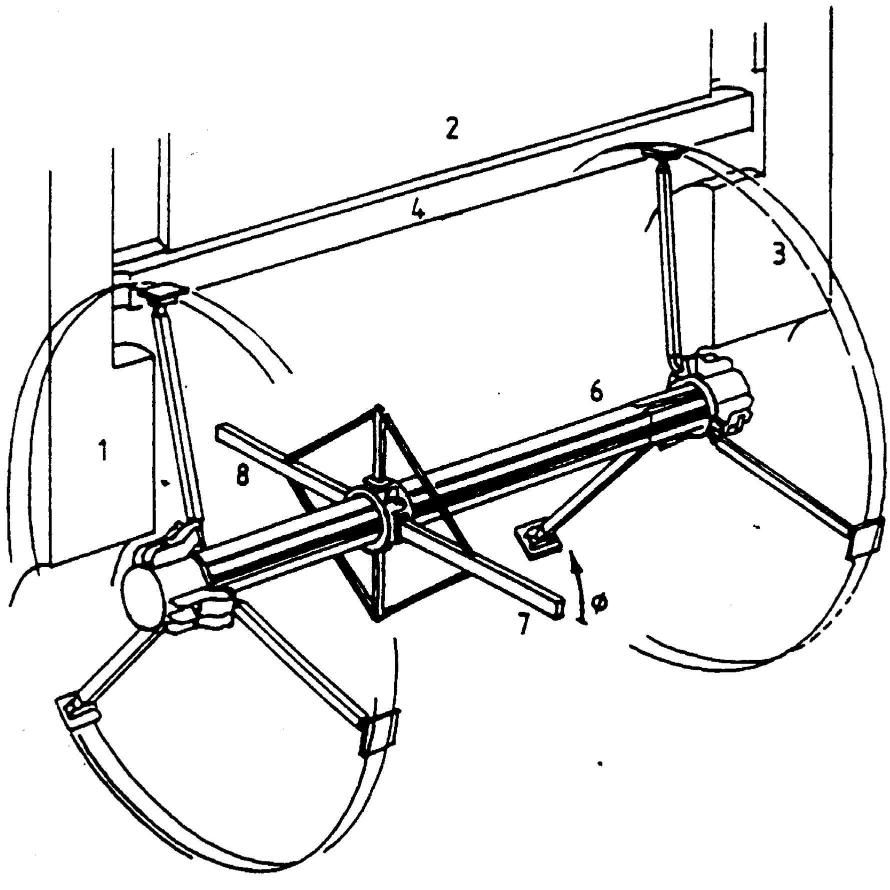

Fig. 5 The measuring machine used for mapping the Aleph, Delphi and H1 magnets

In Fig. 5 the end-caps of the iron return yoke are indicated as 1 and 3, and the barrel part of the yoke as 2. The superconducting coil is shown as 4. An external stepping motor was used to drive a shaft (not shown) through an end-cap hole into one of the two bearings which support the main shaft (6) of the measuring machine. These bearings were mounted from the coil housing, not from the end-caps. This was important because of the end-cap movements under the enormous forces described in section 2. The measuring arms (7 and 8) extended each side of the main shaft. They were fixed into a collar which could be stepped along the shaft. The whole shaft and collar, and thus the measuring arms, could be stepped through azimuthal angle φ from zero to 360 degrees.

The measuring arms carried groups of six Hall plates to measure all field components. Such groups of six were distributed at intervals of 20 cm (at small radius) or 10 cm (at large radius) along the arms. This was the case out to a radius of 2 m for mapping the Delphi magnet, using 120 Hall plates, and a radius of 1.775 m using 96 Hall plates for mapping the H1 magnet. The measuring arms also carried seven NMR probes. Using this machine the extent of the field map was a cylinder of approximately 4 m diameter and 6 m length.

4.2 Static field sensors

A completely different approach has been adopted for mapping the major part of the 1200 m^3 of the L3 magnet. Approximately one thousand static magnetoresistive plates are fixed in the detector to measure the (approx. 0.5 T) main component to the required precision of 0.4 % [4]. The minor components were not measured, but calculated from parameters resulting from a fit to the main component in the manner to be described in subsection 5.3.1.

5. USE OF THE FIELD MAP

One needs to keep in mind the ultimate use of the field map. This will determine the required precision of the magnetic measurements, the degree of detail which should be provided to the user, and the ways in which the field map can be tested.

5.1 Required precision

As explained in section 1 the whole objective is to measure the momentum of each charged particle track in the detector. This clearly depends on the degree of bending which can be established for a track, which in turn depends on the resolution of the track detectors (bubble chamber, optical spark chambers, multi-wire-proportional chambers, drift chambers, etc.). If the momentum is so high that over the observed track length the sagitta is as small as the resolution of the detector then even the sign of charge may be uncertain ! For this reason magnetic detectors are often said to measure $1/p$, with approximately Gaussian errors, rather than the momentum p directly. A typical expression for the uncertainty σ_p on a measurement of p is

$$\frac{\sigma_p}{p} = 0.01 \times p \qquad (3)$$

where p is in GeV/c and of course the value of the constant varies from one detector to another. Clearly a relative precision of 1 % at p = 1 GeV/c becomes 10 % at p = 10 GeV/c. In the other direction it looks as if the relative precision becomes 1 part per thousand at p = 0.1 GeV/c, but the expression becomes invalid when multiple scattering becomes important. That depends on the amount of material in the detector.

These considerations limit the accuracy of momentum determination even if the magnetic field map is known with enormous precision. So there is no point in such enormous precision. Local errors of 1 part per thousand in the main field component, or 1 % in the minor components will not affect the momentum determination, and are unlikely to be of any interest to the physicist user of the field map. Even a global systematic error of 1 part per thousand is usually acceptable. The field mapping is usually planned to determine the main component to 0.1 % and minor components to 1 % , well within the capabilities of temperature controlled Hall probes, or well calibrated search coils.

5.2 Coarse structure and fine structure

When the field mapping is complete it often shows local peculiarities, wiggles in one or more components near to holes in the iron or current lead connections. If these are at the level of 1 or 2 parts per thousand the physicist user does not need to know about them for momentum determination. They may be called "fine structure" effects of the field. With their neglect the field shape needed by the physicist may be called the "coarse structure" of the field. It has to be coded into the software so that a single subroutine call giving the space point will return with the field components. The physicist wants this subroutine to be fast !

The coarse structure of the field may have some symmetry, for example up-down symmetry or left-right symmetry in a rectangular pole-tip magnet as shown in Fig 2, or axial symmetry in a solenoidal magnet as shown in Fig 4. That is valuable for reducing the size of the field map which has to be stored in the fast subroutine. The reduction becomes really worthwhile when the symmetry is complete in one coordinate, like independence of azimuthal angle φ in a solenoidal magnet. Then the field map is essentially two dimensional in z and r with field components B_z and B_r only.

For the field map of the H1 magnet we found [5] several effects at the level of 1 or 2 parts per thousand. Although of interest to the magnet engineers, they were considered unimportant for physics and so were classed as fine structure effects. Apart from these, the coarse structure which was coded into the fast subroutine had two important symmetries, axial symmetry (independence of azimuthal angle φ) and forward-backward symmetry with respect to the median plane.

5.3 Checking the field map

There are two stages of the checking process, one carried out by those responsible for the magnetic measurements before releasing the subroutine for physics use, and then another carried out by the physicists of the collaboration during the subsequent years.

5.3.1 Consistency with Maxwell's equations.

The Maxwell equations constrain the possible variations of the field components as a function of position in space. This fact can be used to check that the field map which it is proposed to release for physics use does not contain any inconsistent values. The technique is to find a magnetic scalar potential, given analytically as a function of position, which satisfies Laplace's equation and can be fitted to all of the field measurements with acceptable accuracy. If any part of the field map is seriously wrong, as could happen if a probe became skewed at some stage, then the wrong values stand out "like a sore thumb" in the fit. This technique was described in some detail in 1992 [5] and need not be repeated here.

5.3.2 Invariant mass histograms.

The classic test of correctly measured momenta is to study the decays of the strange particle

$$K^0 \to \pi^+ \pi^- \quad (4)$$

in which the momenta of the $\bullet^+$ and $\bullet^-$ tracks are measured. Some detectors, with Cerenkov counters for example, can identify the positively charged track as that of a $\bullet^+$ and the negatively charged track as that of a $\bullet^-$. Then the relativistic invariant mass is given by

$$m^2 = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2 \quad (5)$$

$$\tfrac{1}{2} m^2 = m_\pi{}^2 + E_1 E_2 - p_1 p_2 \cos\theta \quad (6)$$

and can be calculated for the $\bullet^+\bullet^-$ pair, where p_1 and p_2 are their momenta making an angle θ at their joint origin, and E_1 and E_2 are their energies given by

$$E_1{}^2 = p_1{}^2 + m_\pi{}^2 \quad (7)$$

$$E_2{}^2 = p_2{}^2 + m_\pi{}^2 \quad (8)$$

Those $\bullet^+\bullet^-$ pairs which came from a kaon decay should have an invariant mass at the kaon mass, known to be [6]

$$m_K = 497.67 \pm 0.03 \quad \text{MeV / c}^2 \quad (9)$$

Those $\bullet^+\bullet^-$ pairs having some origin other than the two-body decay of a particle may have any value for their invariant mass. Even positive and negative pairs not actually pions, but so called for calculating energies from measured momenta, will not have a unique invariant mass. Thus a histogram of invariant mass yields a clear kaon peak; it is only the level of the background under the peak which depends on the contamination from non-pions, and non-kaon decays.

The test of correct momentum determination is whether the position of the peak in the invariant mass histogram comes at the known kaon mass. Figure 6 shows the histogram resulting from studies in the H1 detector [7]. A fitted Gaussian shape to these data had a central value of

$$m_{\pi\pi} = 497.9 \pm 0.2 \pm 0.2 \quad \mathrm{MeV} / \mathrm{c}^2 \tag{10}$$

where the uncertainties are statistical and systematic. A discrepancy of less than 1 part per thousand from the known kaon mass is perhaps surprising, as the coarse structure of the field map was used, and is known to contain local deviations from the measured field by 2 or 3 parts per thousand. The explanation is probably that when averaged over thousands of tracks, in all parts of the detector, any local deviations from the true field become greatly diluted.

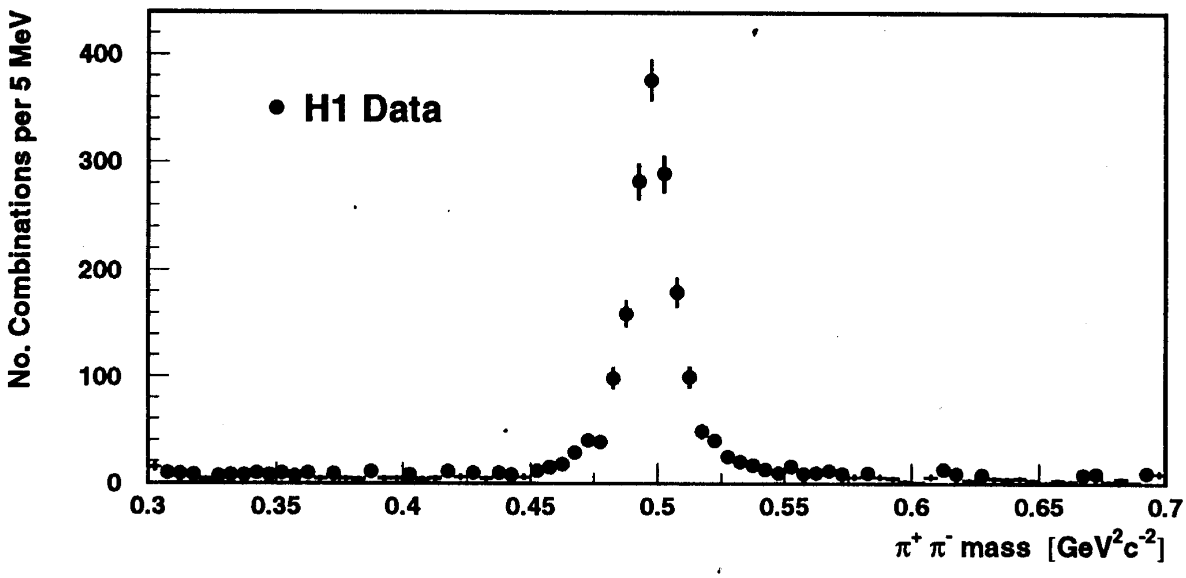

Fig. 6 The mass spectrum of pion pairs to check the momentum determination

6. THE FIELD MAP WITH HINDSIGHT

However carefully one plans the magnetic measurements there often appears in later years (when it is too late because the magnet is full of detectors) some reason why extra measurements would have been useful. Our experience in H1 can be used to illustrate this.

Figure 4 shows schematically a typical solenoid detector like Aleph, Delphi or H1. The superconducting coil is, in principle, coaxial with the beams. The central region indicated with a dashed line surrounds the interaction point and can be taken as the region of the tracking detectors and thus the region over which the detailed magnetic survey was made. For physics analysis this has proved entirely satisfactory for all three experiments.

Figure 4 also shows schematically a few field lines rather parallel to the axis through the region of physics interest, but curving into the iron of the end-caps especially in the beam holes of the end-caps. For the H1 experiment magnetic measurements were not made within these holes of the end-caps.

One reason for regretting this is that physicists have added to the original detector several scintillation counters with phototubes in these holes. In order to optimize the magnetic shielding of the phototubes they wished to know the magnitude and direction of the field as a function of position. A second reason is that it was found that the orbit of the 12

GeV electron beam in HERA, at injection, was dependent on whether the H1 magnet was on or off. As can be seen from Fig. 4 there is a radial component of field inside the end-cap holes which increases with distance off axis. In principle there is no radial component on axis, indeed this can be taken as the definition of the magnetic axis of each end-cap hole. It may not be identical with the geometrical axis of each hole. In fact the HERA experts found that by moving the 12 GeV electron beam by several mm parallel to the geometric axis they could reduce or even eliminate the effect of turning on or off the H1 magnet.

With the benefit of hindsight one can thus say that measurements in the end-cap holes would have been useful for the machine operators, and for the hardware physicists, even though they have no relevance to the primary objective of momentum determination for physics analysis.

7. PROSPECTS FOR FUTURE DETECTOR MAGNETS

One reason for describing, in sections 2,3 and 4, the development of detector magnets over the past three decades, was to attempt to see the next decade in perspective. The technical proposals for the CMS and Atlas detectors for LHC give the magnetic stored energies as thousands of MJ. This is not out of line with the trend already described, roughly an order of magnitude per decade. It is rather frightening nonetheless !

How much of our past experience with detector magnets will be applicable to the future ? Perhaps magnetic measurements will not even be needed ? Have computer codes for magnet design reached such a state of precision that they make measurements unnecessary ? It seems to me prudent to make some form of measurement, even if it is only in limited regions of space, because that will determine the normalization for the calculated field.

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