Large scale application of magnetoresistors in the magnetic field measuring system of the L3 detector


University of Nijmegen and NIKHEF-H, Nijmegen, The Netherlands

K. Freudenreich

Eidgenössische Technische Hochschule, ETH, Zürich, Switzerland

J. Onvlee

National Institute for High Energy Physics, NIKHEF, Amsterdam, The Netherlands

D. Luckey

Massachusetts Institute of Technology, Cambridge, MA, USA

F. Wittgenstein

European Laboratory for Particle Physics, CERN, Geneva, Switzerland

Received 17 September 1991

The design and implementation of the magnetic field measuring system of the L3 detector is described. The system features 992 permanently installed magnetoresistors which serve the mapping of the nominally 0.5 T field of the L3 magnet over its entire 1200 m$^3$ volume. It enables the reconstruction of the magnetic field to an accuracy of better than 0.4%. To allow the magnetoresistors to be used over an extended range of ambient temperatures, a passive temperature compensation scheme has been devised. An internally calibrated read-out system under microprocessor control facilitates easy access to the magnetic field data. Furthermore, the mechanical design of the system, its calibration and the field reconstruction procedures are described.

I. Introduction

The L3 detector is the largest of the four detectors presently operating at the LEP $e^+e^-$ collider at CERN. It focuses on high resolution energy measurements of electrons, photons and muons. The active detector components are installed inside a very large, solenoidal magnet and arranged coaxially around the beam pipe. From the interaction point outwards one encounters a charged particle tracking device (TEC), a BGO high resolution electromagnetic calorimeter, a uranium hadron calorimeter, and a muon spectrometer. The axial magnetic field of 0.5 T (5 kG) enables the determination of the charged particle momenta in the central tracking chamber and in the muon detector. A general view of the L3 detector is presented in fig. 1. A detailed description of the entire detector and its components is given in ref. [1].

The muon spectrometer is designed to give a momentum resolution of $\Delta p/p < 2\%$ at $p = 50$ GeV/c. It consists of three concentric layers of drift chambers (fig. 2) which measure the sagitta $s$ of the muon tracks (fig. 3). From the sagitta measurement, the transverse component $p_t$ of the muon momentum can be calculated by means of the relation

$$p_t = \frac{0.29985 B_z L^2}{8s}.$$

Here $B_z$ is the main (axial) component of the magnetic field and $L$ is the projection of the track length in the muon spectrometer onto a plane perpendicular to $B_z$. Note that for a given accuracy of the sagitta measurement, the momentum resolution $\Delta p_t/p_t$ varies linearly with $B_z$ and quadratically with the track length $L$. For

---

1 Now at CERN, Geneva, Switzerland.
2 Now at Océ Nederland bv, Venlo, The Netherlands.
C. Brouwer et al. / Application of magnetoresistors at L3

this reason the L3 collaboration has opted for a moderate magnetic field \( B_z = 0.5 \) T over a large track length \( L = 2.9 \) m. In this configuration a 45 GeV/c muon from \( Z^0 \) decay gives a sagitta of 3.7 mm. A large volume magnet has been built consisting of an octagonal aluminium coil surrounded by a soft-iron return yoke. The magnet has an inner diameter of 11.4 m, an inner length of 11.9 m, and a total weight of 7800 t. For a 0.5 T field, it uses 4.2 MW of electrical power.

In order to meet the design resolution on the muon momentum of \( \Delta p_t/p_t < 2\% \), both the sagitta \( s \) and the magnetic field \( B_z \) must be known to sufficient accuracy. The accuracy of the field enters twice into the calculation of the muon momentum: once via the relation between the sagitta \( s \) and \( p_t \), and once through the relation between drift time and drift distance. A detailed error propagation analysis yields the following requirements on \( \Delta B \) inside the drift chambers: \( \Delta B_z \leq 2 \times 10^{-3} \) T and \( \Delta B_r \leq 20 \times 10^{-3} \) T [2]. For the main field component \( B_z \) of 0.5 T, this implies a relative accuracy of \( \Delta B_z/B_z \leq 0.4\% \).

Because of the large volume, which is furthermore obstructed by the support tube (see fig. 1), the field measurement has been divided into two parts: The inner volume of the support tube was mapped with Hall plates prior to the installation of detector components. In addition, a series of NMR readings has been taken along the central axis of the detector. Outside the support tube, only a limited number of such field measurements have been made, namely on the inner surface of one of the magnet poles. The remaining volume, which houses the muon spectrometer, is mapped by means of a permanently installed field measuring system consisting of about one thousand field sensors attached directly to the muon drift chambers. In addition five permanently installed NMR probes monitor the absolute value of the field.

In this paper we describe the field measuring system and its application. We commence in section 2 with a discussion of a two-dimensional (2-D) field calculation, the results of which have guided the design of the system. In section 3 we investigate the properties of the magnetoresistor devices which are being used as field sensors. The next section describes the electronic and mechanical design of the system. In section 5 various approaches to reconstruction of the field from the measured values are discussed. Section 6 gives a summary and conclusions.

Fig. 1. General view of the L3 detector. Moving toward the interaction point: magnet yoke, magnet coil, muon drift chambers, hadron calorimeter, BGO electromagnetic calorimeter, and time expansion chamber.
2. Field calculations

To estimate the strength and shape of the L3 magnetic field, a 2-D model approach has been adopted [3]. In this model, the octagonal symmetry of the L3 magnet is approximated by a rotational one, thus reducing the relevant field components to $B_z$ and $B_r$, and ignoring $B_{\phi}$. All radii in the model are chosen equal to the average radii of the corresponding octagonal structures, which is 2.7% larger than the radius of the inscribed circle of the octagon (or, equivalently, 5.4% smaller than that of its circumscribed circle). Accordingly, the return yoke is modeled as an iron cylinder of 0.8 m thickness with end poles of 1 m thick. The end poles have a circular hole in the middle and a 0.1 m wide circular slit to account for the rabbets of the moveable iron doors. The coil is modeled as a single turn with a thickness and total width equal to that of the real coil and a homogeneous current density corresponding to the real number of Ampère-turns.

The field components $B_z$ and $B_r$ have been calculated by means of the computer code POISSON [4]. The field at the muon drift chamber positions is obtained by evaluating the 2-D model at the actual $r$ values of the drift chambers. The resulting $B_z$ values along the centre and along the edge of the outer surface of an octant are presented graphically in fig. 4. For the fiducial volume of the detector, the most important quantitative results of the field calculations are that the main field component $B_z$ lies in the range of $0.45-0.53$ T, that its derivative $\frac{dB_z}{dz} \leq 0.1$ T/m, and that the radial field component $B_r \leq 0.09$ T.

Field calculations have also been performed using the 3-D program TOSCA [5], adopting a simpler model of the magnet which ignores the rabbit slits. Comparison of the TOSCA results with a POISSON calculation for this same model, shows only small differences close to the central holes in the pole pieces.

3. Field sensors

In this section we discuss the properties of the magnetoresistor devices which are used as sensors in the field measuring system. Since the system had to fit in the existing designs of the magnet and the muon chambers, it had to be squeezed into the few centimeters of space between the outer surface of the muon detector and the heat shield inside the magnet coil. Important additional design considerations were the total number of probes and their positions. Since the total surface of the muon chambers is about $1000 \text{ m}^2$, a...
straightforward uniform sampling of the field over the entire surface would easily result in several thousands of probes. It was therefore decided to sample more often in regions where the field has large variations and less often in those regions where the field is more uniform. Nevertheless, the number of installed sensors is about one thousand. These considerations implied the following selection criteria for field sensors:
- The sensors had to be small, since the system had to fit in a space of typically a few centimetres high.
- The sensors needed to be relatively inexpensive, given the large number required.
- The sensors of course needed to be sufficiently accurate and stable.

3.1. Magnetoresistors

In view of these requirements, Siemens magnetoresistors of the type FP30N60K (the suffix K indicating a ceramic backing) are selected. These devices have a field dependent resistance. They are indeed small (some $1 \times 3 \text{mm}^2$) and also inexpensive ($\sim \text{SFr.}10$). For our application, these magnetoresistors have a number of advantages over equally inexpensive Hall plates: As the magnetoresistors are insensitive to the sign of $B$, they are both easier to calibrate and less sensitive to angular alignment errors (cf. section 3.3). In addition, they have only two (rather than four) terminal leads. A feasibility study, the results of which are described below, has established the utility of the magnetoresistors.

Magnetoresistors are semiconductor devices based on the Hall effect. They are made of InSb interspersed with thin, parallel needles of NiSb [6]. Applying a voltage over a slab of this material will cause an electric current to flow which, in the absence of a magnetic field, will experience a resistance $R_0$ (fig. 5a). A magnetic field $B$ normal to the magnetoresistor would change the direction of the current by some
angle. In the absence of the NiSb needles, a Hall voltage would develop across the slab which would straighten out the current flow. The needles, however, have a very low resistivity and in a sense internally "short-circuit" the Hall voltage. The overall effect is that the current follows some zig-zag path through the slab (fig. 5b), the result being an increased resistance. For moderate magnetic fields \( B \leq 0.3 \) T the resulting resistance \( R_B \) has a nearly quadratic \( B \) dependence. For higher fields this dependence gradually becomes linear.

Fig. 6 shows the measured \( R_B \) behaviour of three FP30N60K magnetoresistors. Typically \( R_0 = 60 \ \Omega \pm 20\% \) while the \( R_{0.5} \) values lie in the 160 to 220 \( \Omega \) range. From the curves one sees that at 0.5 T the \( B \) dependence indeed is almost linear with a slope \( dR/dB_{0.5} \) of about 350 \( \Omega/T \).

3.2. Temperature compensation

Unfortunately, the magnetoresistance \( R_{MR} \) shows a large, negative, temperature coefficient which, to make things worse, is even field dependent. In a 0.5 T field its value \( \sigma_{MR} \) is typically of the order \(-0.17\%/K\) (see fig. 7a). Given the fact that the ambient temperature in the experimental hall has variations of plus or minus a few degrees, this effect is incompatible with the required accuracy of 0.4%. The solution is to compensate the thermal variation of the magnetoresistance by placing a (field independent) positive temperature coefficient resistor (PTC) in parallel. For a given \( R_{PTC} \) and

![Fig. 5. Simplified view of current path through magnetoresistor in the absence of a magnetic field (B = 0) and for a magnetic field normal to the plane of the probe (B ≠ 0).](image)

![Fig. 4. Main field component \( B_z \) at the octant outer surface as calculated with the 2-D program POISSON. The curve for \( r = 5.6 \) m corresponds to the centre of the octant surface, the \( r = 6.0 \) m curve corresponds to the edge of the octant.](image)
temperature coefficient \( \sigma_{PTC} \), the condition for cancellation of temperature effects is

\[
\frac{\sigma_{PTC}}{R_{PTC}} + \frac{\sigma_{MR}}{R_{MR}} = 0.
\]

Having at our disposal PTCs with \( \sigma_{PTC} = +0.35\%/K \), the required value of \( R_{PTC} \) can be calculated once \( R_{MR} \) and \( \sigma_{MR} \) are known. Fig. 7b shows that this temperature compensation scheme reduces the net temperature drift to less than 0.10% over the temperature range from 16°C to 28°C. As both \( R_{MR} \) and \( \sigma_{MR} \) show a large variation, application of the compensation scheme requires that both quantities be determined for each magnetoresistor individually. The two parameters also depend on the magnetic field strength, so these measurements have to be done in a 0.5 T field. Although cancellation of temperature effects is only exact for this particular field strength, measurements show that the compensation is still sufficiently effective in a 0.4 T field (see fig. 7c).

A slight drawback of the temperature compensation scheme is that the absolute sensitivity becomes smaller. Using the \( R \) values at 0.4 and 0.5 T from figs. 7b and 7c, we estimate the slope \( dR/\partial B \) for a compensated magnetoresistor to be \( \approx 170 \Omega/T \) (at \( R_{0.5} \approx 115 \Omega \)).

3.3. Minor field components

Before adopting the magnetoresistors to measure the main component \( B_z \) of the L3 magnetic field, we verify that this measurement is not spoiled by the minor field component \( B_r \). To that end, we test a calibrated magnetoresistor in a homogeneous field \( B \) of 0.5 T under various angles \( \theta \) with respect to the field. In this way the probe is simultaneously exposed to a normal component \( B_n = B \cos \theta \) and a surface component \( B_s = B \sin \theta \). The resistance as a function of \( \theta \) is measured and, by means of the known calibration, converted to "effective" field values \( \tilde{B}(\theta) \). We find \( \tilde{B}(\theta) \) to obey the following empirical relation:

\[
\tilde{B}(\theta) = B \sqrt{\cos^2 \theta + \alpha^2 \sin^2 \theta} = \sqrt{B_n^2 + \alpha^2 B_s^2}.
\]

Obviously, the coefficient \( \alpha \) must be interpreted as the fraction of the surface component \( B_s \) "sensed" by the magnetoresistor. We determine the coefficient \( \alpha \) for rotations around each of the two axes I and II indicated in fig. 8, the result being \( \alpha_1 \approx 0.04 \) and \( \alpha_2 \approx 0.01 \).
Fig. 7. Temperature behaviour of magnetoresistance. (a) Bare magnetoresistor \( B = 0.5 \) T, (b) compensated magnetoresistor \( B = 0.5 \) T, (c) compensated magnetoresistor \( B = 0.4 \) T. Note the expanded vertical scale in (b) and (c).

It should be mentioned here that the above empirical relation is only observed for magnetoresistors on a ceramic substrate (type FP30N60K). The same devices on an insulated iron substrate (type FP30N60E) show a completely different behaviour.

The finite values of the coefficients \( a \) imply that a measurement of the component \( B_z \) by means of a magnetoresistor facing the \( z \) direction, is affected by the presence of the non-zero \( B_r \) component. Taking the outer surface of an octant as a reference plane, \( B_r \) gives rise to a “horizontal” and a “vertical” field component \( B_h \) and \( B_v \) in the plane of the magnetoresistor (see fig. 9). Due to these non-vanishing components, a measurement of \( B_z \) will yield the effective field \( \vec{B} \):

\[
\vec{B} = \sqrt{B_z^2 + \alpha_r^2 B_h^2 + \alpha_v^2 B_v^2}
\]

\[
= B_y \sqrt{1 + \alpha_r^2 (B_h/B_z)^2 + \alpha_v^2 (B_v/B_z)^2}.
\]

The difference of \( B_z \) and \( \vec{B} \) is a contribution to the measurement error \( \Delta B_z \). To estimate this contribution, we observe that for \( B_z = B_r \cos \phi \) and \( B_h = B_r \sin \phi \) (fig. 9). For a constant \( B_r \), the maximum values for \( B_v \) and \( B_h \) are found for \( \phi = 0^\circ \) \( (B_v = B_r) \) and \( \phi = 22.5^\circ \) \( (B_h = 0.38 B_r) \). From the field calculations (cf.
cal values of the coefficients \( \alpha \), we find a worst case error contribution \( \Delta B_z / B_z = 0.03\% \).

Similar considerations show that an anticipated angular misalignment of some 2.5° (=45 mrad) gives rise to another error contribution \( \Delta B_z / B_z = 0.10\% \).

Analogously to the effect of angular misalignment, we have to consider the effect of a longitudinal position error \( \Delta z \), which introduces a measurement uncertainty \( \Delta B = (d_B/\Delta z) \Delta z \). For an estimated \( \Delta z \) of less than 4 mm, and using \( d_B/\Delta z \leq 0.1 \) T/m from the field calculations (cf. section 2), we find \( \Delta B_z / B_z \leq 0.08\% \).

In conclusion we expect the following worst case contributions to the error \( \Delta B_z / B_z \): 0.10% from temperature drift effects, 0.03% from the minor field components, 0.10% from angular misalignment, and 0.08% from the error on the \( z \) position. Adding these errors linearly yields a total uncertainty of \( \Delta B_z / B_z = 0.31\% \). Adding them in quadrature we obtain \( \Delta B_z / B_z = 0.17\% \). In view of the accuracy requirement of \( \Delta B_z / B_z < 0.40\% \), this is quite acceptable.

### 4. System design

The design of the field measurement system follows the modularity of the muon detector which is subdivided into 16 independent "octants", 8 on each side of the detector.

![Diagram of muon chamber octant](image)
the central \( z = 0 \) plane (fig. 2). Each octant is equipped with 62 field sensors (see fig. 10).

On the outer chambers, two identical longitudinal strings of 13 field sensors have been installed: each time one in the middle and one near the edge. The probe positions along the strings were based on the 2-D model calculations, probes being placed at \( \Delta B_z = 4 \times 10^{-3} \) T intervals. Two transverse strings of 6 probes each have been added near the high-\( z \) end of the outer chamber. The middle and inner chambers have each been equipped with two longitudinal strings only. Again probes have been placed every \( \Delta B_z = 4 \times 10^{-3} \) T interval, yielding 4 and 6 probes per string for the middle and inner layers respectively. To cover the poles of the surface surrounding the magnetic volume, a string of 4 sensors has been affixed in the middle of the vertical end-frame of each octant. Irrespective of their locations, all sensors are oriented to measure the main component of the magnetic field \( (B_z) \). The entire field measuring system contains 992 field sensors.

4.1. Electronics

Fig. 11 gives a schematic overview of the read-out electronics of the system. It basically consists of an ADC and multiplexing electronics to select individual magnetoresistors for readout.

The resistances of the temperature compensated magnetoresistors are determined by measuring the voltage across the magnetoresistor for a constant electrical current. By chaining a number of probes in series, the same current flows through all probes in the chain. The read-out of the probes is accomplished through independent sense wires. An 8-channel differential analog multiplexer selects the signals from the individual channels. Eight of these multiplexers are combined on one card (PC board) and have their outputs connected together. Only one multiplexer at a time is enabled. The differential output signal of the multiplexers is buffered through voltage followers and amplified. Via an analog switch the signal can be connected to a differential analog bus which is input to a 12-bits ADC. The design is virtually insensitive to the different dc levels at which the various probes in one chain operate. This is the result of the fully differential treatment of the signals up to the ADC and of the use of voltage followers ensuring a high input impedance and preventing parasitic currents through the sense wires which would disturb the measurement. Note that

Fig. 11. Schematic overview of magnetoresistor read-out electronics.
the fully differential design also provides a very good common-mode rejection.

The 8-channel multiplexer fixes the number of read-out positions in a single chain. For calibration purposes each chain has been equipped with a zero resistance position \((R_{\text{short}} = 0 \, \Omega)\) measuring the offset and a field independent reference resistor \(R_{\text{ref}}\) which fixes the scale. The value of \(R_{\text{sensor}}\) is then determined from the raw ADC values \(A_{\text{sensor}}\), \(A_{\text{short}}\), and \(A_{\text{ref}}\) as follows

\[
R_{\text{sensor}} = \frac{A_{\text{sensor}} - A_{\text{short}}}{A_{\text{ref}} - A_{\text{short}}} R_{\text{ref}}.
\]

This method ensures that as long as the system has a linear response, it is intrinsically calibrated. Therefore neither the current source nor the amplification of the system are very critical with regard to medium and/or long term stability. A maximum of six read-out positions in each chain are available for field sensors. The 62 probes of one octant have been grouped into 13 “multiplexer chains”. Unused channels are “filled” with dummy resistors.

The read-out system is controlled by a microprocessor. In order to read a particular sensor, the microprocessor operates the appropriate analog switch to select a card, it enables a multiplexer, and it addresses the proper multiplexer channel. A dummy A/D conversion allows the various signal levels to settle. The actual measurement involves four A/D conversions with 10 ms intervals to cancel the effects of possible 50 Hz pickup. The four ADC values are averaged and stored in memory. The entire procedure takes 50 ms per channel. The microprocessor continuously cycles through all channels to keep its memory up to date. It also communicates with the higher levels in the L3 monitoring subsystem and delivers the most recently measured resistance values when asked for. The microprocessor module is designed as a master in a VME-type crate which may contain up to 16 multiplexer cards. In the L3 experiment two crates are employed, one at each end of the detector. Each crate has its own processor and ADC module and serves 8 octants through 13 multiplexer cards. The distance between the crates and the probes is of the order of 40 m.

4.2. Mechanics

The probes have been mounted into hollow, rectangular aluminium bars, 3 cm wide and 1 cm high, with a slide-cover allowing access to its interior. Inside the bars are cubical precision supports on which the magnetoresistors are glued (see fig. 12). The supports are fastened by means of nylon fixation screws. The bars have been glued onto the outer surface of the muon drift chambers.

Basically, one bar contains all probes of one current chain. A multiwire screened cable connects to the
multiplexer. Chains which extend over more than 1 m, have been subdivided into a couple of shorter bar-

pieces which are interconnected via screened cable. To

allow for a sufficiently accurate angular alignment, the

minimum length of such a bar-piece is 25 cm. Electrical

connections inside the bars are realised on PC

boards, which also carry the temperature compensation

resistors.

4.3. Calibration

The calibration of the field probes consists of the

following steps. First, the temperature characteristics

of each individual probe are determined in order to fix

the value of the compensation resistor. The the bars

are assembled and placed in a homogeneous magnetic

field for calibration. Then bars which are a part of

longitudinal strings are calibrated in a solenoidal mag-

net whereas a dipole magnet is used to calibrate the

transversely oriented bars. In both cases, the calibration

field is monitored by means of an NMR probe. Prior to

the actual calibration, the angular alignment of each

probe is verified by rotating its support around the

fixation screw to obtain maximum resistance reading.

Note that the effect of a possible residual misalignment

is largely calibrated out.

The probes are then calibrated by measuring their

resistances in the absence of a field and for 8 magnetic

field strengths in the range 0.36 to 0.60 T. During the

calibration, the probes are read out with the same

electronics as described above. For each probe, calibration

constants have been determined by fitting the

 calibration data with a third order polynomial.

5. Field reconstruction

For the L3 data analysis the values of the main and

minor components are needed at any point (x,y,z)

inside the fiducial volume of the detector. Since the

eight-fold symmetry of the large magnet results to a

good approximation in rotational symmetry, $B_z$ is neg-

ligible inside the fiducial volume. Therefore, we need

only provide a map of $B_x$ and $B_y$. The field map is

obtained from a fit to the measured distribution of $B_z$

values. Two approaches are investigated to obtain a

field map.

In a first approach, full cylindrical symmetry is

assumed. All measured $B_z$ values from the magnetore-

sistors are projected onto one r-z plane. Then a fit

with a truncated Bessel function and a zero-order

modified Bessel function is done to the data (there

were in total 14 fit parameters). When using field

measurements of the magnetoresistors in the longitudinal

and transverse strings only (cf. section 4), the

central region up to $z$ values of $\pm 4$ m is well repre-

sented by this model. Nearly the full region can be well

described if additional measurements near the magnet

pole are used as input for the fit. These measurements

can either be the sensors in the middle of the vertical

endframe of each octant (cf. section 4) or the original

calibration measurements taken on the inner surface of

one of the magnet poles (cf. section 1). Only a small

region at the extreme $z$ and $r$ corner does not meet

the required precision. Here fit residuals of up to

$5 \times 10^{-5}$ T are observed.

Since some 3-D effects are anticipated, a second

approach is tried to achieve the required precision in

the corners of the fiducial volume as well. In two

slightly different models, an analytic representation of

the fields of several octagonal, coaxial coils is used in

conjunction with an approximate theoretical field map.

The parameters defining these coils are adjusted in a

fit to the measured $B_z$ values. This time, the 3-D

spatial positions of the probes are used.

In the first model of this octagonal approach the

approximate field map consists simply of a constant

value. The currents of 17 "virtual", octagonal coils –

located at the poles of the magnet – are adjusted in a

fit to the measured $B_z$ values coming from two sets of

measurements:

1. $B_z$ values from the magnetoresistors mounted on

   the muon chambers.

2. $B_z$ values from a priori field measurements.

The a priori measurements were performed before the

installation of the physics detectors inside the magnet

volume. They consist of measurements along the cen-

tral axis with a mobile NMR probe, measurements

from the region of one octant close to the pole piece

and measurements from a plane perpendicular to the

symmetry axis, inside the support tube at the limit of

the magnet volume. The latter measurements were

done with a mechanical gear with calibrated Hall plates

which was also used to map the other three LEP

experiments [7].

At this point it is important to note that, both here

and in the 2-D case, especially the addition of mea-

surement points near the boundary of the volume help

to improve the results. An explanation of such an

effect has already been given in ref. [8].

In the second model, the approximate field map is

calculated with the 2-D program POISSON. To this

the fields of four “virtual” octagonal coils are added.

Fit parameters are this time a common scale factor

and a common displacement of the z coordinate of the

2-D field map as well as three parameters for each of

the four virtual coils, i.e. 14 parameters in total. Since

the POISSON model already describes the field quite well

and the virtual coils merely model the field deforma-

tions introduced by the inhomogeneities of the pole,

only the $B_z$ values from the magnetoresistor measure-

ments are used in this case to produce a field map.
Fig. 13. The main field component $B_z$ as a function of $r$ and $z$ ($\varphi = 11.25\degree$). The shaded region in the $r-z$ plane is not part of the fiducial volume of the detector.

Fig. 14. The radial field component $B_r$ as a function of $r$ and $z$ ($\varphi = 11.25\degree$). The shaded region in the $r-z$ plane is not part of the fiducial volume of the detector.
Both octagonal models yield equivalent field maps which meet the accuracy requirements over the entire fiducial volume. Typical fit residuals of \( \lesssim 2 \times 10^{-3} \) T are obtained. Slightly worse residuals are encountered for the bottom octants in the high-\( \phi \) and high-\( r \) corners. This has been traced to the existence of large openings in the iron pole pieces of the magnet which accommodate the magnet door support rail and bearings. As these do not obey octagonal symmetry, they obviously cannot be described by the octagonal models.

The resulting \( B_z \) and \( B_r \) values as a function of \( z \) and \( r \) and for a \( \phi \) value of 11.25° are shown in figs. 13 and 14 respectively (the shaded region in the \( r-z \) plane contains no active detector components and is not part of the fiducial volume). The main field component is rather homogeneous for \( z = 0 \), increasing from 0.500 T in the centre (\( r = 0 \)) to 0.525 T at \( r = 5.5 \) m. Along the beam axis \( B_z \) drops because the pole piece has a large hole in the center. Close to the inner opening of the pole piece an inhomogeneous region is characterized by an increase of \( B_z \) and \( B_r \). In the center \( B_z \) is very small increasing only to 0.06 T in the region of the outer muon chambers close to the pole. The results are in very good agreement with the 2-D calculations described in section 2. The field map obtained through the procedure described here is being applied in the L3 analysis software on a routine basis.

6. Results and conclusions

In its first years of operation, the field measuring system proved to be very reliable. On initial turn-on, three out of the total 992 installed field probes gave no proper signal, probably due to shorts and/or broken wires. However, as the system has a substantial amount of redundancy, this poses no serious problem. No other dead channels have developed since.

The magnetoresistors and the five permanently installed NMR probes are read out on a bimonthly basis since the middle of 1989 as a new fieldmap has to be produced as soon as a significant change is observed. The L3 magnetic field turns out to be very stable. No changes larger than 0.3% have been observed up to now. We find the magnetoresistor readings to scale within 0.1% with the independent readings of the NMR probes.

In conclusion, we successfully developed and implemented a magnetic field measuring system for a very large magnet volume, giving an accuracy of better than 0.4%. We demonstrated that low cost devices (magnetoresistors) can be used as precision sensors in such a system. When thinking of possible other applications one should however keep its limitations in mind. It works for one magnetic field component only and other components should be relatively small. Moreover, the calibration of the sensors is a rather laborious procedure, and the resulting calibration only yields the required precision over a limited range of field values and ambient temperatures.

Acknowledgements

We would like to thank H. Wind for useful discussions. We thank D. Lehn and G. Stefanini for their help with the a priori measurements and we thank the ALEPH collaboration for the use of its test solenoid.

References