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The Forward Muon Detector of L3

The L3 F/B Muon Group

Abstract

Nuclear Instruments and Methods A
The L3 F/B Muon Group


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1 Introduction

1.1 Physics requirements

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

1.2 Overview of the detector
## Table 1: Design parameters of the L3 forward backward muon system

As indicated in Fig. 1, there are two complementary regions, S and T. In each region a different method to measure the muon momentum is used.

### S-region:

- **Field configuration:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **Magnetic field:**
  - Average: 0.7 T
- **Coordinate accuracy:**
  - N=16 m
- **Gas amplification:**
  - 10 x 10 x 5
- **Preamplifier:**
  - 120 mV
- **Threshold:**
  - 40 mV

### T-region:

- **Field configuration:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **Magnetic field:**
  - Average: 0.7 T
- **Coordinate accuracy:**
  - N=16 m
- **Gas amplification:**
  - 10 x 10 x 5
- **Preamplifier:**
  - 120 mV
- **Threshold:**
  - 40 mV

### Notes:

- **Drift chamber gas:** 
  - Ar/02:10, CO/02:1, H/01
- **RPC counters:**
  - Drift chamber gas: Ar/02:10, CO/02:1, H/01
- **Timing accuracy:**
  - 3 ns
- **Magnetic field:**
  - Solenoid: 0.15 T
  - Toroid: 1.24 T

### Alignment:

- **Absolute/relative:**
  - N=16 m
  - N=50 m

### Accelerator:

- **Beam energy:**
  - N=15 GeV
  - N=25 GeV

### Monitoring System:

- **Sensors precision:**
  - 10 μm

### Table 2: Detector description

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>MI, MM</td>
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### Figure 1

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **Y:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **R:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 2

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 3

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 4

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 5

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 6

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 7

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 8

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 9

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 10

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 11

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.

### Figure 12

- **X:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **μ:**
  - Central drift chambers MI, MM and the new forward chamber FI.
- **p:**
  - Central drift chambers MI, MM and the new forward chamber FI.
1.3 Detector design considerations

\[ \mu \quad \mu \]

\[ \times 2 \]

\[ y - z \quad 1) \]

\[ e^+ e^- \]

\[ x - z \]

\[ \mu \quad \mu \quad \mu \quad \mu \]

\[ \text{Octant by octant, we use a local coordinate system in which } z \text{ coincides with the electron beam direction in LEP,} \]

\[ y \text{ points radially outward along the octant centerline, and } z \text{ is perpendicular to } y \text{ and } z. \text{ This corresponds} \]

\[ \text{approximately (along the octant centerline exactly) to } y = r \text{ and } z = \phi. \text{ The solenoidal magnetic field in L3} \]

\[ \text{bends the muon in the } r - \phi \text{ plane, the toroidal field bends in the } r - z \text{ plane.} \]
2 Drift Chambers

2.1 Design Principles
2.2 Calculation of Spatial Resolution

3 Chamber construction and tests

3.1 Chamber enclosures
3.2 Accurate wire positioning

3.3 Chamber wiring procedures
3.4 Chamber tests

4 Infrastructure and Electronics

4.1 Front-end Boards and Amplifiers
4.2 Discrimination Multiplexing and Readout
4.3 Timing Calibration

Relativ ec hannel to c hannel timing calibration of readout electronics is pro vided b y the T/0CAL system/. Pulses are injected at the inputs of preampli/n0cers moun ted at the end of eac h cell with four sense wires/. These pulses mimic the c haracteristics of an electron a v alanc he on a wire and are pro cessed in the usual w a yb y the subsequen t readout electronics/. By kno wing precisely the time of the pulse injection and measuring the arriv al time of the signal as recorded b y the cor/-
response TDC c hannel/, one determines directly the propagation dela y from preampli/n0cer to /n0cnal readout/, including c hannel to c hannel v ariations due to distributions of stop signals to in/-
dividual TDC c hannels/. During o/n0fine reconstruction/, these propagation dela ys are subtracted from measured v alues in determining electron drift times /.

Critical to this calibration pro cedure are stable injection pulses with short rise times requir/-
ing fast electronics and high p erformance/, lo w loss transmission cables b et w een the coun ting
house and the detector/. All T/0CAL electronics along the path of timing signals are Motorola
ECLinPS or ECLinPS Lite logic gates with t ypical rise times of /2/5/0 ps and /3/0/0 ps resp ectiv ely /.

Signals are fanned out in three stages/. The /n0crst stage has the longest span /n29/6/4 m) for whic h
w e use R G/2/1/3 coaxial cables/; the second stage is /2/7 m/, of whic h /2/4 m consists of R G/5/8 coaxial
cables and /3 m /n29lying in a con/n0cned region of limited space) consists of R G/1/7/4 coaxial cable/; the third stage within c ham b er modules consists of /2/-/3 m R G/1/7/8 cables/. All electronic c han/-
nels and long cables w ere individually calibrated b efore or during installation/. Samples of the
shorter cables /n29less than /4 m) w ere measured to ha v e rms propagation dela ys b etter than /1/2/0 ps/. In addition/, a parallel direct return path for all timing signals has b een pro vided/, whic h
allo ws a direct in situ c hec k of absolute timing precision/. This return system/, indep enden to f the readout electronics/, has v eri/n0ced the absolute precision in the T/0CAL injection system to

4.4 High Voltage System

A high v oltage system supplying the four di/n0beren tv oltages to eac h of the /6/1/4/4 drift c ham be r
cells of the detector/, w as designed and built to ful/n0cll the follo wing requiremen ts/:

• of easy and fast w a y of disconnecting high v oltage of a single cell in case of bad insulation/, high dark curren t or brok en wire/.
• of remote curren t con trol of eac hc ham be r l a y er for eac h of the four v oltages and easy and
  fast w a y of disconnecting a giv en la y er in a case of unreco v erable o v ercurren t in a giv en
  cell or group of cells/. 
• of online measuremen t and con trol of all v oltages and curren ts dra wn b y the c ham b ers from
  a giv en c hannel of the high v oltage p o w er supplies/. 
• of capabilit y to supply the c ham b ers inside the L/3 magnet with high v oltages whic h are
di/n0beren t from those supplied to the c ham b ers outside/. 

Voltage lines of /1/6 cells are group ed in to a /3 m long m ultiwire high v oltage cable /n29/1/6
conductors) connected to a patc h panel lo cated near the c ham b er/. A cable carries only one
v oltage /n29sense/, catho de/, /n0celd/, or guard)/, so the four di/n0beren tv oltages are supplied in parallel
4.5 Gas System

4.6 Temperature monitor system

---

4) Connector type MSTB 2,5/4-STZ-5,08 produced by PHOENIX.
5 Trigger RPCs

5.1 The RPC System Layout

\[ \phi \simeq \rho \simeq \mu \]

5.2 Electronics and Tests
5.3 Level-1 Trigger Generation and Data Readout

\[ \mu \]

\[ A_{ij} \]

\[ \cdot N_i \cdot N_j \quad N_i \quad N_j \]

\[ 5) \text{Each beam consisted of 4 trains with 2 to 4 bunchlets each. The bunchlets were separated by 247 ns.} \]
6 F/B Toroids

6.1 Construction

6.2 Magnetic field measurements

6) Metall Inert Gas welding
6.3 Magnetic field calculation

\[
\leq R \leq
\]

7 System assembly and tests

7.1 Modules assembly

7.2 Tests and Spatial Resolution

\[
|\theta_x| < \\
x \quad x_0 \pm v \, t - t_0 \quad v \quad \mu
\]
the drift velocity, \( t \) is the drift time and \( t_0 \) is the time observed corrected for each wire including the electronic delay and the time of night of the track. By selecting tracks perpendicular to the drift direction, second-order effects such as angular dependence of the drift time or the inductive crosstalk between wires could be neglected. The left-right ambiguity was resolved by the half-cell setup between the X and W layers.

The accuracy of track reconstruction is shown in Fig. 26. For this plot the tracks are using only the 4 X-wires in the top and bottom chambers and are required to be on the same side of the wire plane in both chambers. This choice allows to study the reconstruction accuracy independent of the position error introduced by the time-uncertainty of the RPC trigger. The residual distribution in Fig. 26a is with a gaussian of width \( \sigma = 200 \mu \text{m} \). This translates to a single-wire position resolution of \( 250 \mu \text{m} \). A tail due to multiple-scattering is also observed.

The dependence of \( \sigma \) on drift distance is shown in Fig. 26b and is consistent with diffusion broadening.

The setup between X and W layers implies that - for perpendicular tracks - the sum of the drift times in the two layers is a constant, independent of track position. This feature allows a determination of the arrival time of a track with respect to the trigger. It can be used, for example, to associate tracks with closely spaced beam bunches in a collider. For small angles \( \theta_x \) the average drift-time sum of a chamber \( \text{FM or FO} \) is given by:

\[
\frac{1}{2} t_0 = \left( \frac{1}{4} t_x + t_w \right) \pm \theta_x
\]

where \( t_x \) and \( t_w \) are the drift-time measurements (29 ns) in the X and W layers respectively, and the sign of the angular term depends on the sign of \( \theta_x \) and which side of the wire plane the track is in. The average time sum for the 2-chamber package is given by:

\[
\frac{1}{2} \left( \frac{1}{2} \text{FM} + \text{FO} \right)
\]

In tests with cosmic rays described here, the time sum resolution is strongly influenced by the trigger timing uncertainty. In order to cancel this contribution we plot instead in Fig. 27 the difference \( \frac{1}{2} \text{FO} - \text{FM} \) which has the same resolution as the sum would have with a precise trigger. The distribution is best fitted with two gaussians, the narrower one giving a resolution of \( \sigma = 2 \mu \text{ns} \). It is interesting to note that this resolution allows to distinguish, at the 3\% level, tracks that traverse the package in the opposite direction.

Additional checks of individual chamber performance were carried out by comparing the two segments of a track reconstructed in the X and W layers. In particular, requiring that the two segments intersect at the midplane between the two layers provides a strong consistency check of the reconstruction parameters including the drift velocity and the time setup. Fig. 28 shows the difference of intercepts of the two segments at midplane. As an example, the effect of a 200 ns shift in \( t_0 \) is shown as well. This shift is equivalent to a change in the drift velocity of approximately \( 5x \) and cannot be distinguished from it. This method allows for a sensitive monitoring of the stability of the velocity and time setup for individual chambers.

7.3 Attachment to Doors

\[
\theta_x
\]

\[
FM,FO - t_x t_w \pm . \quad \theta_x
\]

\[
t_x t_w
\]

\[
\theta_x
\]

\[
\frac{1}{2} \text{FM} \text{FO}
\]

\[
\frac{1}{2} \text{FO} - \text{FM}
\]

\[
\sigma . \quad \sigma
\]

\[
t_0
\]

\[
t_0
\]

\[
z
\]

\[
\mu
\]
7.4 Alignment systems

Relative alignment between FI, FM and FO layers: T-region

Alignment with respect to the central detector: S-region
8 Performance at LEP

$e^+e^- \rightarrow \mu^+\mu^- \gamma$

7) Type OPTIMESS 30LP by ELAG AG, Winterthur.
8) Type CR18-50K by DATAMEGA S.A., La Chaux de Fonds.
8.1 Muon track reconstruction

\[ e^+ e^- \]

\[ \circ \quad \circ \quad \circ \quad \circ \]

\[ \circ \quad \circ \quad \circ \quad \circ \]

\[ T_0 \quad T_0 \quad T_0 \]

\[ t_0 \quad t_0 \quad t_0 \]

\[ e^+ e^- \]
8.2 Characteristics of the data

\[ Z \rightarrow \mu^+\mu^- \]

\[ e^+e^- \quad \sqrt{s} \quad E_b \quad E_b \quad E_b \]

8.3 Spatial Resolution

\[ dy/dz \quad dx/dz \]
8.4 Momentum Resolution

\[ \frac{\delta p}{p} \]

\[ \frac{\chi^2}{ndf} \]

\[ \mu \]

\[ \sigma_{\text{core}} \pm \mu \pm \mu \]

\[ \sigma_{\text{tail}} \pm \mu \pm \mu \]

\[ \mu \quad x \quad \mu \quad y \quad dy/dz \]

\[ dx/dz \]

\[ E_{\text{beam}}/q \cdot p_{\mu\text{on}} \]

\[ p_{\mu\text{on}} \]

\[ q \]

\[ E_{\text{beam}}/q \cdot p_{\mu\text{on}} \pm . \]

\[ E/p \]

\[ \delta p/p \]

\[ \delta p/p \]
8.5 RPC Performance

8.5.1 F/B trigger efficiency

\[ \epsilon_{\text{dimuon}} \pm \epsilon_{\text{single}} \pm \]

8.5.2 Spatial resolution and detector efficiency
8.5.3 Time resolution and bunchlet identification

- 
- 
- 

\[
\frac{v_p}{\sigma} \pm \sigma
\]

9 Summary

10 Acknowledgement
Technologie/ de Stichting voor Fundamenteel Onderzoek der Materie (FOM) for NIKHEF, the Board of the Swiss Federal Institutes of Technology (BSIT), the Comisiónes Interministerial de Ciencia y Tecnología in Spain, the Schweizerischen Nationalfond in Switzerland and the Department of Energy (DOE) and the National Science Foundation in the US.
References
A309

GARFIELD, a drift-chamber simulation program

A324

the GEANE program

List of Figures

+ → + → $\mu\nu_\mu$

$\nu_\mu$

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On the left, the equipotential configuration of a drift cell with 4 signal wires is shown. On the right, drift field trajectories are shown.

a) Drift velocity along the electrical field for different B field values. The upper curve shows, for B/\text{=}/0, the effect of a 1/N2 contamination. b) Lorentz deconstructions as a function of E for B field values of 0.5 T and 0.55 T.

Monte Carlo simulation of:

a) Spectrum of arrival times for two wires on the left and an outer, on the right an inner wire for a 2/6 mm drift distance. b) Jitter in the arrival of the 8th electron. c) Resolution expected from the time jitter for various drift distances.

View of a chamber. The upper part gives the interior structure of the W, X and Y layers. The lower part depicts the corresponding chamber frame with the holes for the wire planes.

Detailed sketch of an endframe showing:
a) holes where plastic inserts will be placed, b) plastic insert already in place showing the glass cylinder, c) one which has wires on Cu-T blocks, and d) one cell gas sealed and ready for electrical connections.

a) Sketch of the precision template used to position glass cylinders which define wire plane locations. b) Residuals showing template accuracy.

As a schematic drawing of the wiring machine (only one of the nine wires shown), with closeups of the crimping tool with interlock block and different types of Cu-T cubes.

Mechanical tension deviations from the design values for:
a) field and b) signal wires. Shaded are the critical long wires. The dashed lines indicate the design tolerance of 6/4/2.

Typical counting rates using cosmics in one FB chamber. Rates are proportional to wire lengths, which explains the pattern observed in the Y layer's slow increase from cell number 1 to 27 and in the W and X layers increasing from cell number 1 to 11 and staying constant for the rest of the cells.

Preamplifier circuit.

Multiplexer of 8 channels with address recording.

Readout schematic.

T/0CAL test performed to one of the chambers providing the relative channel to channel timing calibration for all wires in all layers.

Cross section of a double-gap RPC (not to scale).

a) Typical plateau curve; b) Distribution of the 90% efficiency working point for all tested chambers.

a) Trigger logic; b) Monte Carlo simulation of the Trigger Matrix for muons with different momenta.

End view of the L3 magnet with the 36 turns of one toroidal coil.
Distribution of the residuals of the cosmic ray tracks. All selected events, see text. The gaussian has a standard deviation of 200 m.

Dependence on the drift distance. The curves $b = 87^\circ + 20^\circ$ distance/mm).

Distribution of the difference of the mean drift-time sums of the two chambers forming a module, see text.

The distance between the two segments of a track detected in the X and W layers measured at the midplane, solid histogram. Tracks on the right (a) and left (b) sides of the X-wires are shown separately together with a gaussian. The shaded histogram is obtained when the same tracks are analyzed with a time offset of 20 ns.

Overview of the alignment system in the F/B region, not to scale. The alignment consists of 4 steps: A) positioning of the sensor's reference marks with respect to the barrel chamber wires, B) a distance measurement by a sensor with respect to FI surfaces, C) positioning of these reference surfaces with respect to the FI chamber wires and D) the internal alignment of the three F/B layers by means of a RASNIK system.

A front view of an FI chamber showing the position of the reference marks for $x, y$ and $z$.

Distance between the muon barrel and the reference marks of a FI chamber recorded by a triangulation sensor over 10 days. The top bar indicates the status of the L3 magnets. A difference in chamber position of about 500 m can be seen for the two periods with both magnets powered.

Side view of a dimuon event in data taken at LEP.

a) Distribution of $j$ cos $j$ of muons with track segments in the F/B muon chambers. The hatched histogram shows the muons in the toroidal region. b) Impact points in the $x$/$y$ plane of reconstructed muon tracks in the FI chambers on one door.

Corrected residuals for hits in the outer wires and inner wires for 8 points in FM and FO X and W layers. The Full Widths at Half Maximum (FWHM) of the distributions are shown in the plots. A detailed discussion of the resolution is given in paragraph 8.

Momentum spread of reconstructed muons in $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$. Plotted is the quantity $E_{\text{beam}}/ q \cdot p_{\mu\text{on}} = E_{\text{beam}}/ p_{\mu\text{on}}$, where $E_{\text{beam}}$ is the LEP beam energy, $q$ is the reconstructed muon charge, and $p_{\mu\text{on}}$ the reconstructed muon momentum, in the S-region (a) and in the T-region (b).

Muon momentum resolution obtained in the F/B muon system as a function of the cosine of the polar angle of the track, for a muon momentum of 45 GeV. 

Time resolution, without subtracting the inter-bunchlet time, versus the RPCs identified bunchlet number.
Figure 1: Side view of the F/n2fB detector of L/3 showing inner FI, middle FM, and outer FO drift chambers and RPCs for triggering. The two angular regions, S and T, are indicated.
Figure 2: Simulated event in the L3 detector. The direction of the undetected jet is indicated. The forward detector is essential for muon detection.
Figure 3: Schematic view of the L3 Fermi muon detector.
Figure 4: Expected muon momentum resolution as a function of polar angle.
Figure 5/: Drift chamber of 3 layers made of cells with 4 signal wires in interspersed with 5 no-wires and guard strips above and below the wire plane.

Figure 6/: On the left, the equipotential configuration of a drift cell with 4 signal wires is shown. On the right, drift cell trajectories are shown.

Guard Strip
Magnet door
Amplifiers
I-beam Cathode
Guard Strip
Magnet door

Guard
Figure 7: 

(a) Drift velocity along the electrical field for different \( B \) values. The upper curve shows, for \( B = 0 \), the effect of a 1% \( N_2 \) contamination.

(b) Lorentz detections as a function of \( E \) for \( B \) field values of 0.5 T and 0.55 T.

Chemical mixture: \( \text{Ar:CO}_2:iC_4H_{10}(86:10:4) \)
Figure 8: Monte Carlo simulation of:

a) Spectrum of arrival times for two wires on the left and an outer, on the right an inner wire) for a 26 mm drift distance.

b) Jitter in the arrival of the 8th electron.

c) Resolution expected from the time jitter for various drift distances.
Figure /9/: View of a chamber. The upper part gives the interior structure of the W, X, and Y layers. The lower part depicts the corresponding chamber frame with the holes for the wire planes.
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Figure 13: Mechanical tension deviations from the design values for (a) field and (b) signal wires. Shaded are the critical long wires. The dashed lines indicate the design tolerance of $4\sigma$. 

- (a) Cu(Be) field wires
- (b) W(Au) signal wires

<table>
<thead>
<tr>
<th>Wire Type</th>
<th>Deviation</th>
<th>Number of Wires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>$-0.5$</td>
<td>10</td>
</tr>
<tr>
<td>Field</td>
<td>$0$</td>
<td>50</td>
</tr>
<tr>
<td>Field</td>
<td>$0.5$</td>
<td>10</td>
</tr>
<tr>
<td>Signal</td>
<td>$-0.2$</td>
<td>50</td>
</tr>
<tr>
<td>Signal</td>
<td>$0$</td>
<td>50</td>
</tr>
<tr>
<td>Signal</td>
<td>$0.2$</td>
<td>10</td>
</tr>
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Force [N]
Figure 1: Typical counting rates using cosmics in one FB chamber. Rates are proportional to wire lengths, which explains the pattern observed in the Y layer's slow increase from cell number 1 to 27 and in the W and X layers increasing from cell number 1 to 11 and staying constant for the rest of the cells.
Figure 1/5: Preamplifier circuit.
Amplifier Discriminator

Threshold 40 mV

OR

Priority Encoder

Timing

Address

Drift timing
FastBus TDC'S
LeCroy 1879

FIFO

F148

8-TO-3

Priority Encoder

Figure 1/6/: Multiplexer of 8:1 channels with address recording.
Figure 1/8: T0CAL test performed to one of the chambers providing the relativ channel to channel timing calibration for all wires in all layers.
Figure 1/9: Cross section of a double-gap RPC (not to scale).
Figure 2.0: a) Typical plateau curve; b) Distribution of the efficiency working point for all tested chambers.

Figure 2.1: a) Trigger logic; b) Monte Carlo simulation of the trigger matrix for muons with different momenta.
Figure 2/2: End view of the L/3 magnet with the /3/6 turns of one toroidal coil.
Figure 2/3: Left side: Location of the measuring devices. Right side: Magnetic field vectors inside the iron according to a TOSCA calculation.
Figure 2.4: Calculated toroidal field strength as a function of the distance to the beam axis \( R \), averaged over the thickness of the door which extends from 0.7 to 0.9 m. The dips correspond to air gaps. The solenoidal part in the air and its return path in the doors are shown as dotted curves.
Figure 2.5: Schematic view of module assembly.

FM Chamber

RPCs

FO Chamber

RPCs
Figure 2a: Distribution of the residual residuals of the cosmic ray tracks (all selected events), see text. The Gaussian has a standard deviation of 200 mm. Figure 2b: Dependence of on the drift distance. The curves = 872 ± 02 q distance (mm).
Figure 2/7/: Distribution of the difference of the mean drift-time sums of the two chambers forming a module (see text).
Figure 2.8: The distance between the two segments of a track measured in the X and Y layers measured at the midplane (solid histogram). Tracks on the right (a) and left (b) sides of the X-wires are shown separately together with a gaussian. The shaded histogram is obtained when the same tracks are analyzed with a time offset of 20 ns.
Barrel muon  |  Alignment  |  Forw/Back muon

MO  |  SENSOR  |  FI  |  FM  |  FO

MM  |  A  |  B  |  C  |  D

MI  |  x  |  y  |  z

Figure /2/9/: Overview of the alignment system in the F/n2fB region, not to scale. The alignment consists of 4 steps: A) positioning of the sensor with respect to the barrel chamber wires, B) distance measurement by a sensor with respect to FI surfaces, C) positioning of these reference surfaces with respect to the FI chamber wires and D) the internal alignment of the three F/n2fB layers by means of a RASNIK system.
Figure 3/0: A front view of an X chamber showing the position of the reference marks for x, y, and z.

○ = GLASS CYLINDERS
Figure 3.1: Distance between the muon barrel and the reference marks of a chamber recorded by a triangulation sensor over 10 days. The top bar indicates the status of the magnets. A difference in chamber position of about 500 µm can be seen for the two periods with both magnets powered.
Figure 3.3: a) Distribution of $|\cos \theta|$ of muons with track segments in the FN2F muon chambers. The hatched histogram shows the muons in the toroidal region. b) Impact points in the $x,y$ plane of reconstructed muon tracks in the FI chambers on one door.

Figure 3.4: Corrected residuals for hits in the outer wires and inner wires for 8 points in FM and FOX and W layers. The Full Widths at Half Maximum (FWHM) of the distributions are shown in the plots. A detailed discussion of the resolution is given in paragraph 3.6.
Figure 3: Momentum spread of reconstructed muons relative to the beam energy $/E_{\text{beam}}/$. Plotted is the quantity $E_{\text{beam}}/(q \cdot p_{\mu\text{on}})$, where $E_{\text{beam}}$ is the LEP beam energy, $q$ is the reconstructed muon charge, and $p_{\mu\text{on}}$ the reconstructed muon momentum, in the $S$-region (a) and in the $T$-region (b).

$e^+e^- \rightarrow \mu^+\mu^-\gamma$

$E_{\text{beam}}/ \frac{q \cdot p_{\mu\text{on}}}{p_{\mu\text{on}}}$
Figure 3/6: Muon momentum resolution obtained in the F/N2B muon system as a function of the cosine of the polar angle $\theta$ of the track, for a momentum of 4.5 GeV.

Figure 3/7: Time resolution
Figure 3.8: RPCs time distribution, without subtracting the inter-bunchlet time, versus the RPCs identified bunchlet number.