STATUS REPORT 1984
ALEPH Collaboration

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1. INTRODUCTION

Here we report on the present state of design and construction of the ALEPH detector, as well as on test results obtained with prototypes in the period since the ALEPH Technical Report was written in 1983. This report is not very homogeneous and the figures are not always up to the required professional standard. Each section was prepared by the group responsible for that particular system, and there was neither the time nor the technical means to put these individual reports into a more cohesive format.

We have taken the opportunity to present quite a few details of the design and of the performance tests; perhaps some of these will be of interest to LEPC members or could prove useful for other people; they can also serve as reference for the ALEPH Collaboration. However, as the report is rather lengthy, we will use this Introduction to give an over-all view.

On-line and off-line data processing are not discussed here, since these were the subject of a recent paper (LEPC/84–8). This present report contains sections which give the design, status, planning, and budget for all other components of ALEPH, with the exception of the trigger system. As the latter will be one of the subjects of our September meeting, this is therefore not an opportune moment for review.

Over-all views of the detector are shown in Figs. 1.1 and 1.2. The ALEPH detector limits itself to four detection elements: drift chambers (Inner Tracking Chamber); streamer tubes (hadron calorimetry and muon identification); proportional wire/lead sandwich pad readout calorimetry (electron identification, $e\gamma$ calorimetry, and luminosity monitor); and a time projection chamber (TPC). Of these, the first two are well-understood techniques, so that the 'milestones' proposed by the LEPC concern only the other two. The ALEPH milestones are:

1) the construction and testing of a TPC with full-size sector and at least 1.5 m drift length;
2) the construction and testing of an $e\gamma$ calorimeter prototype with the proposed tower and layer structure, and large enough to contain electromagnetic showers;
3) the construction and testing of a prototype of a full-size barrel shower module. Our status with respect to these milestones is as follows:

i) TPC90 is the name of our prototype TPC: It provides the possibility to drift 1.5 m but, because of cost, it accommodates only end sectors somewhat smaller than full-size. The magnetic field is pulsed to a maximum value of 12 kG. It is used as a facility for studying all parameters of TPC operation, using both laser tracks and cosmic rays. So far, all experiments have used a sector with 8 mm × 8 mm pads in straight rows. A new sector using 6 mm × 30 mm pads in circular rows is just about ready, and is scheduled to go into TPC90 in September. The value of these tests to the collaboration cannot be overestimated, especially the information gained with the help of the lasers. On the basis of these tests we are convinced that the TPC operation is well understood, and that a sagitta precision of 100 μm on stiff tracks will be obtained. The TPC is no longer the source of concern that it was before these tests were undertaken.

ii) The $e\gamma$ calorimeter prototype: Not one but four such prototypes have been constructed and tested: one to check a construction based on circuit boards; another to test the construction method which was finally chosen (on the basis of cost) for the barrel; a third to test towers at 45°; and finally, one more to test the geometry and constructon details of the end-caps. On the basis of these results the barrel and end-cap full-scale designs have been established.

iii) The $e\gamma$ calorimeter full-scale barrel prototype: This test will not be possible in the sense originally intended, because of the lack of sufficient time. Following the small-scale prototype studies, the mechanical design of the full-scale barrel proved to be quite a challenging undertaking, which could only be completed a few months ago. The construction of the first module is now under way but will be terminated only in the summer of 1985, and tests cannot be finished before the end of 1985. To maintain a production schedule that will ensure completion in time for the LEP start-up, the construction of the remaining modules cannot be delayed until the end of these tests but must continue at a certain rhythm. Small flaws, if observed, might still be correctable. If, however, there are serious faults in the large-scale design, the delivery schedule of the $e\gamma$ calorimeter will be seriously compromised. We are very much aware of this and have hopefully achieved an adequate design.

We will now proceed with a brief summary of the status of ALEPH.

i) Superconducting coil
   a) Ordered from Saclay in July 1983, at a cost of 9.7 MSF.
   b) Cryostat order placed.
   c) Winding machine orders placed.
   d) Conductor order to be placed this month.
   e) Test of coil at Saclay in July 1986.
   f) Coil arrives at CERN in September 1986.

ii) Magnet
   a) Orders placed in April 1984.
   b) Delivery, August 1985.
iii) Magnet and field measurements on surface

iv) TPC
a) A prototype with 1.5 m drift length, magnetic field, and laser calibration has been tested with great success.
b) The mechanical design is complete, the calls for tender for the field cage have been sent out, and the manufacture of the 36 sectors is beginning at MPI, Munich.
c) Designs and prototypes of the amplifier, shaper, and digitizer (two 7-bit FADCs) exist, and the estimated production cost per channel is within the 180 SF which are in the budget.

v) The e⁻γ calorimeter
a) Four prototypes with pad geometry have been successfully tested with electrons.
b) The barrel design is complete; the first module is expected to be ready for cosmic-ray tests in summer 1985.
c) The end-cap design is very nearly complete. Module 1 is expected to be ready for cosmic tests in November 1985.
d) Satisfactory hybrid front-end circuits have been tested, but we hope that a monolithic solution (under development) will be successful. We must decide about this in the second half of 1985.

vi) Hadron calorimeter
a) A tower geometry prototype has been satisfactorily tested.
b) Tube manufacturing production lines have been set up in Frascati, and are nearing completion in Bari, Pisa, and Beijing.
c) Mounting in the barrel is scheduled for early 1986.
Mounting in the end-caps is scheduled for the middle of 1986.
d) The analog circuits have been designed, and satisfactory prototypes have been tested in the beam. They will be produced in Beijing. The digital circuits are being designed monolithically. The present version still has small problems, but it is expected that these will be rectified by the new version to be available this autumn. The cost is well within the SF 10 per channel foreseen in the budget.

vii) Inner tracking chamber
A full-length prototype, to test construction details and the possibility of z determination by timing, has performed satisfactorily. The final mechanical design is in progress. The decision whether to use timing to measure z will be made in November.

viii) Luminosity monitor
A prototype of the luminosity tracking chamber is under construction and is to be tested at the Bonn synchrotron this autumn. The luminosity calorimeter uses the end-cap e⁻γ calorimeter layer structure and is in the process of mechanical design.

ix) Beam pipe
This will be a straight-through thin-walled, ribbed, aluminium tube of the Huguein design, with neither end-cones nor a beryllium centre section.

The construction of ALEPH is progressing according to plan. Prototypes have been extensively tested, and work has started on the parts which require the longest lead time. The costs are within our budget. Barring major design errors, the apparatus will be finished in time. Our two biggest concerns are the installation and the commissioning. We attach primary importance to being ready with the full apparatus and its software for the LEP start-up, and it will be an enormous challenge to bring this complex detector together in the very limited time left after the experimental area is made available to us.
2. SOLENOID

2.1 General status

The first phase of the project, mainly concerned with design studies and development work, has progressed smoothly during the first year of the contract, which was signed between CERN and CEA/Saclay in July 1983.

The development programme for the aluminium-stabilized conductor has been completed and has furnished a wide variety of industrial products that are adequate for manufacturing the solenoid. Tenders have been received, and the order will be placed in September after a complete evaluation of the best candidates has been made.

The over-all design of the solenoid and cryostat has been completed and tenders have been received for the major mechanical parts. The order has been placed for the coil support shells, and another order is being processed for the complete cryostat, including vacuum vessels and thermal shields.

The winding method has been extensively studied, and the design of the main hardware for the winding fixtures has been completed. Special components, such as the pressing device, have been ordered for testing purposes. Tenders are under way for this whole mechanical structure, which will be ready to order in October.

The cryogenic system has been studied in detail in close collaboration with CERN experts. A new scheme has been proposed by Saclay as an interface between the refrigerator and the coil-cooling circuit. This will be incorporated in the solenoid cryogenic system and will be explained further on.

Other interfaces with the detectors have been thoroughly discussed with CERN, such as mechanical support, assembly fixtures, layout of cryogenic circuits, vacuum system, current leads and cables, etc.

It must be pointed out that some important decisions can only be taken after it is known which experimental hall will be allocated to the ALEPH experiment. This concerns, in particular, the position and layout of the chimneys, cold box, and power leads with respect to the solenoid cryostat, and may cause delays in the construction phase if the decision is postponed too long.

However, in view of present progress, and provided the above problem is settled in time, the over-all planning can be followed according to initial forecasts. Delays of one or two months have been accepted in some of the tenders mentioned above, owing to elaborate design tasks and lengthy industrial developments. These delays will be compensated by shorter fabrication times, originally estimated with sufficient safety margins. At present the critical point is that of the winding and impregnation fixtures, which are proving to be far more complex than initially anticipated. However, a considerable effort is being devoted to this area, and all possible measures will be taken to ensure that the equipment is ready on schedule in July 1985.

It is planned that the complete solenoid, in accordance with the contract, will be ready for delivery to CERN in November 1986. A general time schedule, leading to the completion of the solenoid, is shown in Fig. 2.1.

2.2 Conductor development

In view of the particular characteristics of the conductor specified for ALEPH, and in order to stimulate European industry to compete for its fabrication, a development programme was initiated as early as the end of 1982 among firms which had expressed their interest.

The specification calls for a high-current superconductor, massively stabilized by high-purity aluminium, and in the form of a rectangular strip, 3.6 mm × 35 mm in cross-section. About 30 km of this conductor are needed in unit lengths that are as long as possible, and with very tight dimensional tolerances and absolute reliability with regard to electrical performance. Two important parameters are considered:

i) the critical current of the superconductor over the whole length, including adequate safety margin;

ii) the mechanical and electrical quality of the joint at the interface between the superconducting composite and the aluminium, which can be characterized by a contact resistance (associated with a current transfer length) and an interface shear strength.

The response from industry has been very positive. A variety of samples and test lengths have been produced, demonstrating the feasibility of the required conductor. Extensive tests have been carried out at Saclay for qualification and comparison of the various products. Some of the results have been backed up by measurements at the Rutherford Appleton Laboratory, which is also working on the development of a similar conductor for DELPHI.

All the conductors that exhibited satisfactory results were obtained by a co-extrusion process of aluminium around a NbTi/Cu insert. The techniques differ in the type of insert used, which can be either a monolithic composite or a multistrand flat cable. For full reliability of superconducting performance the cable is preferable, as any defect in the material (although highly improbable) will only affect a single strand and will not deteriorate the bulk of the conductor properties. On the other hand, the bonding quality appears generally better in the case of a monolith, although good results have also been obtained with cables. Some typical measurements are shown in Table 2.1.

The final tenders reflect the effort made by the various manufacturers, among which there are four European companies, two Japanese, and two American (the latter offering only the superconducting insert).

In order to establish a clear balance between cost and technical reliability, additional samples of significant lengths have been requested from several tenderers; this has led to the final decision being postponed until September 1984. However, anticipated fabrication times are still adequate for delivery on schedule.
2.3 Solenoid and cryostat

The over-all design of the solenoid and cryostat has been completed together with the relevant stress and safety analyses. The design is basically that of the original proposal, with all engineering details included.

In order to assess the industrial feasibility and to select potential manufacturers, a pre-tendering action was first taken in November 1983 for the major parts of the system. A total of 47 European companies were approached; from among these, 11 showed interest in competing. This consultation also helped to evaluate the technical solutions that could be adapted to such unusually large pieces.

The final calls for tender were sent out in March 1984 for the winding support shells, and in April 1984 for the cryostat. The order for the support shells was placed in July.

The tenders for the cryostat were received in July, and the legal procedure for the order is now being followed. The specification covers: the complete cryostat, including the two large vacuum vessels made of alu-alloy; the two end-plates made of stainless steel; the thermal shields made of separate aluminium panels attached by insulating studs to the vacuum vessels; and the whole arrangement of the superinsulation (blankets of multilayer superinsulation will be prepared in advance by CEA, delivered, and then assembled by them at the cryostat manufacturer’s). Each half cryostat will be completely assembled at the manufacturer’s, and leak tested before shipping to Saclay.

2.4 Winding fixtures

The winding method has been carefully elaborated in order to fulfil the stringent requirements laid down for the solenoid performance.

The conductor will be placed directly on the inside wall of the support cylinder in such a way that it is mechanically and thermally bonded to this cylinder, and at the same time maintained under axial compression.

The main elements of the winding machine are shown in Fig. 2.2:

- The support cylinder is clamped on a turntable with its axis vertical.
- A central cylindrical cage, of diameter close to that of the support cylinder, moves vertically (without rotation) and is guided along a fixed central pillar.
- The bottom part of the cage is equipped with a ring of pneumatically controlled pressing devices, consisting alternately of rollers and flat pads acting separately, which exert a continuous pressure on the turns already laid in the winding.
- When the turntable rotates, only the rollers press on the conductor in order to avoid friction. When the machine is stopped, a higher and more uniform pressure can be applied by means of the pads. At this stage, the packing uniformity of the turns in the winding can be controlled and accurately adjusted.
- The upper part of the cage is equipped with a winding line comprising four machines, one each for planing, driving, bending, and insulation wrapping.

The conductor is fed from an outside storage spool through the above winding line; it is then guided helicoidally down to the bottom of the cage, where it is laid in place in the winding.

The same turntable is used for the compensating coils, but the process is more classical since the conductor is wound on the outside of the support cylinder.

After a half coil has been completely wound, the cylinder is transferred into a potting fixture where vacuum impregnation of the winding is carried out.
At the present stage the detailed design of the mechanical structure of the winding machine has been completed and the tendering action for this structure is under way. The selection of standard equipment for the winding line is being discussed with specialized suppliers. The method of vacuum impregnation and the definition of the equipment needed for this operation are the subject of consultation with experienced manufacturers in the field of heavy electrical engineering. Collaboration with industry is considered essential for the success of this particular operation. A test programme has been initiated to select the basic components, insulating material, and resin, in accordance with the impregnation procedure.

2.5 Refrigeration

The cooling scheme of the solenoid described in the 1983 Technical Report has been revised. Instead of the helium being circulated by forced flow directly from the refrigerator in a single loop attached to the support cylinder, this circulation is now carried out in a multichannel heat exchanger, the helium flowing by natural gravity from an intermediate reservoir installed in the cold box above the solenoid. This scheme (Fig. 2.3) has the following advantages:

- The helium flow in each channel is self-regulated with respect to the heat load which has to be removed by the circuit, and is independent of the actual cooling power of the refrigerator.
- In particular, during current charge or discharge, the power dissipated in the support cylinder by eddy current effect can be absorbed without increasing the capacity of the refrigerator.
- In case of failure and shutdown of the refrigerator, the liquid-helium reserve is sufficient to maintain the cryogenic operation of the solenoid during the time necessary to discharge the current (~ 1 hour), avoiding the need for fast discharge and subsequent quench of the magnet.

Such a scheme has been successfully applied to existing large cryogenic systems, and is fully reliable as it does not require any active devices such as pumps, valves, and regulating systems.

The cryogenic system and its interfaces with the refrigerator supplied by CERN have been extensively discussed with CERN. The definition of the components and the analyses of the various phases of operation have been examined in detail. A full specification of this system is being prepared and should be soon finalized, in agreement with CERN, so that detailed studies of the hardware can be implemented.
2.6 Miscellaneous

Basic studies concerning the operation of the solenoid have been continued in parallel with the technical work. Magnetic field calculations have been refined and updated with respect to the design of the hadron calorimeter which constitutes the iron return yoke of the magnet. Electromagnetic forces have been estimated under realistic conditions of both normal and disturbed operation, so that the support system could be properly designed.

Stability and quench properties of the solenoid have been investigated theoretically and experimentally. In particular, disturbance levels which would affect the superconductor stability have been found, well above those which are likely to occur during operation. This is because of the good thermal diffusivity of the high-purity aluminium stabilizer incorporated in the conductor.

Quench propagation studies are still continuing. To achieve more accurate predictions, a large-scale experiment is being prepared which will provide the essential parameters governing the phenomenon. Results of this experiment are expected to be available before the end of 1984. It must be pointed out that the aim of this study is to reach a complete understanding of the quench behaviour; however, it does not concern the safety conditions of the magnet in case of quench, which have already been fully established in the design of the solenoid.
3. MAGNET IRON YOKE

The mechanical design of the iron yoke has been finalized (see Fig. 3.1). Its structure, size, and weight are virtually unchanged with respect to the Technical Report of 1983. The only modification worth noting concerns the dead space around the axial hole in the end-caps, which has been reduced by suppressing the 5 cm thick cylinder originally located there and extending the size of the modules correspondingly.

3.1 Calculations and test-model measurements

A finite-elements program SAPV was used to provide a good estimate of the stress conditions in the critical end-cap modules and their tying elements. As suggested by this study, the bolting of the end-cap modules has been increased, and it is proposed to make the contact pads between end-caps and barrel partially from stainless steel in order to concentrate the return flux lines on the outside areas with a better balance of the huge magnetic forces.

The interface of the yoke with the adjacent items, and in particular with the coil, has been almost completely defined. In particular, two equal openings will be provided on the upper part of the barrel (one at each end) for the coil services, i.e. transfer lines and pumping ducts.

Extensive 2-D computations have been performed in order to obtain a design that fulfills the severe field requirements. The shim around the end-cap 90 cm diameter axial hole has been determined, and furthermore, three circular grooves have been added in the end-cap pole surfaces. A 1/10 scale magnetic model was built to investigate the effects of 3-D irregularities such as end-caps misalignments, the openings for the cable passage and the coil services, all the azimuthal periodicities, etc. This model (see Fig. 3.2) operates at a field of 0.15 T (that is, 1/10 of the wanted field), but its iron structure has been designed to reproduce as closely as possible the saturation conditions of the real magnet. Among all the effects investigated, only the tilt of the end-cap pole surfaces appeared to be critical, 1 mrad of tilt producing an azimuthal distortion of $\sim 7 \times 10^{-4}$ and radial distortions of $\sim 3 \times 10^{-4}$. Given the imposed mechanical tolerances, field errors five times smaller should be present in the real magnet. The steel-made cryostat supporting rods also produce distortions at the boundaries of the TPC volume, of the order of $4 \times 10^{-4}$. These distortions are vanishing rapidly inside the interesting volume and become negligible on the integrated field values. The openings for the passage of cables and coil services, as well as all the other above-mentioned 3-D irregularities, have no noticeable effects, as already mentioned.

3.2 Construction and time schedule

The tender for the yoke construction was sent out in autumn 1983. Many discussions with possible manufacturers have led to an increase of the plate spacing by 2 mm (from 20 to 22 mm), the maximum admissible thickness of the detectors to be inserted being kept equal to 17 mm. Thirty-five firms submitted valid offers. Two of them have been selected for the construction of the barrel and the two end-caps, respectively. The official adjudication took place in April and the contracts were signed in May 1984. Both contracts foresee delivery of all the modules by October 1985. After premounting the yoke parts at the respective factories. The premounting at the factories will permit a careful check of the over-all mechanical tolerances, as well as the correction of possible errors, and will speed up the operations to be further carried out at CERN. Actually it is foreseen to remount the complete yoke in a surface building at CERN during 1986, after having equipped all its modules with the streamer tubes of the hadron calorimeter. The coil will be mounted in the yoke during the last months of 1986, and a complete test and field mapping — and, if necessary, shimming — will be done at the beginning of 1987. According to this schedule, the magnet will be dismantled for transport into the underground tunnel in spring 1987.

The large and precise gear for the magnetic measurements has been partially designed by MPI in Munich. The design will be completed by the end of 1984 and its construction will take place mainly in 1985. A new data-acquisition program to be used for the magnetic measurements will be written at CERN during 1985.

The design of the magnet supports and platforms and of the various driving and central devices has made progress, and all the basic options have been taken. A good part of the related items such as rollers, dampers, jacks, hydraulic motors, etc., will already be ordered in 1984 and the remaining parts mostly in 1985. Special handling equipment (in particular spreaders) has already been designed and will be built in 1984; part of this equipment will be sent to the yoke manufacturers to be used there in the handling of the real modules.

The time schedule is depicted in Fig. 3.3.
4. THE TIME PROJECTION CHAMBER (TPC)

4.1 Introduction

The Time Projection Chamber (TPC) is the central detector of ALEPH; its dimensions are shown in Fig. 4.1. The drift length is $2 \times 2.2$ m. A plane HV electrode in the centre separates the active volume of the detector into two halves. After drifting along the parallel electric and magnetic field lines, a track is detected on one of the two end-plates.

An end-plate is subdivided into 18 'sectors' of three different types (Fig. 4.2). A striking property of this layout is the radial ‘zig-zag’ boundary between sectors — so straight tracks never fall completely on a radial boundary, i.e. they are always visible.

The most important feature of the end-plate is, however, the arrangement of the pads in 21 concentric circles (Fig. 4.3). The pads have a radial length of 30 mm and a width of 6.5 mm. There are altogether 20500 pads and 3240 wires on an end-plate.

The circular arrangement of the pads is new and therefore merits some discussion.
4.2 Why long and radial pads?

In the PEP 4 geometry of $8 \times 8 \text{mm}^2$ pads arranged in straight lines, and at a gas pressure of 1 atm, the $r\phi$ spatial resolution is dominated by the fluctuations in the size of the avalanche on each wire contributing to the pad signal (Fig. 4.4). This effect adds to the resolution with the term $\sigma^2_{\phi} \tan^2 \beta$, with $\sigma_{\phi} \approx 1 \text{ mm}$. If we consider stiff tracks in this geometry, the angle $\beta$ between the track and the pad axis can assume values of up to $30^\circ$. We have also noted [1] that the $\sigma_{\phi}$ term can be reduced by correcting the space coordinate as measured from the pads with an algorithm that uses the wire pulse heights. With this procedure, $\sigma_{\phi}$ is reduced to $\approx 230 \mu\text{m}$.

![Diagram of pads and wires]

Fig. 4.4

Since this correction procedure is rather clumsy and, even more, it is not always applicable, we decided to reduce the $\sigma_{\phi}$ effect by making $\beta = 0$ for stiff tracks coming from the interaction point, i.e. to orient the pads radially. The new orientation made it possible to have them also longer (30 mm instead of 8 mm) thus collecting more ionization [2]. In the following we summarize some calculations which compare the measuring accuracy and the two-track resolution of the old and new geometries.

Once the $\sigma_{\phi}$ term is eliminated, the resolution is dominated by the $E \times B$ and the angular effect [1]:

$$\sigma^2_{\alpha} (\tan \alpha - \tan \psi)^2,$$

where $\sigma^2_{\alpha} = A^2 \kappa^2 l / 12N$; $\alpha$ is the angle of the track with the normal to the wire; $\psi$ is the Lorentz angle; $A^2 = \sum w_i^2$, with $w_i$ the weight by which the $i^{th}$ wire contributes to the pad signal; $\kappa$ is a factor that takes into account the fluctuations in the cluster size; $l$ is the sense wire spacing; and $N$ is the number of primary ionization clusters per unit length produced by a minimum ionizing particle.

In the old geometry $w_0 \approx 0.4$, $w_{\pm 1} \approx 0.25$, $w_{\pm 2} \approx 0.05$. A accounts for the increase of the effective number of electrons contributing to the pad signal with respect to the electrons coming from a single wire. To reduce $A$ and therefore the $\sigma_{\phi}$ term, we have chosen long pads (30 mm). So about eight wires will contribute to the pad signal, each one with a weight $w_i \approx 0.125$, resulting in $A \approx 0.35$.

The same argument can be applied to the contribution of diffusion to the resolution.

Finally, since we collect the charge from a longer track segment, we expect

i) a reduction of the electronic noise contribution to the resolution;

ii) a reduction of the Landau fluctuations on the pad signal, with consequent reduction of the dynamic range [3].

To summarize the improvement on the $r\phi$ spatial resolution, which can be achieved with the long and radial pad geometry, we give a parametrization of the resolution [4] as well as the averaged contributions of the different terms to the point measurement accuracy of stiff tracks.

$$\sigma^2 \approx \sigma^2_0 + \sigma^2_{\phi} (\tan \alpha - \tan \psi)^2 + \sigma^2_{\alpha} \tan^2 \beta + \sigma^2_0 D$$

<table>
<thead>
<tr>
<th>Term</th>
<th>New geom. ($\mu\text{m}$)</th>
<th>Old geom. ($\mu\text{m}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_0$</td>
<td>$&lt; 100$</td>
<td>100</td>
</tr>
<tr>
<td>$\sigma_{\phi}$</td>
<td>120</td>
<td>190</td>
</tr>
<tr>
<td>$\sigma_{\alpha}$</td>
<td>0</td>
<td>75 (after corrections)</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>60</td>
<td>90</td>
</tr>
</tbody>
</table>
Note that $\sigma_\mu = 75 \mu m$ only after correcting for the wire amplitudes. The new geometry gives the momentum resolution [5] shown in Fig. 4.5.

The main disadvantage of the new solution is the worsening of the two-track resolution. This effect comes from the fact that at polar angles $\theta$ different from $90^\circ$, the charge produced along the track is collected in a time interval $\Delta t = h(v_d \tan \theta)$, $h$ being the pad length and $v_d$ the drift velocity. The worsening of the two-track separation has been computed with a 'jet' Monte Carlo program [6]. The results (Fig. 4.6) show a degradation, which we accept as the price of the improved resolution.

4.3 Prototypes and tests

To be able to define the parameters governing the performance as well as the design of a TPC, many experimental tests have been made. Some of these will be presented here together with their results.

4.3.1 TPC90

In this TPC model we have drifted tracks in a magnetic field over distances ranging up to 1.3 m. We have learnt how to compute and correct the track distortions from the magnetic field map so that the accuracy of track reconstruction is in fact dominated by the ionization statistics and electronic effects alone, as described in the ALEPH Technical Report. This is an important milestone on the way to the ALEPH TPC.

The apparatus (Fig. 4.7)

The set-up consists of a solenoid magnet providing a magnetic field inside a volume of 90 cm diameter and 175 cm length [7]. The magnet was brought into operation in April 1983 and can produce a magnetic field of up to 0.7 T
in d.c. mode and up to 1.2 T in pulsed mode with a peak power consumption of 1.2 MW. The magnetic field has been mapped using Hall plates, and the resulting field map makes it possible to calculate the three components of the magnetic field inside the volume to approx. 1 G [8].

Inserted in the magnet is a field cage that maintains the required electric field. It consists of a fibre-glass cylinder in which Cu electrode rings are embedded so as to establish the proper distribution of the electric potential. The field cage is closed on one side by the HV electrode and can be operated up to 50 kV; this corresponds to a drift field of 375 V/cm. Incorporated into the field cage are 22 quartz windows for laser beams.

A wire chamber is located at one end of the field cage. It represents nearly one sector of the ALEPH TPC. The first prototype sector [9], which is currently under tests, has a design similar to that of the PEP-4 TPC. The cathode plane consists of copper-clad fibre glass with reinforcement ribs on the back. Eight pad rows (the size of each pad is 8 × 7.5 mm²) are machined into the cathode plane. Above this plane there are three layers of wire planes. Figure 4.8 shows a view of the sector outside the field cage. The chamber is equipped with preamplifiers, which in turn are connected by shaping amplifiers to time sampling electronics using charge-coupled devices (CCD) [10]. These electronics channels (256 in total) are of the Berkeley PEP-4 design. Figure 4.9 shows a view of the back of the chamber with the magnet open.

The sensitive volume of TPC90 is connected to a flow-through gas system [11] operating with premixed gases (Ar + 9% or 20% CH₄). The system also includes a monitor chamber to study separately the parameters related to the gas (e.g. drift velocity, gas amplification, electron attachment).

Two types of tracks are being studied in TPC90: cosmic-ray tracks and laser tracks. A scintillator trigger (available for cosmic) and two laser systems are in use. The first system is a pulsed nitrogen laser (MOPA 400, pulse energy 200 μJ). For scans with single tracks, this laser beam can be shot through gaps in the solenoid and the field cage oval windows. It can be used together with a beam splitter to create three tracks in one plane by means of pentaprism. The second laser system [12] is comprised of an excimer laser using krypton + fluorine gas, with a peak energy of 200 mJ, and a beam splitter consisting of mirrors to create two crossing tracks.

Work with the first prototype chamber installed in the apparatus started in July 1983; the results are presented below. During the summer of 1984, a second prototype chamber will be installed in TPC90. This chamber will have all the design features considered for the ALEPH TPC, e.g. aluminium sandwich construction for the cathode plane, and long pads in arcs along constant radii. Furthermore, at the end of the summer, also a new system of electronics (440 FASTBUS channels) will be tested using flash ADCs for the time-sampling electronics.
Tests in TPC90 with laser beams and cosmic rays

The TPC90 has been extensively tested with laser beams and cosmic rays. The laser beams have been used to study the distortions induced by the non-axial components of the fields. They also constitute a very powerful tool for checking and establishing the running conditions, as well as for determining some important geometrical parameters of the chamber. The tests with cosmic rays have allowed us to measure the spatial resolution of the chamber in a large volume, under conditions that are similar to those of the ALEPH TPC.

We now summarize some of the tests and the results achieved:

Study of the calibration procedure: The electronics channels of TPC90 are calibrated by pulsing the field wires [13]. We have made a comparative study of different algorithms to define the induced charge from the measured pulse heights of the time buckets of a given signal. The algorithm that takes into account only the three buckets with the highest pulse height is the most promising for the steep tracks.

Measurement of pad response function (PRF): The geometrical PRF has been measured with an accuracy of better than 1% with two different methods, both of which use laser beams [14,15]. We have also studied the effect of the transverse diffusion on the PRF (Fig. 4.10). The single electron diffusion coefficient in our gas mixture and its dependence on the magnetic field have been measured with an accuracy of better than 1% [15].

Study of the systematic effects caused by the geometry of the fields: The systematic distortions of the electron trajectories caused by the non-axial components of the fields have been investigated. Using a particular technique, we have measured the angle between the axes of the electric and the magnetic fields and the displacements caused by the radial components of these fields [16].

The influence of the magnetic field intensity on the size of these systematic displacements has been determined. We have shown that the three components of the velocity of the electrons drifting inside the TPC depend mainly on the magnetic field, as foreseen by the classical theory [17]. Many details of this theory came out clearly in our measurements; for example when reversing the magnetic field (Fig. 4.11a,b), the antisymmetric track displacements $\langle \Delta \rangle$ are proportional to $\omega r/(1 + \omega^2 r^2)$, the symmetric track displacements $S$ are proportional to $\omega^2 r^2/(1 + \omega^2 r^2)$, $\omega r$ being proportional to the magnetic field.

Using this theory, it is possible to predict the radial component of the magnetic field from the measured displacements [16]. The result of this prediction is in perfect agreement with the measured map of the magnetic field (Fig. 4.12).

With this technique, we have also been able to understand its origin [18] and to correct for it. After these corrections we measured the typical deviation from straightness of a laser beam. We found this to be less than 30 $\mu$m in the full volume which we were able to scan with these beams.

These results show that in TPC90 we have such a grasp of the systematic displacements caused by the fields that they do not affect the resolution on the sagitta measurement.
Measurement of the drift velocity: We have measured the drift velocity, using two laser tracks with known polar angle [19]. This technique has been tested using three laser beams, comparing the results obtained from the two different pairs.

The measurement obtained with a single event has an accuracy of 0.3%, and the two measurements done with the three laser beams on 300 events agree within 0.01%.

Spatial accuracy of the $\rho\phi$ coordinate: We have measured the $\rho\phi$ spatial accuracy using cosmic rays. The geometry of the pad plane of TPC'90 was "standard PEP-4" (we did not yet have the TPC'90/2 with long pads). Therefore we can directly compare the measured spatial resolution with the results obtained from the tests done with a small prototype in a particle beam [1].
For technical reasons our trigger selects tracks at an azimuthal angle of $(13 \pm 2)^\circ$ with respect to the horizontal plane. With these particles we have studied the spatial resolution for tracks at this angle with the two opposite polarities of the magnet. The situation is not symmetric because of the $E \times B$ effect in the amplification region.

Resolutions of $(180 \pm 10) \mu m$ at $B = -1.2$ T and of $(240 \pm 10) \mu m$ at $B = +1.2$ T, averaged over all possible drift lengths from 0 to 127 cm, have been measured (Fig. 4.13). This result is in perfect agreement with the parametrization of the resolution we had used in the 1983 Technical Report to predict the performance of the ALEPH TPC.

Spatial accuracy of the $z$ coordinate: We have used cosmic-ray signals on the wires to measure the accuracy of the $z$ coordinate.

An r.m.s. accuracy of $(1.5 \pm 0.1)$ mm on each wire averaged over all possible drift lengths was obtained. This resolution in TPC90 is dominated by electronic effects.

We have also measured the behaviour of the $z$ resolution with the drift length (Fig. 4.14) showing the effect of the longitudinal diffusion of the drifting electrons.

$dE/dx$ resolution: Cosmic rays have also been used to study the $dE/dx$ resolution. Assuming that all particles which cross the chamber have the same mean energy loss, we get an accuracy of $(13 \pm 0.5)$% on the measurement of the most probable energy loss, using the 56 wires of TPC90 which are equipped with electronics.

Assuming that all particles are muons and correcting for the different ionization at different momenta, this corresponds to an accuracy of $(12 \pm 0.5)$%.

This result is in agreement with the standard parametrization used by us to predict the $dE/dx$ resolution for the ALEPH TPC.

Two-track separation: We have also measured the separability of two tracks close to each other, using two laser tracks crossing at a shallow angle. The measurement of the two coordinates along the pad row is undisturbed down to a distance of 1.4 cm; the error increases by 50% at a distance of 0.9 cm.

4.3.2 Pad response function for long radial pads
The pad response function (PRF) for the 'long radial' pad geometry has been studied in a small prototype chamber. The result [20] is that the PRF has a very weak dependence on the angle $\gamma$ between pad row and wires. This dependence agrees with the expected one:

$$\sigma_{PRF}^2 = \sigma_0^2 + (l^2/12)\sin^2 \gamma,$$

where $l$ is the wire spacing.

Another important result of this test is that the relative calibration of neighbouring pads by pulsing the potential wires works without any problem with the new geometry.

4.3.3 Gating
The static and dynamic aspects of gating have been studied with two special test chambers. A first, small chamber has been used to establish the static conditions required for closing the gating grid [21]. First dynamical measurements of the pick-up problems have also been done with this chamber.
A second chamber, similar to the one in TPC90, has been built to investigate the pick-up in a real-size chamber. It was shown [23] that the residual pick-up could be reduced to a level which corresponds to a few percent of a minimum ionizing particle on the wires, when ramping the grid in 500 ns to $V_g = \pm 30$ V. The pick-up on the pads is smaller than on the wires by an order of magnitude.

TPC90 has then been used to study the static and dynamic aspects of the gating grid under even more realistic conditions. Special attention was paid to the influence of the magnetic field on the gating parameters. In dealing with a new set-up, we had to establish also new values for $V_g$, the condition for full transparency, and for $\pm \Delta V_g$ to close the grid. With a gating grid of 2 mm wire spacing and zero magnetic field, we found

$$V_g = -70 \text{ V},$$
$$\Delta V_g = \pm 40 \text{ V}.$$

Whilst the positive ion current, measured at the central drift electrode, is unaffected by the magnetic field [21], the opaqueness of the gated grid to electrons is significantly reduced with increasing magnetic field. Therefore, depending on the magnetic field strength, $\Delta V_g$ has to be adjusted accordingly in order to close the grid again. This is illustrated in Fig. 4.15a, where, for example for $B = 1.2$ T, $\Delta V_g$ must be raised as high as $\pm 190$ V to keep the TPC proportional cell free from incoming electrons. The systematic dependence of $\Delta V_g$ on the magnetic field $B$ is shown in Fig. 4.15b.

These results [23] are explained by the different or $^*$ values for electrons and positive ions. For electrons, or becomes about 8 at a field of 120 V/cm. Near the gating grid, E and B are no longer parallel to each other; therefore the motion of electrons is determined by the combined action of the electric and magnetic fields. Hence, whilst positive ions, because of their small or value, strictly follow the electric field lines towards the gated grid, electrons will 'leak' through the electrostatically closed grid in the presence of the magnetic field. This diode characteristic of the gated detector is still under investigation.

4.3.4 Tests related to the field cages

Insulator winding tests

Two mandrels (one of 60 cm diameter and 1 m length, the other of 90 cm diameter and 2 m length) have been constructed, and tests are being carried out on methods of producing cylinders from wound polyester foils. Apart from providing experience in winding techniques and in producing bubble-free insulators, these are a source of trial pieces for high-voltage tests. Several types of winding have been tried: i) cylindrical winding in which 1 m wide polyester foil is wound in a spiral fashion; ii) helical winding where a 99 mm wide band is wound with a pitch of 100 mm; iii) three
adjacent 60 cm wide strips are cylindrically wound in a double layer. Figure 4.16 shows the prototype winding machine set-up for helical winding, and Fig. 4.17 the machine set-up for the third method. Test cylinders with very few air bubbles have been produced, and the problems of scaling up the present system to the dimensions of the ALEPH TPC are being studied.
**Insulator breakdown tests**

The intrinsic breakdown field is very much greater than the fields to be encountered in practice, and the main cause of insulator deterioration is discharges in air inclusions. The d.c. breakdown tests using a wound insulator (i.e. Mylar plus glue) have confirmed the published figures for the breakdown strength of polyester foils. In a.c. tests the effect of discharges in air gaps is greatly accentuated since the field is reversed every half cycle; in the d.c. case the discharge frequency is determined by the relaxation time $\varepsilon^\kappa \rho$ ($\kappa$ is the dielectric constant and $\rho$ the resistivity of the insulator), which is of the order of several hours for Mylar. Samples of insulator obtained from early winding tests have resisted — and are still resisting after several hundred hours — the equivalent of 60 kV r.m.s. (at 50 Hz) across a 3 mm insulator.

The microdischarges occurring when high voltages are applied to an air gap of controlled thickness between two polyester foils have been studied in a purpose-built apparatus. These experiments [24] have shown that the charge is not distributed evenly over the insulator faces, and they have allowed predictions to be made of the rate and mechanism of discharge under constant voltage conditions.

**Fabrication of field-defining electrodes**

The advantage of using a highly resistive ink to cover a set of many thin electrodes for producing the electric field is obvious, since in this way it might be possible to define the boundary of the electric field everywhere, avoiding dielectric material. Tests with inks of various conductivity have been carried out and have shown that it seems to be very difficult to produce surfaces with the necessary homogeneity.

A system has been devised for producing Cu electrodes cheaply on polyester foils, which seems to hold out the promise of fabrication of 12 m long bands of electrodes with the required precision, although this still has to be proved.

**Electrode tests**

A test electrode system has been constructed for studying the behaviour of the field-defining structure, described later in subsection 4.4.5; it is about to be installed in TPC90. In particular it is intended to study the nature of the periodic field near the electrode surface, the possible presence of 'hooks', and the effects of deliberately charging up the inter electrode gaps.

A device has been built in which tests of various designs of field-defining electrodes can be carried out. This test device is shown in Fig. 4.18 with two of its four potential grading electrodes removed. The electron source is a tungsten

![Image](image_url)

**Fig. 4.18**

24
wire located in the plane of the cathode and heated to incandescence by an isolating transformer. The current is detected at the anode end by two adjacent rectangular electrodes mounted in the plane of the anode. The distances of both the source and detector from the electrode under test are variable. The system has been shown to work successfully; the electron beam at the anode end can be measured with a precision of about 0.1 mm.

The breakdown between adjacent field-defining electrodes is under investigation. In preliminary tests the breakdown voltage in a gas mixture of methane (10%) + argon (90%) was found to be greater than 700 V. These tests are continuing.

**Resistor tests**

The long-term ageing effects of resistors and their behaviour when subjected to high-voltage transients are under study. The latter behaviour is particularly important for predicting the response of the resistor chain to transient high voltages such as could be produced by a fault in the insulator or a short circuit in the high-voltage cable. The time variation of the voltage across an individual resistor chain, when a step function voltage is input at one end of that chain, has been studied analytically. On account of the inter-electrode capacity, it is found that the transient voltage across any resistor never exceeds about one-fifth of the applied voltage (which will have a maximum value of 60 kV). Transient voltage tests have shown that pulses with rise-time of 2.5 μs, fall-time of 50 μs, and amplitudes of up to 7 kV do not appreciably change the resistance of a 1 MΩ metal film resistor. It is thus hoped that resistor chains can be made to be intrinsically self-protecting, thus obviating the need for such protection devices as spark gaps, etc. Transient voltage tests of resistor chains are in preparation.

**Central electrode**

As mentioned below, the central electrode should deviate very little from a plane. We are testing methods of producing electrodes with the required flatness.

**4.3.5 Tests related to the chamber gas [25]**

A gas monitor chamber with a drift length of 20 cm (Fig. 4.19) was built for precise measurements of the drift velocity, electron absorption, and gas amplification as functions of the gas parameters. In Fig. 4.20 we display the measured influence of oxygen contamination on the absorption of electrons, and Fig. 4.21 depicts the measured variation of the gas amplification A with the concentration of CH₄ in argon. The results from this chamber are important for the specification of the TPC gas system.

![Fig. 4.19](image_url)
4.3.6 Gas ionization by UV laser light

In TPC90 our nitrogen laser (337 nm, 200 μJ) produces tracks in the argon + methane chamber gas with ionization densities corresponding to 5 to 15 minimum ionizing particles. The ionization depends quadratically on the light intensity, therefore it is due to a two-photon process on (unknown) constituents of the gas. We have shown that these constituents can be removed from a test chamber by heating and gas cleaning.

For the ALEPH TPC, each primary beam will be split into 15 beams. Given the unavoidable losses, including beam divergence corrections, we do not yet know whether the 4 mJ total power of the Nd-YAG laser is sufficient for an adequate ionization of the unknown gas constituents. Therefore chemical additives to the TPC gas are being studied [26,27], which should increase the ionization in a controlled way.

We made absolute measurements of the ionization of a Nd-YAG laser (266 nm) in argon + methane, with and without chemical additives. For example, at a power density of 1 μJ/mm² we obtained the values in Table 4.1.

Table 4.1

<table>
<thead>
<tr>
<th></th>
<th>Argon + methane, as purchased</th>
<th>Argon + methane with 1.5 ppm TMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of ion pairs/cm · mm²</td>
<td>7.5</td>
<td>85</td>
</tr>
<tr>
<td>Corresponding No. of min. ionizing particles using 4 mm × 4 mm beam</td>
<td>1.8</td>
<td>20</td>
</tr>
</tbody>
</table>
Other additives, such as dimethylaniline (DMA), were also studied in detail. Some were found to be unsuitable for the TPC because they contaminate the walls. Long-term tests with an $^{55}$Fe source have revealed that measurable deposits on the anode wire of a proportional chamber occurred later when TMA was added.

4.4 Mechanical design

An overview of the TPC was presented in Fig. 4.1. The mechanical design work is well advanced; the status of the major items is listed in Table 4.2. Most parts either have been finalized or will be completed in a few months.

| Table 4.2  |
| Status of TPC design work |

<table>
<thead>
<tr>
<th>TPC module</th>
<th>Completion date for design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sectors</td>
<td>October 1984</td>
</tr>
<tr>
<td>End-plates</td>
<td>Finished</td>
</tr>
<tr>
<td>Field cages</td>
<td>Finished</td>
</tr>
<tr>
<td>Potential graders</td>
<td>December 1984</td>
</tr>
<tr>
<td>Central electrode</td>
<td>December 1984</td>
</tr>
<tr>
<td>HV equipment</td>
<td>March 1985</td>
</tr>
<tr>
<td>Feet of TPC</td>
<td>December 1984</td>
</tr>
<tr>
<td>Water and air cooling</td>
<td>March 1985</td>
</tr>
<tr>
<td>Gas connections</td>
<td>December 1984</td>
</tr>
<tr>
<td>Cabling</td>
<td>June 1985</td>
</tr>
<tr>
<td>Installation tools</td>
<td>Finished</td>
</tr>
<tr>
<td>Test structure</td>
<td>December 1984</td>
</tr>
<tr>
<td>Acess platform</td>
<td>November 1985</td>
</tr>
</tbody>
</table>

4.4.1 TPC sectors

The design of the TPC sectors is well advanced and will be finished in autumn 1984. Solutions for the mechanical design details have been found, and a prototype sector incorporating all design details is being built for TPC90. A side view of a sector is seen in Fig. 4.22. Mechanical rigidity is achieved with a glued sandwich structure made of aluminium.
The sandwich provides a convenient place for the wiring which connects round pad rows to straight preamplifier modules. Each preamplifier will generate up to 100 mW of heat, which will be removed via conducting tongues connected to water-cooled blocks. In addition, cooling air will be blown into the sandwich structure to remove any remaining heat. The sectors will be bolted to the end-plate frame and sealed by O-rings. The wire planes have the 'standard' geometry: a sense/field grid, a ground grid, and a gating grid, at distances of 4 mm, 8 mm, and 14 mm, respectively, from the pad cathode. The sense wires are 4 mm apart, and there is a field wire midway between every pair of sense wires. The wire spacing for the ground grid is 1 mm and for the gating grid is either 1 mm or 2 mm (decision pending). The sense wires are made of gold-plated copper (2%)–beryllium and are 20 μm in diameter. The wires are glued to side walls containing printed-circuit artwork for distribution of signals and voltages. The ground and gating grids will be removable.

The preamplifiers are grouped in modules of 16 on motherboards plugged onto the back of the sector. The motherboards can be removed without disturbing the cooling circuit. The modules are arranged on the back so as to make room for handling equipment, as seen in Fig. 4.23 for an inner sector. Also mounted on the back are the condensor/resistor packages and a test-pulse system. The latter enables pulsing of the field wires or the sending of test pulses to the preamplifiers for calibration and monitoring purposes.

Some of the manufacturing tolerances are the following: pad cathode flatness ±50 μm, wire position ±20 μm, sense-wire diameter ±0.5%, pad position ±30 μm, sector position ±50 μm.

### 4.4.2 TPC end-plates

Each end-plate as shown in Fig. 4.24 supports the 18 sectors and the two field cages which enclose the TPC volume. It also carries the two luminosity monitors. The frame structure consists of hollow beams made of cast aluminium. This fairly complicated piece has more than 1200 holes which need to be drilled or machined or tapped.

### 4.4.3 Sector-handling tool

This tool enables the operator to remove a sector from the TPC without opening the end-plate. Each sector, which weighs about 40 kg, has to be orientated in such a way that it passes through its frame in the end-plate — a frame which is considerably smaller than the outer shape of the sector. The tool has been built (see Fig. 4.25). It weighs 25 kg. The five handwheels allow the sector to be tilted, turned, rotated, retracted, and aligned.

Three dummy sectors are being built to test these operations.

### 4.4.4 TPC installation rails

Two 6 m long rails will be used to move the TPC into its final position inside ALEPH. These rails are subsequently retracted from ALEPH to avoid a concentration of material in front of the e-γ calorimeter barrel.
One of these rails can be seen in Fig. 4.26. On top of the rail there is a crossbar which is connected to two wheel units, each one having three wheels. This serves to retract the rail out of the gap between the TPC and the e-γ calorimeter. It has several adjustment facilities to guide the rail in such a way that it does not scratch the detectors. The rails were tried out under load, and worked well.

4.4.5 Field cage

Tolerances

The distortions of particle tracks in the TPC caused by imperfections in the electric field have been considered analytically [28]. In particular, the effects of having a non-planar high-voltage electrode and a non-uniform potential gradient at the cylindrical walls of the chamber were treated. The result of this analysis is that in order to ensure that the lateral distortion does not exceed 100 μm, and with ωτ greater than 5 (i.e. under the operating conditions of the ALEPH TPC), the central electrode should not deviate from a plane by more than about 1 mm, and that the curve of potential versus distance along the field-defining electrodes should not depart from linearity by more than 0.6 mm. In addition, it
was found that the central electrode and the wire planes should be parallel to better than 0.5 mrad. On the other hand, it was shown that the curved surfaces of the chamber could depart from a cylindrical shape without affecting the performance, on condition that the field-defining electrodes remained parallel to each other and that the inter-electrode distance was unchanged.

**Design**

The field cages consist of the mechanical support (Fig. 4.27) structure plus the insulator and the field-defining electrodes. The support structure of the outer cylinder is made from an aluminium alloy 'honeycomb' material and the inner cylinder (because of the requirement of low mass) consists of a 2 mm thick carbon-fibre tube. Both the outer and inner support structures are separated from the active volume by a multilayer polyester (e.g. Mylar, Melinex, Hostaphan) insulator. Since this material has a breakdown strength of the order of 5 MV/cm, a thickness of 3 mm is considered adequate. Several layers are used to minimize the effects of possible local flaws. The field-defining electrodes are glued directly onto the insulator. These electrodes consist of copper strips, 8.66 mm wide with a pitch of 10.16 mm, mounted on either side of a 125 μm Kapton foil. The electrodes on opposite faces are offset by a half pitch; this configuration is found to be very effective in shielding the high transverse electric fields present in the insulator [29]. In addition, after etching the inter-electrode gap, a layer of epoxy adhesive is exposed which has a measured surface resistivity of some $10^{16}$ Ω per square. This layer has a thickness of approximately 10 μm so that its bulk conductivity is some 5000 times that of the Kapton substrate; consequently it provides additional shielding and allows any charge accumulating on it to be rapidly diffused.

The insulator has a certain finite resistivity, and the current drain through it affects the linearity of the potential drop along the field cage. Although this effect can be partially corrected by reducing the resistance of the elements of the resistor chain, heat dissipation in the resistor chain becomes a problem if these values are too low. The situation at the outer field cage may be particularly serious because of its large area. Figures of $10^{11}$ Ω·cm are quoted for the
resistivity of Mylar. However, because of the glue, a laminar structure will have a lower resistivity, and this might result in unacceptable distortion if reasonable values of resistor chain power dissipation (less than 10 W) are chosen [18]. For this reason it was decided to install a second field cage on the outer cylinder, consisting of the copper–Kapton foils described above on a 1 mm thick fibre-glass sheet held at some 15 mm from the insulator. Recent measurements within the group have indicated, however, that the insulator resistivity may be very much higher than quoted, and if these measurements are confirmed for a complete insulator the outer field cage need only consist of a single set of electrodes. The inner cylinder of the TPC carries the optical equipment for the laser calibration system, and this will be covered by a second electrode structure, similar to the one described above, placed some 20 mm from the insulator.

Each set of field-defining electrodes has an associated resistor chain. In the case of the inner field cage, these resistor chains are concealed in the gap between the two electrode structures. If a second electrode system is not needed for the outer field cage, the resistor chain will be surrounded by a continuation of the electrode structure. The high-voltage cable will be shielded in a similar manner.

For ease of assembly and handling, the central electrode is made of 12 sectors. The final design has yet to be established, but it is possible that, in order to comply with the requirements of planarity, the individual elements will have to be stretched flat.

Manufacture

Specifications and designs for the support structure and insulator for both the outer and inner field cages have been drawn up, and a call for tender has been sent out. Manufacturers have been contacted to find out the price and availability of the various parts of the apparatus, e.g. resistors, field-defining electrodes, HV cables, etc.

4.4.6 Gas system

The TPC is operated with a mixture of argon and methane. We do not yet know the exact mixing ratio, i.e. whether 9% methane, which is intrinsically safe against fire accidents, is enough to guarantee smooth operation of the chamber. We have also not fixed the value of the electric drift field, which is related to the precision with which the mixing ratio, pressure, and temperature have to be monitored to obtain a constant drift velocity. These decisions will be taken before the end of the year on the basis of measurements described under subsection 4.3.5. Meanwhile, we have defined a number of requirements and a tentative plan for the gas system.

Requirements

The gas system envisaged for the ALEPH TPC (Fig. 4.28) will regenerate about 90% of the gas flow. An Ar + 90% (or possibly 20%) CH₄ preparation will be mixed into large-volume buffer vessels in order to reduce the mixture variations and to provide for longer stable operation periods.
The required purity of the gas supply is 99.995% for Ar, with $O_2 < 5$ ppm, $H_2O < 10$ ppm, and 99.95% for $CH_4$ with $O_2 < 10$ ppm and $H_2O < 30$ ppm.

The flow rates will be 2–5 m³/h in the purification loop and 0.2–0.5 m³/h for the fresh (= vented) gas. The flush flow-rate will be $\leq 50$ m³/h. The gas volume required for the flush is about 400–500 m³ of Ar and 20–50 m³ of $CH_4$ ($\approx 5$ TPC volumes of pure Ar followed by $\approx 5$ TPC volumes of the mixture; for 20% $CH_4$ we will need, for safety reasons, $\approx 2$ TPC volume changes of pure Ar prior to any opening of the detector).

The TPC operational overpressure is $\leq 10$ mb, rising to 20–30 mb during flushing periods.

**Surface installation in the SG Building**

Common ALEPH bulk gas storage and distribution will provide Ar (liquid Ar dewar + back-up battery of bottles of compressed Ar) and $CH_4$ (compressed in batteries with automatic switching from empty to full) at a pressure of 6 bar. For the TPC we would like to have two additional batteries of premixed Ar/$CH_4$ with automatic switching from empty to full battery, as a reference and as a back-up.

Two buffer vessels, each 3.2 m in diameter and $\approx 11$ m high ($\approx 22$ t), will be situated in the vicinity of the SG Building. Inside the SG Building will be installed the mixing hardware, flow and pressure controls, purification loop (OXISORBs, molecular sieves, turbine/compressor, vacuum pump), monitoring chamber (drift velocity, attenuation,
mixture), gas analysis equipment (O$_3$ trace analyser; hygrometer; infrared (IR) mixture analyser), gas leak detectors, alarm hardware, electronics, data logging, etc.

For the TPC installation, a dedicated low-impedance exhaust line will be provided.

**Gas connections to the TPC**

The fixed gas installation between the surface (SG Building) and the experimental area will be made of stainless-steel tubes and will be vacuum tested (Viton seals, vacuum bellows, etc.). The TPC input connections will be of Ø 50 mm and the output connections of Ø 80 mm, equipped with corresponding valves. The fixed installation between the beam and the garage position will have similar sections. The maximum overpressure in the input line will be \( \approx 1.1 \text{ bar during flushing.} \)

Two parallel connections, of 18 cm$^2$ section each, are foreseen between the TPC and the 'local' gas racks. The gas will enter the TPC at the bottom in both halves of the detector and will exit at the top.

A recirculation pump will change the TPC gas volume once per hour; heat exchanger and temperature controls will allow the gas temperature to be stabilized.

**Time schedule**

The gas system should be ready by about spring of 1986 for the TPC tests in Building 156. The final version of the gas system will be adapted to the final requirements, taking into account experience gained during TPC tests in 1986 and 1987.

4.4.7 *Laser calibration of the TPC*

There will be one Nd-YAG laser per end-plate outside the magnet (see Fig. 1.1) to provide the light beams, which are split inside ALEPH. The mirrors for the deflections along the TPC support arm will no longer be adjustable, but will be larger (Ø 50 mm) and in fixed positions; all the automatic mirror adjustment will be done in one accessible box on top of the magnet. This box has been built and tested successfully (Fig. 4.29).

![Fig. 4.29](image)

One Nd-YAG laser and the light-pipes leading to the splitter ring have been assembled together with a position monitor. It has been demonstrated that the laser beam will reliably home onto the position monitor, thus compensating for any realistic deformation of the support structure.

The beam-splitter ring which produces the three axial rays is currently being assembled. The mechanical structure as well as the optical elements (Fig. 4.30) and their adjustment pieces have been made. The prisms inside the TPC are now replaced by mirrors mounted as indicated in Fig. 4.31. This makes better use of the space between the inner field cage and its potential grader, so that the laser beam adjustment is less critical. Measurements of the beam cross-section and divergence of the Nd-YAG laser have shown that with a system of two lenses near the laser, the beam
diameter can be 5 mm in the centre of the TPC, varying less than 0.5 mm over the sensitive volume — which is completely adequate for calibration.

We will assemble a transport system from the laser to the splitter ring in the autumn, and connect one distribution system for inside the TPC by the end of the year.

4.5 TPC electronics

The architecture of the electronics system for reading out the information from the TPC has evolved according to the structure given in the 1983 Technical Report. Many discussions have taken place in order to specify the various system elements in detail. This specification ensures that the critical \( r \phi \) coordinate measurement has a total electronic error contribution, from noise, pulse digitization, and non-linearity, not larger than 80 \( \mu \)m r.m.s. [30,31]. The performance of individual components, such as the FADC, has been successfully tested to meet the requirements of the TPC performance. The design of a prototype system has been started.

In the following, a review will be given of the status of development and design of the various parts.

4.5.1 Architecture of the readout system

Layout

The TPC subdetector readout system (Fig. 4.32) consists of 72 Time Projection Processors (TPP), each controlling a set of Time Projection Digitizers (TPD). The TPPs are connected by cable segments to a back-plane segment called the 'SD segment'.

The TPC Event Builder (TEB), connected to the SD segment, is the supervisor of the TPC subdetector system and, as such, is responsible for the final build up and formatting of the TPC data.
**Readout sequence**

The timing signal corresponding to the Bunch Crossing (BC) is distributed together with the sampling clock to the TPDs which, at each BC, automatically go into data-acquisition mode. The first-level trigger decision is also distributed directly to the TPDs. If the first-level trigger result is negative, the TPDs will stop data-taking and resume their previous function. In case of a positive result, the TPDs will continue to take data up to the end of the TPC drift time.

The second-level trigger decision is sent by the central trigger supervisor either as a FASTBUS broadcast command or via a cable to the TPPs. If the second-level trigger result is negative, the TPPs clear the event stored in the front-end buffer of the TPDs. A positive result of the second level involves the transfer of a number of parameters from the trigger supervisor to the TPPs, e.g. type of trigger, event number. The TPPs initiate the zero-skip algorithm in the TPDs and thereafter perform the readout, formatting, and storage of the valid data in their output buffer.

The TEB reads the data from the TPPs, makes the final formatting, and stores the TPC event block in one of its output buffers. The Main Event Builder (MEB) has access to the TEB and other similar units from the other subdetectors via the ‘DAQ segment’ and, when all are ready, reads the different subevent blocks and assembles the final event block.

**Derandomizing and buffers**

There are three levels of buffering and/or derandomizing in the TPC readout system.

i) Front-end buffers: Two complete events can be stored as raw data in the memories behind the FADCs.

ii) TPP buffer: A part of the TPP memory will be used to temporarily store the data read out from the TPDs.

iii) TEB buffer: The TEB has two output buffers, each capable of holding a complete TPC event.

**4.5.2 Preamplifier**

The integration time constant of the charge-sensitive input stage has been increased to 2 µs for better noise performance. The differentiation stage, called ‘preshaper’, has now been discarded from the preamplifier and is put behind the differential line receiver of the shaping amplifier. Electronics noise picked-up on the cable will thus be suppressed by roughly a factor of 20 in the frequency range below 0.5 MHz. The cable driver in the preamplifier has been designed to give a large range of linearity at the low power consumption of 100 mW.

The preamplifier has been produced as a thick-film hybrid with an effective noise corresponding to 600 electrons at the input. In parallel, we are building a monolithic version (integrated circuit) because it would be cheaper and could probably produce less heat. It is uncertain whether it will work at the unusually low noise level required. The decision between the two versions must be taken before spring 1985.
4.5.3 Shaping amplifier

The shaping amplifier has been designed as outlined in the 1983 Technical Report. The present design is based on the use of transistor arrays, but a version based on operational amplifiers is being studied. Prototypes of this amplifier exist as thick-film hybrid circuits. In Fig. 4.33 the larger unit is the shaper, to be mounted on the TPD card, and the smaller unit is the preamplifier, to be mounted on the TPC sector. Figure 4.34 shows the cards for 16 preamplifiers (some of which have their cooling box around them) to be stuck onto the sector.

The sector with the new geometry at present being mounted on TPC90 will be equipped with 440 channels of this kind.

![Fig. 4.33](image1)

![Fig. 4.34](image2)

4.5.4 Time Projection Digitizer (TPD)

The design of this unit is well under way in a configuration as indicated in the 1983 Technical Report, i.e. a three-units wide FASTBUS module containing 64 signal processing channels. A functional block diagram of the device is given in Fig. 4.35.
Two 7-bit FADCs (Fig. 4.36) are now foreseen for obtaining the required 7-bit resolution and 9-bit dynamic range. As these FADCs will be available at a low price, this solution is preferable over the single FADC 'with dynamic attenuator', as initially foreseen. The use of a single 8-bit FADC is also being kept under consideration.

In order to test the various key parameters, a number of prototypes have been constructed:
1) an 8-channel CAMAC module with a single 7-bit FADC per channel and minimal control logic;
2) a CAMAC module with 8 channels in the final configuration (2 FADCs) and the complete readout logic (0-skip, hit list, etc.);
3) a 64-channel FASTBUS module obeying the full specification.

Module 1 has been constructed to test the basic parameters of the shaping amplifier and the FADC, as well as the combination of these elements. Module 2 has allowed the full functionality of the signal processing and the readout logic to be tested, whereas module 3 is the first prototype of the final design. Upon conclusion of the test on this prototype, an in-house pilot series of modules (448 channels) is planned before sending out the calls for tender, in view of production of the complete system.

4.5.5 Clock Fan-out and Trigger Time Interpolator (CFTTI)

A CAMAC unit has been designed and constructed, which contains all the functional elements for testing the CAMAC TPD variants mentioned above. A 50 MHz clock is now used to give an 80 ns sampling period in the TPDs. In the final design the CFTTI module may be merged with the TPP into a FASTBUS module.

4.5.6 Time Projection Processor (TPP) [32]

The tasks of this unit are: readout, formatting and preliminary processing of data, calibration, monitoring, electronics test, etc. It is a FASTBUS module: master on the back-plane to control the TPD boards, and slave on a cable segment port, to be read by an Event Builder without interfering with the activity on the back-plane.
A study has been carried out to compute the amount of pad and wire data in each of the 36 TPC sectors: the GALEPH Monte Carlo and a detailed pulse simulation have been used. As a result, we are now considering associating a TPP with the wires and one with the pads of each sector, for a total of 72 TPPs.

The TPP is built around a processor of the 68K family: we are writing preliminary assembler code in order to understand how much time is spent on the various tasks the CPU is expected to perform; we will decide later on the eventual 'co-processors' to be added for specific mass operations. The amount of processing and its mode carried out in the TPP influence the design of the whole TPC readout, mainly where the buffering scheme is concerned: as an aid to this design we are simulating the whole readout chain, by computer, in order to spot deadlocks and queues.

4.5.7 Test Pulser System (TPS)

The TPS [33] provides for the calibration of the electronics. Figure 4.37a,b is an overview of the system. Specific operations are derived from FASTBUS commands that determine the pulse amplitude and others that determine which pulses are turned on in either the FASTBUS module or the test pulser circuitry on the sector. The FASTBUS modules (one per sector) control the circuitry on the sector, or independently provide 25 linear outputs which are used as inputs to the amplifiers in the digitizer modules (up to 25 modules per sector). The electronics on the sector provides for nine outputs. These outputs are assigned so that four are for pad amplifier inputs, four for wire preamplifier inputs, and one is used to pulse the field wires. The preamplifier inputs (the same pulse to every fourth preamplifier) is useful for calibration and cross-talk measurements. The one input to the field wires is used to measure the relative gain on neighbouring channels.

The sector circuitry is built and the FASTBUS module is being constructed. Both will be tested on the new end-plate of TPC90.

4.6 Time schedule

Since there will be very little time between the installation of the TPC in the underground area and the turning-on of the beams, we decided to run-in the TPC on the surface in 1987. To be able to do this, the sectors have to be put on the end-plates already in 1986. At least half of the electronics should be linked to the sectors by the same cables we will use later at the end of 1986 to start with tests of one end-plate.

The electronics, including cables, will be assembled in the barracks which we will eventually use in the underground area. Their modular structure will allow them to be transported, together with the electronics, to the underground area in the first half of 1988. As electronics will be lacking on the surface after that time, we will do mounting tests of all the equipment which will be attached to the TPC, e.g. the inner tracking chamber, the luminosity detectors, and (hopefully) the vacuum chamber. In this way we hope to reduce installation time in the underground area.
To be ready to mount the sectors on the end-plates in 1986, the work on the field cages and the end-plate structure has to be finalized early in 1986. Since we intend to use the laser calibration system to run-in the TPC, this implies that it will be ready during 1986, together with the gas system.

The details of the design and manufacturing schedule for the mechanics and the electronics as well as their installation in the test area can be found in Table 4.3.

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<tr>
<td>TPC: Installation</td>
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   W.P. Allis, Motion of electrons and ions, Handbuch der Physik, Vol. XXI, p. 381.


The π/e rejection was also studied at two energies: 5 GeV and 10 GeV. Here a very effective algorithm is obtained by summing the energy in the four towers with highest pulse height; this energy is then compared with the incident energy of the beam (as it would be measured in a group of 16 towers). In the ALEPH apparatus, this energy will be predicted by the momentum measurements in the Time Projection Chamber (TPC). This corresponds to requiring a localized energy deposition; 98% of the electrons are kept by a cut on the ratio of these two energies at 0.75, shown in Fig. 5.5a,b. It is a property of our high granularity that this test of localized energy deposition is easy to implement. Usually, in systems with large towers, a cut on the total energy for a shower is used, but as seen in Fig. 5.2b this is less effective. Further cuts were also studied in order to improve the over-all rejection:

- the comparison between the beam particle and shower positions, cutting at 3.5 σx and σy, where σ is the error on the shower position;
- a cut on a minimum energy deposition in the first stack layer (first 4X0).

As seen from Table 5.2, the effect of these additional selection criteria is a gain of a factor of 3 on the π/e rejection at 10 GeV. The single selection on localized energy deposition already achieves a rejection of 3.5 × 10^-3. It is possible to relax the first selection and still keep a good over-all rejection (Table 5.2).

### Table 5.2

Pion rejection at 10 GeV:

<table>
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<th>Number of candidates remaining from a sample of 5630 events</th>
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<tr>
<td>E_{4 \text{ towers}}/E_{\text{tot}}</td>
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<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>&gt; 0.75</td>
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<td>&gt; 0.65</td>
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The final rejection at 10 GeV (correcting for the presence of one e⁻ in the pion candidates owing to Cherenkov inefficiency) is thus 1.1 × 10^-3, the corresponding electron efficiency is 89%.

Similar cuts were studied at 5 GeV. Because of difficulties in obtaining a well-identified pion beam at such a low energy, our pion sample was only 861 events. After the initial cut, only 5 events survived; and after all cuts, none. This implies a rejection of better than 3 × 10^-3 at 90% confidence level.

Because of various technical difficulties, the uniformity of this prototype could only be tested at three points: 0, +4.5 cm, and -4.5 cm. The responses are identical within 1%.

By injection of a gaseous X-ray source, it was verified that all planes have identical gain within ±3%.

Tests with a second prototype calorimeter allowed us to check the uniformity of different towers (Figs. 5.6 and 5.7). The observed non-uniformity is 3%. We suspect this is linked to variations in printed-board thickness, and expect to improve on these numbers with better printed-board and PVC-pad design.

Results of the calorimeter tests with plates at 45° to the beam are currently being processed. Preliminary results indicate a resolution at 5 GeV and 10 GeV of 19%/√E. The position accuracy at 5 GeV is ±2.5 mm; at 50 GeV it is ±1.8 mm.

Tests with the end-cap prototype were begun in July and August 1984. Preliminary analysis of these test runs shows results which are quite compatible with the barrel prototypes, and more detailed analysis is continuing. Further tests will be made in 1985, in particular in conjunction with a hadron calorimeter module behind an e⁻-γ module.

Most important, the prototypes furnished technical information on calorimeter construction methods. After problems with broken wires, for example, it was decided to abandon the ultrasonic bonding of wires used in the first prototype, in favour of the more classical soldering used in another prototype.

The wire supports, and most importantly the PVC cathode planes developed and tested in one of the prototypes, will be used in the final design of the barrel modules. The final cabling technique is also inspired by the prototype construction.
5.4 Effect of mechanical tolerances on uniformity

We have evaluated the dependence of the signals on various mechanical parameters.

- **Wire radius** $r$: The dependence is $S = k \cdot r^4$. Over the length needed for one plane, we have verified that typical wire variations are about 0.1% in radius; variations from plane to plane are less important. Furthermore, showers are measured over about 100 wires and this reduces the fluctuations to a negligible level.

- **Wire position**: The effect of a lateral displacement has been measured (and calculated) to be negligible (less than 1% signal variation for $\pm 200 \, \mu m$ displacement). Using a dry stack made of 40 layers of lead, cathodes, and aluminium extrusions, we have measured the flatness to be typically $50 \, \mu m$ between wire supports (every 45 cm). The wire supports themselves are accurate to $30 \, \mu m$. Averaged over many layers, the non-uniformity from this source should be less than 1%

- **Extrusion size**: The signal is fairly insensitive to the lateral size of the cell (less than 1%/100 $\mu m$, whilst the extrusion precision is $\pm 30 \, \mu m$). The variation with the cell height is 10%/100 $\mu m$ (calculated and measured). Measurements have shown us that a pressure of 100 g/cm$^2$ on the dry stack ensures uniform contact between the cathode and the extrusions. The gap height is therefore defined by the tolerance of the extruded aluminium profile. Typical variations were measured with a 'gap-gauge' inserted inside the dry stack; they were found to be $\pm 30 \, \mu m$. Shower simulation shows that by averaging over the different cells and layers, we should obtain a point-to-point shower response uniformity of $\pm 0.8\%$ over a module. With our dry stack we have also measured the compressibility of the module and its long-term creep. We have thus checked that the mechanical solution adopted (preformed front-plate and spring-loaded tie rods) ensures that the pressure on all layers will always exceed 100 g/cm$^2$, as required.

5.5 Mechanical design of the barrel

Since the publication of the ALEPH Technical Report (CERN/LEPC/83–2) in May 1983, the basic structure has not changed. Nonetheless, considerable effort has been devoted to design details. We have now arrived at a final mechanical design which is described below. All components have been costed after consultation with industry, and all the bids for the main items have been sent out. The construction work has been evaluated in detail and shared among the various institutes. The fabrication plan is given in subsection 5.8.

5.5.1 Stack parameters

As specified in the 1983 ALEPH report, the barrel part of the e–$\gamma$ calorimeter is composed of 12 modules; each module is 4.812 m long and covers an azimuthal angle of 30° (Fig. 5.1). The modules are made of alternate layers of lead and proportional wire tube.

The details of the stack are shown in Figs. 5.8 and 5.9. It should be noted that the stack is read out in three parts:

- 10 layers with a 2 mm lead sampling;
- 23 layers with a 2 mm lead sampling;
- 12 layers with a 4 mm lead sampling.
As can be seen from Fig. 5.9, the dead region between two adjacent modules is $2 \times 12$ mm for the first two stacks and $2 \times 18.5$ mm at the rear. The total inactive region on each side is further increased by about 1.5 mm, on the average, to reach the sensitive gas region. The total 'hole' is thus about 3% of the solid angle. The energy lost in this 'hole' is signalled (and eventually measured with reduced accuracy) by the hadron calorimeter behind it. To this purpose the e-γ calorimeter modules are rotated by 1.87° with respect to the hadron calorimeter modules.

A blow-up of a typical stack section is shown in Fig. 5.8 (insert) and is also sketched in Fig. 5.10.

5.5.2 The stack construction, the new cathode design, and cabling

Compared with the May 1983 design, the major change has been the replacement of the industrial printed-board circuits used for cathode readout with PVC-sheet and copper cathodes (Fig. 5.10). The development of this new type of readout pads, including the problem of fabrication, has been the concern of one of our collaborating institutes (École Polytechnique).

The copper pads, instead of being etched, are cut from a uniform 35 µm copper sheet. The readout lines are made of tin-plated copper wire, and are electrically welded to the Cu pad through holes in the 1 mm PVC insulator. The advantages of this method are the reduced cost and greater uniformity in thickness since the PVC is obtained directly in 1 m × 5 m sheets (tolerance: 50 µm) by extrusion. Furthermore, the readout lines protrude from the edge of the stack and thus simplify the interconnection between the various layers. This is done by pretinned printed circuits; an example of such cabling is shown in Fig. 5.11. It is possible to connect the $2.5 \times 10^6$ pads with a measured time of < 10 seconds per pad (at present, 8 seconds per pad as measured for 4000 solder points). These new PVC-sheet cathode pads have been used satisfactorily in the construction of one of our prototypes. The signals from the towers (printed circuits) are then brought out by flat cables which run up the side of the modules, through gas seals, and then along the back of the module up to the amplifiers.

The end of an extrusion plane is shown in Figs. 5.12 and 5.13. It can be seen that the position of the wire near the end is determined by a wire support press-fitted into the extrusion (it is planned to have such supports every 45 cm along the wires).
The wires are soldered onto a printed-circuit board; each wire is connected in series with a commercial 125 mA fuse. It has been shown (with about 100 fuses) that a broken wire can be cleanly disconnected by blowing out the corresponding fuse with a large current. The open fuse can then stand $\geq 2000$ V, well above our operating voltage at 1450 V.

5.5.3 Structural design, weight support, and gas-tightness

One of the main tasks during the past year has been to obtain a complete mechanical design which — among other things — will allow the barrel elements to be mounted in any of the 12 different positions. The problem is a serious one, considering that the stack consists of a large number of separate layers (including lead sheets).

The final solution is the following:

The 5 cm aluminium extrusions are glued side by side, using a transfer adhesive, on a thin aluminium sheet 0.5 mm thick, 4.615 m long, and about 1 m wide. The thin plates are spot-welded at both ends to a thicker 2 mm plate which has protruding ‘keys’, as shown in Fig. 5.13. These ‘keys’ are inserted in the 22 mm thick aluminium end-plates (Fig. 5.14). The PVC sheets which are used in the cathode layers have a similar key at the ends. By this means the shear forces within the stack are transferred to the aluminium end-plates.

![Fig. 5.14](image)

The mechanical box which supports the structure is composed of a moulded aluminium base-plate, two 22 mm thick end-plates, and a preformed 16 mm front-plate.

The shape of the preformed front-plate corresponds to the curvature of a flat plate, under a uniform load of 400 g/cm², held along the two long (4812 m) edges. After assembling the various layers, the preformed plate is pulled against the stack and is held under tension by tie rods fixed with spring washers. These springs ensure that if the total thickness of the stack decreases owing to mechanical creep (1 mm for example), the front-plate will remain flat and transmit the uniform pressure of 400 g/cm². The springs have been chosen such that a 1 mm stack reduction decreases the uniform pressure by 10%.

Depending on the mounting position, the pressure inside the stack varies owing to the weight of the components; however, in all cases it is more than 100 g/cm². Each lead sheet is pressed between a PVC layer and an aluminium sheet, where the friction force is always eight times greater than the weight of the lead. In this way its weight is transmitted either to the base-plate or, through the key on the aluminium and PVC sheets, to the end-plates.

Mechanical tests of the various parameters and elements involved in this design have been performed so as to ensure its validity (friction coefficients, shape and elastic limit of the aluminium front-plate, stresses on the washers and on the stainless-steel straps pulling on the front-plate, etc.).

The gas-tightness is achieved by means of a welded aluminium cover, 3 mm thick, which has no mechanical function. An O-ring seal is used at the joint between this cover and the base-plate. Furthermore, the cover is bolted to the front-plate. To ensure that the variation of the outside atmospheric pressure will have little effect on the module gas volume (a few %), the modules will be pumped down and then filled with the gas mixture at a fixed absolute pressure (about 1050 mbar).

The gas will be slowly circulated inside each module by a closed-loop system, and the gas gain for each will be monitored using small test chambers. Our present tests indicate that the same gas fillings can be used with only minor gain variation over a few weeks. Periodically the gas mixture will be pumped out, purified, and reinjected.

5.6 Mechanical design of end-caps

The end-caps and the barrel of the electromagnetic calorimeter are designed to achieve a uniform detector covering almost the complete solid angle. Accordingly, the design of the end-caps follows very closely that of the barrel. Any differences between them result from the different module geometry or mechanical loading. The internal structure is virtually identical.
Each end-cap calorimeter is divided into 12 'petals', so that the segmentation matches that of the barrel modules. The pad tower structure is uniform and continuous with the barrel, giving projective geometry over the full angular range. The pad segmentation in $\theta$ is kept uniform, whilst that in $\phi$ changes with $\theta$ (see Fig. 5.15) to keep the area of a tower approximately constant and matched to the shower size. The inner 8 rows have 8 pads, the next 16 rows have 16 pads, the next 16 rows have 24 pads, and the outer 10 rows have 32 pads.

The internal structure is essentially the same as for the barrel. The 45 layers are subdivided in depth into groups of 10, 23, and 12, with the rear 12 layers containing 4 mm thick lead sheets, as for the barrel. Figure 5.15 shows the neighbouring petals, one revealing the pad structure, the other a wire plane. The cathode pads will be made on conventional (but fairly large) printed-circuit boards (PCBs). Five such boards are needed to cover the area of one layer of a petal. The specific $\theta,\phi$ geometry of the end-cap pads makes the technique used on the barrel modules unsuitable here. The artwork masters for the PCBs are being generated directly by computer using a large photo-plotter, thus bypassing expensive art-quality drawings. Boards of the correct size have been successfully made for us by commercial firms, and the call for tender for the production of all pad PCBs will be sent out in October.

Figure 5.16 shows an isometric view of the pad towers, indicating the projective geometry design.
The wire plane shown in Fig. 5.15 gives the layout of the extrusions on the petal. The extrusion, wire, graphited milar, and adhesives to be used will be identical to those for the barrel. Figure 5.17 shows a photograph of the wire support. This support is press-fitted into a groove cut in the extrusion and holds the wire at an accurate depth below the top of the extrusion. Other supports hold the wires in position at 40 cm intervals.

The box enclosure is designed with the requirements that it must support and constrain the internal components (lead, aluminium, PCB, etc.) so that over a period of many years there shall be no excessive movement or slipping which could result in deterioration of performance. It was concluded that the original scheme, i.e. holding the layers by pressure and friction alone, was inadequate for the end-cap modules, where all layers are held vertically. The lead and aluminium sheets are now supported directly on the box. The final design is a 6 mm thick aluminium alloy box which is strong enough to take the internal loads and to withstand evacuation of the vessel. Individual layers will be assembled against thin shims which rest in the corners of the box. Tests have been made on the lead to be used (4% antimony content), to check for adequate safety margin against creep and buckling of the lead.

A pressure of approximately 0.3 bar is applied by means of a bag between the 15 mm aluminium cover plate and the stack. The bag is filled with uncured epoxy resin to the desired pressure; the resin is then allowed to cure. The cover plate acts as a spring which accommodates the eventual small creep of the stack. The gas seals are somewhat awkward. They have been achieved in the manner shown in Fig. 5.18 which, together with Fig. 5.19, shows also other constructional details.
5.7 Planning for barrel production

5.7.1 Construction

It is foreseen that the production of the 12 barrel modules will be carried out in three distinct phases: 1) set-up of the production chain elements and the construction of module 1; 2) series construction of modules 2 to 12; and 3) testing and installation on the ALEPH site. The mechanical construction responsibilities are divided between the laboratories of IN2P3 (Clermont-Ferrand, École Polytechnique Palaiseau, and Orsay–LAL) and the Saclay Laboratory. Work on the basic calorimeter stack subelements and the associated machine tooling is shared as follows: Clermont-Ferrand: HV + fuse boards; École Polytechnique: PVC-pad readout layers; Orsay: aluminium extrusion planes and lead sheets; Saclay: wire plane fabrication. The preparation of the box-mechanics, the stack assembly, the cabling, and testing is divided between Orsay and Saclay in different ways in phases 1 and 2 for reasons of manpower. Marseilles is responsible for the gas system and its monitoring.

**PHASE 1: Assembly chain set-up and construction of module 1**

The task division for phase 1 is shown in Fig. 5.20, and the corresponding planning timetable is presented in Fig. 5.21. The tooling is in preparation and should be complete before the end of autumn 1984.

The assembly of the first module will be done at Saclay and is scheduled to begin on 1 March 1985. The stack assembly is expected to be finished, with the module under pressure, by 15 April 1985. Cabling of the first module is estimated to take two months, thus we can finish the assembly by 15 July 1985. The module should then be ready for cosmic-ray tests in September 1985.

![Diagram](image-url)
PHASE 2: Series production of modules 2 to 12

The task division for phase 2 is shown in Fig. 5.22, and the corresponding planning timetable is presented in Fig. 5.23. In phase 2 the calorimeter stack assembly will be transferred from Saclay to Orsay and the final cabling shared between the two laboratories: Orsay — eight modules; Saclay — three modules (plus module 1). A critical aspect of the planning is that the basic subelement construction (e.g. aluminium extrusion planes and wire planes) will continue during the assembly period of phase 1 in 1985. This will ensure that there will be no delays for these elements during the series assembly period of phase 2, which begins on 1 November 1985. We assume that there will be little or no modifications between module 1 and the series.

The requirement that the calorimeter stack be compressed in a press to a uniform pressure of 400 mbar will be satisfied upon completion of stack assembly. This is a potential source of interference in the series production. In order to assemble our modules most efficiently, we have planned to free the press after a pre-ageing period of compression at 1.0 bar for two weeks, and perform the cabling of the module at another position in the assembly chain. Thus the press will be available for the subsequent module stack, and a separate labour unit will cable the previous module.

The total construction period for the 11 modules of phase 2 is expected to be 20½ months. The final module should be ready for testing by 1 August 1987, and all 12 modules of the barrel calorimeter delivered to the CERN site by 1 October 1987.
5.7.2 Cost and labour evaluation

We have updated our costing of the barrel calorimeter with the completion of the final design. The May 1984 evaluation is summarized in Table 5.3. The increased cost of some items, imposed by the mechanical constraints on the stack, has been largely compensated by our decision (Section 5.3) to use PVC-pad readout layers manufactured by the École Polytechnique, instead of commercially available printed-circuit boards. The total cost of the barrel calorimeter (without electronics) is now estimated to be kFF 12 247.

Table 5.3
Barrel cost (in French francs)

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (kFF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium extrusion planes</td>
<td>609</td>
</tr>
<tr>
<td>Lead</td>
<td>612</td>
</tr>
<tr>
<td>Rear plates (aluminium)</td>
<td>1546</td>
</tr>
<tr>
<td>Preformed front plates (aluminium)</td>
<td>207</td>
</tr>
<tr>
<td>End-plates</td>
<td>38</td>
</tr>
<tr>
<td>Tension straps and spring washers</td>
<td>97</td>
</tr>
<tr>
<td>Covers (aluminium skin)</td>
<td>114</td>
</tr>
<tr>
<td>PVC-pad readout layers</td>
<td>1034</td>
</tr>
<tr>
<td>(including graphited and aluminized Mylar)</td>
<td></td>
</tr>
<tr>
<td>HV + fuse boards</td>
<td>362</td>
</tr>
<tr>
<td>Wire planes</td>
<td>383</td>
</tr>
<tr>
<td>Cable feedthroughs</td>
<td>34</td>
</tr>
<tr>
<td>Internal cabling</td>
<td>438</td>
</tr>
<tr>
<td>Electronics boxes (mechanics)</td>
<td>200</td>
</tr>
<tr>
<td>Rails, rollers and supports</td>
<td>499</td>
</tr>
<tr>
<td>Miscellaneous (seals, fittings, etc.)</td>
<td>1010</td>
</tr>
<tr>
<td>Assembly tooling</td>
<td>3800</td>
</tr>
<tr>
<td>Transport</td>
<td>250</td>
</tr>
<tr>
<td>Labour (outside)</td>
<td>1014</td>
</tr>
<tr>
<td><strong>BARREL TOTAL</strong></td>
<td><strong>12247 kFF</strong></td>
</tr>
</tbody>
</table>

Installation frame                                      350 kFF
Gas system (mechanics and purification)                (350 kSF, CERN)
Gas system                                             548 kFF
Gas filling (xenon)                                    560 kFF
Our spending profile, including electronics, is shown in Fig. 5.24. The purchase of the electronics has been deferred until late in the construction in order to balance the heavy initial mechanics investments needed to prepare the assembly chain.

The total estimated manpower requirements are 49,490 man-hours for the barrel construction. The labour profile is shown in Fig. 5.25. This labour effort is shared between the various laboratories, as illustrated in the section on construction planning (see Figs. 5.22 and 5.23), and corresponds to the work force available for ALEPH.
5.8 Planning for end-cap construction

Because of the tight construction schedule, two assembly lines will be set up, one at RAL and one at Glasgow University. The two groups will collaborate closely at all stages of the project. Design and construction of the tooling has begun. The construction of the first module will begin at RAL in May 1985, to be ready for an extensive programme of laboratory tests in the autumn. Because of the (anticipated) SPS schedule, tests in an electron beam at CERN will not be possible before 1986. The second assembly line will begin in November 1985 in Glasgow. In each case, as shown in the schedule in Fig. 5.26, a longer period of time has been allowed for constructing the first module on each line. The production rate then speeds up as experience is gained. The modules for the first end-cap are scheduled to be completed in February 1987, with the final module of the second end-cap finished in March 1988.

5.9 Calibration procedure

The final calibration procedure will be established after the testing of module 1 in the beam tests of 1986. Our present thinking involves two distinct calibration steps.

5.9.1 The electronics constant

Using samples of hybrid multiplexed front-end electronics, we have checked that the 32 channels of a multiplexer have identical calibration within 1%. Each group of 32 channels will then be calibrated with test pulses and accurate capacitors. The calibration constant thus obtained will be used directly in the data-acquisition modules to correct the data for gain variation.

5.9.2 Constant linked to the structure

a) Module defects

We plan to pulse the wires, thus injecting a known charge on the cathodes. Checks made in our test prototypes show that it is then easy to locate disconnected pads or broken wires. These effects can be corrected for, off-line.

b) Mapping of the module

As explained above, we aim to build modules which will be uniform to 1%. We intend to test all modules with cosmic rays. The cosmic-ray position and angle will be measured by drift chambers, and we will select cosmic rays which have a direction along the tower axis (within ±0.1 rad). In a week of data-taking we will thus acquire about $10^6$ cosmic-ray events, which is sufficient for calibrating to ±0.5% about 100 different regions in a barrel module (i.e. groups of 32 towers). The situation is similar for the end-caps. This calibration procedure will be checked by extensive

<table>
<thead>
<tr>
<th>ALEPH end caps</th>
<th>1984</th>
<th>1985</th>
<th>1986</th>
<th>1987</th>
</tr>
</thead>
<tbody>
<tr>
<td>a/F calorimeter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MJHAMJASOND</td>
<td>JFMAMJASOND</td>
<td>JFMAMJASOND</td>
<td>JFMAMJASOND</td>
</tr>
<tr>
<td>Layouts &amp; Geometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fetal Box spec.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Box Design</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Artworks Design</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PCB's</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supports</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tooling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Materials</td>
<td>5</td>
<td>15</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Component Manuf. &amp; Sub Assemblies</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Wire &amp; Solder etc.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 5.26
beam tests on at least one module. We expect the cosmic-ray test to be sufficient since non-linearity effects as function of energy are small (4% at 40 GeV) and are expected to be constant for all modules.

We are continuing to study the possibility of periodically injecting a radioactive gas (tests have begun with \(^{71}\text{Ge}^{14}\text{C}\)). The X-ray line is used as a reference to monitor the map obtained by cosmics.

The over-all calibration of each module will be obtained periodically by Bhabha events.

5.10 Electronics

The basic design remains as in the 1983 Technical Report, with a total of some 220000 channels to be digitized. Conceptually there are three parts to the system (see Fig. 5.27):

i) the integrator/multiplexer circuits which are mounted on the calorimeter modules (responsibility shared between Rutherford and Orsay);

ii) the analog-to-digital conversion units (Saclay);

iii) the readout into the ALEPH data-acquisition system (École Polytechnique).

5.10.1 The integrator/multiplexer

In this the charge on 32 channels is stored and multiplexed to one channel for readout.

A hybrid version with eight channels per circuit has been developed and tested. It performs as well as — or better than — discrete versions of the same circuit, and fully meets our requirements. Figure 5.28 shows the circuit design and Fig. 5.29 an actual hybrid. The essential parameters are:

- No. of channels: 8
- Size: 56 mm × 20 mm
- Power consumption: 200 mW from ± 7 V
- Average channel pedestal: 20 pC
- Noise charge at readout: \( \sim 50 \text{fC} \)
- Equivalent energy noise: \( \sim 10 \text{MeV} \)

A hybrid circuit containing the summing amplifier, d.c. restoration circuit, and cable drivers is currently being designed and will be available by the end of 1984. Discrete versions of this circuit have been tested, in conjunction with the hybrid multiplexers, on prototype calorimeters in the West Area test beam. The results quoted for these calorimeters were obtained with this electronics.

In parallel, a 16-channel monolithic (special integrated circuit) device is being designed at Rutherford. The design is now complete; prototype amplifiers should be available for testing in September 1984 and the first 16-channel chip should be ready by January 1985. The current programme calls for production of these circuits in late 1986. The already proven hybrid design is the fall-back option, should the monolithic programme run into problems, but the monolithic design is preferred because it should be cheaper, more reliable, and offer improved performance.
5.10.2 The ADC units

Three ADC prototypes have been built and tested: all are based on an 8-way voltage multiplexer followed by a 12-bit successive approximation ADC, with a digitizing time of \( \sim 6 \mu s \). The original version was built in CAMAC for simplicity, and was followed by a FASTBUS version with a reduced number of channels. The third version is used as the development prototype, leading to the final model which will be in FASTBUS with full zero-suppression, etc. This will be ready for tests in September 1985.

5.13 Read-out controller etc.

Each FASTBUS crate of ADC modules has a Read-Out Controller. This will be a FASTBUS module with a fast processor, memory, and control logic. This module is currently in the conceptual design stage: the first prototype will be built and tested by October 1985.

Other FASTBUS modules will be required: these will be developed in conjunction with the on-line group responsible for the ALEPH data-acquisition system.

5.10.4 Cost of electronics

The costings given in the 1983 ALEPH Technical Report remain essentially unchanged. The hybrid-circuit price will be 21.5 FF per channel, compared to the original estimate of 25 FF. The integrated circuit design offers significant saving potential, with a projected price of around 10 FF per channel and a consequent overall reduction of 3.3 MFF (about 1 MSF).

For the rest of the front-end electronics, major component costs have been established, but until details of the circuit boards and connectors are finalized a revised costing cannot be given. There is, however, no reason to expect the cost to exceed the 15 FF per channel in the 1983 Technical Report. The same is true of the ADC/FASTBUS system.
6. THE HADRON CALORIMETER AND THE MUON DETECTOR

6.1 Introduction

The large iron structure, which constitutes the main support of ALEPH and the return yoke for the magnetic field, is fully instrumented in order to measure the flux of hadronic energy and to identify muons.

The iron barrel around the superconducting coil and the two end-caps are subdivided into 23 layers. The outer one is 10 cm thick, all others are 5 cm thick, for a total of 120 cm of iron. The active part of the detector consists of planes of streamer tubes interleaved between subsequent slabs. The basic element is a plastic tube with an outer cross-section of $1 \times 1$ cm$^2$ and an active cross-section of $0.9 \times 0.9$ cm$^2$. A 100 µm wire runs at 4 mm from the lower wall and is held in place every 50 cm by a plastic support. The gas mixture used is one part argon, two parts CO$_2$, and one part n-pentane. The inner walls of the tube have a graphite coating, characterized by a resistivity ranging from 0.1 MΩ to 1 MΩ per square.

Each tube layer is equipped with pad readouts on one side for integrated energy flux measurement, and with strips, parallel to each tube, on the other side, for digital reconstruction of the pattern of individual events. This digital information, which is also read on two double layers positioned outside the magnet, is the basic tool for muon identification. The pads are arranged into projective towers pointing to the interaction vertex (Figs. 6.1 and 6.2).

External to the magnet — both in the barrel and in the end-caps — two double layers of streamer tubes are installed to identify muon tracks crossing the full iron and to measure their angle. See Figs. 1.1 and 1.2 for an overview.
6.2 Prototype and tests

The performance of the calorimeter is being studied in the test beam by means of a prototype detector which reproduces all technical details of the final apparatus. It consists of 23 layers of tubes with an active area of $1 \times 1 \text{ m}^2$, interleaved with iron plates 5 cm thick. The plate in front of the calorimeter is only 5 mm thick, whilst the last one is 10 cm, as in the ALEPH design.

Pad readout is arranged in nine projective towers, as shown in Fig. 6.3a, having the dimensions of the final detector. The analog signals are analysed alternately with standard electronics and with the prototypes of the final circuit described in subsection 6.4. The digital information of the strips is treated with the standard LeCroy electronics developed for the Mont Blanc experiment, whilst waiting for the prototype of the new electronics.

Behind the calorimeter, two sets of tubes are used to identify muons and to reproduce the final structure of the muon chambers. The first block consists of one plane of tubes with x and y strips; the second consists of two staggered layers of tubes, both equipped with x and y readout. Unlike in the final design, the second set of tubes is positioned behind 1.6 m of iron to strengthen the muon identification (Fig. 6.3b).

The test module, with pions and muons of energies ranging between 5 and 30 GeV, has so far been used to study the dependence of the pulse height and of the resolution on the following effects:

i) the uniformity of the response versus the impact point;

ii) the dependence of the response on the angle between the particle and the tower axis, as sketched in Fig. 6.4a;

iii) the dependence of the response on the projective angle of the tower (see Fig. 6.4b);

iv) the noise level produced by individual towers and by sets of towers mixed together for the general level-1 trigger of the experiment;

v) the performance of the calorimeter with the final gas mixture ($\text{CO}_2 + \text{argon} + \text{n-pentane}$) compared with the more usual argon + isobutane mixture.

![a) Calorimeter structure](image1)

![b) Test beam assembly](image2)

Fig. 6.3

Fig. 6.4

Since most of the tests were done in the last beam period in August, the analysis is still in progress. Results on the accuracy of the coordinate measurement by pulse-height interpolation are forthcoming, together with those on the combined measurement of the electromagnetic and the hadronic shower detector and other results.

For reference we note that in standard conditions, i.e. with pions hitting the centre of the central tower orthogonally, the collected charge is linear at least up to 50 GeV/c, and the resolution is well reproduced by the parametrization $\sigma/E = 80\%/\sqrt{E}$. Muons crossing a tower produce an analog signal equivalent to pions of 3.0 GeV with $\sigma/E = 25\%$, whilst the average number of digital signals is 32, corresponding to an average multiplicity of 1.55 hit strips per plane. Electrons can be identified by their sharp clustering of hits in the first planes, and their energy is measured with a resolution $\sigma/E = 50\%/\sqrt{E}$.

The results obtained in these tests are now summarized below.
Impact point dependence

The central tower has been scanned by moving the calorimeter across the beam. The sum of the signals of the nine towers and the energy resolution have not shown any dependence on the x coordinate of the impact point, within the statistical accuracy of the data. This is shown in Fig. 6.5a and 6.5b.

![Impact point dependence](image)

**Fig. 6.5**

Angular dependence

The calorimeter has been tilted by 5° and 10° with respect to the beam. No variation of the over-all pulse height or of the resolution has been noticed at 10 and 20 GeV, within the 3% sensitivity of the measurement.

Dependence on the tower projective angle

In the usual cylindrical geometry of LEP experiments, projective towers at polar angles different from 90° present larger iron thicknesses to the crossing particles, therefore worsening the shower sampling. In addition, the average number of streamers produced in the tubes depends on the crossing angle, more streamers being produced at angles different from 90°.

We have studied these effects, rearranging the prototype calorimeter to simulate a group of towers positioned at θ = 60° as sketched in Fig. 6.4b. Muons, which are not affected by the variation of the sampling, show larger signals, equivalent to 4.4 GeV, and the hit multiplicity per plane increases from 1.55 to 2.0. For hadrons, the over-all pulse height of the towers remains constant, as illustrated in Fig. 6.4a where data at 90° and at 60° are superimposed, showing a compensation of the multiplicity and sampling effects, both depending on θ but in opposite ways. Also the resolution remains the same, as is clearly visible in Fig. 6.4b where the two sets of data are compared. More detailed studies of this compensation will be made in the future, when more test-beam time will be available.

![Dependence on the tower projective angle](image)

**Fig. 6.6**

Noise level for triggering

In the level-1 trigger, the towers will be mixed together to build up 72 supermodules. To be fully efficient, each of these elements must be sensitive to pulse heights as small as 1/3 of a muon signal. We have studied the efficiency of this cut by varying the threshold of the discriminator acting on the sum of the nine towers. Figure 6.7 shows that at 200 mV, 1/3 of a minimum-ionizing particle signal, the efficiency ε of the towers is 97%.
The beam crossing signal has then been simulated by an oscillator, in the absence of beam, and the calorimeter has been read out in correspondence with these triggers. After subtraction of cosmic rays, the counting rate has been obtained for a single tower, for four towers mixed together, and for the full nonet, as shown in Fig. 6.8. The rate increases almost linearly with the number of towers, showing that the background is not uncorrelated among the tubes. Indeed, a scanning of the events shows that the main source of random triggers is due to a full octet of successive tubes fired simultaneously. Using the value of $1.1 \times 10^{-6}$ counts per trigger and per tower measured at the threshold of 200 mV, and multiplying for the beam crossing frequency and for the number of towers in the calorimeter (4776), we expect a trigger rate of 250 Hz, even requesting a single muon in the detector. This figure is compatible with the foreseen rate of the level-1 trigger.

New gas mixture
For safety reasons, the usual gas mixture of argon + isobutane cannot be used in underground experiments. Our substitute is a mixture of 14% argon, 56% CO$_2$, and 30% n-pentane. As most of the previous tests had been performed with argon + isobutane, the behaviour of the calorimeter was thoroughly tested with the new gas composition. The test was completely satisfactory. The working point of the tubes has been reduced from 4500 V to 4400 V, which means improved safety conditions. The linearity is excellent up to 30 GeV, and the resolution turns out to be $0.85/\sqrt{E}$ to be compared with $0.85/\sqrt{E}$ obtained with argon + isobutane in the same period (Fig. 6.9).
6.3 Upgraded design of the hadron calorimeter

The design of the tower structure has been modified with respect to the 1983 Technical Report. The towers now number 4776, with an average cross-section of $23 \times 23$ cm$^2$. In this way, 30% of the hadronic energy leaks, on the average, into the surrounding towers, allowing good identification of the impact point of isolated hadrons. The azimuthal subdivision is $\Delta \phi = 3.75^\circ$, whilst the polar angle has a new subdivision — this preserves the transverse dimensions of the towers as seen from the interaction point, and matches the e.m. calorimeter structure.

A detailed description of the number of tubes, towers, and strips in the hadron calorimeter and in the muon chambers is given in Tables 6.1a–e. Figures 6.1 and 6.2 show the design of the towers in azimuthal and in polar angle.

The final design of the magnet allows us to know the dead regions of the detector in detail. In the barrel, 8% of the average surface is lost because of bars connecting successive iron layers and the notches for cables and pipes: moreover, at the ends of the tubes, 2.5% of the surface is insensitive (6 cm on each side). In the end-caps, spacers holding together the iron sheets of the sextants cause a loss of coverage of 6%, to which the insensitive ends of the tubes (3 cm) add another 1.5%. Figure 6.10 explains the location of the dead regions.

<table>
<thead>
<tr>
<th>Table 6.1a Hadron calorimeter: barrel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules (sectors)</td>
</tr>
<tr>
<td>Layers per module</td>
</tr>
<tr>
<td>Tubes (or strips) per layer (variable)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Tubes (or strips) per module</td>
</tr>
<tr>
<td>Total number of tubes (or strips)</td>
</tr>
<tr>
<td>Towers per module a,b)</td>
</tr>
<tr>
<td>Towers per module fully contained</td>
</tr>
<tr>
<td>Total number of towers b)</td>
</tr>
<tr>
<td>Total number of towers fully contained a,b)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 6.1b Hadron calorimeter: end-caps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules (sextants)</td>
</tr>
<tr>
<td>Layers per module</td>
</tr>
<tr>
<td>inner pole tip</td>
</tr>
<tr>
<td>outer pole</td>
</tr>
<tr>
<td>Tubes (or strips) per layer</td>
</tr>
<tr>
<td>inner pole tip</td>
</tr>
<tr>
<td>outer pole</td>
</tr>
<tr>
<td>Tubes (or strips) per module</td>
</tr>
<tr>
<td>Total number of tubes (or strips)</td>
</tr>
<tr>
<td>Towers per module a,c)</td>
</tr>
<tr>
<td>Towers per module fully contained in the end-cap</td>
</tr>
<tr>
<td>Total number of towers b)</td>
</tr>
<tr>
<td>Total number of towers fully contained</td>
</tr>
</tbody>
</table>

a) The towers are longitudinally divided into two parts.
b) In the angular region from 41° to 50° the end-cap overlaps the barrel. In this region the towers are split into two parts: the beginning of a tower is in the barrel, the end in the end-cap. The two parts will be read out independently.
c) Some pads in the end-caps are split into two parts by the iron spacers. The signals from the two parts will be summed at the input of the electronics.
Table 6.1c  
Muon chambers: barrel

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Table 6.1d  
Muon chambers: end-caps

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<td>lower quadrants</td>
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Table 6.1e  
Muon chambers: middle angle

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<td>2nd layer</td>
<td>7424</td>
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6.4 The muon detector

The two double layers are separated by 50 cm, and the readout strips are each arranged in two orthogonal projections, with an effective pitch of 5 mm.

The muon layers around the barrel are structured in 12 parts, corresponding to the dodecagonal shape of the magnet. Three modules of the second layer are positioned at a longer distance from the magnet to leave space for all the cables going from inside ALEPH to the electronics barracks. Figure 6.11 shows the layout of one of these special regions together with the detail of the support structure. Two out of twelve barrel modules are specially segmented to allow the passage of the magnet legs, causing a 3.5% dead space in the coverage of both muon layers. In addition, the bottom module of the second layer has a reduced length to avoid interference with chariots and rails.

In the end-caps the muon chambers are structured in quadrants, instead of in sextants as in the hadron calorimeter.

In this way the number of tubes is reduced, together with the dead zones at the tube ends. Moreover, whilst the two upper quadrants are shaped as 90° circular sectors, the lower two have a rectangular shape, running down to the floor. This allows us to reduce the dead space caused in the coverage by the end-cap legs in the so-called 'middle-angle muon detector', around $\theta = 45^\circ$.

In fact, since layers backing the barrel and the end-caps reproduce the structure of the hadron calorimeter, additional tubes are needed to cover the gaps left open in the boundary regions. This solution has been chosen — instead of lengthening the barrel tubes — in order to leave the space facing the barrel notches free for all outgoing cables (see Fig. 1.2). The total fraction of solid angle not covered by at least one double layer of muon chambers is then approximately 5%.

Fig. 6.11
6.5 Status of the construction

The construction of a detector involving 160,000 tubes, 220,000 strips, and 108,000 pads is mostly a problem of the reliability of individual components. Much effort has been devoted to improving the design of the tubes, in particular their ends, in order to simplify the mechanical assembly. In order to reduce the dead areas, the new design has also endeavoured to minimize the space needed by the supports for the wires.

The new structure is shown in Figs. 6.12a and 6.12b. At both ends of the eightfold tube a plastic plug, firmly joined to the tube itself, supports the printed board on which the wires are soldered and guides them into their correct position in the "frame" of the tubes. Inside each tube the positioning of the wires is guaranteed by plastic spacers. Neither screws nor glue are used to join together these basic elements, which are held by means of elastic clamps.

The new printed board consists of an alumina sheet on which resistors are printed, thus avoiding a large amount of manual work. Both ends of every wire are soldered at two points to avoid discharges at the end of the wire.

Particular attention has been paid to the precise shape of the eightfold tube profile, since the geometrical quality of the tubes is crucial for the homogeneity of the detector. After several attempts, a set of masks has been produced, which guarantees the equality of the cells to better than 0.1 mm. These masks will be used for all our tubes. All the pieces needed to build 1500 eightfold tubes were delivered in August. They will be used to optimize the performance of the construction chain. The manufacturer will then be ready to start mass production at the end of 1984, at a speed of 0.8 km of profile per day (working 24 hours a day). This means that all barrel elements of the hadron calorimeter can be produced in 3 months, whilst the over-all request of ALEPH can be satisfied in 10 months.
The construction of the tubes will be organized on an industrial assembly line, each eightfold tube passing through a set of machines, at the end of which the element will be completed and ready for testing. The main elements of this chain are as follows:

i) *The painting machine*: a fully automatic machine, 16 m long, able to paint with graphite $\sim 2$ km of eightfold tube per day (Fig. 6.13). This machine is fully operational at Frascati.

ii) *The cutting machine*: a bench positioned parallel to the second part of the painting machine, where the profiles are cut at both ends to the right length (Fig. 6.14).

![Fig. 6.13](image1)

![Fig. 6.14](image2)
iii) The spacer machine: a second bench, parallel to the previous two, where the plastic spacers which hold the wires every 50 cm are joined to the profile.

iv) The wiring machine: again a fully automatic chain, 16 m long, in which the printed boards are inserted into their clamps at both ends, and the wires are soldered. This machine has been built and is being tested in Frascati (Fig. 6.15a). On their way out, the profiles cross a station (Fig. 6.15b) where the wires are attached to the spacers by melting the plastic locally.

v) The closing machine: where the eightfold tube is inserted into its box and the two closing plugs, supporting the high-voltage connectors and the gas pipes, are joined to the box itself by melting the plastic, so that the box is then gas-tight.

All these machines follow the speed of the painting machine, so that in an eight-hour shift the chain can process the 0.8 km (100 eightfold tubes) produced by the manufacturer each day.

Once the tubes for the calorimeter barrel are ready, the first part of the chain is used to paint and cut the tubes for the end-caps, which will then be shipped to Bari and Pisa to be wired. The shape of the chambers required by the end-caps is completely different, and two independent sets of shorter machines are being prepared for Bari and Pisa. The two wiring machines, similar to the machine used by UA1, have been built in Bari and are at the tuning stage.

After construction, all tubes will undergo two different tests. The first one will check their gas-tightness. The second will condition the tubes with variable high voltage, ramping from 2000 V to 5000 V for several hours. During this 'training', all impurities present in the tubes will be burned away, the final good quality being indicated by a dark current smaller than 2 μA per eightfold tube and by a rate of signals consistent with the cosmic-ray flux. We estimate that less than 10% of the tubes will fail this test. From the point of view of organization, this part of the work is the heaviest, since it requires several independent test chains, each one capable of handling 100 eightfold tubes at a time.

Simultaneously, an independent set of machines will prepare the pads and the strips for analog and digital readout. The pads will be made in Pisa from layers of PVC, 1 mm thick, covered on each side by a 50 μm aluminium sheet. Finally, a machine is being assembled in Bari for cutting away a very thin ribbon of aluminium at the separation of two adjacent pads (about 1 mm wide). This machine consists of a large, very flat surface (16 m²) on which a movable arm carries a pair of mills remotely controlled via computer. With this machine all the pads of both end-caps will be produced in six months. A similar but simpler machine is under development at Frascati for the barrel pads (x,y geometry).

Aim of these parallel activities is to be fully ready to start constructing the barrel tubes at the beginning of 1985 and the end-cap tubes in May 1985. This guarantees sufficient time for carefully testing the tubes and assembling them into planes sandwiched between strips and pads before the beginning of the installation, which is planned for the 1 January 1986 (barrel) and the 1 July 1986 (end-caps).
Construction of the first double layer of the muon detector will start in Frascati (the barrel) and in Bari and Pisa (the two end-caps) immediately after the completion of the hadron calorimeter tubes. The installation, which will begin after the complete assembly of the calorimeter, is foreseen to be finished by the end of 1987. The first layer of the middle-angle detector is the responsibility of the IHEP in Beijing, and will be built there using materials and components shipped from Italy. A wiring machine of the UA1 type has been expressly manufactured in China and will be tuned on a test production of tubes before the end of 1984. By this date the hall for the tube factory will also be ready.

The second muon detection layer had been ‘staged’ in our 1983 Technical Report, for budget reasons. However, there is now a good probability that the 20000 tubes of this second layer will be produced in Beijing in time for LEP start-up.

The mechanical support structure for the muon detector is being designed at CERN. The larger part of the barrel section is already done.

6.6 Electronics
6.6.1 Analog electronics and readout
A streamer induces a charge of 14 pC on a pad. For average-size pads, with 2–3 nF capacitance, a single streamer induces a 5–7 mV pulse with a rise-time of 25 ns and a decay-time of 100–150 ns.

Showering hadrons produce eight streamers per GeV on the average, corresponding to a signal of 50 mV/GeV. A muon hitting one tube per layer is equivalent to a shower of 3 GeV and to a pulse of 150 mV.

The readout of each tower is split longitudinally into two parts. This feature, in conjunction with the muon chambers and with the digital readout of the strips, can be useful for identifying muons in jets. Indeed, most of the hadronic showers are concentrated in the first part of the towers because of their low energy and the presence of the e.m. calorimeter and of the coil.

The readout scheme is shown in Fig. 6.16. Positive signals coming from the pads of half a tower are summed, inverted, attenuated by a factor of 4, and collected by an ‘integrate and hold’ circuit. This circuit is based on a LeCroy MIQ–401. The chip has four inputs (two per tower) which are used as nodes for negative current pulses. Two integrators per channel collect 8/11 and 1/11 of the input charge providing low gain/high resolution and a high gain/low resolution output, respectively. Charges up to 1500 pC (150 pC) can be held by the low (high) gain channel for 700 µs with less than 1% loss. A fast signal (I-SUM), proportional to the input charge, is also produced by the circuit in an ungated mode. This signal, through a 6-bit FADC, is used for trigger purposes. A four-channel prototype of the circuits exists. They are being designed in Frascati and will be produced in Beijing.

6.6.2 Digital signal readout scheme
Owing to their smaller capacitance, the strips, even if collecting a smaller charge, produce signals similar to those generated on the pads. These signals are amplified, discriminated, stretched, and stored into shift registers by the circuit shown in Fig. 6.17. A monolithic element containing the shaded part of the circuit is being developed by the SGS
manufacturing company in Italy, in strict collaboration with the ALEPH group which has defined the expected performances and is at present testing the first prototypes. Each chip has four channels and, besides filling the shift-register memories, provides two additional signals: the first is produced if at least one of the four channels has been fired (Dig–OR); the second supplies an output current proportional to the number of activated channels in the chip (An–OR). The shift-register chain reads out serially all the strips of a plane of a barrel module or of an end-cap sextant. Over the same surfaces, Dig–OR and An–OR signals are OR-ed and will be used to trigger on muons. These signals are available 200 ns after the beam crossing.

6.7 Hadron calorimeter cost and construction schedule

6.7.1 Cost

In the budget of the ALEPH Technical Report the cost of the full hadron calorimeter and muon detector was estimated at 6.9 MSF. Since only 5 MSF could be budgeted for this combined system, the second layer of the muon detector as well as half of the digital readout of the hadron calorimeter were deferred ("staged").

Since then, we have increased the number of towers by a factor of four, but the cost is compensated by an even greater level of multiplexing in the analog readout. We expect that the cost of the digital readout per channel will go down to 8 SF from the anticipated 10 SF. Furthermore we now can expect that Beijing will be able to provide the outer muon layer, so that we not only hope to meet the estimates of 1983, but to make some advance on that part of the system that was staged. Figure 6.18 shows the financial profile.

6.7.2 Hadron calorimeter construction schedule

This is shown in Fig. 6.19.

![Hadron Calorimeter and Muon Detector Financial Profile](image1)

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![Hadron Calorimeter and Muon Detector Construction Planning](image2)
7. THE INNER TRACK CHAMBER

7.1 Introduction

The Inner Track Chamber (ITC) serves a dual function. By swiftly finding track trajectories in both the ρ and rz projections it forms an essential part of the level-1 trigger. By giving up to eight accurate ρ points in the radial region from 12 to 26 cm, it complements the tracking information from the TPC. The Imperial College (London) group is responsible for the ITC.

The over-all design of the chamber is nearing completion, but details await the results of prototype tests currently under way in the West Area test beam. Longitudinal and transverse diagrams are given in Fig. 7.1.

7.1.1 Triggering requirements

For triggering, a decision from the associated ITC processors must be ready in < 1 μs, a large solid angle must be covered, and absolute reliability is essential.

The speed of decision dictates that small drift cells must be used. This results in many wires and many channels with consequent problems for the load on the end-plates and the cost and positioning of electronics. However, with small cells, simple single-hit electronics is adequate.

For the solid-angle coverage a long chamber is necessary. The chamber will have an active length of 2.1 m to cover 97% of 4π.

Reliability demands that a broken wire must not cause the trigger to become significantly less efficient. As the chamber will be at the centre of the detector, access to remove a broken wire will be lengthy and therefore we require that the eight sensitive layers be subdivided into groups which are physically separate.

---

**Fig. 7.1**
The use of small drift cells enables cathode hoops to be used for the z readout. Such hoops will be positioned on lightweight shells which then serve the additional function of separating groups of layers. An alternative method of z readout using the time difference for the signals to propagate to each end of the wire would allow thinner spacing shells and give correlated $r\phi z$ information which would improve the trigger. A way to maintain the necessary accuracy of this timing method over long periods is being investigated.

7 Tracking requirements
The chamber will be used to give $r\phi$ tracking information only, with an accuracy of $\pm 100\ \mu m$. Whichever technique is used for extracting the z information for the trigger, it will be of poor quality in comparison with that from the TPC. Hence the main requirements are good point resolution and good two-track resolution in the $r\phi$ plane as well as large solid-angle coverage.

The two-track resolution is achieved by staggering the cells in adjacent layers.

The $r\phi$ resolution requires accurate knowledge of the wire positions and careful choice of the cell configuration and gas mixture.

To examine some of these problems, a prototype chamber has been constructed and is currently under test in the West Area ALEPH test beam.

7.2 ITC prototype
The main purpose of the prototype is to
i) examine construction techniques for the lightweight shells carrying the cathodes;
ii) devise readout schemes for the cathode hoops;
iii) investigate the viability of timing the signal to both ends of the wire as an alternative method of z measurement including methods of autocalibration;
iv) investigate the performance of both the anode and the cathode signals as a function of the polar angle with respect to the chamber axis;
v) investigate cross-talk between adjacent cathodes on a shell, through the shell, and across the sensitive volume containing the sense and field wires;
vi) examine cross-talk in the highly congested front-end electronics on the anodes;
vii) compare front-end preamplifiers for the anodes;
viii) compare real results with the calculated performance of the cell configuration in terms of the time–space relationship and cross-talk from cell to cell;
ix) investigate different gas mixtures.

Establishing the conditions for optimal $r\phi$ resolution will await further tests with small chambers during 1985.

The prototype has the same external dimensions as the final chamber but only three shells: two inner shells and the outmost one. Two layers of 120 sense wires, alternating with pairs of field wires, are contained between the two inner shells: the layers are separated by a layer of 240 guard wires. In practice, to save time and cost, only half of the wires have been inserted. The outer surface of the innermost shell and both surfaces of the second shell carry cathodes. Those on the outer side of the second shell, where there are no wires, are to check for cross-talk through the shell. A diagram of the prototype is given in Fig. 7.2. There are no wires between the second and the outermost shell; this latter shell was constructed purely to examine the mechanical problems associated with a shell of 2 m length and a diameter of 56 cm.

A photograph of the prototype shortly after construction is shown in Fig. 7.3.
7.2.1 Shell design and construction

The shells are constructed of a polystyrene/Kapton laminate. The outer sheets are aluminized Kapton, with the aluminized surface cut to produce the 20 mm wide cathode strips. A central grounded layer of aluminized Mylar reduces cross-talk through the shell. Details of the shell laminate are given in Fig. 7.4.

The problem of readout of the hooped cathodes has been solved by cutting a trench into the outer polystyrene layer, wrapping the aluminized Kapton layer over the wires, and passing the wires in a Kapton sandwich to the ends between the two outermost Kapton layers. This is shown in Fig. 7.5. For normal incidence, each shell presents a radiation length of 0.2%.

---

**Fig. 7.4**

Channel approx. 70mm wide (48 lines)
approx. 1mm deep

Sandwich kaptan/wires-glue/kaplan

---

**Fig. 7.5**

DETAILS OF CATHODE READOUT LINES
7.2.2 Cell design

The design chosen for the cell configuration was based on computer simulations of the performance of a number of similar cells. The configuration chosen is shown in Fig. 7.6a. It is necessarily asymmetric in the radial dimension as it is enclosed by a sheet cathode on one side and earthed ground wires on the other. The criteria used to choose the cell geometry were:

i) to have the early electrons arriving as close as possible in time to give a good rise time;
ii) to achieve an approximately linear space–time relation;
iii) to reduce cross-talk between the cells;
iv) to maintain good symmetry across the cell in a 1.5 T field.

Possible improvements, such as using three rather than two field wires and putting an intermediate voltage on the cathodes, were not employed owing to the increased complexity and, in the case of the extra wires, to the increased load on the end-plates. The predicted equipotentials and electron trajectories in a 1.5 T field are shown in Figs. 7.6b and 7.6c. The performance of this cell on the prototype will be compared with the predictions.

7.2.3 End flanges and feedthroughs

For a point accuracy of \( \sim 100 \, \mu m \), knowledge of the wire positions must be better than \( 40 \, \mu m \). The holes which carry the sense wires in the end flanges of the prototype have been surveyed and give an r.m.s deviation of \( 17 \, \mu m \) with respect to their expected positions. The feedthroughs for the prototype, however, had to be produced quickly and are probably not of sufficiently high quality for this specification.

7.2.4 Front-end electronics on the chamber

The small cells and cathode readout cause extreme congestion of the electronics at the chamber end. This demands careful planning, both for the introduction of the high voltage and reduction of cross-talk. A component block has been developed in which the passive elements for the anodes are contained in blocks of 16 with the components contained between two PCBs shaped to a circular geometry; the whole is then set in a mould and potted in epoxy. The block gives output leads to the sense and field wires at one end, and an edge connector to the outer flange at the other. The HV is also introduced and distributed in the block. This is tidy and compact and works well.

Immediately following the outer flange the anodes are connected to 16-channel boards containing emitter followers to drive the signal to the main discriminators/amplifiers. In addition, the cathode signals have to be passed through to their amplifiers which will be in the end-cap region of ALEPH. The end region of the prototype chamber is shown in

Fig. 7.6
7.2.5 $\tau$ determination by timing

An alternative way of obtaining the $\tau$ information is to use the time difference between the signal reaching the two ends. This is being actively pursued. This provides correlated $\tau$ and $\tau$ information so that three-dimensional trajectories may be used in the trigger.

The feasibility of achieving the required accuracy ($\sigma_\tau < 40$ mm) has been demonstrated by laboratory tests where a resolution of 100 ps on the time difference, equivalent to $\sigma_\tau = 15$ mm, has been achieved under controlled conditions with a simple single-wire chamber. Applying this in an experimental environment requires the ability to calibrate the system frequently so that any drifts may be quickly compensated. A timing card has been developed which can be trimmed under computer control in response to a calibration signal.

Timing card

The timing card would be the first stage of an $\tau$ trigger processor. The principle of the processor is to detect radial tracks from $\tau = 0$, by coincidences in 'time-expanded' pulses derived from track signals in successive layers of the ITC.

A constant current of 10 mA is switched into a 150 pF capacitor for the time period between arrival of pulses from opposite ends of the chamber (START and STOP). The Boolean condition for this is START.(STOP), and this gating is performed with 10,000 series ECL gates, following NIM-ECL converters. The START pulse also sets a latch, switching off a small current clamping the capacitor to a computer-controlled initial voltage.

After the maximum expected drift times, when all valid track pulses would have been received, a RAMP signal is sent to the card, switching on a 1 mA discharge current. The capacitor potential is returned to its starting value at one-tenth of the charging rate. A high-speed comparator, buffered from the capacitor by an emitter follower, provides the expanded output pulse when its input returns past a reference level.

For maximum temperature stability, an integrated circuit incorporating five NPN transistors is used in the critical high-speed part of the design. This includes the 10 mA current generator, current-switch initial voltage clamp, and emitter-follower buffer.
To provide a means of compensating on line for differential delay changes in the amplifier/discriminator paths, the initial capacitor voltage may be varied under computer control. An eight-bit DAC allows a range equivalent to ±3.2 ns in steps of 25 ps. A similar DAC controls the capacitor discharge rate, giving a variation of ±10%.

The time expansion was measured to be linear within 50 ps. The circuit diagram of the timing card is given in Fig. 7.8.

7.3 Test results

The first tests concentrated on the cathodes. The topics being investigated are the dynamic range of the signals as a function of both the applied voltage and the polar angle of the tracks through the chamber, and cross-talk both through the shells and across the sensitive volume. A high-energy hadron beam has been used and two gas mixtures, Ar:CO₂(80:20) and Ar:CO₂:CH₄(78:20:2).

a) Cathodes: We obtain clear cathode signals well separated from the noise, the behaviour with angle is as expected, and there is very little cross-talk between cathodes. A typical ADC spectrum showing clear separation of the signal from the pedestal values is shown in Fig. 7.9a.

i) Variation of pulse height with polar angle

The cathode signals are detected with integrating amplifiers and therefore respond to the total amount of ionization produced when the track crosses the cell. The height of the signal should therefore be proportional to cosec θ, where θ is the polar angle (i.e. the angle between the wires and the beam). Figure 7.9b shows that this behaviour is obtained.

ii) Cross-talk through the shell

In one run, cathodes on the opposite side of the outer shell were instrumented and a correlation was searched for between the cathode signals on the inner surface in the sensitive region and those on the outer surface. Results are shown in Fig. 7.9c, where the mean pulse height on the outer cathodes is plotted against that on the corresponding inner ones. A small correlation is observed corresponding to a 1.1% cross-talk through the shell. This is in agreement with earlier tests on the shells in the laboratory.

iii) Cross-talk across the gap

This is more difficult to measure, as the charged particle naturally causes signals on both the inner and outer cathodes of a gap. However, with the chamber at a very low polar angle so that signals are induced on different inner and outer cathodes, a correlation between the inner and outer signals can be measured. Preliminary results are shown in Fig. 7.9d and suggest a value of ~ 1%.
b) **Anodes**: Investigations of the anode efficiency and any cross-talk, either in the chamber or the electronics, are under way, but no results are yet available. The time–space relation for the cell is also being studied.

c) **Timing**: The main runs to investigate the timing method to determine \( z \) did not take place until August and are under analysis. The very first results are splendid: resolutions of \( \sigma_z = 200 \) ps on the time difference, equivalent to a spatial resolution of \( \pm 3 \) cm, are typical. In Fig. 7.10a we show the distribution of time differences (expressed in centimetres along the wire) for three different beams — each of width 1 cm — crossing the chamber normally at points separated by 10 cm. The mean time difference (expressed in centimetres along the wire) obtained for nine positions along the chamber is plotted in Fig. 7.10b. The corresponding standard deviation of the time difference is given in Fig. 7.10c.
7.4 Mechanical construction

The chamber was shown in Fig. 7.1. It is divided into four sub-chambers, rigidly and reproducibly connected. In each of these there are two layers of 120 sense wires alternating with pairs of field wires; they are separated by a layer of 240 guard wires. The azimuthal position of the sense wires is offset by half a cell from layer to layer in order to resolve left–right ambiguities and achieve good two-track resolution. The sub-chambers are separated by lightweight shells which carry the cathode hoops. The cell configurations, the shell construction, and the method used for the extraction of the cathode signals were discussed in the description of the prototype construction above.

The load of the wires is taken by a 2 mm carbon fibre outer shell which is connected to a similar tube which supports the ITC from the TPC. The critical end areas are shown in detail in Fig. 7.11.

For construction the inner shell and end flanges are fixed to a mandrel which will take the load whilst wiring takes place. After the first two layers have been wired, the second right-hand end flange is bolted to the first, the second shell inserted from the left into a slot in the flange, and then the left-hand end flange is positioned. This is connected rigidly to the inner flange by a segmented ring shown in black in Fig. 7.11. This procedure is continued until all four sub-chambers have been wired. The load-bearing carbon fibre shell is then fastened in place and the inner mandrel removed. The bolts connecting the end flanges take up crucial space in the end area. Figure 7.12 shows the scheme adopted for spacing the segmented rings connecting the end flanges and the cathode readout wires.

The same mechanical construction will be used if z by timing is used. In this case very lightweight spacing shells will be inserted purely to separate the layers.

The dimensions of the chamber are given in Table 7.1.
Table 7.1
Dimensions

| Inner radius (mm) | 128 |
| Outer radius (mm) | 280 |
| Over-all length (mm) | 2400 |
| Radii of sensitive layers (mm): | |
| 142.5 | |
| 157.5 | |
| 177.5 | |
| 192.5 | |
| 212.5 | |
| 227.5 | |
| 257.5 | |
| 262.5 | |
| Active length (mm) | ±1050 |
| Number of cells per sensitive layer | 120 |
| Cathode strip width (mm) | 20 |
| Number of cathodes per layer | 95 |
| Sense wires, gold-plated tungsten (µm diam.) | 30 |
| Field and guard wires, silver-plated beryllium-copper (µm diam.) | 100 |

7.5 Electronics

7.5.1 Drift-time measurement
The anode wires are taken through the feedthroughs to a compartment still within the gas volume where decoupling capacitors and terminating resistors are located. The signals are then passed through a second end flange to PCBs containing preamplifiers. The layout of the electronics in this congested end of chamber region will be very similar to the one described in detail for the prototype. From the preamplifiers the signals pass through connectors at the end of the TPC and then via coaxial cable to constant fraction amplifiers/discriminators in the barracks. The discriminator output is fed into the TDC system.

7.5.2 Cathode readout
The cathode signals are fed via coaxial cable to integrating amplifiers in electronics boxes situated near the forward detector. They then travel via twisted-pair cables to discriminators outside the detector, and the digital signals from the discriminators go to the trigger processor.

7.5.3 Data flow
The basic readout of both the anodes and the cathodes will be controlled by a microprocessor in a FASTBUS crate connected to the main data flow. This will reformat the data before sending them to the main on-line VAX. The scheme is shown in Fig. 7.13.

![Fig. 7.13](image-url)
A second microprocessor will control the trigger processors and monitor their behaviour by feeding in patterns and checking the results.

7.6 Trigger processors

There are two trigger processors.

7.6.1 The (rφ) trigger

uses an algorithm based on patterns of hit anodes to give an estimate of the number of tracks emanating from the origin (in xy) with a transverse momentum greater than 1 GeV/c.

The pattern of sense wires is shown in Fig. 7.1b. Referring to that figure we define 240 cells by:

i) \( a_0 \) AND (\( b_0 \) OR \( h_1 \)) AND \( c_0 \) AND (\( d_0 \) OR \( d_1 \)) AND \( e_0 \) AND (\( f_0 \) OR \( f_1 \)) AND \( g_0 \) AND (\( h_0 \) OR \( h_1 \)),

ii) \( a_0 \) AND \( b_1 \) AND \( c_0 \) AND (\( c_1 \)) AND \( d_1 \) AND (\( e_0 \) OR \( e_1 \)) AND \( f_1 \) AND (\( g_0 \) OR \( g_1 \)) AND \( h_1 \), etc.

Each track cell has eight inputs. These are used to define an address in a 4-bit 256-word memory. The memory contains the number of inputs which were present for that particular track cell. This number is compared with a pre-programmed number to decide if that track cell contains a trajectory. There are 240 of these memories, one for each track cell.

The positive outputs from the comparators are summed to give the number of trajectories.

A total of 120 ANDs are made from the outputs from comparators \( i (i = 1, ..., 120) \) with the OR of the outputs from comparators \( i + 120 (\pm TOL) \) to give a back-to-back trigger.

Appropriate outputs from the comparators are OR-ed together to give a signal which can be correlated with the \( \phi \) trigger segments of the hadron calorimeter.

7.6.2 The (rz) trigger

A very similar scheme is employed to find rz trajectories using the eight cathode layers. A set of cells is defined which correspond to all possible trajectories of straight tracks in rz leaving the interaction point within some tolerance of the nominal crossing point. The number of cells and hence the number of memories depends on the spread of the crossing point in \( z \). Currently, 276 masks are envisaged corresponding to a 30 cm range in \( z \).

The number of trajectories, a back-to-back trigger, and a signal for correlation with the segmentation of the hadron calorimeter trigger segments will be output.

7.7 Construction schedule

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<td>Tests at CERN</td>
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<tr>
<td>Construction and installation</td>
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<tbody>
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<td></td>
<td></td>
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<td>Construction</td>
<td></td>
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<tr>
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### 7.8 Updated cost estimate

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<td>End flanges</td>
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<td>Wires/capacitors/cathodes/feedthroughs</td>
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<td>Gas system</td>
<td>6</td>
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<tr>
<td>Installation</td>
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<table>
<thead>
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<th>Electrics</th>
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<tbody>
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<td>Cables/connectors</td>
<td>30</td>
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<tr>
<td>Amplifiers</td>
<td>33</td>
</tr>
<tr>
<td>TDC system</td>
<td>50</td>
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<tr>
<td>Cathode system</td>
<td>15</td>
</tr>
<tr>
<td>Trigger processors</td>
<td>60</td>
</tr>
<tr>
<td>High-voltage system</td>
<td>6</td>
</tr>
<tr>
<td>Spares/contingency</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td><strong>214</strong></td>
</tr>
</tbody>
</table>

**TOTAL** 298 k£
8. THE LUMINOSITY MONITOR

8.1 Introduction

The luminosity will be determined from the rate of Bhabha events at small scattering angles, measuring in coincidence the signals from the electrons scattered on both sides of the interaction regions.

The basic element of the detector is an electromagnetic calorimeter. Its spatial resolution, however, is not adequate for defining the acceptance domain with the required precision. A tracking device is needed for measuring the angle of the scattered electron.

The space reserved for the luminosity monitor consists of two zones symmetrically situated on each side of the interaction point, in the z region between 2445 and 3080 mm. In these zones we will install a pair of counting devices, each being a combination of a precision tracking device and a shower counter (see Fig. 8.1). Note that the shower counter extends the angular coverage of the e-γ calorimeter. It is in fact constructed in an almost identical way. The tracking device is a multilayer drift-tube arrangement based on thin square tubes, of cross-section 10 × 10 mm².

Copenhagen is responsible for the luminosity calorimeter, and Siegen is responsible for the luminosity track detector.

![Fig. 8.1](image1)

8.2 Prototypes and tests

For the track detector, three 45° sectors in separate gas boxes (Fig. 8.2) have been built and will be tested this autumn with electrons from the Bonn synchrotron. Another prototype of four sectors (complete half ring) in one common gas box (Fig. 8.3)—the same type which will be used in the final detector—is being constructed at the moment. Here we want to investigate possible problems in the construction and to measure the efficiency of the tube.

![Fig. 8.2](image2)

![Fig. 8.3](image3)
chambers near the border, where they are cut at an angle of 22.5°. We are also interested in the efficiency distribution across the tube. A first drift-time/drift-space relation will be derived from the test results as well as the spatial resolution of the chambers.

For the calorimeter we will profit from the experience gained with the e-γ calorimeter, owing to the almost identical design. Prototype beam tests for the luminosity calorimeter are not foreseen.

8.3 Mechanical design

1 Track detector

This now consists of nine identical layers of drift tubes. Each layer consists of eight 45° sectors of identical design. The over-all dimensions have not changed and are summarized as follows:

<table>
<thead>
<tr>
<th>Inner radius</th>
<th>90 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer radius</td>
<td>300 mm (without preamplifiers)</td>
</tr>
<tr>
<td>Z-range</td>
<td>2445–2625 mm</td>
</tr>
<tr>
<td>Angular acceptance</td>
<td>42–89 mrad</td>
</tr>
</tbody>
</table>

In Fig. 8.4 we show the present design. Some details of the actual construction will depend on the results from the prototype chambers currently under study.

8.3.2 Luminosity calorimeter

Only two important changes have taken place in the design parameters since the 1983 Technical Report was published:
- The outer radius is increased from 380 to 520 mm, following an increase in the inner radius of the end-caps of the e-γ calorimeter. This raises the number of electronic channels from ~ 900 to 1728 and the weight to 2.2 t on each side.
- We have decided to follow the design of the e-γ calorimeter using Pb converter sheets of double thickness in the third stack. The available space limits us to 39 layers, so in order to reach 22 radiation lengths, our converter sheets are 2.5 mm and 5.0 mm thick. The energy resolution is, as before, expected to be a factor of 1.1 worse than for the main e-γ calorimeter, i.e. σ/E = 0.19 ⋅ √E(GeV).
The layers (Fig. 8.5) are constructed in very much the same way as the main e-γ calorimeter. One difference is that we plan to use disc springs rather than a deformed back-plate to ensure a constant pressure on the stack. Furthermore, we are planning to use a slightly different construction of the wire support in the tube ends in order to reduce the risk of discharges from the wire to the ends of the tube walls (Fig. 8.6); the construction will be tested early this autumn.

Our special problem is the mechanical stability of the oddly shaped (half a pineapple slice) vacuum-tight containers which, supported at one end, carry the 39-layer deep stacks. The containers are now under study in collaboration with the Mechanical Engineering Division of the Risø Research Establishment.

A computer program has been written which draws the pattern of the pads and extruded profiles for all the layers. An example is given in Fig. 8.7. Another output from the same program is the pad patterns in a form ready to be photographed for printed-board production.

8.3.3 Forward luminosity monitor
This part of the detector has been cancelled because there is no space available, and a similar device will be built by the machine group inside the synchrotron radiation absorbers (LEP Note 462). The signals will be available to the experiment.
8.4 Electronics

The complete readout electronics for the luminosity track detector has been designed. Prototypes of the preamplifier and of the drift-time digitizer are available; the circuit diagram is depicted in Fig. 8.8. Manufacture will begin in August.

Fig. 8.8

The electronics for the luminosity calorimeter is identical to that of the main $e-\gamma$ calorimeter from the front-end amplifier to the recording medium; compare subsection 5.10.

8.5 Time schedule

There is no change in our planning, which is detailed in Table 8.1.

8.6 Updated cost estimate

An updated cost estimate is available for the luminosity track detector, see Table 8.2. The spending profile is given in Table 8.3.
### Table 8.1
Construction schedule

<table>
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<td>Design studies, prototypes and tests</td>
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<td>Drawings</td>
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<tr>
<td>Construction of tools and parts</td>
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<td>Assembly of</td>
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<tr>
<td>Assembly of detector at CERN</td>
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</tbody>
</table>

| **Luminosity track detector** |      |      |      |      |
| Design studies, prototypes and tests |      |      |      |      |
| Drawings |      |      |      |      |
| Construction of tools and parts |      |      |      |      |
| Assembly of modules |      |      |      |      |
| Test of modules |      |      |      |      |
| Electronics |      |      |      |      |
| Preamplifiers |      |      |      |      |
| Cables |      |      |      |      |
| TDCs |      |      |      |      |
| FASTBUS readout |      |      |      |      |
| Monitor/Calibration system |      |      |      |      |
| Gas system |      |      |      |      |
| Assembly of detector at CERN |      |      |      |      |

### Table 8.2
Cost of the luminosity track detector

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost (kSF)</th>
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<td>Preamplifiers</td>
<td>28</td>
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<tr>
<td>Cables</td>
<td>36</td>
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<tr>
<td>TDCs</td>
<td>145</td>
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<tr>
<td>NIM electronics (signal distributions)</td>
<td>22</td>
</tr>
<tr>
<td>FASTBUS readout</td>
<td>72</td>
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<tr>
<td>High voltage</td>
<td>36</td>
</tr>
<tr>
<td>Material, construction</td>
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<tr>
<td>Gas system</td>
<td>16</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>390 kSF</strong></td>
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</tbody>
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### Table 8.3
Spending profile

<table>
<thead>
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<th>Year</th>
<th>Cost (kSF)</th>
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<tbody>
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<td>50</td>
</tr>
<tr>
<td>1984</td>
<td>60</td>
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<tr>
<td>1985</td>
<td>200</td>
</tr>
<tr>
<td>1986</td>
<td>60</td>
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<tr>
<td>1987</td>
<td>20</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td><strong>390 kSF</strong></td>
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</table>
9. INSTALLATION

9.1 Tentative plan

The installation planning has been worked out, using the program POL (Fig. 9.1). It shows that the total installation time needed is 21 months, and we assume that all parts of the detector will be ready as requested. To establish this planning, we have tried to make the best estimate of the time needed for the installation of each item. We have analysed the constraints exerted by a particular part of the detector on the others, because of problems of accessibility, use of the crane, or some other incompatibility.

Until recently it was foreseen in the general planning of LEP that zone 8 would be at our disposal by 1 April 1987; thus, assuming we were given this zone, it would have just been possible to be ready by the end of 1988, at the same time as the LEP machine. At the beginning of August, a new timetable for the LEP civil engineering was given to us: the exact date at which we will be able to start the installation of ALEPH is still not known. In the case of zone 8 (which is the most favourable one), this date should be between 1 August and 1 September 1987. A more precise date will be known by the end of September 1987. Thus the installation of ALEPH will be finished four months later than the LEP machine installation.

As in the new planning the beginning of the installation is delayed by at least four months, we are now studying what can be tested or preassembled at the surface during those months in order to speed up our installation work. We are also studying the possibility of shortening the total installation time (at some extra cost), for example by doing some shift work.

The sequence of operations is thus as follows: first, the mounting of the mobile shielding; followed by the assembly of the platforms supporting the experiment; then the installation of the electronics barrack, on the garage side. These operations must be done sequentially, because any one of them would block the access and the crane. The total time needed is 14 weeks (5 working days per week), up to 15 November 1987.

After this date we can assemble the magnet: first the barrel, then the coil, and finally the end-caps. In fact, the iron yoke of the magnet will already have been assembled at the factory, and again after arrival on the CERN site. The iron yoke should be delivered by November 1985 according to the contracts. The coil should be at CERN by 1 November 1986 (contract with CEN-Saclay). Thus the iron yoke assembly, including the hadron calorimeter mounting, can be finished before delivery of the coil. We estimate that 24 months will be needed for mounting the coil in the barrel and for cooling it down; then 3½ months for magnetic tests and measurements. We consider this amount of time to be sufficient in view of the fact that a first complete test of the coil will have taken place at Saclay before shipping. Then we will have four months at our disposal for preparatory work, in particular for the hadron calorimeter and the electromagnetic calorimeter assemblies. The detailed study of these operations has still to be done. Two months are foreseen for dismantling the coil and the iron yoke after testing, before we begin the final assembly in the experimental zone.

By 15 November 1987 we will begin to reassemble the barrel, which will take 10 weeks. Then the coil will be introduced and fixed on the iron yoke; this will need two weeks. After this we can assemble the refrigerator, install the coil power supplies, and do the piping and cabling work for the coil. At the same time, the reassembly of the end-caps will take place, so that by 15 March 1988 we will be ready to cool down the coil. The assembly of the barrel will require the use of two 40 t chariots on one crane; the introduction of the coil will be made with the help of a special tool and will block the access for two weeks; and the assembly of the end-caps will need two coupled 40 t cranes — therefore these operations can only be made sequentially.

It will be necessary to cool down the magnet and make sure that the coil is functioning correctly before continuing to assemble the detector. We estimate that one month will be needed for this.

At that time (15 April 1988) we will be ready to install the electromagnetic calorimeter, in parallel with the cabling of the hadron calorimeter. The barrel modules and the first end-cap modules of the electromagnetic calorimeter will be installed in parallel in a total time of 2½ months. Before cabling, it will be necessary to check that the electromagnetic calorimeter does not perturb the magnetic field; thus we foresee four weeks for partially remeasuring the magnetic field with the barrel part and one end-cap of the electromagnetic calorimeter in place.

Assuming that this test is successful, we can begin on 1 August 1988 with the installation of the electronics barracks for the TPC, and the preparatory work for the TPC installation, which will start by 15 October 1988 and will take six weeks. The ITC will have been fixed on the TPC main frame, at ground level, after completion of the TPC tests in the laboratory. Thus, as far as installation is concerned, it will be a part of the TPC.

At this time we can do the cabling on the TPC, test it, and in parallel install the second end-cap of the electromagnetic calorimeter. All this work will be finished by 1 March 1989.

One month will then be necessary for installing the luminosity monitors and the vacuum pipe and for closing the detector, which will be ready by 1 April 1989.

We believe that this planning is a realistic one but it does not have any margin, in particular if the perturbation of the magnetic field by the electromagnetic calorimeter is such that we have to remap the field completely.

We can count on one year for the TPC tests, and for a preassembly of the inner tracking chamber, the luminosity monitors, and the beam pipe at the surface.
Fig. 9.1
The installation of the counting rooms in the surface building will be done in parallel, and will be finished at the same time as the detector assembly.

9.2 Barracks

The electronics barracks will be modular in construction, and each module will be equipped, as far as possible, before installation in the experimental zone. In particular, the barracks for the TPC electronics will be delivered early enough, so that all the electronics available will have been installed and tested at the surface level. Each barrack will be mounted as a complete unit. The design of the barracks is finished (Figs. 9.2 and 9.3), and the call for tenders has been sent; the closing date for tendering is 15 October 1984. The call for tenders for the racks will be sent out by the middle of September 1984. A prototype is under construction.

9.3 Cabling

One of the main installation problems is the cabling. To study this question we have built a mock-up, at scale 1:1, representing 1/4 of the length and 1/4 of the diameter. The aim is not only to study the cabling problems but also, as far as possible, to prepare preformed bundles of cables, ready for installation.

9.4 Experimental zone

Studies of various aspects of the experimental zone have been made. We can mention, in particular, the structure of the fixed barracks and their lift, the general layout of the various passages along the zone and around the detector, the emergency exit, and the accesses to the electronics barracks when these are in the data-taking or the garage positions. The safety zone around the access lift has been defined, as well as the location of the ventilation ducts (Fig. 9.4).
10. FINANCES

10.1 Overview

We are beginning to have a rather precise view of our financial situation, since a large part of the material is either on order or its cost is well understood. The ALEPH budget, to the best of our knowledge, is balanced within a few percent.

In the tables, all figures are in MSF (value as at 1 January 1983) and the exchange rates used are (29 March 1984): SF:DM:FF:£ = 1:0.835:0.270:3.14. The numbers in brackets indicate negative balances.

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10.2 Financial profiles

Abbreviations
- CF: Common fund
- Data: Data acquisition
- ey: Electromagnetic calorimeter
- Had: Hadron calorimeter + muon chambers
- ITC: Inner tracking chamber
- Lumo: Luminosity monitor
- Minv: Mini-vertex detector
- TPC: Time projection chamber
- Trig: Trigger

- (a): Assumption; to be confirmed.
- (b): Paid.
- (c): Funding possibly extended into 1988.
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APPENDIX

ALEPH PAPERS

A great deal of the work on the ALEPH detector is communicated inside the Collaboration by means of informal notes and papers. In the beginning they were just called ALEPH Notes and numbered consecutively. Later on, papers on more specialized subjects were freely grouped under the name of a detector or some other field of activity, e.g. ALEPH-TPC, ALEPH-EMCAL, etc.

The following list contains all the papers of the ALEPH Collaboration up to now. (The numbers not listed are those of Minutes of meetings.) The published papers are referenced under ALEPH-PUB.

ALEPH Notes

1 29.10.80 D. Fournier and J. Lefrancois, Particle identification.
2 29.10.80 M. Davier, General considerations on solenoid size and precision in central detector.
3 29.10.80 J.J. Veillet, Detecteur central.
4 2.09.80 G. Blanar, H. Dietl, E. Lorenz, F. Pauss and H. Vogel, BIB - how a LEP detector can be made compact.
6 3.12.80 L. Foà, Study of jets with solenoid and calorimeters.
7 5.12.80 D. Fournier, Cluster counting, energy loss and relativistic rise.
8 30.10.80 J. Heintze, The JADE JET - chamber (transparencies).
9 14.01.81 E.M. Rimmer, E.Lillestol, Proposal for working subgroups on data processing standards for high energy physics.
10 3.12.80 J. May, Particle separation with dE/dx.
11 2.02.81 D. Fournier, Practical considerations on particle identification with dE/dx.
12 4.02.81 J. Lefrancois, Calorimetry of e/γ and hadrons.
13 4.02.81 M. Davier, Parameter group.
14 4.02.81 H. Hilke, TPC.
15 4.02.81 J. Knobloch, Data handling.
16 4.02.81 G. Zobernig, Event generator for LEP energies.
17 4.02.81 G. Petrucci, Sphere design study.
18 5.02.81 M. Schnitt, Central detector study.
19 5.02.81 J. May, Sphere calorimetry.
20 5.02.81 R. Turlay, Superconducting solenoid design study.
21 9.02.81 G. Blanar, H. Dietl, E. Lorenz, F. Pauss and H. Vogel, Monte Carlo studies for event topologies at ECM = 100 GeV for an e+e- collider.
22 9.02.81 G. Blanar, H. Dietl, E. Lorenz, F. Pauss and H. Vogel, Memorandum on shower profiles in NaI and BGO.
23 8.01.81 R.L. Chase and J.J. Veillet, Axial readout possibilities for a cylindrical detector at LEP.
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<td>G. Rudolph, S.L. Wu and G. Zobernig</td>
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