**PERFORMANCE OF A URANIUM / TETRAMETHYLPENTANE
CALORIMETER BACKED BY AN IRON / SCINTILLATOR CALORIMETER.**

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Abstract

We present results from the barrel depleted uranium / TMP calorimeter modules constructed by the UA1 Collaboration. Electromagnetic and hadronic energy resolutions have been measured using electron and pion beams with momenta in the range 7 GeV/c to 70 GeV/c. Results on the energy linearity and the spatial uniformity of response are reported. The electromagnetic shower position resolution has been measured as a function of energy using a fine grained position detector placed at a depth of $\sim 3.5 X_0$. The noise arising both from the electronics chain and from the uranium radioactivity is compared with 70 GeV/c muon signals. The ratio of the electron to pion response has been measured both as a function of the energy and of the electric field. The high lateral and longitudinal granularity of the calorimeter and the presence of a position detector have been used to determine the electron-pion separation as a function of energy.

1. Introduction

Sampling calorimeters using liquid filled ionization chambers as detection elements have several important advantages. The absence of internal amplification of charge results in a stable calibration over long periods of time provided that the purity of the liquid is maintained at a sufficiently high level. The number of ion pairs created is large and hence the electron energy resolution is determined purely by the sampling fluctuations. The considerable flexibility in the size and the shape of the charge collecting electrodes allows high granularity both longitudinally and laterally. However, as the signals are usually small, accurately calibrated low noise amplifiers are needed.

The main item in the UA1 upgrade was the replacement of the lead-scintillator electromagnetic calorimeters ("gondolas"). The design goal was to replace these gondolas by a combined electromagnetic and hadronic calorimeter. Performance goals included good longitudinal and lateral segmentation, good electromagnetic and hadronic energy resolution and equal response to electrons and hadrons of the same energy. The limited space made available by the removal of lead-scintillator calorimeters made depleted uranium the obvious choice for the absorber because of its density. The space required for the cryogenics ruled out the use of liquid argon as the active medium but 2,2,4,4-tetramethylpentane (TMP) operated at room temperature provided a suitable liquid ionization medium. The properties of the suitable room temperature liquids are given in Table 1. Tetramethylsilane (TMSi) has many of the desired properties but was not chosen due to its high flammability and high vapour pressure. TMP was preferred over hexamethylenedisilane (HEDS) due to its higher ion pairs yield. Further details can be found in Reference 1.

We have already published results of beam tests of two types of U/TMP modules (type VFW [2] and FW [3]) which were designed to provide coverage in the forward direction in order to improve the hermeticity of the UA1 detector. In this paper we present results from the barrel U/TMP modules (type Super-gondola, SG). We describe the design of these modules in Section 2. The electronics chain is described in Section 3. The test beam layout is outlined in Section 4. In Section 5 we present and discuss the results from the beam tests.

2. Design of the U/TMP Calorimeter Modules

The barrel of the UA1 calorimeter is formed by 10 half-cylindrical Super-gondolas each consisting of 16 modules. The structure of one of these modules is illustrated in Fig.1. They are subdivided into six samplings in depth. The first four samplings form the electromagnetic section and consist of 2 mm thick U plates sandwiching TMP filled ionization chambers of 3.3 mm thickness. The last two samplings consist of 5 mm thick U plates sandwiching the ionization chambers. The thickness of these samplings in terms of radiation and interaction lengths is given in Table 2. The

thickness of the electromagnetic section is $26 X_0$ and the total thickness of the modules is $\sim 2.35 \lambda_I$ at normal incidence.

The main problem in the construction of ionization chambers filled with room temperature liquids is the difficulty in achieving the required level of purity of the liquid and in order to maintain the purity of the liquid the ionization chambers have to be extremely clean and leak tight. The ionization chambers are made entirely out of stainless steel. The details of the procedures used for the cleaning of the components, the chambers and the assembled modules, of the purification of TMP and of the filling of the chambers are given in Reference 1.

An exploded view of the ionization chambers is shown in Fig. 2. The skins, each 0.15 mm thick, are laser welded on a frame of cross-section $3 \times 3 \text{ mm}^2$. Eight electrodes, each of size $\sim (11 \text{ to } 15) \times 13 \text{ cm}^2$ and thickness 0.5 mm, are held in the middle of the chamber by ceramic spacers resulting in a liquid gap of 1.25 mm on either side of the central electrode. The skin is partially welded onto a central bar, also of $3 \times 3 \text{ mm}^2$ cross-section, to provide the chambers with additional mechanical rigidity. The chambers are filled with TMP via two small tubes that are welded into the external frame. Holes in the central bar allow free circulation of liquid between the two halves of the chamber. High voltage and signal connections are made through a single feedthrough to each central electrode. Positive high voltage is applied to the central electrodes with the skins held at ground potential.

A fine grained position detector (Fig. 3) [4], with two planes of orthogonally arranged strips, is placed between the first two samplings. The design is an extension of that for the standard chambers. The chamber encloses three planes of electrodes instead of the one for the standard type. The central plane consists of 8 standard electrodes which are connected into the second calorimeter sampling. On either side of this electrode is a plane of strips, each running orthogonally to the other. Each strip has a width of 7.1 mm with an interstrip pitch of 9.1 mm. All planes are separated from each other by a spacing of 1.25 mm. Positive high voltage is applied to the central electrodes, which are connected to the preamplifiers of the second samplings, and to the chamber skins. The position detector chamber has thus to be electrically insulated from the rest of the calorimeter module.

The length of each uranium plate is 110 cm while the width varies from 23.4 cm at the front to 31.8 cm at the rear of the module. Each U plate thus covers two ionization chambers. Each module has 16 towers, with the electrodes of each tower connected in depth as indicated in Table 2. The overall assembly of plates and chambers is held together by 8 straps spanning a 15 mm thick aluminium plate at the front and an 18 mm stainless steel plate at the rear of the module. All the preamplifiers are placed on the front face of the module. The signals from the position detector strip electrodes are brought to the front via flexible multilayer printed circuit boards.

Most of the results presented here are from a module in which 16 electrodes out of a total of 1008 were disconnected due to large currents drawn at relatively low voltages. However at 1000V only 3 electrodes were disconnected in the towers numbered 1 - 6 in Fig.1 where most of the electron and hadron beam data were taken. The high voltage problem arose due to the presence in the liquid of

small inert particles (dust, small fibres etc.) found after filling. New modules have been prepared under stricter purity control to eliminate such particulate matter. These have been taken up to 1700 V and show a much better behaviour.

3. The Electronics Chain

A schematic diagram of the electronics chain for the calorimeter is shown in Fig. 4. and further details can be found in Reference 5. The detector capacitance, C_D , varies from 435 pF for the smallest electrode to 590 pF for the largest one. A test capacitor, C_T , measured to a precision of a few per mille, is used to inject a precisely known test charge to calibrate the electronics chain. After the blocking capacitor, C_B , all the electrodes of a given sampling are connected to one preamplifier. The capacitance seen by the preamplifiers varies between 2.2 and 7.2 nF depending on the number and the surface area of the electrodes connected. The same quantity for the position detector is 125 pF for the shorter strips and 175 pF for the longer ones.

The preamplifiers [5] for the calorimeter were designed for a high detector capacitance and a large dynamic range. The preamplifiers are mounted as close as possible to the detector electrodes in order to minimize the stray capacitance. As the modules have to work in a large magnetic field transformer matching was not possible and an input stage consisting of 4 jFET's in parallel is employed. The shaping is carried out with a filter of the type $(t/\tau)^2 e^{-t/\tau}$ with $\tau = 1 \mu s$. This is a compromise between a good noise performance and a fast return to the baseline for the Sp $\bar{p}$ S collider operation where the bunch crossing time is 3.8 μs . The 96 preamplifier channels of each module are connected through a two-stage multiplexer to a multirange ADC with a dynamic range of 2^{15} and an 8 bit resolution.

4. The Beam Layout

The calorimeter modules were tested in the CERN SPS X1 test beam which provides particles with momenta ranging from 7 to 70 GeV/c. The layout, shown in Fig. 5, included beam-defining trigger scintillation counters (S1, S2), beam halo veto scintillator (V), two Cerenkov counters (C1 and C2) to select electrons, and wire chambers (MWPC's) to measure the position of the beam particles. Further wire chambers placed before and after a bending magnet in the SPS beamline enabled momentum measurement of each incident particle.

An iron/scintillator calorimeter (C- Module, cf. Table 2) with two depth segments, each read out by two photomultipliers, is placed behind the U/TMP calorimeter to simulate the experimental setup of the UA1 experiment. This is followed by two more scintillation counters (M1 and M2) sandwiching a 1.6 m thick iron block to allow triggering on muons. The U/TMP module was

mounted on a platform which enabled it to be moved both horizontally and vertically with respect to the beam.

5. Results

The data presented here were taken at an electric field of 8 kV/cm unless specified otherwise.

5.1 Measurement of the free electron lifetime in a module filled with TMP

If the lifetime (τ_e) of the free electrons, produced in TMP by ionization, is long compared with the time (t_d) taken by an electron to drift from one electrode to the other then the collected charge, and hence the calibration, is insensitive to small changes in τ_e and in the externally applied voltage, V . When $t_d \geq \tau_e$ the time evolution of the signal pulse is dominated by the finite free electron lifetime. This condition is satisfied at low electric fields and can be used to determine τ_e . However for large electron lifetimes ($\tau_e \geq 100 \mu\text{s}$) and small drift gaps (1.25 mm in our chambers) a very low voltage has to be applied. The systematic errors then become prohibitively large and hence we can only give a lower limit on τ_e , usually around 30 μs , for the electron lifetime in TMP contained in the calorimeter ionization chambers.

The observed pulse shape was compared with the one expected for a given lifetime after convolution with the amplifier response function. High energy electron showers were used to generate the prompt signal pulses in a single ionization chamber, at a depth of $\sim 6X_0$, run at an electric field of 0.16 kV/cm. The pulse shapes were digitised by LRS2256 waveform digitisers. The drift time was left as a free parameter to allow for the uncertainties in the size of the drift gap ($\leq 10\%$), in the magnitude of the electric field ($\leq 7.5\%$) and in the measured value of the electron mobility which ranges from 24 - 32 $\text{cm}^2 \text{s}^{-1} \text{V}^{-1}$ [6]. Fig. 6 shows the results of a fit to the average of many pulse shapes with t_d left as a free parameter and τ_e fixed at 35 μs . The drift time, found to be 37.5 μs , is consistent with 26 μs for the nominal values of the drift gap, the electric field and an electron mobility of 30 $\text{cm}^2 \text{s}^{-1} \text{V}^{-1}$. There is a small correlation between τ_e and t_d as high values of τ_e result in smaller fitted values of t_d . From such fits it can be deduced that the electron lifetime is greater than 25 μs at 95 % CL.

5.2 The Equivalent Noise Charge (ENC) and the response to muons

The total noise in all the calorimeter channels was measured at several electric fields. The equivalent noise charge is given by the r.m.s. of the pedestal distribution and is shown in Fig.7 for a first electromagnetic sampling. The contribution to the noise of ionizing particles from radioactive decays in uranium, estimated from the difference between the measurements made at 8 kV/cm and zero field, is also shown in Fig. 7. At 8 kV/cm we measure a total ENC ~ 6600 e's for a first

sampling. The size of the uranium signal is found to be ~ 3300 e's. The total ENC varies from ~ 6000 e's for the first samplings to ~ 15000 e's for the sixth samplings.

The preamplifiers of the position detector were designed for a low detector capacitance. The ENC values at 8 kV/cm were found to be 1000 e's for the long strips and 800 e's for the short ones.

The pulse height distribution of 70 GeV/c muons, summed over all the six samplings of a single tower, is compared in Fig. 8a with that from the pedestal events (hatched histogram). Defining the signal to noise ratio as $S/N = (\text{peak of the pedestal subtracted signal} / \text{r.m.s. of the pedestal distribution})$ gives $S/N \sim 3.6$. The mean value of the signal distribution is found to be $\sim 60\%$ higher than the peak value. A more relevant parameter is the percentage of pedestal events that pass a cut on the pulse height for a given muon detection efficiency : for a cut set at $2\sigma_{\text{ped}}$ only 3.9% of the muons are removed while retaining only 2.3% of pedestal events.

Fig. 8b compares the distribution of muon pulse height, observed in the short strips of the position detector, with that from the pedestal events (hatched histogram). Using the above definition for signal over noise we find $S/N \sim 2.0$ in the position detector. It should be noted that this is the signal seen in 2.5 mm of TMP.

5.3 Response to electrons

Electrons of momenta of 7, 10, 20, 40, 70 GeV/c were fired in the centre of tower 4. Ten thousand events were taken at each energy and cuts on wire chamber position, S1, S2, C1 and C2 pulse heights and $\Delta p/p$ were applied. A single tower is large enough to contain high energy electromagnetic showers laterally and there is negligible longitudinal leakage of energy ($\leq 0.5\%$) beyond the fourth sampling even at the highest energy. The electron energy measurement is thus made using the first four samplings of a single tower ; the reconstructed energy, E_{rec} , is given by

$$E_{\text{rec}} (\text{GeV}) = \alpha \sum_{i=1,4} Q_i (\text{fC})$$

where α is assumed to be an energy independent calibration factor and is found to be 0.028 GeV/fC. The momentum of each incident electron was measured using the multiwire proportional chambers before and after a bending magnet in the beamline. The pulse height distribution for 50 GeV/c electrons is shown in Fig. 9a. The energy equivalent of the r.m.s. of the electronic and uranium noise is found to be 105 MeV. This was quadratically subtracted from the r.m.s. of the signal to enable the evaluation of the intrinsic sampling and constant terms of the resolution function. The result of the fit to the measured energy resolution is shown in Fig. 10 and yields

$$(\sigma(E) / \langle E \rangle)^2 = (0.120 \pm 0.004 / \sqrt{E})^2 + (0.009 \pm 0.001)^2$$

where E is in GeV. If the noise is not subtracted and an additional term (added quadratically) of the

form $(b/E)^2$ is allowed in the fit the same result is found with ~ 100 MeV for the coefficient b . The sampling term is well reproduced by the GEANT Monte Carlo program. The constant term is believed to be due to residual beam energy mismeasurement, sampling to sampling intercalibration uncertainty, longitudinal energy leakage and other smaller effects.

The energy linearity has been examined and is shown in Fig. 11 where the charge collected in the first four samplings of a SG tower is plotted against the beam energy. The linearity is found to be better than 1% and is limited by the lack of knowledge of the exact beam energy.

5.4 Response to pions

Electron and pion data were taken with the beam incident at the point A (Fig.1a) situated 1.2 cm below the horizontal boundary between towers 3 and 4. Data were taken at 7, 10, 20, 30, 50 and 70 GeV. Ten thousand events were recorded for each energy except for 7 (1.5k) and 10 (5k) GeV/c due to the low pion flux at these momenta. The longitudinal energy leakage, and some of the lateral leakage, was captured by the C module. The lateral energy leakage is estimated from recent measurements with a three module assembly to be less than 5%. However, we have not applied any leakage corrections to the results which follow. The C module is a non-compensating ($e/\pi \sim 1.4$) hadron calorimeter with a hadronic energy resolution of $\sim 100\% / \sqrt{E}$. The pion showers are thus sampled longitudinally with three different sampling fractions. The reconstructed energy for pions is taken to be the sum of energies seen in all the samplings of towers 1 to 6 and the two samplings of the C-Module i.e.

$$E_{\text{rec}} (\text{GeV}) = \sum_{T=1,6} \left\{ \alpha \sum_{i=1,4} Q_i (\text{fC}) + \beta \sum_{i=5,6} Q_i (\text{fC}) \right\} + \beta_c \sum_{i=1,2} E_i^c (\text{GeV})$$

where α is fixed to the value found for electrons and β and β_c , also assumed to be energy independent calibration factors, are determined from the minimisation of the difference between the reconstructed and the beam energies. The ratio β/α and the value of the parameter β_c are found to be 2.55 and 1.44 respectively. We have again subtracted the noise contribution, amounting to 940 MeV, and obtain an energy resolution (Fig.12) that can be parameterized by

$$(\sigma(E) / \langle E \rangle)^2 = (0.581 \pm 0.009 / \sqrt{E})^2 + (0.068 \pm 0.002)^2.$$

The energy resolution can also be parameterized as

$$\sigma(E) / \langle E \rangle = (0.500 \pm 0.014 / \sqrt{E}) + (0.037 \pm 0.002).$$

The relatively large constant term is due to the non-uniform sampling of the hadronic showers. The pulse height distribution of 50 GeV/c pions is shown in Fig. 9b and has negligible residual tails when compared to the result of a Gaussian fit.

The β coefficients, with α fixed, can also be determined by minimizing the pion energy resolution at a single energy, for example 70 GeV. The values of β and β_c are found to differ by less than 1 % from the ones found above.

5.5 The ratio of the electron / pion response.

Electron and pion data were taken at the impact point, A, indicated in Fig. 1a. The energies were reconstructed using the α and β coefficients determined above. Fig. 13 illustrates, as a function of the particle energy, the ratio of the reconstructed electron ($E_{\text{rec}}(e)$) and pion ($E_{\text{rec}}(\pi)$) energies taken from the mean of a Gaussian fitted to the measured energy distributions. This ratio varies between 1.08 at 7 GeV to 1.02 at 70 GeV. It can be seen that a 2.35 λ SG U/TMP module backed by the C module results in a configuration that is compensating.

5.6 Uniformity of response

A beam of 70 GeV electrons (5 k events) was fired at the centres of all towers to study the uniformity of the response. After correcting the pulse height for the disconnected electrodes, using an average shower profile determined from Monte Carlo calculation, we find that the responses show an r.m.s. variation of 0.7 % (Fig. 14).

A more detailed scan, in bins of 2 mm, over areas with cracks or steel bars was also carried out with a 40 GeV electron beam (5 k events). The scan was performed with the beam incident perpendicularly to the front face. The position of each incident electron was measured with a proportional wire chamber situated just in front of the module. The results (Fig. 15a) show clearly the decrease in the collected charge when the electron shower is centred on the stainless steel frames of the chambers. The decrease is largest where two adjacent chambers meet. The small increase in the collected charge when the beam is fired between towers 7 and 5 is due to the liquid gap being larger by 0.5 mm in between adjacent electrodes.

The calorimeter was designed for a non-pointing geometry and hence particles enter at an angle. A better uniformity is obtained for electrons incident at an angle of 25° as can be seen from Fig. 15b. The normalization is taken from the runs at normal incidence.

5.7. The influence of the electric field

We have studied the dependence on the electric field of

- i) the ratio $E_{\text{rec}}(e) / E_{\text{rec}}(\pi)$,
- ii) the electron and pion energy resolution.

The electric field was varied between 0.8 kV/cm and 8 kV/cm. 10 k events were taken for each value of the field and at three momenta (20, 40 and 70 GeV/c) for both electrons and pions. $E_{\text{rec}}(\pi)$ was not corrected for transverse energy leakage. Fig. 16 shows the variation of the ratio $E_{\text{rec}}(e) / E_{\text{rec}}(\pi)$ for different electric fields and different incident energies. The variation is not as marked as has previously been observed in the deeper (3λ) and coarser sampling (1cm U) VFW U/TMP module [2]. However the variation for 20 GeV particles is significant and lower energy measurements are needed to study the trend. The pion energy resolution (Fig. 17b) improves significantly with higher electric field whereas the electron energy resolution (Fig. 17a) does not change above a relatively low electric field of ~ 2 kV/cm, as previously observed in the VFW module. The improvement in pion energy resolution is due to the different electric field dependence of the collected charge for heavily ionizing particles, as opposed to minimum ionizing ones. Heavily ionizing particles are usually present in hadronic showers, and especially in hydrogenous active materials like TMP due to interactions of low energy neutrons with almost free protons. A detailed study of the variation of the collected charge as a function of the electric field for muons, electrons and pions is in progress. The results will be reported in a subsequent paper.

5.8. The position detector

Results from the position detector (PD) have been reported in an earlier publication [4]. Those data were taken with six 2 mm U plates, separated by 3 mm air gaps, placed in front of a stand-alone PD. Here we report on the results obtained from the position detectors integrated into the calorimeter modules. We have determined the position resolution for single electromagnetic showers by comparing the position of each incident electron, measured by the wire chamber placed directly in front of the calorimeter module, with that evaluated by the method of weighted mean (weighted by pulse height). It is well known that this method results in a systematic shift of the reconstructed position towards the centres of the strips. As can be seen in Fig. 18a this shift is well defined and hence a correction can be made for it. In Fig. 18b is plotted, as a function of energy, the r.m.s. of the distribution of the difference between the positions measured by

- i) the weighted mean and the wire chamber,
- ii) the corrected weighted mean and the wire chamber and
- iii) as (i) but for a thin slice at the position 4.5 mm in Fig. 18a which gives the smallest r.m.s.

The wire chamber measures the position of the incoming particles with a resolution of 200 μm . The spatial resolution achievable in an experimental situation, as in (ii), is better than 1 mm at high energies.

5.9 The electron - pion separation.

The difference between the development of electromagnetic and hadronic showers, both laterally and longitudinally, can be used to distinguish electrons from pions. We have studied the electron-pion separation for single particles with an incident particle energies of 7, 10, 30, 50 and 70 GeV using the method outlined below. Since we use six towers to measure the energy of pions there are 39 distinct energy measuring elements (6x6 in the SG, 2 in the C and 1 for both planes of strips of the PD).

For a sample of N electrons we constructed a 39 x 39 covariance matrix, M_{ij}^e , whose elements are given by

$$M_{ij}^e = \frac{1}{N} \sum_{n=1}^N (E_i^{(n)} - \bar{E}_i^e) \times (E_j^{(n)} - \bar{E}_j^e)$$

where $E_i^{(n)}$, $E_j^{(n)}$ are the energies observed in the i th, j th element for the n th electron and $\bar{E}_i$, $\bar{E}_j$ are the average energies deposited in the respective elements by electrons. Similarly a matrix, M_{ij}^π , is constructed for pions. The inverse matrix $H = (M)^{-1}$ can be used to define a particle "likeness" variable, e.g. ζ^e for an electron test, for any arbitrary event,

$$\zeta^e = \frac{1}{39} \sum_{i,j=1}^{39} (E_i - \bar{E}_i^e) (H)_{ij}^e (E_j - \bar{E}_j^e)$$

The probability density function (p.d.f.) of ζ^e for electrons, of the same energy as the ones used to determine M^e , should have a mean of 1 and a shape consistent with that for a χ^2 distribution if the individual reconstructed energies were Gaussian in shape (which they are not). A similar result would be obtained for ζ^π determined for pions. The difference in the shower profiles of electrons and pions will lead to very different shapes, as compared with χ^2 ones for ζ^e and ζ^π determined for pions and electrons respectively. The standard Neyman - Pearson test, known to be optimal in such a case of two separate hypotheses, suggests a cut on the ratio of the two p.d.f. of the observations. In the case of Gaussian shaped energy deposits this would be equivalent to a cut on the variable $\Delta = \zeta^e - \zeta^\pi$. Although the individual energy distributions in this study are not Gaussian in shape we nevertheless use the difference Δ to discriminate between the electron and pion hypotheses. The distribution of the difference Δ is shown in Fig.19a for electron events and in Fig. 19b for pion events for an incident beam energy of 30 GeV. Fig.19c shows the latter distribution on a coarser horizontal scale. The electron identification efficiency, ϵ_e , is determined by a cut in the Δ distribution shown in Fig.19a., below which $\epsilon_e\%$ of the events are kept. The same cut is then used on the distribution shown in Fig. 19b. to determine the probability that a pion looks like an electron. This probability is shown in Fig. 20a for electron identification efficiencies of 90% and 97%. The indicated error bars are purely statistical. Fig. 20b shows the same distribution when the pulse height from the PD is not used.

We have also determined the electron - pion separation capability of the position detector when used alone. The total pulse height in 5 vertical and 5 horizontal PD strips centred on the beam impact point is compared in Fig. 21 for electrons and pions of energy of 70 GeV. The electron identification efficiency is defined by a cut on the electron pulse height distribution. The same cut is applied to the pion pulse height distribution and the resulting probability that a pion passes the electron cut is shown in Fig. 22 for electron identification efficiency of 90%. It can be seen that the PD on its own can provide a pion rejection factor of greater than twenty for pion energies larger than 10 GeV.

6. Conclusions

The results from the beam tests of a UA1 U/TMP gondola calorimeter module are summarized below:

- i) the modules can be operated at electric fields in excess of 8 kV/cm and perform well as a combined electromagnetic and hadronic calorimeter. A high lateral and longitudinal segmentation has been possible including two orthogonal planes of position measuring strips, embedded at a depth of $3.5 X_0$.
- ii) the energy resolution for electrons and pions has been measured and is found to be in agreement with expectation from Monte Carlo studies. It is given by $(\sigma(E) / E)^2 = (0.12 / \sqrt{E})^2 + (0.009)^2$ for electrons and $(\sigma(E) / E)^2 = (0.581 / \sqrt{E})^2 + (0.068)^2$ for pions for $7 < E < 70$ GeV. The energy equivalent of the noise is found to ~ 100 MeV for electrons and ~ 1 GeV for pions.
- iii) the signal from 70 GeV muons, summed over all the samplings of one tower, yields a signal to noise ratio of 3.6 if the peak of the deposited energy distribution is used.
- iv) the ratio of the electron and pion energies measured using the U/TMP and the Fe/scintillator modules is found to be close to 1 implying that compensation can be attained in a calorimeter with a non-uniform sampling without sacrificing energy linearity or introducing tails in the reconstructed energy distributions. However a large constant term is present in the pion energy resolution function.
- v) the pion energy resolution improves significantly as the applied electric field is increased though neither the electron energy resolution nor the ratio $E_{rec}(e) / E_{rec}(\pi)$ show much dependence above a relatively modest electric field of ~ 2 kV/cm. The dependence on the electric field of the latter was only studied for energies greater than 20 GeV.
- vi) the point to point uniformity of response is clearly affected by the presence of stainless steel bars used as frames for the chambers. However, it is better than 1% in regions more than 1cm away from these bars.
- vii) the spatial resolution measured in the position detector for single electromagnetic showers is better than 1 mm for energies greater than ~ 30 GeV.
- vii) the $e-\pi$ separation is $\sim 10^{-4}$ for energies greater than ~ 50 GeV for an electron identification efficiency of 90 %.

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Figure Captions

- Fig. 1. Schematic view (a) and cross-section (b) of a Super-gondola Module.
- Fig. 2. An exploded view of the mechanical structure of an ionization chamber.
- Fig. 3. Mechanical structure of a position measuring ionisation chamber.
- Fig. 4. Schematic diagram of the electronics chain for the U/TMP calorimeter.
- Fig. 5. Layout of the elements in the CERN SPS X1 test beam.
- Fig. 6. The time evolution of the observed charge in an ionization chamber at a depth of $\sim 6X_0$ for 70 GeV electrons. The line represents a fit to the data with the normalization and the drift time as free parameters.
- Fig. 7. The measured equivalent noise charge (ENC) as a function of the electric field. The contribution from the ambient uranium radioactivity is extracted from the total ENC.
- Fig. 8. Comparison of the signal from 70 GeV muons and the pedestal distribution (hatched histogram) for a) the sum of all 6 samplings of one SG tower and b) the short strips of the position detector.
- Fig. 9. The reconstructed energy distribution for (a) electrons and (b) pions of an energy of 50 GeV.
- Fig.10. The energy resolution for electrons as a function of energy.
- Fig.11. Comparison between the charge collected in the first four samplings of a SG tower and the incident beam energy for electrons.
- Fig.12. The energy resolution for pions as a function of energy.
- Fig.13. The ratio of the reconstructed electron to pion energies as a function of the incident particle energy.
- Fig.14. The uniformity of response to 70 GeV electrons incident in the centre of the 16 towers of a SG module.
- Fig.15. The uniformity of response to electrons incident over areas which include ones with cracks or steel bars a) perpendicularly and b) at an angle of 25° .
- Fig.16. The ratio of the reconstructed electron and pion energies as a function of the electric field.
- Fig.17. The energy resolution for (a) electrons and (b) pions as a function of the electric field.
- Fig.18. a) The difference between the reconstructed position (y_{PD}) given by the PD and the one given by the wire chamber (y_{WC}) versus the PD reconstructed position for 30 GeV electron showers. Zero represents the centre of a strip.
b) The r.m.s. of the distribution of the difference between the positions as a function of the beam energy measured by
i) the pulse height weighted average and the wire chamber (triangles),
ii) the corrected pulse height weighted average and the wire chamber (squares) and
iii) as (i) but for a thin slice in Fig. 18a that gives the smallest r.m.s. (crosses).
- Fig.19. The distributions of the electron likeness minus the pion likeness for a) electron events, b) pion events and c) pion events for a coarser horizontal scale. The incident energy of the particles is 30 GeV.
- Fig.20. The probability, as a function of energy, that a pion looks like an electron a) using the PD signals and b) without using the PD signals.

- Fig.21. The measured pulse height in the two planes of strips in the PD for a) electrons, b) pions and c) pions for a coarser vertical scale. The incident energy of the particles is 70 GeV.
- Fig.22. The probability, as a function of energy, that a pion passes the electron cuts in the PD for an electron efficiency of 90%.

Table 1 Properties of some of the room temperature calorimeter liquids.

	TMS	TMP	HEDS
Chemical formula	$C_4H_{12}Si$	C_9H_{20}	$C_8H_{22}Si_2$
Density (g/cm ³)	0.65	0.72	~0.75
dE/dx (MeV/cm)	1.36	1.58	~1.60
G_{fi} at 15kV/cm (ion pairs/100eV)	1.12	1.29	0.76
Mobility at 15kV/cm (cm ² /V.s)	110	30	45
Drift time (ns)	75	250	185
at 15 kV/cm and for 1.25 mm gap			
Flash point (°C)	-18	7	~10
Boiling point (°C)	27	123	150
Vapour Pressure (Torr at 20°C)	650	15	< 10
Dielectric constant	1.92	1.98	-

Table 2. Parameters of the U/TMP Super-Gondola and the Iron/Scintillator C Modules

Sampling Number	Plate Thickness (mm ²³⁸ U)	No. of TMP Chambers	Radiation Lengths	Interaction Lengths
Super-Gondola (SG)				
e.m. 1	2	5	2.9	0.15
2	2	9	6.1	0.23
3	2	15	10.1	0.39
4	2	10	6.7	0.26
Total e.m.			25.8	1.03
Had. 5	5	12	19.3	0.66
6	5	12	19.3	0.66
Total e.m. + had			64.5	2.35
C Module				
1	8 x (5cm Fe + 1cm scintillator)			2.50
2	7 x (5cm Fe + 1cm scintillator)			2.19

Fig. 1

Fig. 2

Fig. 3

Fig. 4

TRIGGERS

$$e : S1 \cdot S2 \cdot \overline{V} \cdot C1 \cdot C2 \cdot \overline{M1}$$

$$\pi : S1 \cdot S2 \cdot \overline{V} \cdot \overline{C1} \cdot \overline{C2} \cdot (\overline{M1} \cdot \overline{M2})$$

$$\mu : S1 \cdot S2 \cdot \overline{V} \cdot M1 \cdot M2$$

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22