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**A STACK OF TWO-DIMENSIONAL MULTIWIRE PROPORTIONAL CHAMBERS
AS PART OF AN ELECTROMAGNETIC CALORIMETER**

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ABSTRACT

A set of four multiwire proportional chambers with analog readout were inserted in the calorimeter of the R704 experiment at the CERN ISR. In this experiment, charmonium ($c\bar{c}$) resonances were directly formed through $p\bar{p}$ annihilation. Owing to the high hadronic background, only electromagnetic final states (e^+e^- and $\gamma\gamma$) were detected. Located near the maximum of the electromagnetic shower development, the stack of four chambers had as its main purpose a fine spatial localization, together with a good electron-hadron discrimination and multi-shower rejection in the critical few GeV region.

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1. INTRODUCTION

Good energy resolution is usually the primary goal in designing a calorimeter but for specific experiments other considerations have to be taken into account. This was the case of the R704 experiment at the CERN Intersecting Storage Rings (ISR) [1], where position determination, multi-shower rejection, and particle identification, as well as high detection efficiency for low-energy photons, were also important points to be taken into consideration.

Although, on the one hand, the best energy measurement is given by homogeneous calorimeters, the other requirements generally lead to much more complexity in the structure of the calorimeter. The determination of the detector characteristics involves compromises since the parameters which optimize the different responses are conflicting.

The aim of our experiment was to study charmonium ($c\bar{c}$) resonances directly formed in $p\bar{p}$ annihilation of a molecular hydrogen jet target with a cooled antiproton coasting beam in ring 2 of the ISR.

All these resonances are detected in electromagnetic final states either directly [1]:

$$p\bar{p} \rightarrow J/\psi \rightarrow e^+e^- \quad (1)$$

$$p\bar{p} \rightarrow \eta_c, \chi_2 \rightarrow \gamma\gamma \quad (2)$$

or in their decay through J/ψ [2]:

$$p\bar{p} \rightarrow \chi_{1,2} \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^- ,$$

$$p\bar{p} \rightarrow {}^1P_1 \rightarrow XJ/\psi \rightarrow Xe^+e^- .$$

The cross-section for these reactions is in the nanobarn region as compared to the total antiproton-proton cross-section of about 70 mb. Therefore, very high selectivity of electromagnetic showers and rejection against hadronic background was necessary.

The numerous π^0 produced in the $p\bar{p}$ annihilation lead to an important background for channel (2). Symmetric π^0 decays give overlapping showers which could be difficult to disentangle. Very asymmetric π^0 decays produce a high-energy γ whose direction mimics that of the electromagnetic shower in the two-body reaction (2), and the only way to get rid of these events is to be able to detect the low-energy partner. Therefore, the possibility of extracting reaction (2) is ultimately limited by the degree of multi-shower rejection of the apparatus and by the ability of detecting low-energy photons.

The R704 detector was a two-arm non-magnetic spectrometer (fig. 1) complemented by a large-acceptance veto system. Both arms, which were identical, included an upstream section for tracking charged particles, with scintillator counter hodoscopes, multiwire proportional chambers (MWPCs) with digital readout, and Cherenkov counters, followed by an electromagnetic calorimeter.

The combination of a 4.7 radiation lengths highly segmented lead/scintillator sandwich (the so-called precalorimeter) and a 10 radiation lengths lead-glass wall assured the shower containment of electrons below 5 GeV and gave, together with a satisfactory energy resolution, a good detection efficiency for low-energy photons (down to 50 MeV), as well as a first determination of particle position and identification.

To have a better shower localization, and both high two-shower resolving power and electron-hadron discrimination, we needed a third detector to be inserted between the precalorimeter and the

lead-glass wall. It had to be a compact and low-absorbing device with high granularity near the maximum of the shower development.

Three kinds of detectors were considered: a fine-grained scintillator hodoscope, proportional tubes, and MWPCs. The scintillator hodoscope offers evident advantages, especially if compared to the intrinsic complications of the gas-gap detectors. However, the fine transverse modularity and multilongitudinal depth sampling involve more expense and technical problems than we could cope with.

The choice between proportional tubes and MWPCs mainly depended on the local facilities of manufacture. The latter, which is compact, reliable, and has a well-known and easy construction technique, seemed to us still the most suitable one [3].

Nevertheless, some difficulties are inherent in this kind of device for calorimetry: the fluctuations of the energy deposit in the shower process are very much worse in the case of the gas-gap detectors, because of their sensitivity to the incoming as well as back-scattered transverse soft rays in the gap [4] which sometimes leave a parasitical ionization density higher than that due to the central part of the shower itself.

Although they cause some amelioration, the efforts to stop these large-angle soft electrons before they cross the chamber gap are not sufficiently effective. So the shower sampling often shows important distortions, in such a way that the expected shape of the distribution can become hardly recognizable. Therefore, the performances of a single gas gap inserted in a calorimeter, at any depth of the shower development, and used as a discriminator and position detector, could suffer serious problems in the few GeV region [5].

On the other hand, cuts on the track length in transverse propagation into the gap [4, 6], for instance by the wall of proportional tubes, can appear as a rather random action, in the case of a local insertion in a calorimeter. The starting idea, in our set-up, was that software methods could take effect against the troublesome large-angle deposits. Several successive layers with two-dimensional measurements could allow the retrieval of the real correlated shower development in depth, and eliminate the parasitic parts of the distributions as uncorrelated ones.

In order to check our assumptions, we first built a 1 m² prototype, two-gap wire chamber, with two-dimensional readout on each gap. Tests were performed in the q₁₂ beam at the CERN Proton Synchrotron (PS) with electrons of 1 to 4 GeV. Then, two final stacks of five gaps each were constructed as part of the R704 calorimeter. One of them was tested in the t₆ beam at the PS, before installation in the ISR experimental area.

In section 2, we describe the prototype and present the main results obtained with it. Section 3 is devoted to the description of the final detector and its monitoring system. In section 4, we report on its performances, with emphasis on the electron-hadron separation and multi-shower rejection.

2. PROTOTYPE DETECTOR

2.1 Main features

The two-gap prototype was built from Vetronite frames and aluminium supports. The cathode planes were made from a copper-Kapton printed circuit strongly stretched and cemented on two Vetronite frames and divided into X and Y strips. Another Vetronite frame supported the anode layer of gold-plated tungsten wires parallel to the X cathode plane strips.

Two aluminium planes formed the middle walls of the modules, a space between them allowing the insertion of lead foils of different thicknesses.

The main features of each chamber of the prototype were the following:

half gap: 5 ± 0.05 mm

anode pitch: 4 mm

anode wire diameter: 20 μm
cathode strip pitch: 8 mm
cathode strip width: 6 mm
sensitive area: 1160 $\times$ 905 mm²
aluminium plate thickness: 4 mm
gas composition: Ar 80% + CO₂ 20% (vol.)

2.2 Electronics and readout

Low-noise charge amplifiers were connected to the cathode strips via 2 m, thin coaxial cables; 24 $\times$ 24 X/Y strips were read out from each gap in the central part of the chamber area, the other ones being coupled to the ground.

After amplification, the signals were sent to the analog-to-digital converters (ADCs) via coaxial cables, 80 m in length, simulating the conditions of the experiment. The white noise at the ADC input was about twice the noise of the amplifiers themselves (13 mV compared to 6 mV). Twelve-bit LeCroy 2282B ADCs were used, driven by a 2280 LeCroy processor. The HV anode wires were not read out during these tests.

2.3 Experimental test set-up

Electrons of the q₁₂ beam in the South Hall of the CERN PS were tagged by two Cherenkov counters. An array of scintillation counters and digital-readout MWPCs defined the incident trajectories and multiplicities. Simulating the R704 precalorimeter (fig. 1) a lead/plexiglas sandwich converter, whose length could vary, was put in front of the first gap of the stack.

2.4 General results

The first investigations on the electron shower sampling mainly concerned the following parameters:

- energy of incoming electrons
- conversion length before the stack
- distance between the end of the precalorimeter and the first detection gas gap
- lead thickness between the chambers.

The aim was to get a clear insight into the behaviour of the prototype, especially its capability of separating multi-showers while keeping a good spatial resolution, and finally to arrive at the optimized parameters of the final stack, in particular the number of chambers to be put in and the pitch of the cathode strips.

The gain of the chambers was kept around 5×10^3 , which was at the limit of the readout saturation for the highest pulses. Figure 2 shows the linearity of the total collected charges with the energy of incoming electrons. The mean number of the strips fired in the first gap (fig. 3) and the experimental profiles for four incident energies (fig. 4) are also shown, after 4 radiation lengths of converter. The average radial shower development at different depths, for 4 GeV incoming electrons, is presented in perspective view (fig. 5). The fast degradation of the shower deposit shape with the distance between the end of converter and the first detection plane was again confirmed [9, 3b] (fig. 6).

There is a marked difference between the well-known shower distributions, integrated over a lot of events, and those, often very complicated, observed for a single event, in each gap. In the latter case, the distribution of the energy deposits shows several maxima of various amplitudes, sometimes far from the shower axis. Thus, the part of the distribution due to the large number of electrons of the shower core, and that due to the high ionization density coming from a single slow electron

crossing the chamber at a large angle or a low-energy photon converting in it cannot be discriminated in a single gap.

If the fluctuations due to the soft rays are not longitudinally correlated, adding several gas layers along the shower development will allow extraction of the central part (correlated) from the sometimes numerous peaks observed in each gap. In addition, we tried to act against persistent correlations coming from soft rays crossing more than one gap by inserting thin lead foils between the gaps. A slightly cleaner effect could be seen with 1 mm thickness or more.

Figure 7a shows the density of maxima in a single chamber as a function of the radial distance from the reference track given by the digital MWPCs. The existence of a second chamber substantially decreased the number of possible tracks (by a factor of 3 to 6) in particular far from the incident impact point. We checked, in different ways, that the remaining tracks were entirely compatible with a random origin, first through a simple calculation of the number of tracks haphazardly produced, secondly by comparing the number of correlations obtained by associating the maxima of the first plane with those of the second plane, taken either on the same side of the shower axis or on the opposite side (fig. 7b).

We concluded that all the accompanying tracks were due to fortuitous coincidences. A way to lower them would be to increase the number of chambers. Choosing a total of four gas layers for the final stack would sufficiently reduce the number of random correlations, while maintaining the whole detector within our financial and technical limitations.

Spatial localization was investigated by comparing the analog chamber results with the information given by the set of digital MWPCs. A value of $\sigma = 2.4$ mm (98% of events inside 10 mm) was obtained for 4 GeV shower electrons after 4 radiation lengths (fig. 8). The resolution deteriorated quickly for lower energies ($\sigma = 5.9$ mm, 91% of events inside 10 mm at 2 GeV) and for wider strips ($\sigma = 5.3$ mm, 86% of events inside 10 mm for 4 GeV electrons, when going from 8 mm to 16 mm strip width).

The conversion length before the chamber is an important parameter. A compromise had to be made between poor shape at the end of the detection for early showers of lower energies, and loss of the latest conversions. Choice of the $t_{\max}$ (about 4.5 radiation lengths) corresponded to only 4% of unconverted photons.

One of the outstanding problems in the R704 experiment was the ability to separate events coming from π^0 (containing two showers) from single-shower events. So it was of a major interest to evaluate the possibilities of our prototype in distinguishing single photons from a photon-photon pair. To check the efficiency of various algorithms, we constructed a sample of two-shower events by randomly pairing individual shower events. The separation could be simulated and varied by shifting one of the showers relative to the other. We compared single-shower events of energy E with two-shower events assembled from a sample at energy $E/2$. The two-shower events roughly simulated the distribution of distances from symmetric decay of π^0 in $p\bar{p} \rightarrow \pi^0\pi^0$, the most dangerous background reaction at the centre-of-mass energy of the η_c (25% of events with distance less than 10 cm) (see inset of fig. 9).

Different variables were tried. The second moment of the distribution gave far better separation. Combining the information coming from one single plane, one chamber, and finally the two-chamber prototype (fig. 9) we could, with an adequate cut, find a working point with 95% of two-shower rejection and 95% of single-shower efficiency.

In conclusion, the strip-chamber prototype used in the q_{12} beam gave very satisfactory results concerning spatial resolution of electromagnetic showers and rejection of multi-shower events, thus predicting the final stack detector performances to be very consistent with our requirements.

3. FINAL DETECTOR FEATURES AND OPERATION

3.1 Stack structure

Our confidence, which came from the good behaviour of the prototype, without any problems even when pushed into the beginning of the Geiger region, led us to a very simplified manufacturing structure of the final stack. We followed the accurate and well-suited method of making a cathode foil originated by A. Gandi at CERN. The X/Y cathode prototype array was maintained, the strip pitch being extended to 10 mm to conciliate good spatial resolution and channelling cost.

We chose a modular assembly of five chambers in a stack, the manufacturing process of each chamber module being the following. We reduced the width of the module frames, without any joint between them, and we sealed by calibrated 20 μm epoxy film all the gap constituents themselves, enclosing the gap between two aluminium plates, also glued on the outside of the cathode frames, with a thin spacer.

These aluminium plates had both a quenching effect for the large-angle soft rays before they crossed the gap, and a stiffening action, so that a monoshell laminated effect was obtained for the module rigidity. Thus five identical modules were accurately piled up, the fifth being a spare one, with a compactness of 20 mm thickness per module of 1 m^2 of sensitive area. The first three modules were separated by 1 mm thick lead foil. Figures 10 to 13 show different views of the chamber stack.

Twenty-five monitor sources of ^{55}Fe (a few nCi each) were diagonally deposited on the outside Kapton face of one of the cathode foils of each chamber. In this way we could avoid the Auger effect in the X-ray absorption spectrum, trapping the electrons crossing the foil. The anode wire signals were ORed in strips of 20 cm width, with the aim of generating the gates of the control monitor system.

The features of one chamber module of the final stack were the following:

half gap: 5 ± 0.02 mm

anode pitch: 4 mm

anode wire diameter: 20 μm

cathode strip pitch: 10 mm

cathode strip width: 9 mm

sensitive area: 1100×970 mm^2

gas composition: Ar 80% + CO_2 20% (vol).

The total stack thickness was 1 radiation length.

3.2 Electronics and readout

Each cathode strip was directly connected to a charge amplifier of a classical type, made from three transistors. The output stage delivered feedback to the input from the emitter and shaped output from the collector with a short-circuit delay line. The nominal length was 100 ns, giving a pulse width of 200 ns. A differential output stage was provided to drive twisted-pair transmission lines. Thus 816 preamplifiers, corresponding to the eight cathode planes of the four chambers, were enclosed in the stack box itself, with an appropriate air cooling system. Connection to the main amplifiers, located in the processing control room, went through multi-line twisted-pair cables 80 m long, to a fast analog differential receiver system (HA-5195-5). An external emitter-follower stage provided feedback in order to get a linear dynamic range of 4 V on 50 Ω . A separate output from the collector allowed summing of 24 channel on each cards through an 'op-amp' to the OR-output.

Finally, signals were sent, via multicoaxial flat connectors, to 12-bit charge-sensitive ADCs (LRS 2280 system) and read with an integration gate of 500 ns width.

The main features of the cathode charge amplifier chain (fig. 14) were the following:

sensitivity: 190 mV/pC

output pulse width: 200 ns

noise level: corresponding to 2000 electrons r.m.s.

dynamic range: 4 V on 50 Ω output.

The anode wires were arranged in five strips per chamber, and the charge amplifier of each anode strip was implanted on the wire-chamber printed circuit itself. A cable, 80 m long, sent the signal directly to the logic gating circuitry for self-monitoring purpose. The sensitivity of the anode amplifier was 1.3 V/pC, with a dynamic range of 3 V on 50 Ω .

3.3 Working conditions

The gain variations of the complete chain, including the chamber itself, were found to be less than 2% during the running time. All the gas system, from bottles to chambers, profited from the ISR air-conditioning complex. Nevertheless, the stability of the gas mixture had to be checked very carefully: even small changes in temperature and pressure, in the gas mixer, could easily increase these gain variations by an order of magnitude. A proportional tube with an inlaid ^{55}Fe source, at the exit of the gas mixer supply, drove both a watcher system and a control scaler. The recorded output followed accurately the gas stability: a 1% variation of the CO_2 proportion in the gas corresponded to a 17% variation of the pulse height.

The working point of the chambers was chosen such as to combine an inefficiency of less than 5% for the minimum-ionizing particles and about 10% saturation for the largest shower-energy deposits. It corresponded to a chamber amplification of 3100, giving 0.11 pC for the 5.9 keV X-ray absorption (fig. 15).

A check of the performances of all the chambers was performed in the laboratory, by means of the 5.9 keV X-ray spectra of the embedded ^{55}Fe sources. An example of such a cathode spectrum is shown in fig. 16.

3.4 Monitoring

The control of 1632 analog channels required appropriate means:

– *Specific triggers*

- a) A self-trigger coming from the internal ^{55}Fe sources. It contained also a subsequent amount of cosmic-ray events. Its main use was in the setting-up phase.
- b) A special trigger requesting a single charged track in each arm and nothing outside. The recorded data (30 events per second) contained about 50% of events with a clear signature of a minimum-ionizing particle. A magnetic tape was filled with these data once or twice a week.

– *Software tools*

- a) One program monitored the ^{55}Fe source data, looking at the working conditions outside normal beam periods.
- b) Another program managed all pedestal and data processing, interactively with the LRS 2280 processor. So pedestal stability, readout thresholds, noisy or abnormal channels (currently a few %), were constantly supervised.
- c) A third program was dedicated to the analysis of minimum-ionizing particles giving a reference charge, which was a powerful measure for monitoring all the analog chambers in the very location of the experiment. The gain of each channel was taken as the mean charge per strip corresponding to the energy deposit of the minimum-ionizing particle (fig. 17). The characteristic variables of such events, as seen by the detector, were also useful to fix some cuts applied in the analysis. This concerned the released energy and the second moment, but also variables which defined the track direction and the spatial resolution.

Owing to the four independent samplings made on each event, the detector had a capability of self-analysis: if special pattern conditions, leading to a very clean sample of events, were fulfilled into

three out of the four chambers, data from the fourth would provide helpful precisions about deviations, inefficiencies, or any other characteristics applicable to the whole detector.

4. FINAL DETECTOR PERFORMANCES

4.1 Extraction method

In this subsection we describe the methods used, firstly to select interesting events, and secondly to extract three different types of information: the spatial localization of the shower axis, the second moment of the lateral distributions, and the total energy released by the shower. These results were used in three different ways during the filtering and final candidate selection: the kinematic fit to select two-body candidate events corresponding to the $\gamma\gamma$ or e^+e^- channel, the hadron rejection, and the multi-shower event rejection.

To work out different algorithms, we used different samples of well-defined particle types:

- A raw hadron sample including pions and elastic proton-antiproton events.
- A sample with 'pure' minimum-ionizing particles defined by the appropriate program constraints.
- An electromagnetic shower sample obtained in the t_6 test beam at 1, 2, 4, and 5 GeV.
- A J/ψ event sample defined without the help of the analog chamber information. Shower energies were between 1.3 and 3.6 GeV.

Our analysis proceeded through three steps:

- i) A fast algorithm selected events with a single electromagnetic shower in each arm. To tag high-energy electromagnetic showers, we used a logical AND between the four chamber patterns. Each strip whose analog content was greater than a given threshold was set ON. Events coming from the vertex with correlated energy in the four chambers were thus selected and classified according to their multiplicity.
- ii) From the centre of mass of the resulting AND cluster taken in the median plane of the stack, we defined a window (fig. 18) in which we computed relevant variables and extracted further constraints on the event selection. The data inside the window were used to deduce in each chamber the centre of mass, the second moment, and the energy deposit of the shower. The algorithm included various features to prevent inefficiencies due to the large shower fluctuations.
- iii) The final selection was done through a visual scan of remaining events based on a graphical interactive program. It gave not only a better rejection for complex events but also an improvement on the spatial resolution of the chambers.

4.2 Spatial localization

The calorimeter structure was chosen to emphasize the two-body kinematic selection. We have already shown the good spatial resolution obtained with the prototype. We tested several methods with the final detector to extract the spatial localization of showers. The J/ψ sample allowed us to check algorithms which could then easily be transposed to the search for $\eta_c \rightarrow \gamma\gamma$ events.

A straight-line fit gave the particle direction used to compute the coplanarity and $\Delta\theta$ difference. The coplanarity is defined as the smallest distance h between the beam axis and the line joining the two impact points in the arms; $\Delta\theta$ is the angular difference between the measured particle direction and the corresponding two-body kinematics.

Three methods were tried, using:

- i) information from the four planes without any weighting,
- ii) information from the four planes but weighting each individual result with the total charge in each plane,
- iii) information from three planes only, rejecting information from the plane having the highest second moment.

The spatial resolution was at an optimum for a window of 9 cm width, and when using the third method. Results for the J/ψ sample are given in table 1. Note that these results depended not only on the analog chamber resolution but also on the interaction volume. Monte Carlo calculations showed that the variable $\Delta\theta$ strongly depended on the transverse dimension of the gas jet target, while the coplanarity distribution came mainly from the spatial resolution of the analog chamber. So any improvement in this domain would be followed by a better coplanarity resolution, and thus a better background rejection. The graphical interactive program allowed the tracking from the vertex through the chambers to be refined, integrating all the distributions in the four planes; the resolution thus went from 7.1 to 5.3 mrad for $\Delta\theta$ and from 4.1 to 3.2 mm for the coplanarity. Improvement came mainly from a better treatment of complex events. The results are in agreement with Monte Carlo calculations, taking the spatial resolution deduced from the prototype data.

4.3 Electron-hadron discrimination

We discuss here the separation between electrons and hadrons, obtained with the analog chambers alone (fig. 19). The results are independent of those coming from the Cherenkov counters [7].

Taking the prototype results into account, we used the second moment of the charge profile and the energy release in the different gaps. Statistics came from the raw hadron sample and the J/ψ for electrons (see subsection 4.1).

The X and Y views could be quite different for the same shower owing to a different propagation in the two projections. Best results for the second moment $\mathfrak{M}$ ($\Delta\mathfrak{M}/\mathfrak{M} \approx 24\%$ for J/ψ events) were obtained with the following computation:

$$\mathfrak{M}_j = \Sigma_i a_i (x_i - \bar{x})^2 / \Sigma_i a_i$$

with $\bar{x} = \Sigma_i a_i x_i / \Sigma_i a_i$, a_i charge on strip i ,

$$\mathfrak{M}_x \text{ or } \mathfrak{M}_y = 1/4 \sum_{j=1}^4 \mathfrak{M}_j$$

$$\mathfrak{M}_{arm} = (\mathfrak{M}_x \mathfrak{M}_y)^{1/2}.$$

Figure 19a shows the results of electron-hadron discrimination using only the second moment. Optimum results were obtained with a 9 cm window. Working with 4% inefficiency for electrons, the hadronic contamination was less than 6.5%.

To get the best energy information, one had to try to get data on the core energy, disregarding the part due to fluctuations. For this one needed:

- to measure the charge in the central part of the shower,
- to disregard the information when the profile was dominated by fluctuations,
- to use truncated means in an attempt to lessen the core fluctuations. This was particularly important for minimum-ionizing particles, where very often ($\approx 10\%$ of events) δ -rays contributed significantly to the results of at least one of the chambers.

Different algorithms, more or less involved, were used, with the daunting results that the less sophisticated they were, the better. We also observed no big variation with the window width. So we obtained the best energy resolution for J/ψ events taking for one chamber the average of the X and Y readings and for the energy in the arm the average of the results of the four chambers. This gave us a resolution of $\Delta E/E \approx 23\%$ (r.m.s.) at J/ψ energy (see table 2).

However, as far as electron-hadron separation was concerned, the truncated mean taking the two smallest out of the four chamber values gave a better discrimination power. This followed from the improvement on the Landau tail when using only the three smallest or the two smallest ionizations. Results did not critically depend on the window width. Combining both second moment and energy led to curve b in fig. 19. A rejection factor of 30 was reached, still with 4% electron inefficiency.

A further cut was applied, based on the angular distribution of the emerging trajectories from the precalorimeter through the analog chambers. Indeed, most of the hadrons interacting in the precalorimeter (that is those which often looked like electrons) crossed the gap with a significant deflection when compared to the incident trajectories. So setting a cut on the difference between the deduced position of the shower and the extrapolated input line resulted in an improvement of the hadronic rejection factor of nearly 2 (fig. 19c).

Scanning visually at the remaining hadrons one clearly saw hadronic reaction events with several ionization tracks pointing either to the precalorimeter or the lead-glass. Electron showers had a quite different behaviour. In this case also our visual method proved to be very efficient, giving as much as a factor of 4 improvement for the hadron rejection. This corresponded to a total rejection factor of 200 at 4% electron inefficiency, and 400 at 6% electron inefficiency (fig. 19d). Figure 20a, b, c shows results concerning separation in one arm using our samples. The electron and hadron energies cover a whole range between 1.3 and 3.6 GeV.

4.4 Multi-shower rejection

We checked the multi-shower rejection capability with the electron sample from the t_6 test beam, following the method described in subsection 2.4.

Figure 21 shows the variation, with incident momentum, of the released energy and of the total second moment. If linearity is observed for the energy, the second moment and its fluctuation distribution show only a small dependence on the incident momentum. This makes this variable very suitable to discriminate single from overlapping showers in events.

As an example, we show the discrimination obtained with the second moment for a 4 GeV single shower and a set of 2 GeV two-shower events with separation between the two tracks between 6 and 10 cm (fig. 22).

In the conditions of the R704 experiment, the AND algorithm allowed well-separated tracks to be rejected but a more complex algorithm than the raw second-moment distribution had to be used to cope with the variety of situations encountered.

The following cut was based on the total correlated energy outside the window, the correlation requiring aligned signals along a vertex direction in at least three out of four individual planes. Thus showers not fully developed (owing to late conversion or to a low-energy γ) could be eliminated. Finally, the second moment taken inside the window allowed further rejection of double-shower events. Optimum results were obtained for a total width of 12 cm.

Figure 23 shows the final results of the discriminating algorithm, using a distribution peaking at a distance of 6.6 cm with $\sigma_{\text{rms}} = 1.3$ cm for the sample of multi-shower events. With an 80% efficiency for single-shower events, less than 3% of multi-shower events from the sample distribution went through the different cuts. Table 3 shows the results of rejection as a function of the distance between showers (with an 80% efficiency of detection for single-shower events). As the minimum distance between the two γ coming from the π^0 in the R704 experiment was around 7 cm, the described algorithm reduced the background contribution of overlapping showers to a negligible level.

Still a substantial increase of the rejection factor could be gained through a visual scan of the events. Correlating both the four distributions along the shower track, and the X and Y projections,

it was still possible to distinguish two showers in events where our software cuts were ineffective, without changing the single-shower efficiency. The improvement factor went from 3 for distances between 2 and 3 cm, to more than 10 for shower separations above 5 cm (total rejection factor > 400).

5. CONCLUSION

The analog chamber stack detector inserted inside the R704 electromagnetic calorimeter gave us a good accuracy of the shower-position determination, allowing a high selectivity of two-body e^+e^- or $\gamma\gamma$ events.

It proved to be very valuable for electron-hadron discrimination, in the few GeV energy region where large fluctuations were observed in the energy deposit, both longitudinally and transversally, and in such a situation where the E/p method could not be used to select electrons (as in our non-magnetic detector).

The possibility of following both the lateral and longitudinal shower extensions along four layers allowed the application of very efficient algorithms, both in order to separate electrons from hadrons, and to distinguish single shower from multi-shower events generated by π^0 .

A rejection factor against hadrons of 200 was observed while the electron detection efficiency in the 1.3–3.6 GeV range was 96%. The number of π^0 with overlapping showers accepted as single photons was reduced to a negligible amount. The single-shower to multi-shower rejection factor was 10 for distances of 3 cm between showers.

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Table 1

Results for the J/ψ sample (electron showers of energies from 1.3 to 3.6 GeV) concerning the coplanarity and $\Delta\theta$ (r.m.s.) of the kinematical variables, obtained by the different methods described in the text. Column d shows the results obtained from the visual-scan method.

Method	a	b	c	d
Coplanarity (mm)	4.7	5.2	4.1	3.2
$\Delta\theta$ (mrad)	7.4	8.5	7.1	5.3

Table 2

Energy resolution in % (r.m.s.) obtained for J/ψ events. Taking the average of the X and Y readings of each chamber in a window width of 9 cm, the energy information is processed following the four different methods for one arm.

Mean of the four values	23.2
Mean of the three smallest values	25.0
Mean of the two smallest values	27.4
Mean of the two intermediate values	25.0

Table 3

The measured inefficiency of rejection η for showers whose distance d is between two given limits; R_D is the extra rejection factor obtained through the visual-scan method and R_T is the total rejection factor. The efficiency for single-shower events is 80%.

d (cm)	η	R_D	R_T
1-2	0.70 ± 0.05	3.0	4.3
2-3	0.67 ± 0.05	2.9	4.3
3-4	0.47 ± 0.04	5.6	12
4-5	0.14 ± 0.02	9.7	69
5-6	0.03 ± 0.01	> 12	> 400

Figure captions

- Fig. 1 : Top view of the R704 two-arm detector.
- Fig. 2 : Collected charge in the chamber as a function of incoming electron energy, after 4 radiation lengths.
- Fig. 3 : Mean number of fired strips per plane as a function of incident energy, after 4 radiation lengths.
- Fig. 4 : Experimental profiles in a chamber plane for different incident electron energies, after 4 radiation lengths.
- Fig. 5 : Perspective view of the 4 GeV electron mean shower development in a gas gap at different depths.
- Fig. 6 : Mean shower extensions in the first gap as a function of the distance between the absorber and the first gap.
- Fig. 7 : a) Density of maxima in one gap and b) correlated maxima in two gaps, versus the distance to the reference track (4 GeV electrons after 4 radiation lengths).
- Fig. 8 : Spatial resolution (σ_{rms}) for 4 GeV electron showers (taking the maximum which is nearest to the incident track) versus depth insertion.
- Fig. 9 : Two-shower rejection ρ as a function of single-shower efficiency ϵ taking the information from a) one plane, b) one chamber, c) the two-chamber stack. The variable is the second moment. The distribution of distances is given in the inset.
- Fig. 10 : a) Single-gap reading principle; b) single-gap cross-section arrangement.
- Fig. 11 : Cross-section structure of the first module of the stack.
- Fig. 12 : Schematic exploded view of the first modules of the stack: 1 – Aluminium plate 4 mm; 2 – Vetronite spacer frame 1.5 mm; 3 – Copper-Kapton printed circuit 125 μm (sealed on 4), X-cathode foil, 108 strips, 9 mm wide, 1 mm between them; 4 – Half-gap Vetronite frame 5 mm; wire anode layer, 270 gold-plated W 20 μm wires, 4 mm pitch; 5 – Half-gap Vetronite frame 5 mm; 6 – Copper-Kapton printed circuit 125 μm (sealed on 5), Y-cathode foil 96 strips, 9 mm wide, 1 mm between them; 7 – Lead foil 1 mm.
- Fig. 13 : One stack with 3 out of 4 gaps already installed with their connectors receiving the cathode preamplifiers on the edges.
- Fig. 14 : Schematic basic diagram of the amplifier chain.
- Fig. 15 : Charge at the chamber output (5.9 keV ^{55}Fe) as a function of voltage, and the corresponding gain A .
- Fig. 16 : Spectrum of the ^{55}Fe 5.9 keV cathode.
- Fig. 17 : Gain of all planes, both arms, defined as the minimum-ionizing particle mean charge deposit per strip.
- Fig. 18 : Example of distributions observed in one projection for an electron shower event. The incident electron trajectory coming from the vertex is indicated. Below the pattern in the four chambers the result given by the AND algorithm is indicated. The shaded region in the distributions shows the extension of the window deduced from the centre of mass of the AND cluster.
- Fig. 19 : Electron-hadron separation obtained using one stack of four analog chambers. Hadron contamination is plotted as a function of electron inefficiency. For each curve the window is 9 cm. a) Second moment only. b) Second moment and mean energy taking the two smallest of the four values. c) Same as (b) plus cut on divergent tracks. d) Visual scan on remaining unseparated events.
- Fig. 20 : The two-dimensional plots (energy versus second moment) for a) the electron and b) the hadron sample.

- Fig. 21 : Variation with the electron incident energy a) of the energy released, b) of the second moment.
- Fig. 22 : Separation between single-shower events and overlapping-shower events, using the second moment variable. The distribution of the two-track distances peaks at 8 cm ($\sigma_{\text{rms}} = 1.4$ cm).
- Fig. 23 : Discrimination between one and two showers. Inefficiency of two-shower rejection η is plotted as a function of one-shower efficiency ϵ . The total energy is 4 GeV. (The distribution of distances between showers peaks at 6.6 cm with a FWHM of ≈ 3 cm.)

Experiment R 704

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

CATHODE ELECTRONICS

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19

Fig. 20

Fig. 21

Fig. 22

Fig. 23