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**A LEAD/PROPORTIONAL-TUBE ELECTROMAGNETIC
CALORIMETER FOR DIRECT PHOTON DETECTION**

The UA6 Collaboration

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ABSTRACT

The fine-grained lead/proportional-tube electromagnetic calorimeter used in CERN Experiment UA6 is described. Test-beam results demonstrate linear energy response over a wide dynamic range, position resolution for shower localization reaching 1.7 mm for 70 GeV electrons, and good electron/hadron differentiation. Electron shower transverse widths are measured to be less than 9.0 mm for energies between 3 and 70 GeV. This feature allows us to identify neutral-meson decays yielding two close photon showers that constitute the main background to single-photon detection.

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1. INTRODUCTION

The gas-sampling electromagnetic (e.m.) calorimeter described in this report is part of the double-arm spectrometer of Experiment UA6 at the CERN $p\bar{p}$ Collider. Located in a 13 m straight section of the Super Proton Synchrotron (SPS) ring, UA6 is a fixed-target experiment that employs an internal hydrogen gas-jet target to measure in both $p\bar{p}$ and pp interactions at $\sqrt{s} = 24.3$ GeV:

- i) Hard scattering processes, such as
 - single- and double-photon production [1];
 - J/ψ and high-mass electron pair production;
 - high- p_T inclusive π^0 and η production [2];
 - single-electron production.
- ii) Low- t elastic scattering and diffraction dissociation using a set of solid-state counters at 90° in the lab. frame [3].

The calorimeter design was motivated by the need to differentiate single e.m. showers from two or more close showers, to distinguish e.m. showers from hadronic showers, and to subtend the largest possible solid angle in the confined space of the SPS tunnel. A design using layers of lead sheets and proportional-tube planes was chosen in order to provide fine lateral segmentation and allow a threefold longitudinal segmentation.

The jet target [4] projects a continuous stream of molecular hydrogen clusters through the circulating 315 GeV/c antiproton and proton beams in the SPS vacuum pipe. Each cluster contains about 10^5 molecules. The vertical jet column has a cross-section of 8 mm along the beam and 3 mm transverse to it. The full jet intensity of about 4.0×10^{14} hydrogen atoms per cubic centimetre yields an instantaneous antiproton-proton luminosity of $4.1 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with 3.0×10^{11} antiprotons stored in six bunches. A higher luminosity is possible in pp mode because of higher proton-bunch intensities in the Collider.

2. EXPERIMENTAL LAYOUT

The hydrogen jet target and the double-arm spectrometer are shown in fig. 1, with the spectrometer positioned to observe final states from antiproton-jet collisions. The detector components in the spectrometer can be dismantled and reassembled on the other side of the jet for the study of proton-jet collisions. Each arm of the spectrometer (one above and one below the SPS beam pipe) covers 20 to 100 mrad in polar angle and 75° in azimuthal angle for an integrated geometrical acceptance of 1.8 sr, and includes the following:

- i) a 2 m long dipole magnet with a vertical field and a bending power of $2.3 \text{ T} \cdot \text{m}$;
- ii) two multiwire proportional chambers (PC1,2) before the magnet and three (PC3-5) after it;
- iii) an ionization chamber (dE/dx) to distinguish single electrons from electron-positron pairs, of very small opening angle, arising from photon conversions and Dalitz decays;
- iv) a transition radiation detector [5] (TRD) based on lithium radiator foils and a Xe-He-CO₂ proportional chamber;
- v) the lead/proportional-tube, gas-sampling calorimeter.

Not shown in fig. 1 are the silicon detectors near 90° in the laboratory frame to measure low- t recoil protons from the jet. Counting rates in the recoil detectors provide a continuous luminosity measurement.

3. THE CALORIMETER

The e.m. calorimeter (see fig. 2) is located 9.5 m from the jet target. The main design and performance characteristics are listed in table 1. In each arm, 30 lead plates (95% Pb, 5% Sb), 4.0 mm thick, are interleaved with alternating planes of horizontal (H) or vertical (V) gas-filled proportional-wire tubes for a total of 24 radiation lengths X_0 (0.75 nuclear interaction length λ). The

metallic proportional tubes are rectangular in cross-section, with outer dimensions $10.16 \text{ mm} \times 5.08 \text{ mm}$ and a wall thickness of 0.25 mm . The 10.16 mm sides are parallel to the face of the calorimeter and this determines the transverse segmentation of the H and V views. Each calorimeter arm covers an area of $1.25 \times 0.83 \text{ m}^2$.

With its fine transverse segmentation and large active area, the calorimeter is well-suited to the study of single-photon production where the main background is from π^0 and η decays. The minimum separation for the two photons from a $100 \text{ GeV } \pi^0$ is 28 mm on the face of the calorimeter, and the resulting two showers are usually distinguishable from a single shower.

Each calorimeter arm is divided longitudinally into three identical modules (A, B, and C) of $8X_0$ each. A hodoscope of scintillation counters, consisting of seven $125 \times 12 \times 1 \text{ cm}^3$ strips, is located between the first and second modules. The light at each end of a given scintillator strip is viewed by a wavelength-shifting light-guide and a 1.27 cm diameter ten-stage Hamamatsu photomultiplier tube^{*)}. The hodoscope is used as part of a first-level trigger for e.m. energy deposition in the calorimeter (subsection 4.3). The shower from a 20 GeV electron, for example, yields a pulse height in the hodoscope equivalent to about 110 minimum-ionizing particles, so the hodoscope trigger effectively discriminates against hadronic showers that generally develop more deeply in the calorimeter (subsection 5.5) and against minimum ionizing tracks.

Each calorimeter module consists of 5 H-V planes, which were constructed as separate units. The layers of one H-V plane are shown in fig. 3. The three 1 mm thick stainless-steel sheets make the planes rigid, and extensions on the central stainless-steel sheet are used for mounting the planes on a support frame. The planes were assembled on a horizontal table and the layers were cemented with epoxy. To ensure flatness, a hydraulic press applied uniform pressure while the epoxy cured.

The proportional tubes are composed of an alloy known as German silver (61% Cu, 21% Zn, 18% Ni). This alloy was chosen because it is easily extruded to form thin-walled tubes that are rigid, have smooth inner and outer surfaces, do not tarnish, and are reasonably priced. The horizontal tubes are 135 cm long and the vertical tubes are 90 cm . They extend 5 cm beyond the active area of the calorimeter, which is determined by the size of the lead sheets, so that gas manifolds could be attached. A $50 \text{ }\mu\text{m}$ diameter stainless-steel anode wire runs through the length of each tube, and rectangular plastic inserts close the ends. The wires were strung through hollow metallic pins at the centre of the inserts, tensioned with a 100 g weight, and secured by crimping the pins. Tests were performed using 3.5 MeV electrons from a collimated ^{106}Ru source to study the collection efficiency for ionization electrons liberated at different regions within the rectangular proportional tubes, and no variation in pulse height was found for ionization created throughout the volume of the tubes.

The gas manifolds distribute the gas mixture [Ar (90%) + CO_2 (10%)] through each tube via a small hole drilled into the tube at the ends, as shown in fig. 3. The gas flows in parallel through the 123 vertical and 82 horizontal tubes of each H-V plane and is then output to the atmosphere. Safety considerations in the SPS tunnel led to the choice of this non-flammable gas mixture. The operating high voltage of $+1160 \text{ V}$ on the anode wires yields a gas multiplication factor of about 1000. The tubes are at ground potential.

The calorimeter was assembled over a period of seven months by a team of nine technicians and physicists. Each plane was tested after assembly by recording the pulse-height spectrum produced in each tube by a movable ^{60}Co source mounted outside the plane. Tube-to-tube gain variations were found to be less than 5%, and gains were observed to be constant along the length of the tubes.

Figure 4 shows the readout scheme for the proportional-tube layers in one module of the calorimeter. The charge pulses are summed through the depth of each module by connecting the five

^{*)} Model R647-01, Hamamatsu Corporation, Hamamatsu City, Japan.

anode wires in parallel layer-to-layer. This scheme preserves the transverse segmentation of the 10.16 mm wide tubes, and provides three samplings of the longitudinal development of showers. The summed pulses are injected through coupling capacitors to charge preamplifiers, which are mounted on double-sided printed-circuit ‘motherboards’ located on two sides of each calorimeter module. The low voltage to power the preamplifiers and the high voltage for the anode wires are distributed to the preamplifiers through the motherboards. The preamplifier outputs are symmetric, bipolar pulses, which travel on 50 m long twisted-pair cables to delaying and pulse-shaping amplifiers (DPSAs) located in the UA6 counting room. The DPSAs transform the bipolar input signals into 220 ns wide trapezoidal output pulses, which are referred to ground and delayed by 270 ns. The DPSAs have two types of outputs: analog signals from individual calorimeter channels for digitization by a LeCroy 2280, d.c.-coupled, charge ADC system^{*)}, and analog signals corresponding to the sum of six adjacent calorimeter channels that serve as inputs to fast-trigger processors (subsection 4.3). The gains of the electronic channels (preamplifiers to ADCs) are monitored with identical test pulses injected at the input of the preamplifiers.

4. CALORIMETER READOUT

Figure 5 is a schematic of the readout chain for one channel (five tubes in parallel), showing the shapes, maximum amplitudes, and timing of the signals.

At the nominal gas multiplication of 10^3 , determined by the high voltage applied to the anode wires of the tubes, a maximum of 6.25×10^7 electronic charges q_e are delivered to the input of the charge preamplifiers QPA, in the time interval determined by the width of the shaped pulse at the input of the ADC. The gain, defined as the ratio between the electric charge at the input of the ADC and that at the input of the QPA, is 100.

4.1 Preamplifiers and signal transmission

The calorimeter and the preamplifiers were designed to remain in place in the SPS tunnel even during the SPS accelerated proton runs for fixed-target experiments, typically a few months per year. The preamplifiers are exposed to a radiation dose of 10 to 50 Gy per month during such periods. Radiation hardness and electronic noise considerations led to a preamplifier design using discrete components with a J-FET input. The degradation under irradiation of a J-FET input preamplifier is slow and shows itself by increased noise, entirely due to radiation damage in the FET. Such preamplifiers have been shown to remain operational after exposure to an integrated dose of 800 Gy as measured by RPL (radio photoluminescence) dosimetry during tests at the CERN Intersecting Storage Rings beam dump.

In the simplified diagram of the preamplifier (fig. 6), A is a large open-loop gain amplifier made of discrete bipolar transistors (2N3904 and 2N3906), the current amplification factor of which may drop, after irradiation, from an initial value greater than 100 to less than 20 without noticeable effect. For calibration purposes, a precisely known charge can be injected into the preamplifier input by applying a voltage step to the CAL input. The electronic noise of the preamplifiers is less than $3 \times 10^3 q_e$ r.m.s. with $C_{\text{input}} = 75$ pF, and contributes negligibly to the calorimeter energy resolution. Each preamplifier circuit is assembled on a 55×60 mm² double-sided printed-circuit board. The preamplifiers are positioned at a 10.16 mm pitch, and a ground plane on the solder side of each preamplifier helps reduce cross-talk between the channels. The preamplifiers are powered with ± 12 V, using radiation-hard voltage regulators made of HEXFETs [6] and discrete bipolar transistors, which are also located in the SPS tunnel above the calorimeter.

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Two pulses of opposite polarity are sent by the driver D into the symmetric line linking the preamplifier to the remote DPSA. Using symmetric drivers and differential receivers allows low-loss transmission of the preamplifier signals along inexpensive cables made of polyethylene-insulated twisted pairs bundled under a common grounded screen. Twelve preamplifier outputs are carried on each cable. Cross-talk between channels is negligible and there is excellent rejection of common mode noise.

4.2 Pulse shaping and digitization

The DPSA shown in fig. 7 transforms an input tail pulse into a delayed trapezoidal pulse of finite duration and provides a summed output. The necessity to delay the calorimeter signals into the ADCs is discussed in subsection 4.3.

The DPSA design was based on a similar amplifier [7] for multiwire proportional chamber (MWPC) cathode-strip readout. The gain of the input differential amplifier (A/L) can be raised in five discrete steps from -6 to $+6$ dB in order to adjust the amplification to the operational characteristics of the calorimeter. The DPSAs and ADCs are easily checked by pulsing the TEST input. The signal is sent into a delay line DL, impedance-matched on the driver side only. The signal is totally reflected with a change of polarity at the grounded far end. The capacitive tap sees the difference between the incoming signal and the delayed reflected signal as a pulse with delay that is fixed by its position. The tap is a 2.54 mm wide copper band glued around a colour-TV delay line [8]. This inexpensive delay line is 110 mm long and 6 mm in diameter. The transit time from one end of the line to the other is 390 ns, and the tap is positioned to give a signal delay of 270 ns, as shown in fig. 5. The delay line replaces 50 m of delay cable and distorts the pulse shape much less.

The gated base-line restorer (A1), based on an operational transconductance amplifier (CA3280G), is optimized for the minimum interval, $3.8 \mu\text{s}$, separating the $\bar{p}$ or p bunches in the SPS six-bunch collider mode.

Throughout the entire duration of the GATE pulse, I_G is switched off and the base-line is therefore kept at the potential that it had just before the switching. Any electronic noise at the DPSA input will thus be memorized as a random base-line shift which, using d.c.-coupled charge ADCs, will be integrated for the duration of the gate and, by adding random fluctuations to the measured charge, will degrade the energy resolution of the calorimeter. The capacitor C_G is part of a low-pass filter that reduces this effect by eliminating the fast components of the noise.

Twelve DPSA channels are packed on a $290 \times 230 \text{ mm}^2$ four-layer printed-circuit board. Twenty-one such modules (252 channels) fit into a dedicated 19-inch crate. Short, flat, twisted-pair cables transmit the DPSA OUT pulses from each DPSA module to the LeCroy 2280 ADC system.

The ΣOUT output is the sum of six adjacent channels; there are two per DPSA module. Pushing the GATE VIEW button allows an easy check of the DPSA timing through these outputs. The ΣOUT signals are used by the fast-trigger processors.

4.3 Triggering and trigger processors

In order to select high- p_T π^0 's, η 's, and direct photons in a single arm of the calorimeter, and high-mass electron or photon pairs, one in each arm, two trigger processors are used. The SINGLES processor selects events with localized, high- p_T energy deposition in a single arm, and the MASS processor searches for combinations of localized energy deposition, one in each arm, with a high invariant mass.

The triggering and readout of the experiment were designed to be used both in the SPS bunched collider mode and in the accelerated mode for fixed-target experiments, during which the protons are distributed uniformly around the SPS ring. For this reason, the overall trigger is based on a fast, first-level trigger indicating a beam-jet interaction, followed by a second-level decision from the

processors. In the collider mode, the first-level trigger uses discriminated signals from the scintillator hodoscopes within the calorimeter arms in coincidence with a particle bunch crossing the jet target. The hodoscope part of the first-level trigger is either a signal-over-threshold from the scintillators in a single arm, or a coincidence between the top and bottom scintillators using lower thresholds. When the first-level trigger is satisfied, gates are sent to the calorimeter ADCs, the processors are started, and further triggers are suppressed. Then, depending on the processor decisions, the event is either cleared and the experiment is re-enabled or the event is read out and written to tape. The DPSAs delay the calorimeter signals into the ADCs so that they are in time with the gates generated by the first-level trigger.

The inputs for both processors are the analog pulses from the Σ OUT outputs of the DPSAs from modules A and B. These signals are first sent to integrating sample-and-hold (ISH) circuits [9] that were developed for the UA2 experiment. The ISH outputs are then digitized using individual 500 ns successive-approximation 8-bit ADCs (TRW TDC1001). The digitized pulse-heights are clocked serially, with a cycle time of 100 ns, into a pipeline where corresponding pulse heights from modules A and B are added in depth. These sums are then grouped pairwise into overlapping bands of 12 channels in both the horizontal and vertical views. Intersections of H and V bands define a grid on the face of each calorimeter arm. Figure 8 shows the H and V bands used by the processors, and a sample grid square is shown in the top arm.

Data words containing both pulse-height and position information for the bands are output from the pipeline as four parallel streams, one word per clock cycle, one stream per view. They are sent to both the SINGLES and MASS processors where the data from the separate views are correlated. The two processors were built to CAMAC standard and use the backplane to communicate with the on-line computer. The two processors are hard-wired and operate parallel to and independently of each other.

The SINGLES processor in each arm cycles through the $19V \times 13H$ band energies, comparing each $H + V$ energy sum with a stored threshold that depends on the position of the corresponding grid square. This accounts for the variation of energy across the calorimeter face for a fixed value of transverse momentum p_T . The processor accepts an event when at least one of the squares has an energy above its corresponding threshold. The SINGLES processor decision requires about $40 \mu s$ when all $H + V$ combinations are considered, but it is normally used in a 'fast' running mode so that H or V bands that contain energy less than an adjustable pre-threshold, usually set at about 4 GeV, are eliminated from the 19×13 pairing cycle. In this mode, the decision time depends on the complexity of the event and has an average value of $4 \mu s$.

The MASS processor works in a similar fashion. It calculates the energy product of each two-square combination, one in each arm, for which the four bands (2H and 2V) that make up the combination all have energy above a separate adjustable pre-threshold. For each combination, the differences between the horizontal and vertical positions of the squares determine the opening angle and define an address in a memory. This memory contains the values of the energy product required to form a given invariant mass for the different opening angles. An event is accepted if the energy product for at least one top-bottom combination is above the threshold determined by the opening angle. The MASS processor decision requires an average time of about $10 \mu s$.

Data are typically collected with the intensity of the jet target adjusted for an instantaneous luminosity of about $2.0 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. Under these conditions, the first-level trigger rate is about 5 kHz. This rate is reduced to 20–30 Hz by the processors, using thresholds for the SINGLES processor adjusted to accept π^0 's and single photons with p_T greater than 3.2 GeV/c, and thresholds for the MASS processor corresponding to 2.5 GeV/c².

5. PERFORMANCE IN A TEST BEAM

The performance of the calorimeter was studied in two series of test-beam runs, one in 1984 and one in 1987, using two beam lines in the SPS West Area. Both calorimeter arms were tested in 1984 with electrons and negatively charged pions of momenta from 10 to 100 GeV/c. The runs in 1987 were used to study the response of the calorimeter to lower-energy particles and to measure the position resolution for shower localization, using a wire chamber in front of the calorimeter to define the incoming beam position. One calorimeter arm was tested in 1987 with positrons and positively charged pions of momenta ranging from 2 to 70 GeV/c. Some of the results from the 1984 test-beam runs have been given in a previous report [10].

5.1 Linearity of response

Figure 9 shows the distributions of measured energy in the calorimeter for electrons of energy 10, 50, and 100 GeV. The measured energy is the sum of tube energies in all three modules, where a given tube energy is defined as the pedestal-subtracted number of ADC counts divided by the gain of the tube as determined by the calibration pulses. The distributions were obtained with a gas mixture of Ar (90%) + CO₂ (10%) and +1145 V on the anode wires. Gaussian fits to such distributions yield means and r.m.s. widths which are used to examine the linearity and energy resolution of the calorimeter, respectively. Figure 10a shows the means of five measured energy distributions as a function of beam energy with a linear fit to the points. No deviation from linearity is apparent. Figure 10b shows the deviations of the data points from the linear fit; the error bars represent the uncertainties in the means obtained from the Gaussian fits. The deviations, including uncertainties, are all less than 0.6%.

5.2 Energy resolution

Figure 11a shows the fractional energy resolution as a function of beam energy, with error bars representing the uncertainties obtained from the Gaussian fits. In fig. 11b the fractional resolution is plotted as a function of $1/\sqrt{E}$, where E is the beam energy measured in GeV. We assume that the dependence of the energy resolution is of the form

$$\sigma(E)/E = a + b/\sqrt{E}.$$

Fitting the data points to this form yields $a = 0.0058 \pm 0.0012$ and $b = 0.278 \pm 0.008$. Included in the measured energy resolution is the momentum resolution of the test beam, which for our run conditions was $\sigma(p)/p \approx 1\%$.

5.3 Response versus anode voltage

The response of the calorimeter to 25 GeV electrons was measured using anode voltages ranging from +1090 to +1280 V, and only a small variation in energy resolution was observed, as shown in fig. 12. In this range, changing the anode voltage by 60 V changes the calorimeter gain by a factor of about 2. The operating voltage of +1160 V was chosen so that the electronic channels (preamplifiers to ADCs) did not saturate for showers depositing 150 GeV of e.m. energy in the calorimeter—the highest expected during experimental data-taking. At this voltage, the full-scale ADC range for an individual channel corresponded to about 22 GeV and a sensitivity of 6 MeV per ADC count.

5.4 Position resolution

To define the impact position of incoming particles in the test beam, a wire chamber using delay-line readout was placed about 1 m upstream of the calorimeter in the 1987 runs. This 'delay wire chamber' [11] (DWC) measured impact positions in the horizontal and vertical directions with a

resolution of about 200 μm (r.m.s.). The position resolution of the calorimeter for electron showers was determined by comparing the centroid values of the tube-energy distributions in a given module with the positions measured by the DWC on an event-by-event basis. The centroid of a given shower is defined as the energy-weighted position,

$$\bar{x} = \Sigma x_i E_i / \Sigma E_i ,$$

where x_i is the coordinate of the centre of the i^{th} tube and E_i is the energy recorded for that tube. The sum runs over all tubes with energy above the range of pedestal fluctuations. For each test-beam energy, a Gaussian fit to the difference distribution (DWC-measured position minus calorimeter-measured position) was performed for each of the first two modules in each view. Figure 13 shows the widths of the Gaussians as a function of energy for the horizontal view of the first two modules. The position resolution in the first module is seen to improve from 4.8 mm at 3 GeV to 1.7 mm at 70 GeV. The resolution in the second module is worse owing to the angular spread of the secondary particles as the shower develops through the calorimeter. The position resolution of the DWC contributes negligibly to the total resolution.

An estimate of the position resolution that is independent of the DWC can be obtained by comparing the centroid positions in modules A and B for test-beam showers. Gaussian fits to the distributions of the centroid position differences (module A – module B) were performed, and the r.m.s. widths are also plotted in fig. 13. The points are seen to lie between those for modules A and B as measured with the DWC, since this measurement reflects the correlated fluctuations of the centroids in both modules. The correlation between the A and B centroids is strong enough to justify the target pointback requirement, which we use in the depth association part of the clustering algorithm for neutral showers, described in Section 6, where tracking-chamber information is not available.

The ability to distinguish two close showers has been studied by investigating the lateral extent of test-beam showers at different energies. Figure 14 shows the energy/tube profiles in the three modules of the bottom calorimeter arm for a 50 GeV electron shower. It can be seen that e.m. showers are very well collimated, and shower widths of the order of one tube (10 mm) are obtained in the first two modules.

The widths of the lateral shower profiles in each module were determined using a third-order spline fit to the energy/tube distributions. The means of the width distributions for the horizontal tubes in modules A and B are plotted in fig. 15 for different beam energies. Between 3 and 70 GeV, the shower widths in module A are measured to be less than 9.0 mm with little dependence on incident energy. Widths in module B are slightly greater.

Since e.m. showers are narrow and can be localized precisely over a wide energy range, it is usually possible to distinguish the two close showers from π^0 and η decays, which constitute the main background to the detection of direct photons.

5.5 Electron/hadron discrimination

For the study of electron final states, the most troublesome contaminating hadrons are those that survive matching requirements between the energy measured in the calorimeter and the momentum measured in the magnetic spectrometer, i.e. those that deposit a large amount of energy in the calorimeter. Rejection of such hadrons is achieved through shower-shape cuts based on longitudinal energy deposition and lateral spread of the showers in the calorimeter.

A comparison of longitudinal-energy deposition for 70 GeV electrons and pions from the test beam is shown in fig. 16, where the distributions of the ratios $E_{\text{module}}/E_{\text{total}}$ are plotted for the three calorimeter modules. The pion events used in this plot are those that deposited more than 40 GeV in

the calorimeter. For electrons, one sees that the total energy is shared approximately equally between modules A and B, with little energy in module C. Pion showers, on the other hand, are generally initiated deeper in the calorimeter, so that modules B and C contain most of the energy. Hence, cuts on module/ E_{total} in modules A and C yield a strong electron/hadron rejection.

Cuts on the lateral shower width are similarly effective. In modules A and B, electron showers are narrow — of the order of 10 mm r.m.s. — whereas pion showers often spread across three or four calorimeter tubes.

Cuts based on shower shape and energy-momentum matching will yield hadron rejection factors of order 10^4 , i.e. not more than one charged hadron out of 10^4 will be misidentified as an electron. Hadron rejection based on shower shape will be described in greater detail in a future publication. In the UA6 experiment, the transition radiation detector [5] provides an independent hadron rejection factor of the order of 10.

5.6 Energy response versus position, incident angle, and gas mixture

By displacing the calorimeter horizontally and vertically in the test beam, the uniformity of response across the face was studied. Variations in mean measured energy were found to be less than 5%, and no variation in energy resolution was observed. Changing the incident angle of the beam from 0° (normal incidence) to 10° varied the response by less than 2%. The calorimeter response was studied with 10% and 15% concentrations of CO_2 in argon. Increasing the CO_2 concentration from 10% to 15% resulted in a decrease in gas amplification of about 40% at a fixed voltage. The operating gas mixture with 10% CO_2 was chosen because the desired gain could be reached with lower anode voltage. The energy resolution of the calorimeter at a given gas amplification was observed to be independent of the CO_2 concentration.

6. PERFORMANCE AT THE SPS COLLIDER

At the CERN $p\bar{p}$ Collider the calorimeter has been used to detect electrons and photons. As an example, fig. 17 shows the energy deposition in the three horizontal and three vertical views of the bottom arm of the calorimeter from the two-photon decay of a 50 GeV π^0 . The photons are separated by about 5 cm on the face of the calorimeter. A clustering routine was developed to identify individual e.m. showers and to calculate their energies and impact positions on the face of the calorimeter. For each view, the routine searches for clusters of energy deposition in the three modules; clusters are associated from module to module when a line through the cluster centroids extrapolates to the jet target. A cluster in the horizontal view is then matched with a cluster in the vertical view if the corresponding partial energies are approximately equal.

A sample of data collected from antiproton-proton collisions was used to form the mass distribution (fig. 18) of all two-cluster combinations found in the bottom arm of the calorimeter with total $p_T > 2.5$ GeV/c. Clear peaks from the two-photon decays of π^0 and η mesons are seen. The widths of the peaks, 20 MeV/ c^2 for the π^0 and 40 MeV/ c^2 for the η , result from the inherent energy resolution and position resolution of the calorimeter and from the clustering algorithm. The overall energy scale for each arm of the calorimeter was determined by centring the π^0 mass peak at its known value of 135 MeV/ c^2 .

Short-term drifts in the calorimeter gain can be monitored from the position of the π^0 peak. Figure 19 shows the measured π^0 mass as a function of run number for the top and bottom arms. Each run, lasting approximately one hour, yielded a sufficient number of π^0 's to determine the calorimeter gain to $\pm 0.4\%$. Gain shifts are due primarily to changes in temperature and atmospheric pressure in the SPS tunnel, which influence the gas multiplication in the proportional tubes. The figure demonstrates how the gains of the two arms are time-correlated. The gains were observed to

vary within $\pm 8\%$ of the nominal value, and gain adjustment factors were introduced for off-line analysis of the data on a run-by-run basis.

7. CONCLUSION

A lead/proportional-tube gas-sampling e.m. calorimeter has been built and operated for five years in the UA6 experiment. It was designed to be able to distinguish the two photon showers originating from decays of high-energy π^0 's and η 's produced in pp and $\bar{p}p$ collisions at $\sqrt{s} = 24.3$ GeV.

Test-beam studies demonstrate the excellent linearity of response and good position resolution for shower localization over a wide dynamic range. These features have made this calorimeter an effective detector for the study of direct photons and other high- p_T processes with e.m. final states.

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REFERENCES

- [1] A. Bernasconi et al., Phys. Lett. **206B** (1988) 163.
- [2] J. Antille et al., Phys. Lett. **194B** (1987) 568.
- [3] R. Breedon et al., Phys. Lett. **216B** (1989) 459.
- [4] L. Dick and W. Kubischta, Physics with jet targets at the SPS $p\bar{p}$ Collider, *in* Hadronic physics at intermediate energy, eds. T. Bressani and R.A. Ricci (Elsevier Science Publishers B.V., Amsterdam, 1986).
- [5] A. Vacchi, Proc. Wire Chamber Conf. Vienna, 1986 [Nucl. Instrum. Methods **A252** (1986)], p. 498.
- [6] S.S. Seehra and W.J. Slusark, Jr., IEEE Trans. Nucl. Sci. **NS-29** (1982) 1559.
H. Volmerange and A.A. Witteles, IEEE Trans. Nucl. Sci. **NS-29** (1982) 1565.
- [7] J. Antille et al., Nucl. Instrum. Methods **217** (1983) 327.
- [8] Sprague Engineering Bulletin Z-45100A, 1974 (Sprague Electric Co., North Adams, Mass., USA).
- [9] G. Schuler, Report CERN 82-07 (1982).
- [10] G. Snow, Proc. Gas Sampling Workshop II, Batavia, Ill., 1985 (US Government Printing Office, Washington, 1986), p. 174.
- [11] A. Manarin and G. Vismara, CERN LEP/BI-TA/ Note 85-3 (1985).

Table 1

UA6 calorimeter characteristics and performance

Active area	$1.25 \times 0.83 \text{ m}^2$ per arm
Number of Pb plates	30
Thickness of Pb plates	$4.0 \text{ mm} = 0.7X_0$
Depth	$24X_0 = 0.75\lambda$
Proportional tube cross-section	$10.16 \times 5.08 \text{ mm}^2$
Anode wires	$50 \mu\text{m}$ diam. stainless steel
Number of electronic channels per arm	612
Gas mixture	Ar (90%) + CO ₂ (10%)
Nominal anode high voltage	+ 1160 V
Gas multiplication	$\approx 10^3$
Energy resolution	$\sigma(E)/E = 0.006 + 0.278/\sqrt{E}$
Resolution for shower localization	$\sigma(E) = 4.8 \text{ mm}$ at 3 GeV $= 1.7 \text{ mm}$ at 70 GeV

Figure captions

- Fig. 1 Layout of Experiment UA6 in the SPS tunnel in the $\bar{p}p$ collision mode.
- Fig. 2 Schematic of the UA6 gas-sampling calorimeter.
- Fig. 3 Assembly of one x-y plane of the UA6 electromagnetic calorimeter.
- Fig. 4 Readout scheme for one calorimeter module.
- Fig. 5 Readout scheme for one proportional-tube channel.
- Fig. 6 Block diagram of a preamplifier.
- Fig. 7 Block diagram of one channel of a delaying and pulse-shaping amplifier (DPSA): A/L, A1, A2, and A3 are gated operational transconductance amplifiers (CA32806); B is an FET input buffer amplifier; D is a line driver (LH0002C).
- Fig. 8 The pattern of 19V and 13H bands of 12 calorimeter channels used by the trigger processors. Highlighted is one combination of 12V and 12H tubes with its corresponding grid square.
- Fig. 9 Measured total energy distributions in arbitrary units (a.u.) for different electron beam energies.
- Fig. 10 a) Calorimeter energy response versus electron beam energy. The line represents a linear fit to the data points.
b) Deviations of the data points from the linear fit.
- Fig. 11 a) Energy resolution versus electron beam energy.
b) Energy resolution versus $1/\sqrt{E}$.
- Fig. 12 Energy resolution versus high voltage. The operating voltage of +1160 V is indicated.
- Fig. 13 Vertical position resolution for modules A and B as measured using the DWC. Also shown is the resolution as determined from the centroids in modules A and B.
- Fig. 14 Energy/tube profiles in the three modules of the bottom-arm calorimeter for a 50 GeV electron shower. Note the expanded energy scale for module C.
- Fig. 15 Shower width as measured in modules A and B (horizontal tubes) versus shower energy.
- Fig. 16 Comparison of energy sharing among three calorimeter modules for electron and pion showers.
- Fig. 17 Energy/tube profiles for a 50 GeV π^0 .
- Fig. 18 An invariant mass distribution of all two-cluster combinations in the bottom arm of the calorimeter.
- Fig. 19 Measured π^0 mass versus run number for the top and bottom arms of the calorimeter. The dotted lines indicate the actual π^0 mass.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

⊗ Beam

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

Fig. 19